

THÈSE pour obtenir le grade de

DOCTEUR DE L'UNIVERSITÉ GRENOBLE ALPES

et de

SAO PAULO STATE UNIVERSITY

École doctorale : Ingénierie pour la Santé, la Cognition et l'Environnement

Spécialité : MCA - Mouvement et Comportement pour la santé et l'Autonomie

Unités de recherche : AUTONOMIE, GÉRONTOLOGIE, E-SANTÉ, IMAGERIE & SOCIÉTÉ (AGEIS)

École doctorale : Post-Graduate Program in Movement Sciences

Spécialité : Movement Sciences

Unités de recherche : HUMAN MOVEMENT RESEARCH LABORATORY (MOVI-LAB)

Les effets du surpoids et de l'obésité lors du franchissement d'obstacle pendant la marche

The effects of overweight and obesity on obstacle crossing while walking

Présentée par :

Matthias CHARDON

Thèse soutenue publiquement le **20/09/2024**, devant le jury composé de :

Patrice FLORE

Professeur des Universités, Université Grenoble Alpes, France

Président

Anthony FLEURY

Professeur des Universités, IMT Nord Europe, France

Rapporteur

Pascal MADELEINE

Full Professor, Aalborg University, Denmark

Rapporteur

Ricardo Augusto BARBIERI

Assistant Professor, Università di Bologna, Italy

Examineur

Clint HANSEN

Researcher, University of Kiel, Germany

Examineur

Julie SOULARD

PhD, Université Grenoble Alpes, France

Examinatrice

Fabio Augusto BARBIERI

Associate Professor, Sao Paulo State University, Brazil

Directeur de thèse

Nicolas VUILLERME

Professeur des Universités, Université Grenoble Alpes, France

Directeur de thèse

C471e Chardon, Matthias Michel François
Les effets du surpoids et de l'obésité lors du franchissement
d'obstacle pendant la marche / Matthias Michel François Chardon.
-- Bauru, 2024
331 p. : il., tabs.

Tese (doutorado) - Universidade Estadual Paulista (UNESP),
Faculdade de Ciências, Bauru
Orientador: Fabio Augusto Barbieri

1. Obésité. 2. Franchissement d'obstacles. 3. Démarche.
4. Fiabilité. 5. Dégagement. I. Título.

ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DE MATTHIAS MICHEL FRANÇOIS CHARDON, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DO MOVIMENTO, DA FACULDADE DE CIÊNCIAS - CÂMPUS DE BAURU.

Aos 20 dias do mês de setembro do ano de 2024, às 09:00 horas, por meio de Videoconferência, realizou-se a defesa de TESE DE DOUTORADO de MATTHIAS MICHEL FRANÇOIS CHARDON, intitulada **Les effets du surpoids et de l'obésité lors du franchissement d'obstacle pendant la marche**. A Comissão Examinadora foi constituída pelos seguintes membros: Prof. Dr. PATRICE FLORE (Participação Virtual) do(a) Université Grenoble Alpes, Prof. Dr. ANTHONY FLEURY (Participação Virtual) do(a) IMT Nord Europe, Prof. Dr. PASCAL MADELEINE (Participação Virtual) do(a) Department of Health Science and Technology / Aalborg University, Prof. Dr. RICARDO AUGUSTO BARBIERI (Participação Virtual) do(a) Università di Bologna, Prof. Dr. CLINT HANSEN (Participação Virtual) do(a) University of Kiel, Profa. Dra. JULIE AURORE SOULARD (Participação Virtual) do(a) Université Grenoble Alpes, Prof. Dr. FABIO AUGUSTO BARBIERI (Orientador(a) - Participação Virtual) do(a) Departamento de Educação Física / Faculdade de Ciências - Unesp Bauru, Prof. Dr. Assistente NICOLAS CLAUDE ROLAND VUILLERME (Orientador(a) - Participação Virtual) do(a) Faculty of Medicine / AGEIS, Univ. Grenoble Alpes. Após a exposição pelo doutorando e arguição pelos membros da Comissão Examinadora que participaram do ato, de forma presencial e/ou virtual, o discente recebeu o conceito final: _____ APROVADO _____. Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelo(a) Presidente(a) da Comissão Examinadora.

Prof. Dr. PATRICE FLORE



Abstract

Being overweight or obese is a major public health issue. According to a report by the World Obesity Observatory, 38% of the world's population aged 5 and over were overweight or obese in 2020, a figure that is forecast to rise to 51% by 2035. In addition to its well-documented harmful effects on the cardiovascular system, overweight and obesity also lead to functional deficits related to mobility. Balance and gait disorders are thus frequently observed in overweight and obese people, sometimes leading to falls. To date, however, few studies have focused on a locomotor task that is particularly at risk of falling, yet frequently encountered in our daily lives: crossing an obstacle while walking.

In this context, the aim of this doctoral work was to assess the effect of overweight on obstacle crossing during walking.

To meet this main objective, we first carried out two reviews of the literature on this topic. The main conclusions of these reviews led us to compare a group of overweight and normal-weight individuals during an obstacle-crossing task through spatiotemporal gait parameters and horizontal and vertical clearances relative to the obstacle. They further highlighted the existence of pre-existing data from which a secondary analysis could advantageously address our main objective. We thus felt that re-using these existing data - for a purpose other than that of the initial study - was highly relevant, especially considering the high financial, material, human and time costs involved in producing new data.

We therefore set out to re-analyse the experimental data collected in 3 of the studies included in the previous literature reviews. Our dataset consisted of 5 spatiotemporal gait parameters and 3 clearance parameters measured on each foot during 3 trials using a system of 10 infra-red cameras among 43 young adults who were asked to walk at a comfortable speed over an 8.5-metre course and to cross a fixed-height vertical obstacle of 15cm positioned in the middle of this course.

Our results showed that:

(1) spatiotemporal gait parameters and horizontal and vertical clearances in young adults during an obstacle crossing task were reliable over 3 trials,

- (2) compared to individuals with a normal body mass index (BMI), overweight young adults exhibited greater horizontal clearances before and after the obstacle, whereas kinematic parameters and vertical clearances remained unchanged, and
- (3) age and anthropometric characteristics of individuals were correlated with several spatiotemporal gait parameters and horizontal clearances, which was not the case for vertical clearances.

Overall, the results of this doctoral work suggest that being overweight has a minimal impact on obstacle crossing during walking, and does not seem to increase the risk of tripping in young adults and under these particular experimental conditions. In these particular conditions, which were relatively mild and easy in that the task consisted of crossing a vertical obstacle 15 centimeters high at a comfortable speed without any other particular constraint. Hence, several perspectives arise from this doctoral work. On the one hand, it will be about implementing more demanding obstacle-crossing tasks and/or closer to those encountered in daily life. On the other hand, it will involve assessing individuals with a wider range of BMIs corresponding to different categories of overweight and obesity (moderate, severe and morbid), but also of different ages and health conditions.

Résumé

Le surpoids et l'obésité représentent un problème majeur de santé publique. Selon un rapport de l'Observatoire Mondial de l'Obésité, 38% de la population mondiale âgée de 5 ans et plus était en surpoids ou en situation d'obésité en 2020, chiffre qui, selon les prévisions, devrait atteindre 51% en 2035. En plus de ses conséquences délétères largement documentées sur le système cardio-vasculaire, le surpoids et l'obésité induisent également des déficits fonctionnels liés à la mobilité. Troubles de l'équilibre et de la marche sont ainsi fréquemment observés chez les personnes en surpoids ou en situation d'obésité, pouvant parfois conduire à la chute. Or, à ce jour, peu d'études se sont intéressées à une tâche locomotrice particulièrement à risque de chute, et pourtant fréquemment rencontrées dans notre quotidien : le franchissement d'un obstacle pendant la marche.

Dans ce contexte, l'objectif de ce travail doctoral était d'évaluer l'effet du surpoids sur le franchissement d'obstacle pendant la marche.

Pour répondre à cet objectif, deux revues de littérature ont dans un premier temps été réalisées. Les conclusions de ces deux revues nous d'une part ont amenés à vouloir comparer un groupe d'individus en surpoids et en poids normal lors d'une tâche de franchissement d'obstacle au travers de paramètres spatio-temporels de la marche et de dégagements horizontaux et verticaux par rapport à l'obstacle. Elles nous ont d'autre part encouragé à re-exploiter des données existantes - pour une autre finalité que celle de l'étude initiale - compte tenu notamment des coûts financiers, matériels, humains et temporels élevés de la production de nouvelles données.

Nous nous sommes dès lors attachés de ré-analyser des données expérimentales collectées dans 3 des études incluses dans les précédentes revues de la littérature. Notre jeu de données était ainsi constitué de 5 paramètres spatio-temporels de la marche et 3 paramètres de dégagements mesurés sur chaque pied lors de 3 essais au moyen d'un système de 10 caméras infra-rouge auprès de 43 jeunes adultes à qui il avait été demandé de marcher à vitesse confortable sur un parcours de 8,5 mètres et de franchir un obstacle vertical d'une hauteur fixe de 15 cm positionné au milieu de ce parcours.

Nos résultats ont montré que :

- (1) chez de jeunes adultes, les paramètres spatio-temporels de la marche et des dégagements horizontaux et verticaux sont reproductibles sur 3 essais de franchissement d'obstacle;
- (2) comparés aux individus avec un indice de masse corporel (IMC) normal, les jeunes adultes en surpoids présentent des dégagements horizontaux supérieurs avant et après l'obstacle, alors que les paramètres cinématiques et les dégagements verticaux restent inchangés, et
- (3) l'âge et les caractéristiques anthropométriques des individus sont corrélés à plusieurs paramètres spatio-temporels de la marche et de dégagement horizontaux, ce qui n'est pas le cas des dégagements verticaux.

Dans leur ensemble, les résultats de ce travail doctoral suggèrent que le surpoids a un impact minimal sur le franchissement d'obstacle pendant la marche, et ne semble pas augmenter le risque de trébuchement, chez de jeunes adultes et dans des conditions expérimentales particulières relativement clémentes dans la mesure où la tâche consistait à franchir un obstacle vertical de 15 centimètres de hauteur à vitesse confortable sans autre contrainte particulière. Dès lors, plusieurs perspectives découlent de ce travail doctoral. Il s'agira, d'une part, de mettre en œuvre des tâches de franchissement d'obstacle plus contraignantes et/ou plus proches de celles rencontrées dans la vie quotidienne. Il s'agira, d'autre part, d'évaluer des individus présentant non seulement un éventail d'IMC plus large correspondant à plusieurs catégories de surpoids et d'obésité (modérée, sévère et morbide), mais aussi d'âges et de conditions de santé différentes.

Detailed abstract

Being overweight or obese is a major public health issue. According to a report by the World Obesity Observatory, 38% of the world's population aged 5 and over were overweight or obese in 2020, a figure that is forecast to rise to 51% by 2035. In addition to its well-documented harmful effects on the cardiovascular system, overweight and obesity also lead to functional deficits related to mobility. Balance and gait disorders are thus frequently observed in overweight and obese people, sometimes leading lead to falls.

To date, however, few studies have focused on a locomotor task that is particularly at risk of falling, yet frequently encountered in our daily lives: crossing an obstacle while walking.

In this context, the aim of this doctoral work is to assess the effect of overweight on obstacle crossing during walking.

To meet this main objective, we first carried out a systematic review of the literature on this topic. The results show that very few published studies have addressed this research question, and that overweight and obesity modify the kinematic and kinetic parameters of walking over a vertical obstacle in adults. This literature review also opens up some interesting avenues of original research, since none of the included studies compared a group of overweight individuals (body mass index, or BMI, between 25.0 and 29.9 kg/m²) and normal-weight individuals (BMI between 18.5 and 24.9 kg/m²). In addition, certain parameters considered to be the most important for assessing the risk of tripping over obstacles, such as the horizontal and vertical distances of the feet relative to the obstacle, commonly referred to as horizontal and vertical clearances, have not to date been the subject of specific analysis in overweight or obese adults. These two main conclusions led us to compare a group of overweight and normal-weight individuals during an obstacle-crossing task through spatiotemporal gait parameters and clearances relative to the obstacle.

The aim of a second study was to identify the anthropometric characteristics of height, weight and BMI of Brazilian adults included in published studies on obstacle crossing. The results showed that no published study had been conducted using BMI, height or weight values as inclusion and/or exclusion criteria for participants. Moreover, BMI was very rarely reported (4 studies out of the 35 included, 11%). Interestingly, of the 7 groups of participants included in

these 4 studies, 6 had a mean BMI greater than 25 kg/m². The average height and weight of the participant groups were reported in 34 of the 35 included studies (97%), which enabled us to recalculate the BMI of each group. In a very large majority of these studies (29 out of 35, 83%), at least one group of included participants had an average BMI of 25.0 kg/m² or higher. Finally, the individual weight and height characteristics of each participant were reported in 4 studies (11%), enabling us to calculate the BMI of each participant. Of the 63 participants included in these 4 studies, 25 (40%) had a BMI between 25.0 and 29.9 kg/m², and 8 (13%) above 30 kg/m². In other words, our results highlight that a significant proportion of the Brazilian participants included in the published studies on obstacle crossing during walking were overweight or obese. More generally, these results suggest the existence of pre-existing data from which a secondary analysis could advantageously address our main objective. We thus felt that re-using these existing data - for a purpose other than that of the initial study - was highly relevant, especially considering the high financial, material, human and time costs involved in producing new data.

We therefore set out to re-analyse the experimental data collected in 3 of the studies included in the previous literature reviews. Our dataset consisted of 5 spatiotemporal gait parameters and 3 clearance parameters measured on each foot during 3 trials using a system of 10 infra-red cameras among 43 young adults who were asked to walk at a comfortable speed over an 8.5-metre course and to cross a fixed-height vertical obstacle of 15cm positioned in the middle of this course.

Three sub-objectives were successively addressed:

- (1) to assess the intra-session reliability of spatiotemporal gait parameters and horizontal and vertical clearances in young adults during an obstacle crossing task (n=43);
- (2) to compare these parameters obtained in young adults of normal weight (n=28) with those obtained in overweight young adults (n=15); and
- (3) to assess the correlations between anthropometric characteristics and obstacle crossing performance in these same young adults (n=43).

Our results showed that

- (1) spatiotemporal gait parameters and clearances were reliable over 3 trials,
- (2) compared to individuals with a normal BMI, overweight young adults exhibited greater horizontal clearances before and after the obstacle, whereas kinematic parameters and vertical clearances remained unchanged, and

(3) age and anthropometric characteristics of individuals were correlated with several spatiotemporal gait parameters and horizontal clearances, which was not the case for vertical clearances.

Overall, the results of this doctoral work suggest that being overweight has a minimal impact on obstacle crossing during walking, and does not seem to increase the risk of tripping in young adults and under these particular experimental conditions. In these particular conditions, which were relatively mild and easy in that the task consisted of crossing a vertical obstacle 15 centimeters high at a comfortable speed without any other particular constraint. Hence, several perspectives arise from this doctoral work. On the one hand, it will be about implementing more demanding obstacle-crossing tasks and/or closer to those encountered in daily life by testing, for example several obstacle heights, imposing walking speeds, or conducting these protocols under dual-task conditions, or in different fatigue states. On the other hand, it will involve assessing individuals with a wider range of BMIs corresponding to different categories of overweight and obesity (moderate, severe and morbid), but also of different ages and health conditions.

Résumé détaillé

Le surpoids et l'obésité représentent un problème majeur de santé publique. Selon un rapport de l'Observatoire Mondial de l'Obésité, 38% de la population mondiale âgée de 5 ans et plus était en surpoids ou en situation d'obésité en 2020, chiffre qui, selon les prévisions, devrait atteindre 51% en 2035. En plus de ses conséquences délétères largement documentées sur le système cardio-vasculaire, le surpoids et l'obésité induisent également des déficits fonctionnels liés à la mobilité. Troubles de l'équilibre et de la marche sont ainsi fréquemment observés chez les personnes en surpoids ou en situation d'obésité, pouvant parfois conduire à la chute.

Or, à ce jour, peu d'études se sont intéressées à une tâche locomotrice particulièrement à risque de chute, et pourtant fréquemment rencontrées dans notre quotidien : le franchissement d'un obstacle pendant la marche.

Dans ce contexte, l'objectif de ce travail doctoral est d'évaluer l'effet du surpoids sur le franchissement d'obstacle pendant la marche.

Pour répondre à cet objectif principal, nous avons dans un premier temps réalisé une revue systématique de la littérature sur ce sujet. Les résultats montrent d'une part que très peu d'études publiées ont adressé cette question de recherche, et que, d'autre part, le surpoids et l'obésité modifient les paramètres cinématiques et cinétiques de la marche lors du franchissement d'un obstacle vertical chez l'adulte. Cette revue de littérature ouvre également des pistes des recherches originales intéressantes puisqu'aucune des études incluses n'a comparé un groupe d'individus en surpoids (indice de masse corporelle, ou IMC, compris entre 25 et 29,9 kg/m²) et en poids normal (IMC compris entre 18,5 et 24,9 kg/m²). De plus, certains paramètres considérés comme les plus importants pour évaluer le risque de trébuchement lors du franchissement d'obstacles, tels que les distances horizontales et verticales des pieds par rapport à l'obstacle couramment nommés dégagements horizontaux et verticaux, n'ont à ce jour pas fait l'objet d'analyse spécifique chez des adultes en surpoids ou en situation d'obésité. Ces deux principales conclusions nous ont dès lors amenés à vouloir comparer un groupe d'individus en surpoids et en poids normal lors d'une tâche de franchissement d'obstacle au travers de paramètres spatio-temporels de la marche et de dégagements par rapport à l'obstacle.

L'objectif d'un deuxième travail était d'identifier les caractéristiques anthropométriques de taille, de poids et d'IMC des adultes brésiliens inclus dans des études publiées sur le franchissement d'obstacles. Les résultats montrent qu'aucune étude n'a été conduite en considérant des valeurs d'IMC, de taille et de poids comme critères d'inclusion et/ou d'exclusion des participants. De plus, l'IMC n'a que très rarement été rapporté (4 études sur les 35 incluses, 11%). De manière intéressante, parmi les 7 groupes de participants inclus dans ces 4 études, 6 présentaient un IMC moyen supérieur à 25 kg/m². La taille et le poids moyen des groupes de participants ont en revanche été rapportés dans toutes les 35 études incluses (100%), ce qui nous a permis de recalculer l'IMC de chaque groupe. Dans une très large majorité de ces études (29 sur 35, 83%), au moins un groupe de participants inclus présentait un IMC moyen supérieur ou égal à 25 kg/m². Enfin, les caractéristiques individuelles de poids et de taille de chaque participant ont enfin été rapportées dans 4 études (11%), ce qui nous a permis de calculer les IMC de chaque participant. Parmi les 63 participants inclus dans ces 4 études, 25 (40%) présentaient un IMC compris entre 25 et 29,9 kg/m², et 8 (13%) supérieur à 30 kg/m². Autrement dit, nos résultats soulignent qu'une proportion non négligeable des participants brésiliens inclus dans les études publiées portant sur le franchissement d'obstacle pendant la marche était en surpoids ou moins. Plus largement, ces résultats suggèrent l'existence de données déjà constituées à partir desquelles une analyse secondaire pourrait avantageusement permettre de répondre à notre objectif principal. Aussi, re-exploiter ces données existantes - pour une autre finalité que celle de l'étude initiale - nous a paru très pertinent, compte tenu notamment des coûts financiers, matériels, humains et temporels élevés de la production de nouvelles données.

Nous nous sommes dès lors attachés de ré-analyser des données expérimentales collectées dans 3 des études incluses dans les précédentes revues de la littérature. Notre jeu de données était ainsi constitué de 5 paramètres spatio-temporels de la marche et 3 paramètres de dégagements mesurés sur chaque pied lors de 3 essais au moyen d'un système de 10 caméras infra-rouge auprès de 43 jeunes adultes à qui il avait été demandé de marcher à vitesse confortable sur un parcours de 8,5 mètres et de franchir un obstacle vertical d'une hauteur fixe de 15cm positionné au milieu de ce parcours.

Trois sous-objectifs ont été adressés successivement :

(1) évaluer la reproductibilité intra-session des paramètres spatio-temporels de la marche et des dégagements horizontaux et verticaux chez de jeunes adultes lors d'une tâche de franchissement d'obstacle (n= 43) ;

- (2) comparer ces paramètres obtenus chez de jeunes adultes de poids normal ($n=28$) à ceux obtenus chez de jeunes adultes en surpoids ($n=15$); et
- (3) évaluer les corrélations entre les caractéristiques anthropométriques et la performance en franchissement d'obstacle chez ces mêmes jeunes adultes ($n=43$).

Nos résultats ont montré que

- (1) les paramètres spatio-temporels et les dégagements sont reproductibles sur 3 essais de franchissement d'obstacle,
- (2) comparés aux individus avec un IMC normal, les jeunes adultes en surpoids présentent des dégagements horizontaux supérieurs avant et après l'obstacle alors que les paramètres cinématiques et les dégagements verticaux restent inchangés, et
- (3) l'âge et les caractéristiques anthropométriques des individus sont corrélés à plusieurs paramètres spatio-temporels de la marche et de dégagement horizontaux, ce qui n'est pas le cas des dégagements verticaux.

Dans leur ensemble, les résultats de ce travail doctoral suggèrent que le surpoids a un impact minimal sur le franchissement d'obstacle pendant la marche, et ne semble pas augmenter le risque de trébuchement, chez de jeunes adultes et dans ces conditions expérimentales particulières relativement clémentes dans la mesure où la tâche consistait à franchir un obstacle vertical de 15 centimètres de hauteur à vitesse confortable sans autre contrainte particulière. Dès lors, plusieurs perspectives découlent de ce travail doctoral. Il s'agira, d'une part, de mettre en œuvre des tâches de franchissement d'obstacle plus contraignantes et/ou plus proches de celles rencontrées dans la vie quotidienne en testant par exemple plusieurs hauteurs d'obstacles, en imposant des vitesses de marche, ou encore en réalisant ces protocoles en double tâche et dans différentes conditions de fatigue. Il s'agira, d'autre part, d'évaluer des individus présentant non seulement un éventail d'IMC plus large correspondant à plusieurs catégories de surpoids et d'obésité (modérée, sévère et morbide), mais aussi d'âges et de conditions de santé différentes.

Resumo detalhado

Obesidade é um grande problema de saúde pública. Além dos bem documentados efeitos nocivos no sistema cardiovascular, o sobrepeso e a obesidade também levam a déficits funcionais relacionados à mobilidade. Distúrbios de equilíbrio e marcha são frequentemente observados em pessoas com sobrepeso e obesidade, às vezes levando a quedas. No entanto, poucos estudos focaram em uma tarefa locomotora que representa um risco particular de queda, mas que é frequentemente encontrada em nossas vidas diárias: ultrapassar um obstáculo.

Nesse contexto, o objetivo desta tese é avaliar o efeito do sobrepeso na ultrapassagem de obstáculo durante o andar em adultos jovens.

Para atingir esse objetivo principal, esta tese é composta por 5 estudos. No primeiro estudo, foi realizada uma revisão sistemática da literatura que apontou que poucos estudos publicados abordaram essa questão de pesquisa e que o sobrepeso e a obesidade modificam os parâmetros cinemáticos e cinéticos da ultrapassagem de obstáculo durante o andar em adultos. Além disso, nenhum dos estudos incluídos comparou um grupo de indivíduos com sobrepeso (índice de massa corporal – IMC - entre 25,0 e 29,9 kg/m²) e indivíduos com peso normal (IMC entre 18,5 e 24,9 kg/m²). Além disso, certos parâmetros considerados os mais importantes para avaliar o risco de tropeçar em obstáculos, como as distâncias horizontais e verticais dos pés em relação ao obstáculo, não foram, até o momento, objeto de análise específica em adultos com sobrepeso ou obesidade.

A segunda revisão identificou as características antropométricas de altura, massa corporal e IMC de adultos brasileiros incluídos em estudos publicados sobre ultrapassagem de obstáculos. Os resultados mostraram que nenhum estudo publicado havia sido conduzido usando valores de IMC, altura ou massa corporal como critérios de inclusão e/ou exclusão para os participantes. Além disso, o IMC foi muito raramente relatado (4 estudos dos 35 incluídos, 11%). Interessantemente, dos 7 grupos de participantes incluídos nesses 4 estudos, 6 tinham um IMC médio superior a 25 kg/m². A altura e a massa corporal médios dos grupos de participantes foram relatados em todos os 35 estudos incluídos (97%), o que nos permitiu recalcular o IMC de cada grupo. Na maioria desses estudos (29 de 35, 83%), pelo menos um grupo de participantes incluídos tinha um IMC médio de 25,0 kg/m² ou superior. Finalmente, as características individuais de massa corporal e altura de cada participante foram relatadas em 4

estudos (11%), permitindo-nos calcular o IMC de cada participante. Dos 63 participantes incluídos nesses 4 estudos, 25 (40%) tinham um IMC entre 25,0 e 29,9 kg/m², e 8 (13%) acima de 30 kg/m². Em outras palavras, nossos resultados destacam que uma proporção significativa dos participantes brasileiros incluídos nos estudos publicados sobre ultrapassagem de obstáculos durante o andar estavam com sobrepeso ou obesos. De forma mais geral, esses resultados sugerem a existência de dados pré-existentes dos quais uma análise secundária poderia abordar vantajosamente nosso objetivo principal.

Os próximos 3 estudos se propõem a reanalisar os dados experimentais coletados nas revisões de literatura anteriores. O conjunto de dados usado nesta tese consistiu em 5 parâmetros de marcha espaço-temporais e 3 parâmetros de distância dos pés para o obstáculo durante 3 tentativas usando um sistema de 10 câmeras infravermelhas entre 43 jovens adultos que foram solicitados a andar em velocidade preferida por um percurso de 8,5 metros e ultrapassar um obstáculo vertical de 15 cm de altura posicionado no meio deste percurso.

Três objetivos específicos foram sucessivamente abordados:

- (1) avaliar a confiabilidade intra-sessão dos parâmetros espaço-temporais da marcha e das distâncias horizontais e verticais para o obstáculo em jovens adultos durante o andar com ultrapassagem de obstáculo (n=43);
- (2) comparar esses parâmetros entre jovens adultos com peso normal (n=28) e jovens adultos com sobrepeso (n=15); e
- (3) avaliar as correlações entre as características antropométricas e o desempenho na ultrapassagem de obstáculos (n=43).

Nossos resultados mostraram que:

- (1) os parâmetros espaço-temporais da marcha e as distâncias para o obstáculo foram confiáveis ao longo de 3 tentativas,
- (2) em comparação com indivíduos com IMC normal, jovens adultos com sobrepeso exibiram maiores distâncias horizontais antes e depois do obstáculo, enquanto os parâmetros cinemáticos do andar e as distâncias verticais permaneceram inalterados, e
- (3) a idade e as características antropométricas dos indivíduos foram correlacionadas com vários parâmetros de marcha espaço-temporais e distâncias horizontais para o obstáculo, o que não foi o caso para as distâncias verticais.

De forma geral, os resultados desta tese sugerem que estar acima do peso tem um impacto mínimo na ultrapassagem de obstáculo durante o andar, e não parece aumentar o risco de tropeçar em jovens adultos sob essas condições experimentais específicas, que são relativamente fáceis, consistindo na tarefa de ultrapassar um obstáculo vertical de 15 centímetros de altura a uma velocidade confortável, sem qualquer outra restrição particular. Assim, várias perspectivas surgem desta tese. Por um lado, incluir análises em tarefas de ultrapassagem de obstáculos mais exigentes e/ou mais próximas daquelas encontradas na vida diária, por exemplo, várias alturas de obstáculos, aumentando velocidades do andar, ou conduzindo esses protocolos sob condições de dupla tarefa ou em diferentes estados de fadiga. Por outro lado, é importante avaliar indivíduos com uma gama mais ampla de IMCs correspondentes a diferentes categorias de sobrepeso e obesidade (moderada, severa e mórbida), mas também de diferentes idades e condições de saúde.

Acknowledgments

“No one has ever become poor by giving.”

Anne Frank, *The Diary of a Young Girl*, 1947

This PhD thesis, subjected to the PhD Cotutelle Agreement signed between the University Grenoble Alpes (UGA), Grenoble, in France and the São Paulo State University (UNESP) Bauru in Brazil, has been carried out at the AGEIS lab from UGA and at the MOV-LAB from UNESP.

This PhD thesis was supported by the French National Research Agency (ANR) in the framework of the Investissements d’avenir program (ANR-10-AIRT-05) and the MIAI @ Grenoble Alpes (ANR-19-P3IA-0003).

First of all, I would like to express my gratitude to my two thesis supervisors, Nicolas Vuillerme and Fabio Augusto Barbieri.

Nicolas, it has now been 5 years since you welcomed a somewhat lost STAPS student eager to discover the world of academic research. I thank you for the trust you placed in me from the outset by offering me an international collaboration during my first internship. I am also grateful for involving me in projects beyond my PhD thesis. I particularly think of my (failed) attempt to establish shared gardens for students, and the various reviews that opened up previously unknown horizons to me. In addition, you gave me the opportunity to teach my first courses at the faculty, to assist you in the defenses of STAPS master's students and supervise the numerous interns we hosted in the lab during my time there. These experiences significantly contributed significantly to my growth. Beyond the professional aspects and the opportunities you offered, I would like to highlight your human qualities, which were decisive in my choice to pursue a PhD after my two university internships at the laboratory. Your professional guidance, marked by your unquestionable expertise, and your personal support, reflecting values that resonate with mine, have been of great help during challenging times.

Fabio, I also want to thank you for all the support you provided throughout this project. You have been guiding me for 5 years now since the first systematic review project. Thank you for accepting my stubbornness (or my "*cabeça dura*" as you taught me). Your expertise in human movement science was crucial to the success of this project. I am grateful for the time you took to help me develop and refine my scientific thinking. Meeting you in person allowed me to get to know and appreciate you better. I sincerely hope to collaborate with you on various upcoming projects.

I would also like to extend my thanks to Patrice Flore, Anthony Fleury, Pascal Madeleine, Riciardo Augusto Barbieri, Clint Hansen, and Julie Soulard for honoring us by being part of the jury for this PhD thesis. The written assessments from Anthony Fleury and Pascal Madeleine significantly helped us to improve the readability of this manuscript. Their insights and suggestions were invaluable, and I greatly appreciated their support.

A special thank you goes to all my colleagues. First, my "*querido colega*", Valkiria Amaya, who shared her office with me and was patient with my inability to sit still for more than 45 minutes. Thank you, also for always bringing me a little something from your trips and for being the best office mate one could hope for. Then, Pascal Petit, your "*magic tricks*" with R will always impress me, as well as your ability to reason on subjects outside your expertise. Thank you also for mentoring the novice I was in statistical analysis. On the Brazilian side, I extend my gratitude to Tiago Penedo, my Brazilian "*alter ego*". Thank you for all those Zoom meetings to

advance our reviews. I also thank Paulo Cezar Da Rocha Dos Santos for his scientific support in this thesis project and the time he dedicated to my work.

I would like to acknowledge the various interns in the laboratory: Tracy, Lea, the two Quentins, Yanis, Antonin, Mathias, Oceane, Dorian, Norman, Mathis, Tamara, Thomas, Majd, Enzo, Vincent, and Reine, to name but a few. Thank you for your enthusiasm and energy, which boosted my morale more than once. From a somewhat selfish perspective, thank you for being reference points to judge my progress during my thesis, something not easily perceived daily.

To the joy of my life, my family, my words go beyond gratitude. Mom, thank you for your unique and extroverted personality, for always considering me your little boy and offering unwavering support even in my moments of doubt, for raising me the way you did, and for giving me my brothers and sisters. Thank you also for regularly preparing delicious meals, whose secrets only you know. Elsa, Thomas, Julia, and Swan, my siblings, my clan, as well as your partners, Samuel, Rebecca, and Aziz. I thank you for your distinct personalities, strong opinions, and the convivial moments we regularly share. Thank you for my nephew already here, for the next one expected (or a niece), and for all those to come, I hope. I am a Chardon before I am Matthias. I also extend my gratitude to my extended family, my uncles, aunts, and cousins.

Dad, no one can imagine the pain that accompanies me when I think of you and the fact that you will not see your son defend his thesis. You were, you are, and you will forever be my hero. I cannot find better words than those of my cousin Alexandre, which I would like to address to you again: "*SIT TIBI TERRA LEVIS*" May the ground be light to you, forever.

Finally, Grandpa Claude or "*Pipa Declau*", this thesis is also for you. I know that if life had offered you different opportunities, you would have pursued a brilliant academic career, but you have nothing to be ashamed of when facing your grandson, for whom you have been a driving force throughout this project. I hope you are proud of your "*little rascal*".

To concluded, I would like to thank all my friends for their unwavering support and for helping me remember the essentials of a balanced life. Therefore, thank you to my "*Kikitoss*" friends in Grenoble: Nicolas, Marie, Remi, Léon, Bastien, Mélodie, Simon, Hugo, Edouard, Maxime, and your respective partners. Thanks also to my former roommate, Jonas, whose perseverance is beyond question, for regularly accepting to be my "*whipping boy*" at squash, and to his partner Luna for her everyday kindness. I would also like to mention my friends from Chamonix, even though our lives no longer allow us to maintain the same relationships, you still hold an important place in my life. So, thank you to Pierre, Tanguy, Alexandre, Nelson, Jean, and especially Kevin, my best friend, the smartest and silliest person I have ever had the pleasure of meeting.

To all of you, thank you for everything.

Scientific contributions

This work has been the subject of scientific contributions published in international peer-reviewed journals

-Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N. The Effects of Overweight and Obesity on Obstacle Crossing During Walking: Protocol for a Systematic Review. *JMIR Res Protoc*. 2022 May 20;11(5):e36234. doi: 10.2196/36234.

-Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N. A Systematic Review of the Influence of Overweight and Obesity across the Lifespan on Obstacle Crossing during Walking. *Int J Environ Res Public Health*. 2023 May 23;20(11):5931. doi: 10.3390/ijerph20115931.

-Chardon, M., Barbieri, F. A., Petit, P., & Vuillerme, N. (2024). Reliability of Obstacle-Crossing Parameters during Overground Walking in Young Adults. *Sensors (Basel, Switzerland)*, 24(11), 3387. <https://doi.org/10.3390/s24113387>.

-Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N. The effects of experimentally-induced fatigue on gait parameters during obstacle crossing: A systematic review. *Neurosci Biobehav Rev*. 2022 Nov;142:104854. doi: 10.1016/j.neubiorev.2022.104854.

This work has been the subject of scientific contributions submitted, under review in international peer-reviewed journals:

-Chardon M., Barbieri FA, Petit P, Vuillerme N. Obstacle avoidance task during walking and body mass index: a scoping review of Brazilian studies. (submitted)

-Chardon M., Barbieri FA., Petit P., Hansen C., Vuillerme N. Obstacle avoidance has minimum impact on spatial-temporal parameters in young overweight adults. (submitted)

-Chardon M., Barbieri FA., Petit P., Vuillerme N. Determinants of obstacle crossing performance in young male adults: do anthropometrics and age matter? (submitted)

Additional work has been the subject of scientific contributions published in international peer-reviewed journals:

-Amaya V, Chardon M, Klein H, Moulaert T, Vuillerme N. What Do We Know about the Use of the Walk-along Method to Identify the Perceived Neighborhood Environment Correlates of Walking Activity in Healthy Older Adults: Methodological Considerations Related to Data Collection—A Systematic Review. *Sustainability*. 2022; 14(18):11792. <https://doi.org/10.3390/su141811792>.

-Correno MB, Hansen C, Chardon M, Milane T, Bianchini E, Vuillerme N. Association between Backward Walking and Cognition in Parkinson Disease: A Systematic Review. *Int J Environ Res Public Health*. 2022 Oct 6;19(19):12810. doi: 10.3390/ijerph191912810.

-Milane T., Hansen C., Chardon M., Bianchini E., Vuillerme N. Comparing Backward Walking Performance in Parkinson's Disease with and without Freezing of Gait-A Systematic Review. *Int J Environ Res Public Health*. 2023 Jan 4;20(2):953. doi: <https://doi.org/10.3390/ijerph20020953>.

-Amaya, V., Chardon, M., Moulaert, T., Vuillerme, N. Systematic Review of the Use of the Walk-Along Interview Method to Assess Factors, Facilitators and Barriers Related to Perceived Neighborhood Environment and Walking Activity in Healthy Older Adults. *Sustainability* **2024**, 16, 882. <https://doi.org/10.3390/su16020882>.

-Suau, Q., Bianchini, E., Bellier, A., Chardon, M., Milane, T., Hansen, C., & Vuillerme, N. (2024). Current Knowledge about ActiGraph GT9X Link Activity Monitor Accuracy and Validity in Measuring Steps and Energy Expenditure: A Systematic Review. *Sensors (Basel, Switzerland)*, 24(3), 825. <https://doi.org/10.3390/s24030825>.

-Milane, T., Hansen, C., Correno, M. B., Chardon, M., Barbieri, F. A., Bianchini, E., & Vuillerme, N. (2024). Comparison of sleep characteristics between Parkinson's disease with and without freezing of gait: A systematic review. *Sleep Medicine*, 114, 24–41. <https://doi.org/https://doi.org/10.1016/j.sleep.2023.11.021>.

-Milane, T., Hansen, C., Correno, M. B., Chardon, M., Barbieri, F. A., Bianchini, E., & Vuillerme, N. (2024). Comparison of number of people with freezing of gait in Parkinson's disease with and without sleep disturbances: A systematic review. *Sleep Medicine*, 121, 32–41. <https://doi.org/https://doi.org/10.1016/j.sleep.2024.06.001>.

Abbreviations list

BMI	Body Mass Index
CCC	Lin's Concordance Correlation coefficient
ICC	Intraclass correlation coefficient
LOA	Limits of Agreement
MDC	Minimal Detectable Change
SEM	Systematic Error of Measurement
WHO	World Health Organization

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This PhD project specifically examines overweight individuals (Population), focusing on their ability to cross obstacles during walking (Intervention). This capability is compared with that of normal weight individuals (Comparator), highlighting differences in spatial-temporal parameters and obstacle clearance (Outcomes). This introductory chapter provides a comprehensive exploration of the complex nature of overweight and obesity, delving into the assessment, prevalence, root causes, and health impacts of these conditions, as well as their implications for functional capacities. This chapter further elucidates the significance of obstacle crossing in addressing mobility issues among the overweight and obese populations. Finally, the objectives and methodology employed throughout this PhD project are outlined.

1. General introduction

1.1. Overweight and obesity: A growing global health crisis

It is recognized that dietary habits [1] and physical activity [2] are two major health-related lifestyle determinants of an individual's health and well-being [3] as they are reported to influence the incidence of non-communicable diseases such as cardiovascular diseases [4,5], cancer [6,7], and diabetes [4,8] to name a few. Poor diet and/or lack of physical activity are also associated with adverse effects such as overweight and obesity [9], which is defined by the World Health Organization (WHO) as “condition/disease of excessive fat deposits” [10]. In fact, obesity and overweight have emerged as challenges to public health worldwide, with their prevalence reaching alarming levels in recent years. Overweight and obesity are even considered the global epidemic of the 21st century [10,11]. According to the WHO, worldwide adult obesity doubled since 1990 [10]. Additionally, over 390 million children and adolescents (5-19 years old) were overweight, including 160 million of obese children in 2022 [10].

1.1.1. Overweight and obesity: Assessment and classification

Various metrics, including body mass index (BMI), waist circumference, and body fat percentage, are used to classify individuals as underweight ($BMI < 18.5$), normal weight ($18.5 \leq BMI < 25$), overweight ($25 \leq BMI < 30$), obesity class I ($30 \leq BMI < 35$), obesity class II ($35 \leq BMI < 40$), obesity class III ($40 \leq BMI$) overweight or obese or not [10,12]. Among them, BMI is the most used tool to define the weight status of an individual [12], due to its straightforward, cost-effective approach that estimates body fat based on weight and height. BMI is calculated using body height and body mass with the following equation: $BMI (kg/m^2)$

= (Body weight (kg) / Body height² (m)). Several BMI thresholds are used to define weight status as in clinical practice an increased BMI correlates with a large number of individuals found to be overweight [12]. These BMI categories provide valuable insights into the distribution of overweight across different demographic groups and geographical regions. The different weight categories according to BMI are presented in Figure 1.

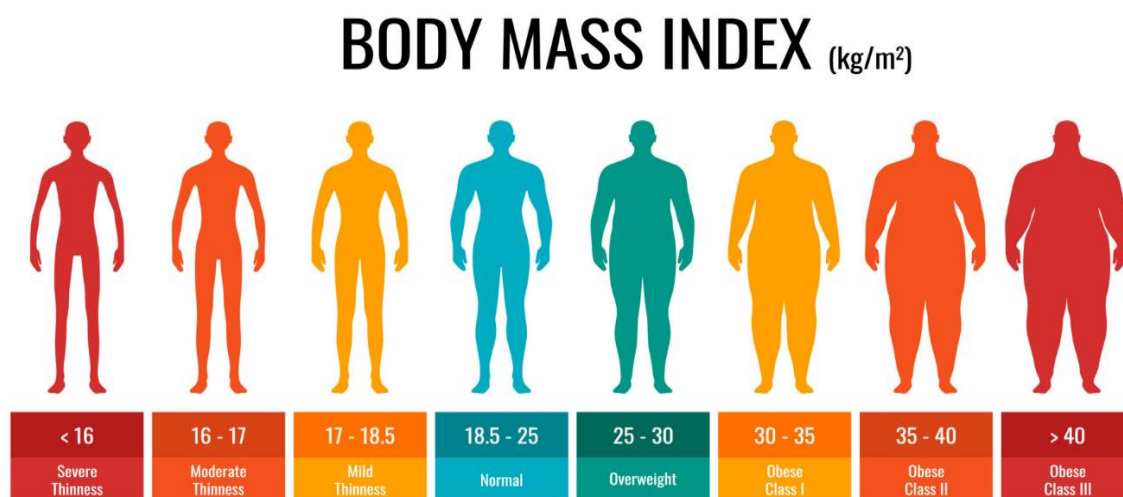


Figure 1. Different weight categories according to BMI.

Source: <https://www.vecteezy.com/vector-art/5905467-bmi-classification-chart-measurement-man-set-male-body-mass-index-infographic-with-weight-status-from-underweight-to-severely-obese-medical-body-mass-control-graph-vector-eps-illustration>.

1.1.2. Overweight and obesity: Prevalence

Assessing the prevalence of overweight and obesity is crucial for understanding the scope of the problem and informing public health interventions. Figure 2 (A-B) shows the worldwide prevalence percentages of overweight and obesity categories according to the WHO in 2022, respectively. These figures highlight the geographical variation in the prevalence of overweight and obesity. Countries from specific regions, such as North and South America, the Middle East, and Australia, have the highest prevalence rates for both overweight and obesity. In contrast, the regions with the lowest prevalence of overweight and obesity are Asia and Central Africa. Globally, approximately 38% of the population aged 5 years old and older were living overweight in 2020, with projections indicating an increase to 51% by 2035 [13]. These statistics and other reports [10,11,13] hence underscore the urgent need for addressing the overweight and obesity epidemic and its association with health risks linked to functional status.

Focusing on Brazil, according to the WHO, in 2022, 34.9% of the adult population was overweight [14] and 28.1% was obese [15]. Regarding France, in 2022, 24.6% of the adult population was overweight [14], and 9.7% was obese [15].

According to the Obesity Atlas report, the projected trends of the prevalence of obesity are 41%, and 34% of adults living with obesity in 2050 for Brazil and France respectively, which is considered “*Very High*” for both countries [13].

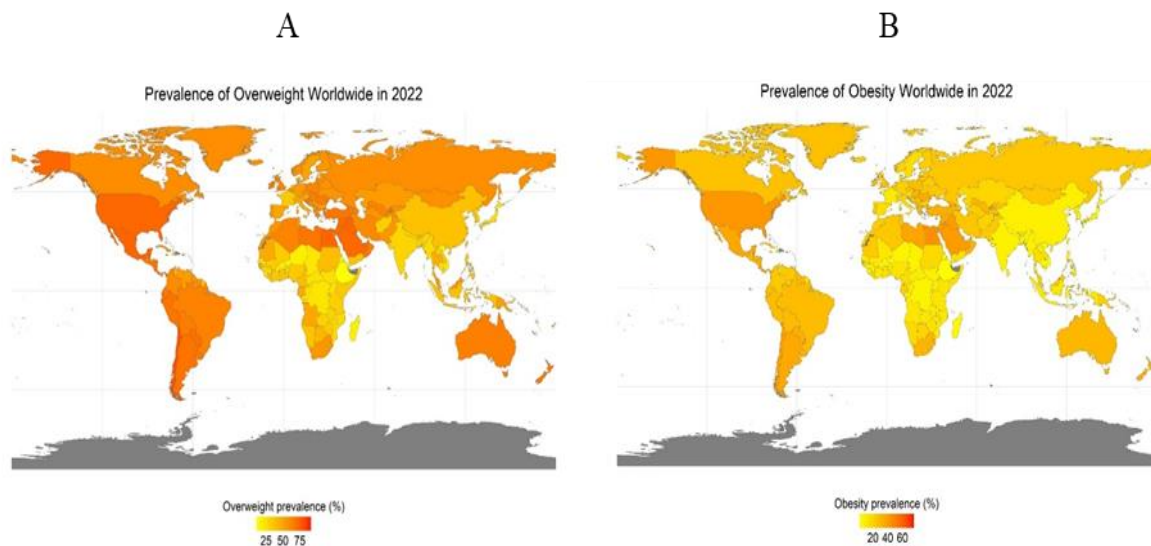


Figure 2. Prevalence of overweight (A) and obesity (B) worldwide [14,15].

Note: country with no data available are represented in gray

1.1.3. Overweight and obesity: A complex etiology

The etiology of overweight and obesity is multifactorial [16,17], reflecting the complex interplay of genetic, environmental, lifestyle, and socio-economic factors. Previous studies showed an association between genes and protein and obesity. As an example, a deficiency of the proopiomelanocortin gene (i.e., an appetite inhibitory gene) leads to hyperphagia and a lower resting metabolic rate [18], which can result in severe obesity. Regarding suggested environmental risk factors, there is a suggestion that a lack of access to healthy food is associated with obesity [19]. In addition, sedentary lifestyles and physical inactivity [20], increase the risk of being obese. Socioeconomic factors, including income level, education [21], and access to healthcare [22], play a significant role in shaping individual health behaviors and outcomes. There is a notable inverse relationship between socioeconomic status and obesity across different income-level countries. In lower-income countries, such as Brazil, higher socioeconomic groups are more likely to experience overweight and obesity, while in higher-income countries, it is the lowest socioeconomic groups that are more frequently obese [23].

Therefore, it is crucial to consider these multifactorial risk factors when developing strategies to prevent and manage obesity effectively.

1.1.4. Overweight and obesity: Impact on health status

Overweight and obesity are associated with a wide range of adverse health outcomes, including cardiovascular diseases, such as hypertension [24], coronary artery disease [25], and heart failure [24]. Obesity can also affect individual's quality of life [26,27] and is linked with various mental health problems, especially depression [28]. These conditions are driven by the increased body fat which often leads to elevated blood pressure, cholesterol abnormalities, and impaired glucose tolerance, all of which contribute to the heightened cardiovascular risk type. Additionally, obesity can exacerbate heart disease through the promotion of chronic inflammation and the disruption of metabolic homeostasis, further compounding the cardiovascular burden [29]. Beyond cardiovascular issues, obesity significantly impacts the risk of developing type 2 diabetes by promoting insulin resistance [30]. Adipose tissue, particularly when excessive, serves not only as a fat storage depot but also as an active endocrine organ, secreting various substances that influence insulin sensitivity [31]. The resultant insulin resistance hampers glucose uptake by cells, leading to high blood sugar levels, which over time can lead to the chronic condition of diabetes, characterized by serious complications such as kidney damage, vision impairment, and an increased risk of heart disease. Moreover, recent evidence showed the association between obesity and several types of cancer (including pancreas, uterus stomach among others) [32], but also the association with cancer recurrence and mortality in cancer survivors [33,34]. However, a recent review showed that BMI was poorly reported and considered regarding drug medications in individuals with breast cancer despite the impact of obesity on cancer biology [35]. Therefore, the authors recommended to systematically reporting individuals' BMI to evaluate its possible negative impact on treatment efficacy [35]. Furthermore, obesity increases the likelihood to have obstructive sleep apnea [36]. The accumulation of fat and adipose tissues induces a narrowing of the upper respiratory muscles causing obstruction in breathing [37].

Apart from the physiological impact of obesity on health, obesity is also associated with psychological/mental conditions. Obesity is also linked to various mental health problem including depression [38,39], anxiety [40], eating disorders such as binge-eating (a large food consumption in a reduced amount of time) or night eating (excessive food intake during evening

or nocturnal eating) [41]. Obesity also impacts negatively body image and self-esteem [42]. From a global health perspective, overweight and obesity were responsible for approximately 5 million deaths due to noncommunicable diseases in 2019 (including cardiovascular diseases, diabetes, cancers etc.) [43]. Economically, the cost of the overweight and obesity pandemic is predicted to reach \$3 trillion by 2030 and could expand six-fold by 2060 [13,44].

1.1.5. Overweight and obesity: Impact on functional capacities

The excess weight associated with overweight and obesity places additional stress on the musculoskeletal system [45], particularly the joints [46]. This can accelerate the wear and tear that leads to osteoarthritis [46], especially in the knees [47] and hips [48], severely impacting mobility [49] and quality of life [50]. Moreover, overweight and obesity compromise functional capabilities such as balance [51,52], walking [53,54] and overall mobility. These functional impairments associated with overweight, and obesity could be exacerbated in more challenging walking conditions such as crossing an obstacle along the pathway.

Excessive body weight impairs the body's ability to perform basic movements and maintain balance. Previous studies have reported the negative impact of increased body weight on balance stability, with individuals with overweight and obesity exhibiting greater postural sway compared to their normal-weight counterparts [55]. Efficient balance control relies on integrating information from the sensorimotor system—including vision, proprioception, and vestibular senses—which may be compromised in individuals with high BMI. For instance, obesity can diminish the quality and amount of mechanoreceptor feedback from the foot due to increased pressure and larger plantar contact areas [56], and there is evidence suggesting that obesity impairs the capacity to utilize proprioceptive information effectively [57]. Furthermore, being overweight or obese leads to modifications in body geometry and adds passive mass to various regions [58] altering body biomechanics and postural stability. As a result, previous studies have shown that the center of pressure displacement is greater in overweight and obese individuals [55,59], and that weight loss in obese individuals leads to increases in postural stability [60]. This information is crucial for activities of daily living, as an impaired balance control can lead to falls [61]. Additionally, studies have shown that obese individuals possess higher absolute muscle strength, but their normalized muscle strength for actions like knee flexion, trunk extension, and handgrip is reduced compared to normal-weight individuals [62]. These observations could be the reflection of the overall impairment of physical fitness in obese

individuals, which could lead to difficulties in postural corrections during balance disturbances. Furthermore, overweight and obesity also affects dynamic tasks such as overground walking.

Previous studies have reported that, compared to normal weight individuals, obese adults walk slower [63–65] by reducing both step length and walking cadence [63–68]. Obese individuals decrease the swing phase time whereas an increase in stance time is observed [63], likely as a strategy to minimize the duration spent in single-leg dynamic balance (swing time) and maximize the period spent in double-leg stance, possibly due to weaker leg strength. Additionally, step width is greater in overweight individuals [64] and obesity [68]. The authors speculated that this behavior was adaptative to face unstable postural control by increasing their base of support [68]. Regarding joint motion and mechanics, obese individuals have less knee flexion [54]. In addition, increased transversal plane motion of the pelvis and greater knee abduction and adduction moments have been observed in overweight and obese adolescents [69]. These biomechanical deviations are likely to heighten the risk of injuries during activities of daily living [70], contribute to musculoskeletal disorders [52,71], and increase the likelihood of falls among overweight and obese individuals [72].

1.2. Obstacle crossing during walking

Mobility challenges during daily living extend beyond upright standing and level-ground walking. Daily activities inherently involve individuals interacting and coping with their physical environment [73]. Among others, one particular task often encountered during daily living is avoiding/crossing an obstacle in the travel path [74], which can pose a challenge to the center-of-mass control and maintenance of forward progression [73].

To gain a comprehensive understanding of obstacle crossing during walking, a first bibliometric analysis was conducted using Web of Science database. The keywords used were focused on obstacle crossing and its variant terms: (ts= ("obstacle crossing" OR "obstacle negotiation" OR "obstacle avoidance" OR "obstructed walking")). Reports were included if they discussed obstacle crossing tasks during walking in humans, with no restriction criteria based on the study design. The database search was performed on December 11th, 2023. The 200 most cited reports investigating an obstacle crossing task during walking in humans were selected. A total of 2341 abstracts were reviewed. After screening titles, abstracts and keywords, 44 full texts were read to verify and confirm their eligibility, resulting in the inclusion of the 200 most cited records that have investigated obstacle crossing tasks during walking in humans.

Examining highly cited papers helps in understanding the historical development and evolution of the research area, providing valuable insights into which topics have garnered the most attention and recognition from the academic community. The choice of 200 records strikes a balance between depth and manageability. Note that this method (i.e., bibliometric analysis of the 200 most cited papers in a research area) has been used in recent research [75–79].

Figure 3 presents the flowchart of the article selection process.

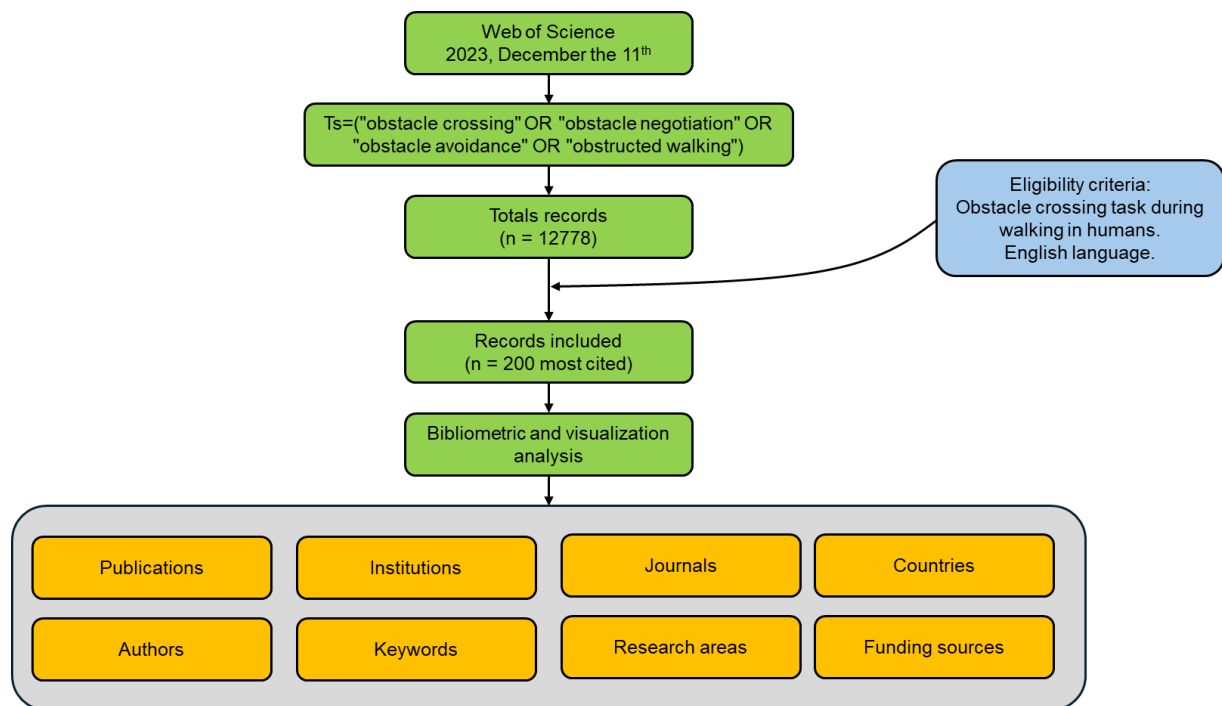


Figure 3. Flowchart of the study selection and analysis of the bibliometric analysis.

The reports retrieved were published between 1991 and 2020 with varying numbers published each year (from 2 in 1991, 1994, 1995, 1998, and 2020 to 20 in 2012). Of these, 19 reports (9.5%) were published in the 1990-2000 decade, 97 reports (48.5%) in the 2000-2010 decade, and 84 reports (42%) in the 2010-2020 decade. Figure 4 presents the number of documents included per year.

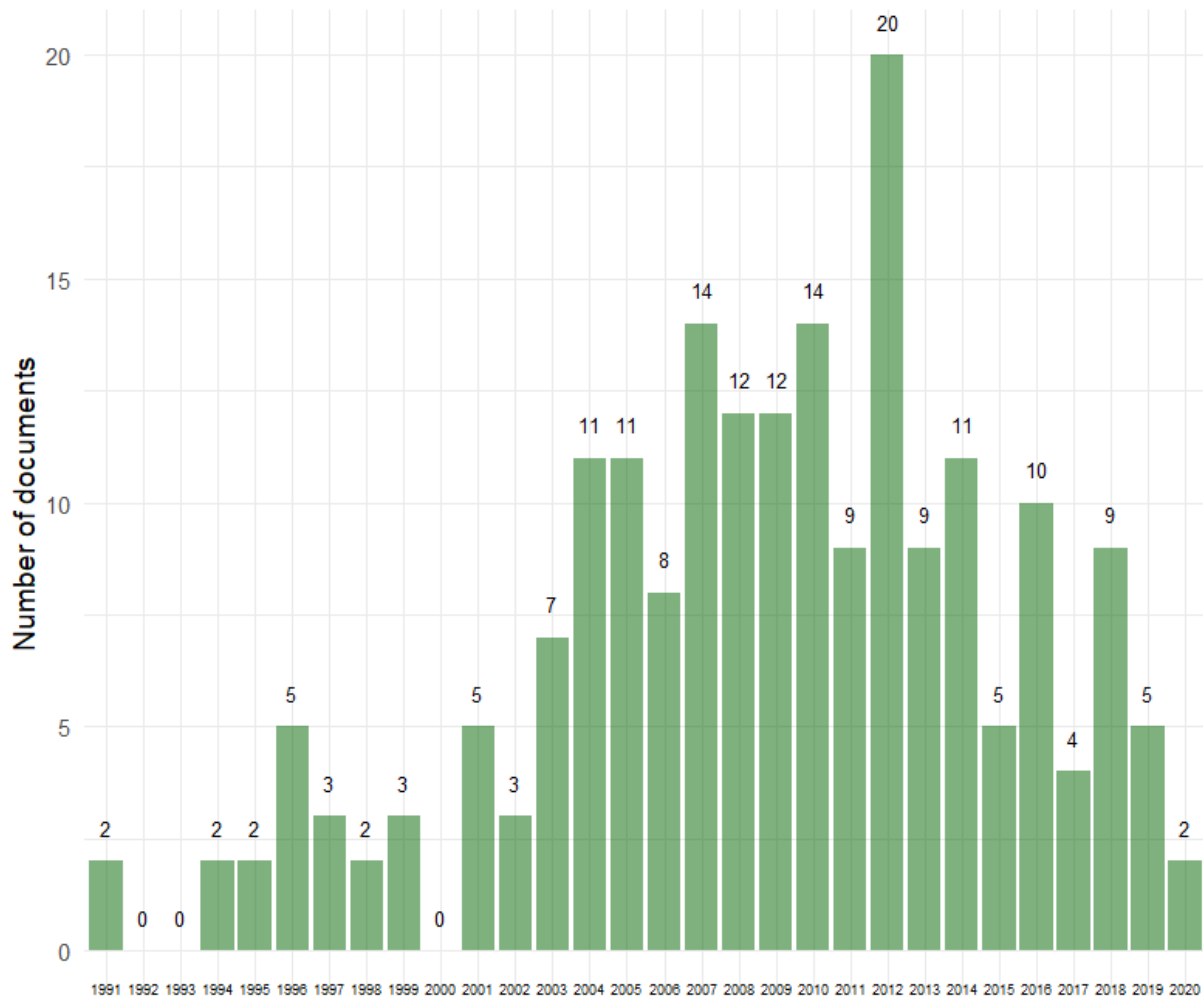


Figure 4. Number of documents published per year.

1.2.1. A common daily task more challenging than usual level ground walking

Obstacle crossing during walking is a ubiquitous activity encountered in daily life, requiring individuals to navigate environmental barriers such as curbs, stairs, or uneven terrain. Figure 5 presents a schematic representation of an obstacle crossing task (A), depicts a typical obstacle that might be encountered (B) during daily walking and illustrates an individual crossing an obstacle on his travel path (C).



Figure 5. Schematic representation of an obstacle crossing task (A), a typical obstacle during daily walking (B), and a representation of an individual crossing an obstacle on his travel path (C).

Unlike level ground walking, which involves a straightforward locomotion, obstacle crossing introduces additional complexities that challenge balance, coordination, and spatial awareness. Even simple obstacles, such as a curb or a small step, can significantly alter gait patterns and require adjustments in stride length, foot placement for both leading and trailing limb, and body posture [80]. To adequately avoid collision while crossing an obstacle, individuals need to integrate visual information available [81]. From a neurological point of view, a smoother steering performance during obstacle crossing was associated with a greater activation of the superior parietal lobe [82]. Moreover, Chen and colleagues (2017) showed that the activation of the prefrontal cortex increased while crossing obstacle compared to unobstructed walking, especially in individuals with mobility limitations [83]. Beyond vision and brain activity, the use of other sensorimotor information is a crucial element in the body's motor control. Proprioception (i.e., the ability to sense body position and movement) is one of the key elements of sensorimotor control and movement [84]. Hosp and colleagues (2018) showed that in individuals with impaired knee proprioception due to experimentally-induced fatigue (i.e., the experimentally-induced fatigue protocol was designed to decrease knee proprioception), participants with kinesiology tape (i.e., used to enhance knee proprioception) had lower impairments in dynamic stability while crossing and obstacle [85].

In addition to the neurological and sensorimotor components, crossing an obstacle places greater muscular demand on the individual. For instance, greater activation of the knee flexor was found while crossing an obstacle compared to unobstructed walking [86] but also with increased obstacle height. As above mentioned, excess body weight can exacerbate the

challenges associated with obstacle crossing during walking, potentially compromising balance, coordination, and muscular strength. Moreover, overweight-related comorbidities such as musculoskeletal disorders and reduced proprioceptive acuity may further impede obstacle crossing capabilities.

1.2.2. A task with a risk of falling

Despite its frequent occurrence, obstacle crossing carries a heightened risk of falls, especially among older adults or individuals with mobility impairments [87,88]. The consequences of falls can be severe, leading to injuries, hospitalizations, and functional decline [89]. As an example, more than half of falls in older adults are due to trips over an obstacle [87]. Some parameters are considered crucial to assess the risk of falls during an obstacle crossing task. These parameters, often called obstacle clearances parameters, are the horizontal (between the toe and the obstacle before crossing it and between the heel and the obstacle after crossing it) and vertical (distance between the toe and the obstacle while crossing it). Figure 6 describes the different obstacle horizontal (A) and vertical (B) clearance parameters. Previous studies showed that trips were more frequent with reduction in vertical clearance [80,90,91]. Indeed, it seems obvious that when the vertical distance between the foot and the obstacle is reduced, the likelihood to trip over the obstacle increases. Therefore, combined with gait spatial-temporal, the investigation of such parameters could reveal people who are at risk of trips, thus that might fall while crossing an obstacle in a large boarder of population with different health and functional status.

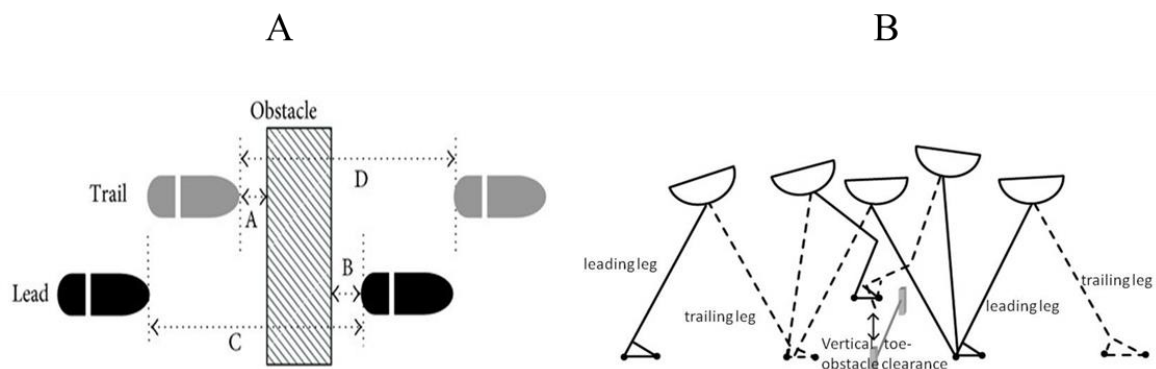


Figure 6. Horizontal (A) and vertical (B) obstacle clearance parameters.

Note: A: Trailing limb horizontal clearance before the obstacle, B: Leading limb horizontal clearance after the obstacle, C: Leading limb horizontal clearance before the obstacle, D: Trailing limb horizontal clearance after the obstacle.

Moreover, the results of our bibliometric analysis showed that “Fall” was the second most used keyword (n = 71 studies out of 200, 35.5%) by the authors from the articles selected, even before keywords related to the task (i.e., “Obstacle avoidance” n = 56, “Obstacle” n = 48, and “Obstacle crossing” n = 20). This emphasize that a large number of studies were conducted in regard to the fall risk associated with the performance of the obstacle crossing task. Figure 7 shows the 30 most used keywords in the included studies. Identifying and mitigating fall risks associated with obstacle crossing during daily living is essential for promoting safe mobility and reducing the burden of fall-related injuries. Additionally, the neighborhood walkability environment is linked to physical activity levels [92], a crucial factor in managing the obesity pandemic [93]. Indeed, neighborhoods with higher walkability are associated with lower obesity rates [94]. The task of obstacle crossing not only highlights individuals at risk of falling but can also shed light on elements of the urban environment that may hinder physical activity.

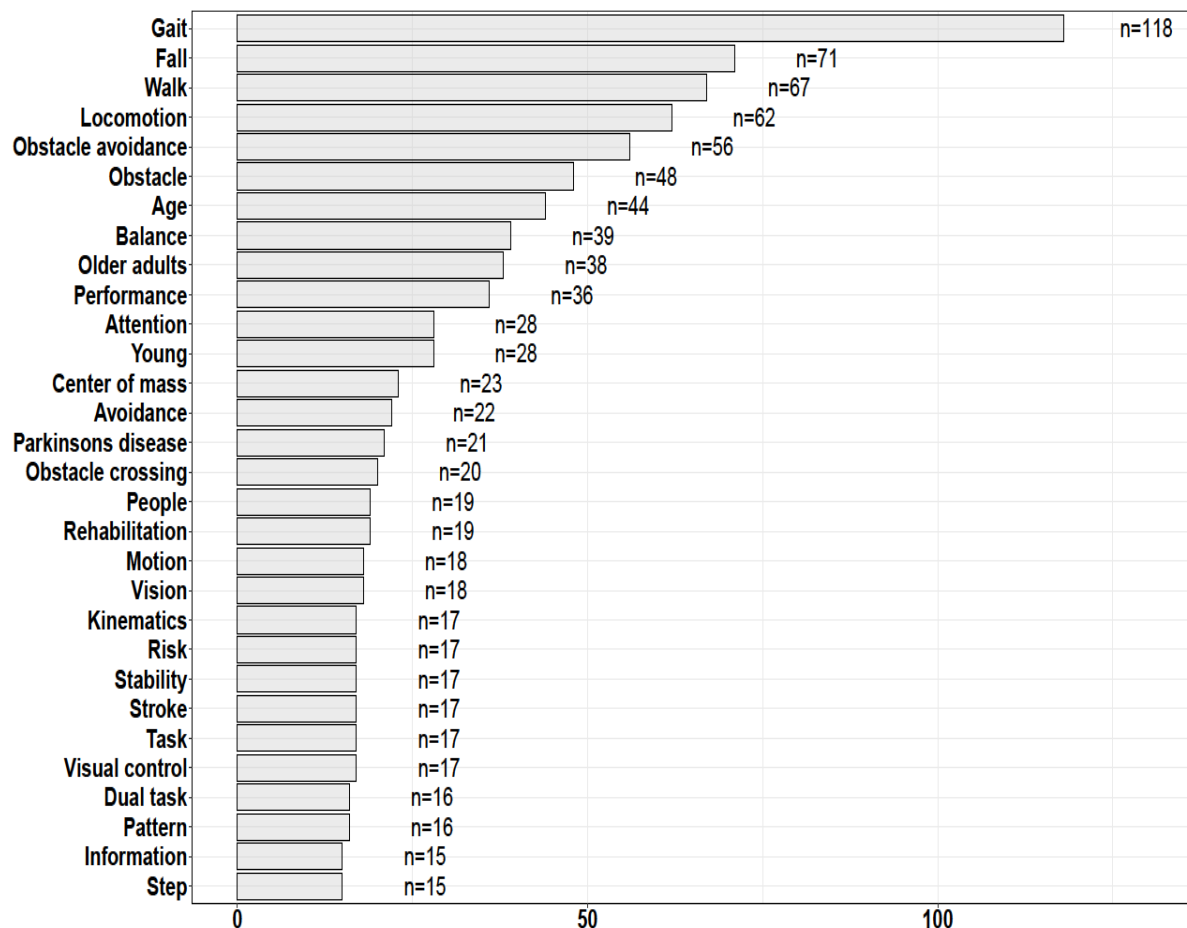


Figure 7. The 30 most used keywords in the 200 most cited obstacle crossing studies.

1.2.3. Previous works

Previous research on obstacle crossing has provided valuable insights into the biomechanics, fall risk, and rehabilitation potential of this complex task [80,90,91,95,96]. Published studies have extensively examined the kinematic and kinetic adaptations involved in negotiating obstacles, highlighting the factors that contribute to falls during this activity. Notably, much of this research has focused on comparing the obstacle crossing performance of various populations including older adults (see for a review [97]), and individuals with conditions such as stroke [88], Parkinson's disease (see for a recent review [98]), multiple sclerosis [99,100], and knee osteoarthritis [101,102]—to healthy, non-pathological groups. These comparisons have been set to know how these conditions affect mobility and the specific challenges they pose during obstacle crossing. For example, a recent review aimed to compare the spatial-temporal gait parameters of people with and without Parkinson's disease while stepping over obstacles and including 25 articles, showed that individuals with Parkinson's disease tend to adopt a conservative strategy when crossing obstacles [98]. This strategy is characterized by reduced step length and walking speed during the crossing step [98]. This reduction in step length affects foot horizontal clearance, decreasing both the trailing foot placement distance before the obstacle and the leading foot placement after the obstacle. However, this review did not identify differences in toe clearance for both legs between Parkinson's disease and healthy individuals. Similar conservative strategies (i.e., reduced step length and speed) are observed in older adults as shown by a review of 15 articles comparing obstacle crossing performance between younger and older adults [97]. However, compared to young adults, older adults contacted the obstacle more frequently, particularly under time-constrained conditions, suggesting that this conservative approach may not always be sufficient to prevent risky situations during obstacle crossing [97].

People with stroke also exhibit differences during all phases of obstacle crossing (approaching, crossing and after crossing phases) to increase safety while crossing the obstacle [103] compared to healthy individuals. People with stroke exhibit adaptations during all phases of obstacle crossing—approaching, crossing, and post-crossing—to enhance safety, such as not reducing pre-obstacle horizontal clearance to avoid early contact during the swing phase [88], a contrast to the approach seen in Parkinson's disease. This observation indicates that motor adaptations vary significantly among different populations with functional impairments. Regarding obstacle contacts, in a previous systematic review designed to identify and

synthesize available evidence on the effects of experimentally-induced fatigue on gait parameters during obstacle crossing by healthy individuals, results showed that the occurrence of obstacle contacts was higher when individuals are in a fatigued state [104]. It is worth noting that this information was poorly reported in the review investigating the effects of experimentally-induced fatigue (2 studies out of 9 studies included) [104] compared to the review investigating obstacle crossing in older adults (10 out of 15 studies) [97]. Perhaps surprisingly, this parameter (i.e., contact with the obstacle while crossing) was not reported on the review investigating the influence of Parkinson disease on obstacle crossing behavior. In addition to the diversity of populations studied, various obstacle crossing protocol modalities have also been investigated, including dual-task conditions [105,106], varying walking speeds [107] and crossing different obstacle heights [108–110] or crossing multiples obstacles [111,112], the use of different footwear [113,114] and light conditions [115] or while using an exoskeleton [116]. These specific conditions aimed to better simulate real-life scenarios and enhance our understanding of how individuals navigate obstacles in everyday environments. Consequently, various internal factors such as health and functional status as well as fatigue levels and external factors have an influence on individuals' performance during obstacle crossing leading to risky situations. Nevertheless, to date, only a few studies have focused on the influence of anthropometric factors, in particular BMI, on obstacle crossing performance in adult populations [63,68,117].

1.2.4. Practical use of obstacle crossing

Obstacle crossing during walking serves as a valuable exercise in rehabilitation settings [103,118], enhancing gait symmetry, and dynamic stability [119]. Rehabilitation programs that include obstacle negotiation exercises have proven effective in improving functional outcomes [118], and reducing fall risks [119,120]. These interventions typically focus on exercises that enhance lower limb strength and balance, along with cognitive training to improve spatial awareness and executive function. Studies have demonstrated that obstacle crossing training programs are more effective than overground walking training in enhancing functional abilities during gait and balance tests in individuals post-stroke [121], and with spinal cord injuries [118]. Additionally, such programs have been shown to alleviate symptoms of freezing gait in people with mild to moderate Parkinson's disease [122] and are more effective than conventional training programs in reducing fall risks and improving gait parameters in geriatric

populations [120]. The increased complexity and intensity required by these tasks make obstacle crossing training particularly beneficial for populations with poor gait endurance and balance abilities. This demonstrates that the ability to cross obstacles not only reflects an individual's functional capabilities but also appears to enhance them. Therefore, it seems essential that individuals be able to regularly navigate obstacles along their path.

Additionally, the results of our bibliometric analysis showed that “Rehabilitation” was the 4th research areas with most occurrence on the obstacle crossing studies selected (n = 28 out of 200, 14%), the 3 research areas with more occurrences were “Neurosciences & Neurology (n = 130), “Sport Sciences” (n = 80), and “Orthopedics” (n = 64). Figure 8 presents the occurrence of the different research areas in the obstacle crossing studies selected. By integrating obstacle crossing into rehabilitation protocols, clinicians can address the specific functional challenges faced by individuals with mobility impairments and promote optimal recovery and autonomy.

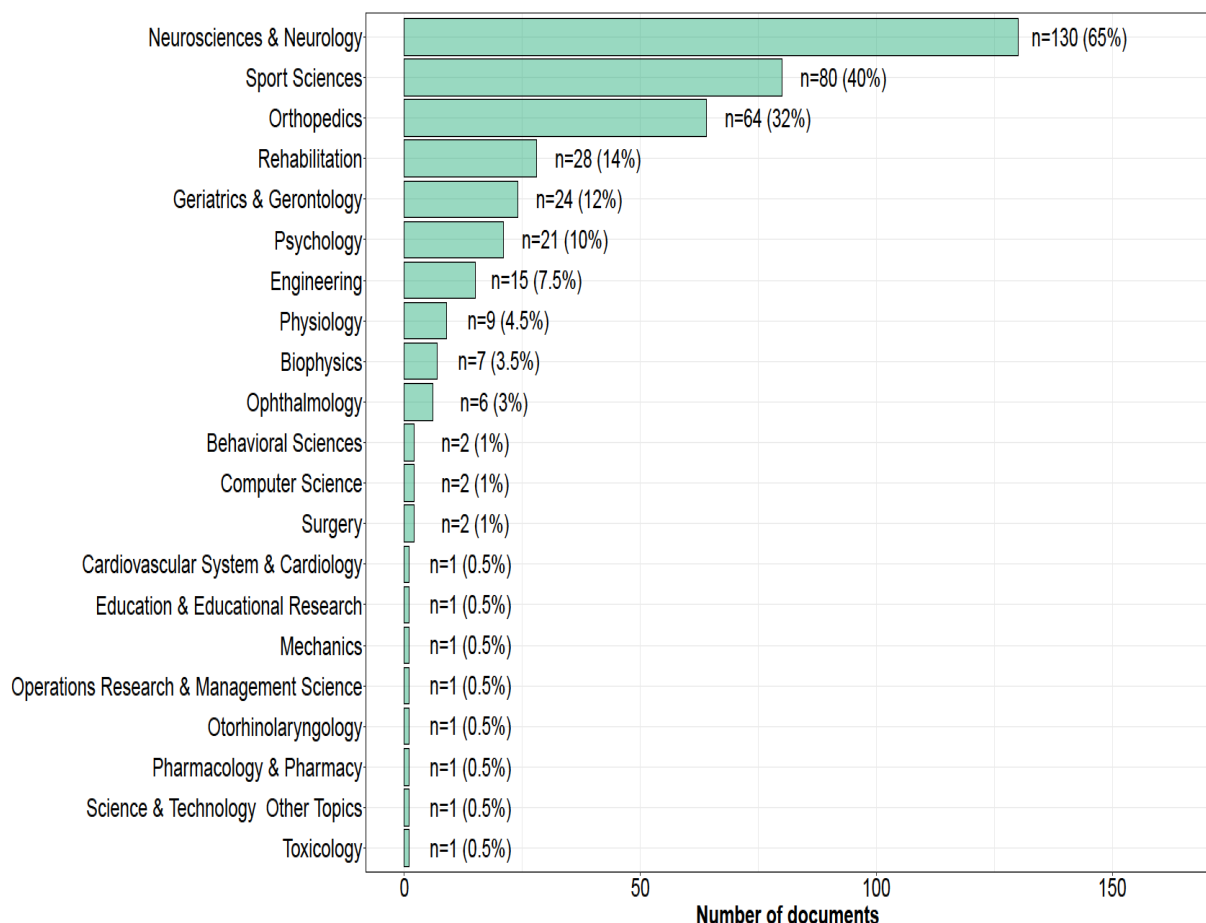


Figure 8. Research areas in the 200 most cited obstacle crossing studies.

2. Rationale and Thesis aims

The framework of this PhD thesis is presented in Figure 9.

Overweight and obesity have become alarming public health issues due to their detrimental effects on individuals' health and their increasing prevalence. The influence of an increased BMI on gait has been extensively studied [53,54,63,69,123–125], revealing that excess weight places significant strain on the musculoskeletal system, particularly on weight-bearing joints during walking [54], which could lead to musculoskeletal conditions such as osteoarthritis [58], and to injuries and functional task limitations [126]. Moreover, the gait pattern during level ground walking of overweight or obese individuals is altered compared to normal weight individuals [66,127–129]. Furthermore, a previous research have reported that higher BMI levels (i.e., the overweight, and obesity classes, see fig. 1. are associated with more pronounced impacts on gait characteristics [63], underscoring the need for research that examines the effects of BMI on distinct groups based on the class of overweight and obesity.

Daily living often requires navigating various physical environments, not just on flat-ground surfaces [73]. Environmental factors such as obstacles in one's path can change gait patterns and strategies [74], and obstacle crossing is a significant cause of falls in older adults due to tripping [87]. Indeed, crossing an obstacle demands greater neuromuscular [83], cognitive, and sensory resources [82], posing additional challenges for individuals with high BMI who already face impairments in gait and balance. This complex interplay between individual functional status and environmental demands highlights the critical need to explore how individuals with high BMI manage obstacle crossing to safely navigate their daily environments and reduce the risk of falls.

In this context, the aim of this doctoral work is to assess the effect of overweight on obstacle crossing during walking in young adults.

To achieve this general objective, a systematic review was first conducted to identify and synthesize existing knowledge about how overweight and obesity influence obstacle crossing during walking. This work was completed with a second review designed to identify the anthropometric characteristics of height, weight, and BMI of Brazilian adults included in published studies on obstacle crossing. There were two main reasons for focusing on the Brazilian population in this PhD. First, the Brazilian population is notably affected by overweight and obesity. Second, through this international collaboration, we had the opportunity to re-analyze data previously collected from a Brazilian cohort. The insights gained

from these two reviews enabled to clearly define new specific research sub-objectives and methods aimed at deepening our understanding of how overweight affects obstacle crossing during walking.

Three sub-objectives were then successively addressed:

- 1. To assess the intra-session reproducibility of spatial-temporal gait parameters and horizontal and vertical clearances in young adults during an obstacle crossing task: 43 young adults crossed a 15-cm high obstacle placed in the middle of an 8.5-m long pathway, both relative and absolute reliability were investigated;

- 2. To compare these parameters obtained in young adults of normal weight with those obtained in overweight young adults: the same participants were split in a normal-weight ($n = 28$) and overweight groups ($n = 15$) to compare their obstacle crossing performance; and

- 3. To assess the correlations between anthropometric characteristics and obstacle clearance performance in the same young adults: correlation and regression analysis between age, anthropometric parameters and obstacle crossing spatial-temporal and obstacle clearance parameters were investigated in the same 43 participants.

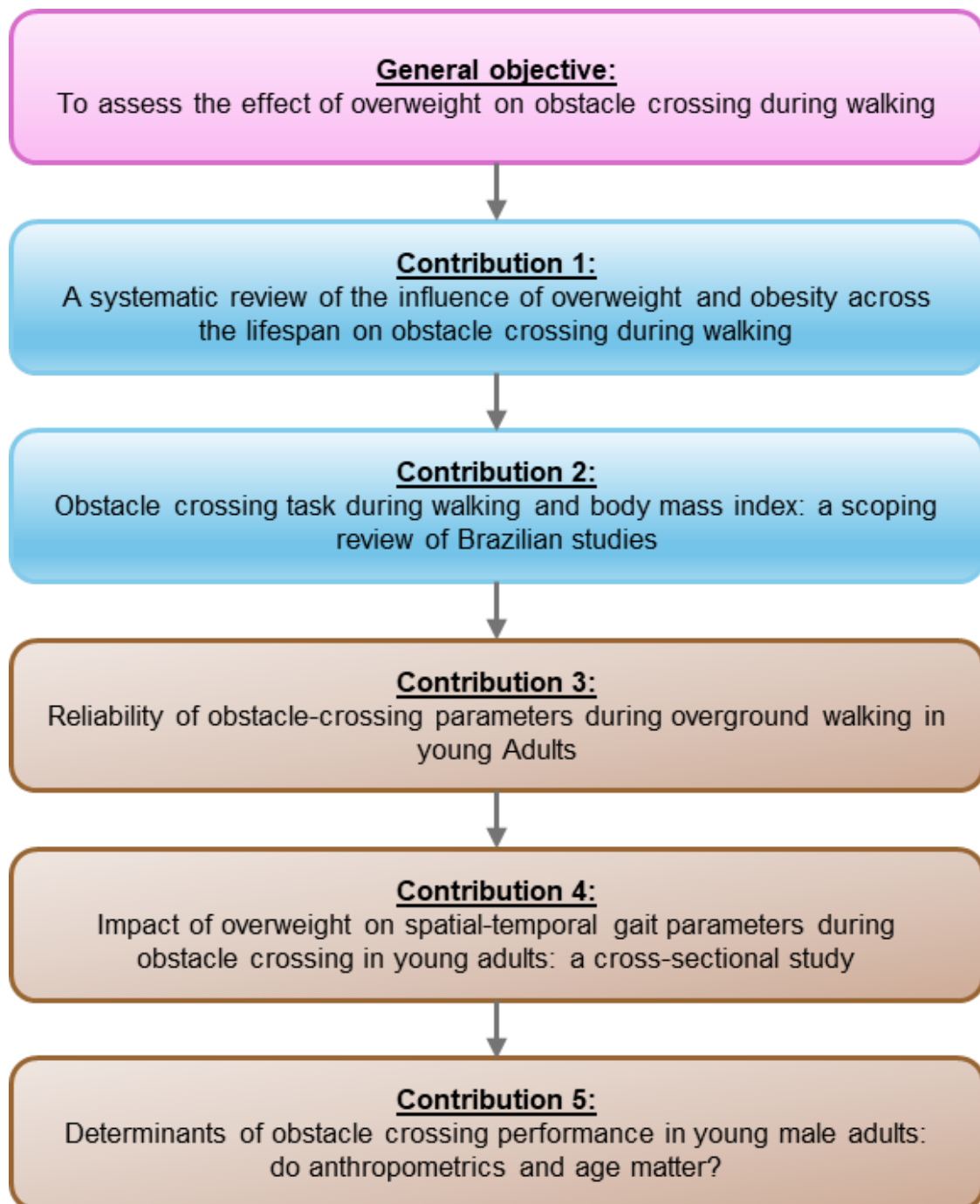


Figure 9. Framework of the PhD thesis.

3. Contribution 1: A Systematic Review of the Influence of Overweight and Obesity across the Lifespan on Obstacle Crossing during Walking

Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N. A Systematic Review of the Influence of Overweight and Obesity across the Lifespan on Obstacle Crossing during Walking. Int J Environ Res Public Health. 2023 May 23;20(11):5931. doi: 10.3390/ijerph20115931.

Abstract: This study aimed to systematically review and summarize the available data regarding the influence of overweight and obesity across the lifespan on obstacle crossing during walking. Four databases were systematically searched with no limitation on publication date following the Cochrane Handbook for Systematic Reviews and PRISMA guidelines. Only full-text English-language articles published in a peer-reviewed journal were eligible. They had to compare obstacle crossing during walking by overweight or obese individuals with individuals of normal body weight. Five studies were considered eligible. All the studies assessed kinematics; only one assessed kinetics, but none investigated muscle activity or obstacle contact. Compared to normal individuals crossing obstacles, overweight or obese individuals exhibited lower velocity, shorter step length, lower cadence, and less time spent in single-limb support. They also exhibited increased step width, more time spent in double support, and greater trailing leg ground force reaction and center of mass acceleration. Overall, the small number of included studies did not allow us to draw any conclusions. However, being overweight or obese seems to have a potentially negative influence on the kinematics of gait parameters due to a tendency to trip, fall, and suffer severe fall-related injuries when negotiating obstacles on foot in real-life environments.

Keywords: obesity; overweight; obstacle crossing; gait; systematic review

1. Introduction

The World Health Organization defines overweight (OW) and obesity (OB) as “abnormal or excessive fat accumulation that may impair health” [1]. OW and OB have become major health issues worldwide, and the prevalence of obesity continues to increase [2]. A 2016 World Health Organization report [1] estimated that 39% of the world population was considered OW and 13% was OB. Specific data for children and adolescents indicated that ~340 million 5–19-year-olds were OW or OB [1]. OW and OB are commonly characterized based on body mass index (BMI). For adults, a BMI of 25.0–29.9 kg/m² is defined as OW, and a BMI of 30 kg/m² or greater is defined as OB [3]. One emerging public health concern is that OW and OB are associated with several comorbidities that accentuate the risks of hospitalisation [4], sudden death [5] and functional impairments [6]. Among these functional impairments, static and dynamic balance and gait behaviours are particularly affected [7–9].

Molina-Garcia et al. [9] recently reported that OW and OB children and adolescents exhibited different gait behaviours than their normal-weight peers, including greater pelvis transversal plane motion, internal rotation/flexion, extension and abduction moments, power generation and absorption, knee abduction and adduction motion, and knee abduction and adduction moments. These biomechanical alterations are likely to increase the risk of injuries during the activities of daily living [10], musculoskeletal disorders [7,11], and fall risk [12] among individuals with OW and OB. However, although much has been reported about the influence of OW and OB on gait during unobstructed walking [13–18], little is known about how these conditions might impact gait under more challenging conditions, such as environments with obstacles [18–22].

Indeed, tripping during obstacle crossing represents one of the main causes (up to 53%) of falls among healthy older adults [23]. Over the past 25 years, obstacle crossing has been reported to reflect a greater risk of imbalance and trips and could lead to falls [24–29]. A possible explanation for the increased risk of tripping during obstacle crossing could be the increased neuromuscular demands during this activity compared to unobstructed walking [26,30,31]. Accordingly, given the functional limitations that OW and OB impose on the musculoskeletal system (see [9,10,32] for recent reviews), it seemed particularly interesting to evaluate whether and how OW and OB might impact obstacle crossing during walking. The present study aimed to systematically review and summarize the available data regarding the influence of overweight and obesity across the lifespan on obstacle crossing during walking.

2. Methods

2.1. Protocol and Registration

This systematic review's protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) (CRD#42021269949) and published in May 2022 [33]; it follows the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [34] (checklist available in the Supplementary Materials: Supplementary File S1) and the guidelines of the Cochrane Handbook for Systematic Reviews [35]. As this review was limited to publicly available materials, it did not require any ethical approval. Note that there was no deviation from the recently published protocol for systematic review [33].

2.2. Eligibility, Inclusion, and Exclusion Criteria

A population, intervention, comparison, outcome and study design (PICOS) tool was used to select the eligibility, inclusion and exclusion criteria for the studies reviewed. Two reviewers (MC and TP) independently included studies based on samples of OW or OB individuals (together defined as having a BMI ≥ 25 kg/m² for adult studies or being at or above the 85th percentile of the Centers for Disease Control and Prevention's Weight-for-recumbent-length Growth Charts for child studies [36]), excluding studies that selected participants with acute or overuse injuries or with neurological, musculoskeletal, or systemic diseases unrelated to OB comorbidities (population). We included studies addressing the influence of an obstacle-crossing task (intervention: obstacle-crossing while walking). Included articles must have compared obstacle-crossing during walking by OW or OB individuals to individuals of normal weight (NW) (BMI 18–24.9 kg/m²). No other walking tasks were considered (comparison). We included studies reporting kinematic, kinetic, or electromyographic parameters, and the following outcomes were also extracted (outcomes): gait spatial and temporal stride parameters (e.g., stride length and duration; and horizontal and vertical foot–obstacle clearance distances), kinetics (e.g., force outcomes such as momentum, work, power, and ground reaction force), muscle activation outcomes (e.g., amplitude, muscle onset, muscle activation duration, muscle synergy, mean frequency, and power density) and obstacle contact. Randomised controlled trials, non-randomised controlled trials, and non-randomised, non-controlled trials (study design) were all included. Accordingly, study design inclusion criteria required original articles to have been published in English in a peer-reviewed scientific journal. Finally, we excluded case reports, abstracts, editorials, letters to the editor, case studies, reviews, meta-analyses,

theses, grey literature (annual, research, technical, or project reports), working papers, and government documents. The inclusion and exclusion criteria using the PICOS tool are described in Table 1.

Table 1. Eligibility criteria of the included studies using PICOS.

	Inclusion criteria	Exclusion criteria
Population	Overweight or obese individuals	Acute or overuse injuries or with neurological, musculoskeletal or systemic diseases unrelated to OB comorbidities
Intervention	Obstacle-crossing task during walking	Obstacle avoidance during a non-walking task Walking task without obstacle crossing
Comparator	Healthy normal-weight individuals	Non-healthy normal-weight individuals
Outcomes	Kinematic, kinetic, and electromyographic	None
Study design	Randomised controlled trials, non-randomised controlled trials, and non-randomised, non-controlled trials. Published in English in a peer-reviewed journal	Case reports, abstracts, editorials, letters to the editor, case studies, reviews, meta-analyses, theses, grey literature (annual, research, technical, or project reports), working papers, and government documents

2.3. Data Sources and Search Strategy

Team members developed and agreed upon the search strategy and selection criteria in line with the review questions. Following the recommendations in the PRISMA statement [34] and the guidelines in the Cochrane Handbook for Systematic Reviews [35], two reviewers (MC and TP) independently performed a systematic computerised literature search of PubMed, Web of Science, Scopus, and SportDiscus from their dates of inception to April 2022, and the search was repeated on February 2023. The search strategy targeted articles containing information relating to overweight or obesity and gait during obstacle-crossing tasks and all subsets of these terms. No filters were used, and the full combination of keywords for all the databases was: (obes* OR overweight OR over-weight OR adipos* OR “body mass index” OR BMI) AND (“obstacle crossing” or “obstacle negotiation” or “obstacle avoidance” or “obstructed walking”). The references of included studies were not checked for potential citations. No experts in the field were contacted.

2.4. Study Selection

The same two reviewers (MC and TP) independently selected the studies, screened the titles, abstracts, and keywords identified via the search strategy, and applied the eligibility criteria. After this initial selection, full-length texts were subjected to the same procedure. In

cases of disagreement, and if subsequent discussions between the two reviewers were inconclusive, a third reviewer (NV) was contacted to arbitrate until a consensus was found.

2.5. Data Extraction

In line with the PRISMA guidelines [34], the number of citations reviewed at each stage of the review was summarised in a flow diagram. The same two reviewers (MC and TP) independently completed the data extraction process using a standardised data extraction form. The following four datasets were extracted from each article retrieved:

- (1) Study characteristics: first author, title, year of publication, journal name, country, study design, mention of any adverse events occurring during the study, and funding;
- (2) Sample description: sample size, age, sex, body weight, body height, body mass index, lower limb length, health status, fall status, and limb preference;
- (3) Obstacle-crossing protocol: task requirement, instrumentation, data acquisition methodology, and gait parameters assessed;
- (4) Main results obtained from gait measurement: spatial-temporal parameters, muscle activity, joint angle and moment, ground reaction force, and obstacle contacts.

2.6. Quality Assessment

The same two reviewers (MC and TP) independently performed a qualitative analysis of the selected studies [34]. To do this, they used a grid specifically developed by Galna and colleagues to assess the quality of the evidence contained within a systematic review investigating obstacle crossing by older adults [37]. Quality issues and risks of bias in the present systematic review centered on the internal validity, external validity, and reproducibility of the methods used in the articles retained. However, Galna and colleagues' grid [37] contains no items related to the study participants' anthropometric characteristics. We thus modified the grid to allow us to address our review question: "How do overweight and obesity influence gait parameters during obstacle crossing across the lifespan?" (CRD#42021269949). The items of body mass and body mass index were added to the grid. The scoring system developed by Galna and colleagues [37] was used to quantify the quality of each of the studies retained and to assess the methodological strengths and weaknesses of those reviewed. Each question in our modified quality assessment [37] was scored as follows: 1 = assessment criterion met, 0 = assessment criterion not met, and 0.5 = lack of information or clarity on that criterion. Any discrepancies

between the two reviewers' findings were resolved by consensus. If disagreements persisted, a third reviewer (NV) was consulted to arbitrate a final decision.

2.7. Data Synthesis

Given the small number of included studies, the wide range of age of the participants included in these studies, and the variety of experimental protocols and reported outcomes, we were unable to conduct meta-analyses of the extracted data. As an alternative, we provided a narrative synthesis of the available data regarding the influence of overweight and obesity on kinematic (Section 3.6.1) and kinetic parameters (Section 3.6.2) related to executing the obstacle-crossing task.

3. Results

3.1. Study Selection

The study selection process is presented in Figure 1.

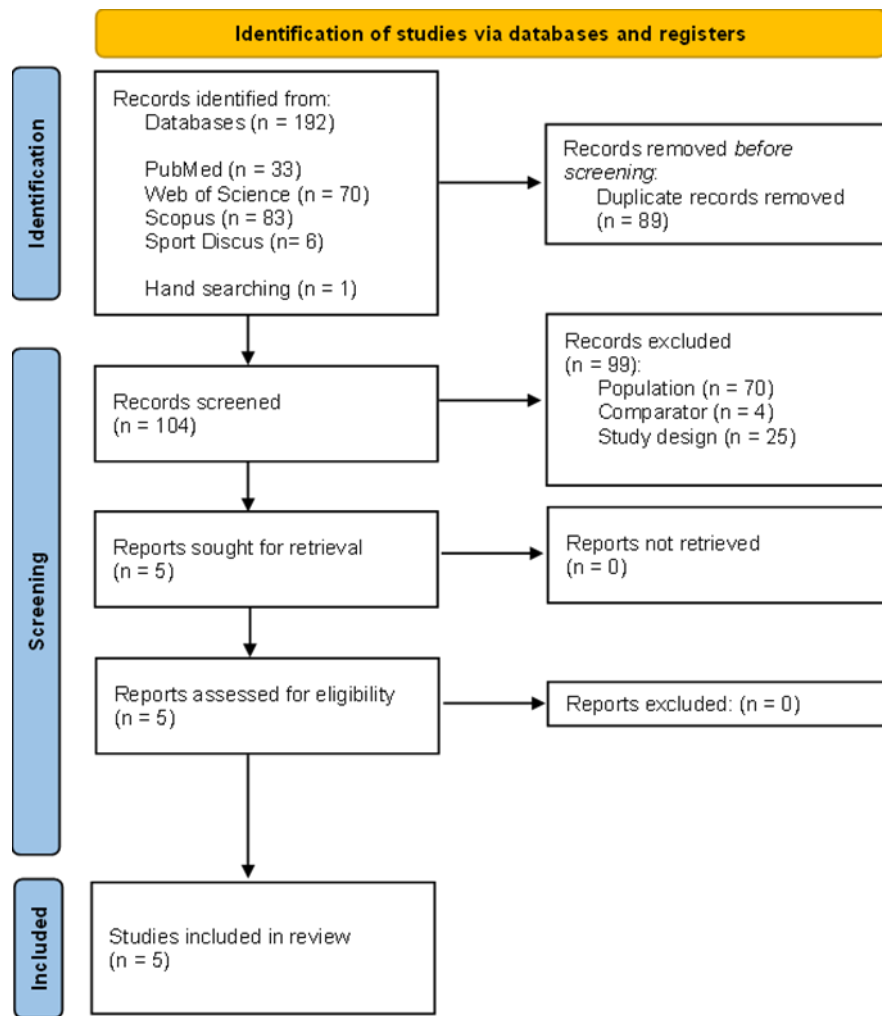


Figure 1. Flow diagram of the articles included in the review. The number of original articles is indicated at each stage of the search.

Our searches of PubMed, Web of Science, Scopus, and SportDiscus resulted in 33, 70, 83 and 6 records, respectively. One article was found via hand searching [21]. After duplicate removal ($n = 89$), 104 records remained. After screening titles, abstracts and keywords, five full texts were read to verify and confirm their eligibility [18–22]. All five met our eligibility criteria and were retained for review [18–22]

3.2. General Information about the Studies Included in the Systematic Review

Table 2 shows the basic information about the studies included in the systematic review.

Table 2. Studies included in the review in order of publication.

Author	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Publication year	2012	2014	2018	2019	2021
Country	USA	USA	Portugal	USA	USA
Title	Influence of weight classification on children stepping over obstacles	Effects of overweight and obese body mass on motor planning and motor skills during obstacle crossing in children	Foot rollover temporal parameters during walking straight ahead and stepping over obstacles: obese and non-obese post-menopausal women	Effects of obesity class on flat ground walking and obstacle negotiation	Association between the Functional Gait Assessment and spatiotemporal gait parameters in individuals with obesity compared to normal-weight controls: A proof-of-concept study
Journal	<i>American Journal of Physical Medicine and Rehabilitation</i>	<i>Research in Developmental Disabilities</i>	<i>Journal of Aging and Physical Activity</i>	<i>Journal of Musculoskeletal Neuronal Interactions</i>	<i>Journal of Musculoskeletal Neuronal Interactions</i>
Study design	Observational cross-sectional	Observational cross-sectional	Observational cross-sectional	Observational cross-sectional	Observational cross-sectional, proof-of-concept
Main objective	To examine how weight classification relates to children's ability to meet a task constraint: crossing obstacles of various heights.	To examine whether body mass index would influence the ability of 4- to 13-year-olds to plan and coordinate their movements to cross obstacles of various heights.	To explore the potential differences between walking straight ahead and walking stepping over obstacles for OB and NOB post-menopausal women.	To investigate how increasing obesity classes affected gait and gait variability in adults.	To determine how to capture gait and balance impairments in adults with obesity using an inexpensive method as a proof-of-concept for possible future validation.

Author	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Main Findings	During obstacle crossing, children who were overweight or obese took longer to cross obstacles and had a dorsiflexed ankle position when landing. We also found that children demonstrated high variability in ankle position when crossing medium obstacles and during the final baseline trials.	Differences in motor planning and motor skills between normal weight and overweight/obese children during obstacle crossing may reflect movement patterns evident during early skill acquisition in which children attempt to freeze degrees of freedom, exhibit difficulty planning and controlling their movements with excess adiposity, or use unknown mechanisms responsible for motor planning and motor skill abilities	Significant differences were found in temporal characteristics of foot rollover during walking straight ahead and stepping over obstacles in both groups, with most of these differences being common for both OB and NOB subjects.	Increases in classes of obesity are associated with more difficulties with spatiotemporal gait and gait variability. Most importantly, there were few differences between Class II and Class III obesity.	Poorer FGA scores in the obese group were associated with slowing of gait when encountering obstacles but not during flat over-ground walking. Further, the presence of obstacles during gait tasks may be helpful in revealing meaningful gait impairments in obesity and other populations.
Funding	No funding information reported.	Boston University start-up funds.	European Investment Funds via FEDER/COMPETE/POCI—Operational Competitiveness and Internationalisation Programme, under project POCI-01-0145-FEDER-006958 and National Funds via FCT—Portuguese Foundation for Science and Technology, under project UID/AGR/04033/2013	R03 AR066344-01 A1 (Gill, PI). NIH R03 AR066344-01 A1 (Gill, PI).	

Note: FGA: Functional Gait Assessment; NOB: non-obese; OB: obese

3.3. Study Characteristics

Table 2 summarises the characteristics of the studies included in the review in order of publication.

The studies retained were published from 2012 to 2021, with one study each published in 2012 [19], 2014 [20], 2018 [21], 2019 [22] and 2021 [18].

The articles were published in four different journals: two in the Journal of Musculoskeletal Neuronal Interactions [18,22], and one each in the Journal of Aging and Physical Activity [21], Research in Developmental Disabilities [20] and the American Journal of Physical Medicine and Rehabilitation [19].

The studies originated from just two countries: four from the USA [18–20,22] and one from Portugal [21].

3.4. Quality Assessment

Table 3 summarises quality assessment for each article retained [18–22].

Table 3. Methodological quality appraisal results adapted from the grid developed by Galna et al. [36].

Question	Scoring Criteria	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]	AVERAGE
1. Research aims or questions stated clearly	Y = 1; L = 0.5; N = 0	1	1	1	1	1	1
2. Participants detailed	Number	1	1	1	1	1	1
	Age	1	1	1	1	1	1
	Sex	1	1	1	1	1	1
	Height	0	0	1	0	1	0.4
	Body mass	0	0	1	0	1	0.4
	Body mass index	1	1	1	1	1	1
	Subtotal	0.67	0.67	1	0.67	1	0.8
3. Recruitment and sampling methods described	Y = 1; L = 0.5; N = 0	1	1	1	1	1	1
4. Inclusion and exclusion criteria detailed	Y = 1; L = 0.5; N = 0	1	1	1	1	0.5	0.9
5. Covariates controlled for	Age	1	1	1	1	1	1
	Sex	0	0	1	1	0	0.4
	Height	0	0.5	1	0	0	0.3
	Body mass	0	0	0	0	0	0
	Body mass index	1	1	1	1	1	1
	Limb asymmetries	0	0	1	0	1	0.4
	Strength	0	0	0	0	0	0
	Stride/step Speed	1	1	1	1	0	0.8
	Subtotal	0.38	0.44	0.88	0.5	0.38	0.52

Question	Scoring Criteria	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]	AVERAGE
6. Key outcome variables clearly described	Y = 1; L = 0.5; N = 0	1	1	1	1	1	1
7. Adequate methodology able to repeat study	Participants	0.5	0.5	1	0.5	1	0.7
	Equipment	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1
	Processing	1	1	1	1	1	1
	Statistics	1	1	1	1	1	1
	Subtotal	0.9	0.9	1	0.9	1	0.94
8. Methodology able to answer the research question	Participants	1	1	1	1	1	1
	Equipment	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1
	Processing	1	1	1	1	1	1
	Statistics	1	1	1	1	1	1
	Subtotal	1	1	1	1	1	1
9. Reliability of the methodology is stated	Y = 1, N = 0	0	0	0	0	0	0
10. Internal validity of the methodology was stated	Y = 1, N = 0	0	0	0	0	0	0
11. Research questions were answered adequately in the discussion	Y = 1, N = 0	1	1	1	1	1	1
12. Key findings were supported by the results	Y = 1, N = 0	1	1	1	1	1	1
13. Key findings were interpreted logically, supported by references	Y = 1, N = 0	1	1	1	1	1	1
14. Clinical implications were stated	Y = 1; L = 0.5; N = 0	0	0.5	0	0	0	0.1
Study average		0.69	0.71	0.85	0.72	0.75	0.74

Y = yes; L = lacking detail or clarity; N = no. A score of 1 indicated high-quality research, and 0 indicated lower quality.

The articles included adequately stated their objectives, provided an appropriate description of their participants (although three studies reported participants' BMI but not their height or body mass [19,20,22]), described their inclusion and exclusion criteria, detailed their main findings, used appropriate methodologies to answer their research questions, and appropriately discussed their study results. The details provided were adequate to replicate their study. All five studies lacked detail and clarity on the clinical implications of their research [18–22].

Sample Characteristics

The basic demographic and anthropometric characteristics of each study's participants are presented in Table 4.

Sample Characteristics

The basic demographic and anthropometric characteristics of each study's participants are presented in Table 4.

Table 4. Basic demographic and anthropometric characteristics of the participants in each study.

Author	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Number of groups (n)	2: Normal BMI (between 5th and 85th percentile). ^[C] High BMI (children at or above 85th percentile and below 95th percentile were classified as OW; those above 95th percentile were classified as OB). ^[C]	2: Normal weight (between 5th and 85th percentile). ^[C] OW/OB (children at or above 85th percentile and below 95th percentile were classified as OW; those above 95th percentile were classified as OB). ^[C]	2: Non-OB (<27 kg/m ²). OB ^[Z] (>27 kg/m ²).	4: Normal BMI (≥18.5 kg/m ² and <25 kg/m ²). OW/Class I OB ^[C] (≥25 kg/m ² and <35 kg/m ²). Class II OB ^[C] (≥35 kg/m ² and <40 kg/m ²). Class III OB ^[C] (>40 kg/m ²).	2: Normal BMI (≥19 kg/m ² and ≤25 kg/m ²). OB BMI (≥30 kg/m ²). ^[C]
Number of participants (n)	Non-OB: 10 OW/OB: 12	Non-OB: 10 OW/OB: 12	Non-OB: 27 OB: 40	Normal BMI: 13 OW/Class I OB: 18 Class II OB: 16 Class III OB: 20	Non-OB: 20 OB: 14
Sex (F: female; M: male) (n)	Non-OB: F:6; M: 6 OW/OB: F:5; M: 7	All participants: F: 9; M: 13	Non-OB: F: 27 OB: F: 40	Normal BMI: F: 13 OW/Class I OB: F: 18 Class II OB: F: 16 Class III OB: F: 20	Non-OB: F: 14; M: 6 OB: F: 12; M: 2

Author	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Exclusion criteria	Not reported.	Not reported.	(1) Diabetes and/or signs associated with neuropathy, (2) acute foot pain and deformities, (3) severe lower extremity trauma, and (4) coordination problems resulting from eye disorders. Scheduled to undergo knee surgery, having no significant cardiovascular, musculoskeletal, vestibular or other neurological disorders. These criteria were confirmed via participant reports and investigators' observations.	Scheduled to undergo knee surgery, having no significant cardiovascular, musculoskeletal, vestibular or other neurological disorders. These criteria were confirmed via participant reports and investigators' observations.	Not reported.
Inclusion criteria	Being free of intellectual impairment or physical conditions that precluded independent walking based on parents' reports and investigators' observations and being 4–13 years old.	Having normal cognitive abilities, no known physical conditions that would preclude independent walking, and being 4–13 years old.	Not reported.	All participants could walk without the aid of an assistive device.	All participants were free of neurological difficulties, had normal or corrected-to-normal vision, and could walk without assistive devices.
Age, mean (SD) (Range), years	Non-OB: 8.42 (1.00) (4.5–13).	-All participants: 8.62 (0.93) (not reported).	-Non-OB: 58.2 (4.8) (not reported).	-Normal BMI: 33.2 (7.04) (not reported).	-Non-OB: 45.55 (8.77) (35–64).
	OW/OB: 8.58 (0.73) (6–13).		-OB: 57.1 (4.7) (not reported).	-OW/Class I OB: 36.16 (12.76) (not reported). -Class II OB: 41.17 (5.89) (not reported) -Class III OB: 42.72 (11.43) (not reported).	
Height, mean (SD) (Range), cm	-Not reported.	-Not reported.	-Non-OB: 155.8 (5.2) (not reported).	-Not reported.	-Non-OB: 170.15 (8) (150–180). ^(X)
			-OB: 156.3 (4.5) (not reported).		-OB: 168.83 (8.69) (155–184). ^(X)

Author	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Body mass, mean (SD) (Range), kg	-Not reported.	-Not reported.	-Non-OB: 58.4 (7.1) (not reported). -OB: 73.1 (7.3) (not reported).	-Not reported.	-Non-OB: 69.36 (12.17) (47.20–86.20). ^(X) -OB: 120.58 (20.13) (99.20–173.01). ^(X)
BMI, mean (SD) (Range), kg/m ²	-Non-OB: 15.85 (0.68) (11.65–18.35). ^(C) -OW/OB: 21.41 (1.31) (16.67–31.23). ^(C)	-Non-OB: 15.85 (0.68) (not reported). ^(C) -OW/OB: 21.85 (0.50) (not reported). ^(C)	-Non-OB: 24.0 (2.0) (not reported). -OW/OB: 29.9 (2.5) (not reported).	-Normal BMI: 22.56 (1.61) (not reported). -OW/Class I OB: 29.36 (3.19) (not reported). ^(C) -Class II OB: 37.78 (1.42) (not reported). ^(C) -Class III OB: 44.31 (4.24) (not reported). ^(C)	-Non-OB: 23.77 (2.53) (18.59–27.55). ^(C) -OB: 40.95 (5.46) (35.3–52.64). ^(C)

BMI: body mass index. Class I obesity: $30 \text{ kg/m}^2 \leq \text{BMI} < 35 \text{ kg/m}^2$; Class II obesity: $35 \text{ kg/m}^2 \leq \text{BMI} < 40 \text{ kg/m}^2$; Class III obesity: $\text{BMI} > 40 \text{ kg/m}^2$. ^(C) indicates an OW and OB classification according to the Centers for Disease Control and Prevention [38]; ^(Z) indicates that OB levels were determined using the cut-off value of 27 kg/m^2 : Brochu et al., 2008. “*Contribution of the Lean Body Mass to Insulin Resistance in Postmenopausal Women With Visceral Obesity: A Monet Study*” [39]. ^(X) indicates that the value was calculated by the reviewers. Non-OB: non-overweight/obese individuals; OW: overweight individuals.

Regarding sample size, a total of 132 OW/OB individuals and 82 NW individuals were included. Sample sizes ranged from 12 [19,20] to 54 [22] for OW/OB individuals and from 10 [20] to 27 [21] for NW individuals.

Regarding sex, two studies only included female participants [21,22], with 134 female participants in total (94 OW/OB; 40 NW). Three studies included male and female participants [18–20], totaling 34 males and 46 females. Two of these studies also reported the number of male and female participants in each BMI group, namely 9 OW/OB males and 17 OW/OB females vs. 12 NW males and 20 NW females [18,19]. No sex comparisons were made.

Regarding age, two studies only included children [19,20], with a total of 46 children (24 OW/OB individuals and 22 NW individuals). Children ranged from 4 to 13 years old across both studies [19,20]. Gill and Hung in 2012 reported their mean participant age as 8.58 ± 0.73 years for OW/OB individuals and 8.42 ± 1.00 years for NW individuals [19]. The mean participant age in the other study (including NW and OW/OB children) was 8.62 ± 0.93 years [20]. Three studies included adults [18,21,22], with a total of 168 participants (108 OW/OB; 60 NW), with mean ages ranging from 36.2 ± 12.8 [22] to 57.1 ± 4.7 [21] years for OW/OB individuals and from 33.2 ± 7.0 [22] to 58.2 ± 4.8 [21] years old for NW individuals. None of these three studies reported age inclusion criteria [18,21,22].

Considering anthropometry, two studies reported the heights and weights of their adult participants [18,21]. Heights ranged from 156.3 ± 4.5 cm [21] to 168.83 ± 8.69 cm [18] for OW/OB individuals and from 155.8 ± 5.2 cm [21] to 170.15 ± 8 cm [18] for NW individuals. Weights ranged from 73.1 ± 7.3 kg [21] to 120.58 ± 20.13 kg [18] for OW/OB individuals and from 58.4 ± 7.1 kg [21] to 69.36 ± 12.17 kg [18] for NW individuals. For the two studies involving children [19,20], BMIs were 21.41 ± 1.31 kg/m² [19] and 21.85 ± 0.50 kg/m² [20] for OW/OB individuals and 15.85 ± 0.68 kg/m² for NW individuals [19,20]. For the three studies involving adults [18,21,22], BMIs ranged from 29.9 ± 2.5 kg/m² [21] to 43.31 ± 4.24 kg/m² [22] for OW/OB individuals and from 22.56 ± 1.61 kg/m² [22] to 24.0 ± 2.0 kg/m² [21] for NW individuals. Only Desrochers et al. (2021) reported participants' heights and weights using fixed obstacle height [18].

Regarding obesity classification, four studies [18–20,22] used the Centers for Disease Control and Prevention classification [36,38], and the fifth [21] used a classification developed for Brochu et al.'s study [39] of post-menopausal women, where participants were considered OB above a BMI cut-off value of 27 kg/m². In Desrochers et al.'s 2021 study involving adults [18], OB individuals had a BMI above 30 kg/m². In another study, three OW/OB groups were

established according to their BMI: OW/Class I OB ($25 \text{ kg/m}^2 \leq \text{BMI} < 35 \text{ kg/m}^2$); Class II OB ($35 \text{ kg/m}^2 \leq \text{BMI} < 40 \text{ kg/m}^2$); and Class III OB: ($\text{BMI} \geq 40 \text{ kg/m}^2$) [22].

In the two studies involving children aged 4–13 years old [19,20], participants at or above the 85th percentile and below the 95th percentile were classified as OW (approximately $17\text{--}25.2 \text{ kg/m}^2$ and $17.2\text{--}26.2 \text{ kg/m}^2$ for boys and girls, respectively), and those above the 95th percentile were classified as OB (approximately 17.8 to more than 25.2 kg/m^2 and from 18 to more than 26.2 kg/m^2 for boys and girls, respectively) [36].

3.5. Obstacle-Crossing Task

The obstacle-crossing tasks used in the retained studies are described in Table 5.

Table 5. Description of the obstacle-crossing tasks used in the retained studies.

Author	Gill & Hung [19]	Gill & Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Task	Participants first walked once along a 406-centimeter-long walkway. In balance order, they walked and stepped over low, medium, and high obstacles.	Children walked along a 406-centimeter-long walkway and crossed low, medium, and high obstacles.	Walking straight ahead with or without stepping over an obstacle whose height was 30% of the leg length in a two-step protocol.	Participants walked down a 1600 cm walkway with a gait carpet (610 cm long × 89 cm wide) in the centre and crossed 3 obstacles of low, medium, and high height placed halfway down the path.	Participants walked along the GAITRite (488 cm long × 61 cm wide) walkway under five conditions.
Obstacle	A wooden dowel inserted into two 25-centimeter-high wooden towers at 4 cm (low obstacle), 11 cm (medium obstacle), and 16 cm (high obstacle).	A wooden dowel inserted into two 25-centimeter-high wooden towers at 4 cm (low obstacle), 11 cm (medium obstacle), and 16 cm (high obstacle).	Not reported.	The obstacles were created using a wooden dowel (121 cm long) and two rectangular towers (9 cm × 10 cm × 22 cm) with holes drilled at 4 cm, 8 cm, and 16 cm (low, medium, and high).	The obstacle was a wooden dowel suspended across the walkway that was inserted into holes in two wooden towers. Participants encountered small (4 cm), medium (8 cm), or large (16 cm) obstacles.
Expected/ Unexpected	Expected.	Expected.	Expected.	Expected.	Expected.
Starting point	Not reported.	203 cm from the obstacle.	Two-step protocol with the left leg as the leading limb during obstacle crossing.	800 cm from the obstacle.	244 cm from the obstacle.
Number of sessions	1.	1.	1.	1.	1.
Number of conditions	5: No obstacle = flat surface without obstacle (baseline initial and final trials). Low obstacle height (4 cm). Medium obstacle height (11 cm). High obstacle height (16 cm).	5: No obstacle = flat surface without obstacle (baseline initial and final trial). Low obstacle height (4 cm). Medium obstacle height (11 cm). High obstacle height (16 cm).	2: Straight ahead walking without obstacle = flat ground surface without obstacle. Straight ahead walking and stepping over an obstacle height of 30% of leg length.	5: No obstacle = flat ground surface without obstacles (baseline initial and final trials). Low obstacle height (4 cm). Medium obstacle height (8 cm). High obstacle height (16 cm).	5: No obstacle = flat ground surface without obstacles (baseline initial and final trials). Low obstacle height (4 cm). Medium obstacle height (8 cm). High obstacle height (16 cm).

Author	Gill & Hung [19]	Gill & Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Obstacle condition order	Initial and final overground trials. Obstacle conditions were counterbalanced.	Not reported.	Two-step protocol without obstacle. Two-step protocol with obstacle.	Initial and final overground trials Obstacle conditions were randomised.	Initial and final overground trials Obstacle conditions were counterbalanced.
Number of trials per condition	5 for obstacle-crossing trials. 1 for baseline and final trials (no obstacle condition).	5.	5 valid trials. ^[y]	5.	5.
Walking speed	Self-selected pace.	Self-selected pace.	Self-selected pace.	Self-selected pace.	Self-selected pace.
Experimental condition	Single task.	Single task.	Single task.	Single task.	Single task.
Practice	Not reported.	3 practice trials.	10 min familiarisation period.	Not reported.	Not reported.

^[y]: Whenever a participant trod on the pressure platform, if foot contact was incomplete or the coefficient of variation of the duration of contact was greater than 4%, the trial was discarded. Note that all studies included single-task conditions and self-selected walking speed instruction and had the same number of experimental session and trials per obstacle crossing conditions.

Regarding the walkway, four studies [18–20,22] reported fixed walkway lengths between 406 cm [19,20] and 1600 cm [22], and one [21] used a two-step protocol (left leg as the leading limb during obstacle crossing). Three studies placed their obstacles in the middle of their walkway [18,20,22], and one [19] did not report the obstacle's location.

Concerning the starting point, studies' starting points and walking distances before arriving at their obstacles ranged from 203 cm [20] to 800 cm [22] or two steps before the obstacle [21]. Gill and Hung's 2012 study did not report the starting point's distance from the obstacle [19].

For the obstacle conditions and experimental conditions, all five studies performed an overground gait task and obstacle-crossing tasks [18–22]. Four studies used baseline and final overground walking trials [18–20,22]; three studies executed five consecutive overground walking trials before and after their obstacle-crossing tasks [18,20,22] Desrochers et al., 2021 used a single overground walking trial before and after the obstacle-crossing task [19]. In the last study, participants performed five trials using the two-step protocol without the presence of the obstacle [21].

Regarding obstacle height and shape, Silva et al., 2018 [21] used an obstacle height that varied according to the participant's leg length (30% of leg length), with obstacle heights of 22.2 ± 0.9 cm for non-OB participants and 22.1 ± 1 cm for OB participants. The obstacle's shape was not described, however. Four studies [18–20,22] used three fixed obstacle heights: two [19,20] used small (4 cm), medium (11 cm), and high (16 cm) obstacles; two [18,22] used different respective small (4 cm), medium (8 cm), and high (16 cm) obstacles. All four [18–20,22] used a wooden dowel suspended across the walkway and inserted into holes in two wooden towers as their obstacle.

As concerns instructions, in all five studies, participants were instructed to walk at a self-selected speed and cross an obstacle. In the study by Gill (2019) [22], participants walked barefoot; in the other four studies [18–20,22], footwear was not specified. The obstacle's presence on the walkway was expected in all five studies. Participants executed 5 consecutive trials for each obstacle condition [18–22]. The mean [18–22] or mean and SD were used to calculate coefficients of variation using the following equation: the mean/SD [22] of the 5 trials was used for data analysis. Three studies reported that the obstacle condition order was counterbalanced [18,19] or randomised [22] across individuals; Gill and Hun, 2014 did not mention any obstacle condition order [20].

Regarding practice and familiarisation, two studies [20,21] reported that the participants were allowed to practice before the experimental trials, with one permitting three practice trials [20] and the other allotting a 10 min familiarisation period [21].

Table 6 reports the categories of parameters related to the performance of the obstacle crossing tasks assessed in each of the retained studies, including the parameters measured during obstacle crossing, and the data acquisition methods for kinematic and kinetic gait parameters related to the performance of the obstacle-crossing tasks.

Table 6. Gait parameters measured and data acquisition methods.

Author	Gill and Hung [19]	Gill and Hung [20]	Silva et al. [21]	Gill [22]	Desrochers et al. [18]
Parameters measured	Kinematics: Time from foot lift to maximum knee height, time from maximum knee height to foot contact, and maximum knee height. Ankle angles at foot contact to determine neutral (angles near 90 degrees) or dorsiflexed ankle positions (angles <90 degrees) and sagittal knee and ankle angles at maximum knee height. Estimated variability of ankle positions at foot contact by calculating the coefficient of variation.	Kinematics: Maximum toe height for each leg during obstacle crossing; hip and knee angles in sagittal and frontal planes; vertical, anterior/posterior, and medial/lateral acceleration of centre of mass. Kinetics: Ground reaction force: normalised vertical, anterior/posterior, and medial/lateral ground reaction forces of both legs.	Kinematics: Plantar pressure parameters: relative foot temporal data for the initial contact, final contact, and duration of contact.	Kinematics: Velocity, percentage of gait cycle spent in swing and in stance, and coefficient of variation for each support variable to obtain a measure of variability.	Kinematics: Gait velocity, step length and width, cadence, and single- and double-limb support during leading leg step across the obstacle.
Acquisition system	Vicon Nexus Model 1.4 motion capture system (120 Hz) and 41 reflective markers.	Whole-body plug-in-gait model of Vicon Nexus 1.51 (120 Hz) with 7 infrared cameras and 41 reflective markers.	Two Footscan platforms (100 × 40 cm, 8192 sensors; RSscan International, Olen, Belgium; 250 Hz).	Gait carpet (Protonetics, LLC; Peekskill, NY, USA; 610 cm long × 89 cm wide; 120 Hz).	-GAITRite software and custom Matlab scripts (Mathworks, Inc., Natick, MA, USA) (488 cm long × 61 cm wide; 120 Hz).

All five studies assessed kinematic parameters [18–22], but only one assessed both the kinematic and kinetic parameters related to executing the obstacle-crossing task [20]. None of the studies assessed muscular activity or obstacle contacts.

Regarding kinematic parameters, the kinematic measurement tools used were Protokinetics LLC's 610 cm long x 89 cm wide gait carpet [22], GAITRite's 488 cm long x 61 cm wide carpet [18] and two Footscan platforms (100 x 40 cm) [21]. Two studies used the Vicon Nexus Model motion capture system [19,20].

The only kinematic parameter investigated by two studies was gait velocity during obstacle crossing [18,22]. The following 63 kinematic parameters were only assessed in one study each:

- Step length, width, cadence, and single- and double-limb support phases [18];
- Stance and swing time and their coefficients of variation, and the coefficient of variation of velocity [22];
- Time from foot lift to maximum knee height and from maximum knee height to foot contact, maximum knee height (plus sagittal knee and ankle angles at maximum knee height), and ankle angle at foot contact [19];
- Leading- and trailing-leg toe clearance, hip and knee angles at maximum knee height in the sagittal and frontal planes, COM (center of mass) anterior and posterior, and medial, lateral and vertical acceleration at the leading and trailing legs' maximum knee height during crossing [20];
- Relative foot temporal data at initial and final foot contact and duration of contact of the HL (lateral heel), HM (medial heel), MF (midfoot), M1-5 (metatarsal areas), T2-5 (toes), and T1 (hallux) areas of the leading and trailing legs [21].

Regarding kinetic parameters, Gill and Hung, 2014 [20] assessed six kinetic parameters using two AMTI OR6-6 force platforms (46 cm x 50 cm): leading and trailing leg normalised anterior and posterior; and medial, lateral, and vertical ground reaction force at maximum knee height of the contralateral leg during obstacle crossing [20].

3.6. Influence of Overweight/Obesity on Obstacle Crossing during Walking

3.6.1. Kinematic Parameters

Table 7 reports the influence of OW/OB on kinematic parameters during obstacle crossing.

Table 7. The influence of overweight/obesity on gait parameters during obstacle crossing.

Gait Parameters	Number of Studies	Study	Between-Group Differences	Results (Mean $\pm$ SD or Median (IQR)) and Direction of Difference ($\uparrow\downarrow$)
Kinematics outcomes				
	2	Gill, 2019	NW vs. OBI: $p = 0.03$ NW vs. OBII: $p = 0.000002$ NW vs. OBIII: $p = 0.000000058$ OBI vs. OBII: $p = 0.018$ OBI vs. OBIII: $p = 0.001$	NW = 125.08 ± 1.98 OBI = 105.72 ± 3.08 ($\downarrow$ 15.5% vs. NW) OBII = 91.46 ± 3.06 ($\downarrow$ 26.9% vs. NW; $\downarrow$ 13.5% vs. OBI) OBIII = 85.46 ± 2.43 ($\downarrow$ 31.7% vs. NW; $\downarrow$ 19.2% vs. OBI).
		Desrochers et al., 2021	$p = 0.0001$ (OB vs. C)	NW = 97.49 ± 6.14 OB = 67.53 ± 5.83 ($\downarrow$ 30.7% vs. NW)
Leading-leg step length (cm)	1	Desrochers et al., 2021	NW vs. OB: $p = 0.01$	NW = 60.40 ± 0.37 OB = 51.94 ± 0.18 ($\downarrow$ 14.0% vs. NW)
Leading-leg step width (cm)	1	Desrochers et al., 2021	NW vs. OB: $p = 0.01$	NW = 8.40 ± 0.21 OB = 11.54 ± 0.70 ($\uparrow$ 37.4% vs. NW)
Leading-leg single-limb support (% of gait cycle)	1	Desrochers et al., 2021	NW vs. OB: $p = 0.001$	NW = 41.38 ± 1.16 OB = 38.87 ± 1.03 ($\downarrow$ 6.1% vs. NW)
Double-limb support (% of gait cycle)	1	Desrochers et al., 2021	NW vs. OB: $p = 0.001$	NW = 8.90 ± 0.85 OB = 11.09 ± 0.96 ($\uparrow$ 24.5% vs. NW)
Cadence (steps/min)	1	Desrochers et al., 2021	NW vs. OB: $p = 0.001$	NW = 104.46 ± 2.33 OB = 90.24 ± 3.07 ($\downarrow$ 13.6% vs. NW)
Stance time (% of gait cycle)	1	Gill, 2019	NW vs. OBI: $p = 0.012$ OBI vs. OBII: $p = 0.029$ NW vs. OBI, low obstacle: $p = 0.004$ NW vs. OBI, medium obstacle: $p = 0.007$	NW = 61.64 ± 1.71 OBI = 65.13 ± 0.35 ($\uparrow$ 5.7% vs. NW; $\uparrow$ 4.6% vs. OBII) OBII = 62.83 ± 0.02 <u>Low obstacle (4 cm):</u> NW = 60.79 ± 6.97 OBI = 64.85 ± 2.31 ($\uparrow$ 6.7% vs. NW) <u>Medium obstacle (8 cm):</u> NW = 60.52 ± 8.04 OBI = 65.01 ± 3.71 ($\uparrow$ 7.4% vs. NW)
Swing time (% of gait cycle)	1	Gill, 2019	NW vs. OBI: $p = 0.003$ NW vs. OBII: $p = 0.001$ NW vs. OBIII: $p = 0.00024$	C = 42.55 ± 0.85 OBI = 38.42 ± 0.85 ($\downarrow$ 9.7% vs. NW) OBII = 37.72 ± 0.02 ($\downarrow$ 11.4% vs. NW) OBIII = 37.14 ± 0.21 ($\downarrow$ 12.7% vs. NW)
CV velocity	1	Gill, 2019	NW vs. OBII: $p = 0.00042$ OBI vs. OBII: $p = 0.00015$ NW vs. OBIII: $p = 0.000023$ OBI vs. OBIII: $p = 0.000006$	NW = 0.03 ± 0.01 OBI = 0.03 ± 0.01 OBII = 0.06 ± 0 ($\uparrow$ 80% vs. NW and OBI) OBIII = 0.07 ± 0.01 ($\uparrow$ 100% vs. NW and OBI)

Gait Parameters	Number of Studies	Study	Between-Group Differences	Results (Mean $\pm$ SD or Median (IQR)) and Direction of Difference ($\uparrow\downarrow$)
CV stance time	1	Gill, 2019	NS	
CV swing time	1	Gill, 2019	NS	
Time from foot lift to maximum knee height (s)	1	Gill and Hung, 2012	NW vs. OB, high obstacle: $p = 0.04$	<u>High obstacle (16 cm):</u> NW = 0.08 ± 0.01 OB = 0.11 ± 0.01 ($\uparrow$ 37.5% vs. NW)
			NW vs. OB, low obstacle: $p = 0.41$	
			NW vs. OB, medium obstacle: $p = 0.31$	
Time from maximum knee height to foot contact (s)	1	Gill and Hung, 2012	NW vs. OB, high obstacle: $p = 0.04$	<u>High obstacle (16 cm):</u> NW = 0.0011 ± 0.001 OB = 0.0006 ± 0.0005 ($\downarrow$ 45.5% vs. NW)
			NW vs. OB, low obstacle: $p = 0.13$	
			NW vs. OB, medium obstacle: $p = 0.96$	
Maximum knee height	1	Gill and Hung, 2012	C vs. OB: $p = 0.57$	
			C vs. OB, low obstacle: $p = 0.04$	<u>Low obstacle (4 cm) :</u> NW = 99.24 ± 6.18 OB = 79.90 ± 6.18 ($\downarrow$ 19.5% vs. NW)
			NW vs. OB, medium obstacle: $p = 0.07$	
Ankle angle at foot contact ($^{\circ}$)	1	Gill and Hung, 2012	NW vs. OB, high obstacle: $p = 0.89$	
			NW vs. OB: $p = 0.65$	
Sagittal ankle angle at maximum knee height ($^{\circ}$)	1	Gill and Hung, 2012		
Sagittal knee angle at maximum knee height ($^{\circ}$)	1	Gill and Hung, 2012	NW vs. OB: $p = 0.18$	
Leading-leg toe clearance (cm)	1	Gill and Hung, 2014	NS	
Trailing-leg toe clearance (cm)	1	Gill and Hung, 2014	NW, high low obstacle: $p = 0.02$	<u>Low obstacle (4 cm):</u> NW = 13.73 ± 1.47 O = 23.13 ± 1.53 ($\uparrow$ 38% vs. high obstacle)
			OB, low vs. high obstacle: $p = 0.01$	
				<u>High obstacle (16 cm):</u> NW = 18.38 ± 1.53 ($\uparrow$ 33.9% vs. low obstacle) OB = 16.76 ± 1.59

Gait Parameters	Number of Studies	Study	Between-Group Differences	Results (Mean $\pm$ SD or Median (IQR)) and Direction of Difference ($\uparrow\downarrow$)
Leading-leg hip angles at maximum knee height in 1 frontal plane ($^{\circ}$)	1	Gill and Hung, 2014	OB, high vs. medium and low obstacles: $p = 0.02$ No other effects were observed.	<u>Low obstacle (4 cm):</u> OB = 47.28 ± 0.47 <u>Medium obstacle (11 cm):</u> OB = 50.28 ± 0.52 <u>High obstacle (16 cm):</u> OB = 66.75 ± 0.57 ($\uparrow$ 32.8% and 41.18% vs. medium and low obstacles, respectively)
Trailing-leg hip angles at maximum knee height in 1 frontal plane ($^{\circ}$)	1	Gill and Hung, 2014	No BMI or BMI*condition effects were observed ($p > 0.05$).	
Hip angles at maximum knee height in sagittal plane ($^{\circ}$)	1	Gill and Hung, 2014	No BMI or BMI*condition effects were observed for both legs ($p > 0.05$).	
Trailing-leg knee angles at maximum knee height in 1 in sagittal plane ($^{\circ}$)	1	Gill and Hung, 2014	NW vs. OB, high obstacle: $p = 0.04$ NW vs. OB, low obstacle: $p = 0.04$ No other effects were observed.	<u>Low obstacle (4 cm):</u> NW = 6.99 ± 0.66 OB = 11.09 ± 1.16 ($\uparrow$ 58.7% vs. NW) <u>High obstacle (16 cm):</u> NW = 4.64 ± 0.64 OB = 12.02 ± 1.05 ($\uparrow$ 159.1% vs. NW)
COM acceleration in anterior/posterior direction at maximum knee height of leading leg during crossing	1	Gill and Hung, 2014	NW vs. OB, low obstacle: $p = 0.006$ No other effects were observed.	<u>Low obstacle (4 cm):</u> C = 0.63 ± 0.08 OB = 1.05 ± 0.05 ($\uparrow$ 66.7% vs. NW)

Gait Parameters	Number of Studies	Study	Between-Group Differences	Results (Mean $\pm$ SD or Median (IQR)) and Direction of Difference ($\uparrow\downarrow$)
COM acceleration in anterior/posterior direction at maximum knee height of trailing leg during crossing	1	Gill and Hung, 2014	NW vs. OB, low obstacle: $p = 0.01$ OB, low vs. medium and high obstacles: $p = 0.01$	Low obstacle (4 cm): NW = 0.66 ± 0.12 OB = 1.02 ± 0.12 ($\uparrow$ 54.5% vs. NW; $\uparrow$ 45.7% and 82.1% vs. medium and high obstacles, respectively) Medium obstacle (11 cm): NW = 0.83 ± 0.06 OB = 0.70 ± 0.06 High obstacle (16 cm): NW = 0.73 ± 0.09 OB = 0.56 ± 0.09
COM acceleration in medial/lateral direction at 1 maximum knee height		Gill and Hung, 2014	No BMI or BMI*condition effects were observed for both legs ($p > 0.05$).	
COM acceleration in vertical direction at maximum knee height	1	Gill and Hung, 2014	No BMI or BMI*condition effects were observed for both legs ($p > 0.05$).	
Duration of contact of HL, HM, MF, M5, M4, M3, M2, M1, T2-5, T1 of leading and trailing leg (ms)			No difference between OB and C for any area for both legs.	
	1	Silva et al., 2018		

Gait Parameters	Number of Studies	Study	Between-Group Differences	Results (Mean $\pm$ SD or Median (IQR)) and Direction of Difference ($\uparrow\downarrow$)
Kinetics outcomes				
Trailing-leg normalised, anterior/posterior ground reaction forces at maximum knee height of leading leg during crossing (N/kg)	1	Gill and Hung, 2014	OB, low vs. medium and high obstacles: $p = 0.001$ NW, high vs. medium and low obstacles: $p = 0.001$ No other effects were observed.	<u>Low obstacle (4 cm):</u> NW = 0.17 ± 0.06 OB = 0.66 ± 0.02 ($\uparrow 266.7\%$, and 100% vs. medium and high obstacles, respectively) <u>Medium obstacle (11 cm):</u> NW = 0.29 ± 0.03 OB = 0.18 ± 0.08 <u>High obstacle (16 cm):</u> NW = 0.33 ± 0.04 ($\uparrow 94.1\%$, and 13.8% vs. low and medium obstacles, respectively) OB = 0.33 ± 0.12
Leading-leg normalised, anterior/posterior ground reaction forces at maximum knee height of trailing leg during crossing (N/kg)	1	Gill and Hung, 2014	No BMI or BMI*condition effects were observed ($p > 0.05$).	
Trailing-leg normalised, medial/lateral ground reaction forces at maximum knee height of leading leg during crossing (N/kg)	1	Gill and Hung, 2014	OB, high vs. medium obstacle: $p = 0.01$ No other effects were observed.	<u>Medium obstacle (11 cm):</u> NW = 0.19 ± 0.06 OB = 0.04 ± 0.02 <u>High obstacle (16 cm):</u> NW = 0.12 ± 0.07 OB = 0.19 ± 0.05 ($\uparrow 375\%$ vs. medium obstacle)
Leading-leg normalised, medial/lateral ground reaction forces at maximum knee height of trailing leg during crossing (N/kg)	1	Gill and Hung, 2014	No BMI or BMI*condition effects were observed ($p > 0.05$).	

Gait Parameters	Number of Studies	Study	Between-Group Differences	Results (Mean $\pm$ SD or Median (IQR)) and Direction of Difference ($\uparrow\downarrow$)
Trailing-leg normalised, vertical ground reaction forces at maximum knee height of leading leg during crossing (N/kg)	1	Gill and Hung, 2014	OB, high vs. medium obstacle: $p = 0.05$ NW, medium vs. low obstacle: $p = 0.05$ No other effects were observed.	<u>Low obstacle (4 cm):</u> NW = 1.38 ± 0.27 OB = 1.99 ± 0.19 <u>Medium obstacle (11 cm):</u> NW = 2.14 ± 0.22 ($\uparrow$ 55.1% vs. low obstacle) OB = 1.58 ± 0.29 <u>High obstacle (16 cm):</u> NW = 1.92 ± 0.26 OB = 2.23 ± 0.24 ($\uparrow$ 41.1% vs. medium obstacle)
Leading-leg normalised, vertical ground reaction forces at maximum knee height of leading leg during crossing (N/kg)	1	Gill and Hung, 2014	No BMI or BMI*condition effects were observed ($p > 0.05$).	

CV: coefficient of variation; COM: centre of mass; HM: medial heel; HL: lateral heel; M1-M5: metatarsal areas, MF: midfoot; NS: non-significant differences; NW: normal-weight group; OB: overweight/obese group; OBI: Class I obesity group; OBII: Class II obesity group; OBIII: Class III obesity group; T1: hallux; T2-5: toes.

Regarding gait velocity, both studies that investigated gait velocity [18,22] reported that the OB (>30 BMI), [18] OW/Class I OB ($25 \text{ kg/m}^2 \leq \text{BMI} < 35 \text{ kg/m}^2$), Class II OB ($35 \text{ kg/m}^2 \leq \text{BMI} < 40 \text{ kg/m}^2$), and Class III OB ($\text{BMI} \geq 40 \text{ kg/m}^2$) [22] groups' step crossing velocities were slower than those of the NOB (non-OW/OB) group ($\geq 18.5 \text{ kg/m}^2$ and $< 25 \text{ kg/m}^2$) [18,22]. Results also showed that Class II OB and Class III OB participants had a slower step-crossing velocity than Class I OB participants [22].

Being OB led to a significantly lower crossing step length [18].

The OB group showed a significantly lower cadence [18].

OB individuals spent less time in single limb support [18].

The OB group had a greater step width [18].

OB individuals spent more time in the double-limb support phase [18].

The OW/Class I OB group spent more time in stance than the NOB and Class II OB groups [22].

The OW/Class I OB, Class II OB, and Class III OB groups had lower swing times during crossing [22].

OB individuals showed faster COM anterior/posterior (A/P) acceleration when crossing the low obstacle (4 cm) during both-leg crossing [20]. Additionally, when the trailing leg crossed the obstacle, COM A/P acceleration was faster on low obstacles than on medium and high obstacles, but only for the OB group [20].

Regarding leg motion during crossing, OB individuals took longer from foot lift to maximum knee height and less time from maximum knee height to foot contact in the high obstacle (16 cm) condition, with obstacle conditions having no effects on maximum knee height [19].

The OB group had a smaller ankle angle at foot contact during the low obstacle (4 cm) condition [19]. Regarding vertical clearance, OB individuals showed greater trailing-leg toe clearance in the low (4 cm) obstacle condition than in the high one (16 cm), whereas the NOB group showed greater trailing-toe clearance in the high obstacle condition than in the low one. No influence of OB was observed for leading-leg toe clearance [19].

The OB group's leading-leg frontal hip angle at maximum knee height was greater in high (16 cm) obstacle conditions than in medium (11 cm) and low (4 cm) ones. No effects were observed for the NOB group [20].

The OB group showed a greater trailing leg sagittal knee angle at maximum knee height than the NOB group for the low and high obstacle conditions, but no effect was observed for the medium obstacle condition [20].

Regarding temporal foot data, there were no differences between the OB and NOB groups regarding their relative temporal data at initial and final contact or the contact duration of the plantar areas assessed (HL; HM; MF; M1; M2; M3; M4; M5; T2-5; T1) [21].

Regarding the coefficient of variation of gait velocity, no differences were found between the OW/Class I OB and NOB groups [22]. The Class II OB and Class IIB OB groups had a greater coefficient of variation of velocity than the NOB and OW/Class I OB groups [22].

3.6.2. Kinetic Parameters

Table 7 reports the influence of OW/OB on kinetic parameters during obstacle crossing. Gill and Hung, 2014 investigated kinetic parameters during obstacle crossing [20].

Regarding trailing-leg normalised ground reaction forces (GRF), the OB group showed a greater trailing-leg normalised A/P GRF during the low obstacle condition (4 cm) than in the medium (11 cm) and high conditions (16 cm) [20]. The NOB group showed greater trailing-leg normalised A/P GRF in high obstacle conditions than in medium and low ones [20]. Trailing-leg normalised medial/lateral (M/L) GRF was only greater in the high obstacle condition than in the medium one for the OB group [20]. In the OB group, trailing leg normalised vertical GRF was greater in the high obstacle condition than in the medium the medium obstacle condition than during the low one.

For leading-leg normalised GRF, no effects on the OB group were observed for any GRF [20].

3.7. Synthesis

Five studies were considered eligible and were retained [18–22]. Overall, these studies were evaluated as “good” despite their lack of detail and clarity on the clinical implications of their research. Among these 5 studies, 2 included children [19,20], and 3 included adults [18,21,22]. One study used an obstacle height that varied according to the participant’s leg length (30% of leg length) [21], while four studies used three fixed obstacle heights [18–20,22]. All the studies [18–22] included single-task conditions, used self-selected walking speed instruction, and had the same number of experimental sessions ($n = 1$) and trials per obstacle crossing conditions ($n = 5$). Finally, all the studies assessed kinematics [18–22], one assessed

kinetics [20], and none investigated muscle activity or obstacle contact. Compared to normal individuals crossing obstacles, overweight or obese individuals exhibited lower velocity [18,22], shorter step length [18], lower cadence [18] and less time spent in single limb support [18]. They also exhibited increased step width [18], more time spent in double support [18], and greater trailing leg ground force reaction [20] and center of mass acceleration [20]. Furthermore, these observed between-group differences were also dependent on obstacle height [19,20].

4. Discussion

This work aimed to systematically review and summarize all the available biomechanical-parameter data regarding the influence of OW and OB across the lifespan on obstacle crossing tasks during walking tests. Our broad search and selection retained five studies for evaluation. Two studies involved children [19,20], and three involved adults [18,21,22], for a total of 82 NW individuals and 132 OW/OB individuals. Their performances in the different obstacle-crossing tasks were assessed using a wide variety of kinematic and kinetic parameters. Overall, results suggested that compared to NW individuals, OW and OB individuals walked more slowly and with a lower cadence, shorter step length, shorter single-limb support duration, shorter swing time, longer leg-raising and shorter leg-dropping times, and a smaller ankle angle at foot contact.

4.1. Influence of Overweight/Obesity on Kinematic Parameters during Obstacle Crossing

The most consistent between-group difference (NW vs. OB) in obstacle-crossing performance was the lower gait velocity in OB adults reported in two studies comparing them to NW adults [18,22]. One of those two studies [22] reported that adults in the OW/Class I OB (≥ 25 kg/m² and < 35 kg/m²) group had faster gait velocities and less variable velocities than those in the Class II OB (≥ 35 kg/m² and < 40 kg/m²) or Class III OB (> 40 kg/m²) groups. In addition to slower velocity, Desrochers et al. (2021) [18] reported that OB adults had a greater step width and double-limb support duration and shorter step length, single-limb support duration, and cadence than NW individuals. This study's authors [18] proposed the following interpretation for their results: "These gait changes likely represent adaptive behaviors in the face of unstable postural control, where obese individuals increase their base of support for a greater amount of time relative to a single gait cycle" [18]. It is noteworthy that these authors [18] further speculated that the shorter single-limb support duration measured in OB adults

might increase the likelihood of tripping as they cross the obstacle more quickly and with less clearance.

All five studies assessed spatial outcome measures of gait [18–22]. Ankle angle at landing after obstacle crossing differed significantly between NW and OB children in the low obstacle condition (4 cm) [19]. NW children tended to land in a neutral ankle-angle position (around 90°, corresponding to a flat-foot landing strategy), whereas OB children were more dorsiflexed (<90°, corresponding to a heel–toe landing strategy) [19]. The study authors [19] suggested that NW children may have used a flat-foot strategy during obstacle crossing because it was the most useful for increasing landing stability, as a heel–toe strategy was less stable. Walking impairments could lead to falls and injuries in OB children [40]. Note that the heel–toe landing strategy reported in OW/OB children was not observed in OB post-menopausal women, who exhibited similar relative initial, final, and duration of contact for all ten-foot areas and foot total-contact duration to NW post-menopausal women [21]. NW and OB children had different trailing-vertical-toe clearances depending on the obstacle condition [20]. Interestingly, OB children had a higher clearance over low obstacles than over high ones, whereas NW children had a higher clearance over high obstacles than over low ones. This study’s authors [20] suggested that: “overweight/obese children’s difficulty with motor planning may have contributed to the use of a less effective strategy when crossing high obstacles. (...) differences in motor skills and strategies used during obstacle crossing can increase the risk of injury; less toe clearance on high obstacles increases the chance of tripping and falling” ([20], p. 51).

All five studies assessed temporal outcome measures of gait [18–22]. Compared with NW children, OB children took longer to reach maximum knee height and less time to move from maximum knee height to foot contact in the high (16 cm) obstacle condition [19]. These authors suggested that this behaviour could stem from OB children’s relatively limited capacity to accelerate lower-leg segments due to the relatively higher effort and energy they expend compared to NW children [19]. They also suggested that the longer time OB children required to lift their knees (with no difference in knee height) compared to NW children may be due to musculoskeletal difficulties [19], especially due to OB children’s heavier lower limbs [41]. This interpretation is supported by overground level-walking data showing that even when over-activating ankle muscles, obesity-typical spatiotemporal changes in gait were observed [42]. However, it is important to mention that this interpretation remains speculative since no studies have directly measured muscle activation during obstacle crossing to compare OB and/or OW individuals to NW ones. This point reinforces the relevance and necessity of future studies

investigating physiological and mechanical mechanisms related to impaired gait control in OW/OB individuals. Interestingly, significant differences in COM anterior/posterior acceleration between NW and OB children were only observed in the low obstacle condition (4 cm), where COM acceleration at the maximum knee height of both legs during crossing was higher among OB children [20]. The authors suggested that this observation could reflect the difficulties OB children had in controlling forward acceleration [20] when crossing a low obstacle.

4.2. Influence of Overweight/Obesity on Kinetic Parameters during Obstacle Crossing

The impaired gait control and stability observed during obstacle crossing due to OW/OB were reiterated in the kinetics results. NW and OB children exhibited significant differences in trailing-leg ground force reactions. Compared to the NW group, in the anterior/posterior direction, OB children had a higher normalised ground reaction force in low obstacle conditions than in medium or high obstacle conditions, and in the vertical and medial/lateral directions, their ground forces were significantly higher in the high obstacle condition than in the medium one (Table 7, [20]). Among NW children, differences in obstacle conditions were only observed in the anterior/posterior direction (a higher value on the high obstacle condition than on the medium or low ones) and the vertical direction (a higher value on the medium obstacle condition than on the low one) [20]. This study's authors [20] suggested that OB children's balance issues [43] and musculoskeletal disorders [41] could have been exacerbated by their larger hip abduction angles and higher vertical and medial/lateral ground reaction forces, especially on high obstacles. They also suggested that OB children's efforts to maintain stability could have been more difficult due to changes in hip abduction angles and the vertical and medial/lateral ground reaction forces on high obstacles [44].

4.3. Limitations and Strengths

The present systematic review had some limitations, most notable of which was the low number of studies ($n = 5$) [18–22] meeting our selection criteria and their heterogeneity, including differences in the sample populations, experimental procedures, and gait outcomes. Indeed, participants' age groups differed widely between the 5 included studies; two included children aged 4–13 years old [19,20], while three included adults [18,21,22] aged 36.16 ± 12.76 [22] and 57.1 ± 4.7 years old [21], resulting in small sample sizes within each age category (with a total of 24 OW/OB child participants vs. 22 NW child participants [19,20] and 108

OW/OB adult participants vs. 60 NW adult participants) [18,21,22]. However, the large age range of the individuals can also be regarded as a strength of the present review that allowed us to summarize the available data regarding the influence of overweight and obesity across the lifespan on obstacle crossing during walking. Another limitation is that none of the studies that included both male and female participants [18–20] evaluated the influence of sex on gait outcomes, although previous studies have reported sex differences in gait patterns during unobstructed level walking [45]. It is also noteworthy that although all the studies included had assessed BMI-group-related differences in gait outcomes during obstacle crossing [18–22], none had specifically reported the possible influence of body mass and body height, i.e., the two constitutive anthropometric parameters of BMI. This observation is all the more important given that 4 of the 5 included studies [18–20,22] used three fixed obstacle heights (low, medium and high obstacles, measuring from 4 cm to 16 cm), i.e., not personalised to each participant's bodily dimensions. Note that, in an effort to scale the difficulty of an obstacle crossing task to each participant's bodily dimensions, one of the five included studies [21] used an obstacle height that reflected a percentage of each individual's leg length (i.e., 30%, representing approximately 22 cm for NW and OW/OB individuals) [21]. In addition to the above-mentioned differences in sample populations and experimental procedures, the present systematic review also revealed the heterogeneity in gait outcomes in each of the included articles, which further hampered the comparison of published results. Interestingly, although it is likely that greater toe–obstacle clearance may help decrease the risk of tripping over an obstacle (e.g., [31,46–49]), this parameter (namely leading-leg toe clearance and trailing-leg toe clearance) was reported in only one of the five included studies [20]. Furthermore, participants' obstacle contacts (errors) during the execution of the obstacle-crossing task were not reported in any of the 5 included studies.

4.4. Practical Implications and Future Directions

Given the results, limitations, and strengths of the present review, several practical implications can be considered. It is presumable that the performance of an obstacle crossing task depends on the participant's height (and/or their lower limb length) and the height of the obstacle [31]. Accordingly, a description of the participant's height and leg length should be reported in a systematic way. As above-mentioned, in addition, or in combination with the influence of anthropometric parameters, future studies should investigate how sex could affect the performance of obstacle-crossing tasks in normal weight and OW/OB individuals. Finally,

we believe that obstacle contacts and foot clearances should be assessed and reported in a systematic way. We believe, indeed, that these parameters could be used to identify OW/OB individuals at risk of falling and to evaluate the outcomes of interventions aimed at fall prevention

5. Conclusions

Despite the small number of studies included, the present findings suggest that overweight and obesity do indeed affect kinematic and kinetic gait parameters during obstacle-crossing tasks executed by both children [19,20] and adults [18,21,22]. At this point, however, the kinematic parameters assessed in each study were diverse; only one of these five studies investigated kinetics, and none assessed muscular parameters or obstacle contacts. These could be appropriate research elements for future studies, as could investigating the influence of specific anthropometric parameters. Finally, these findings should be interpreted with caution as no overarching or generalizable conclusions could be drawn regarding the influence of overweight and obesity across the lifespan on obstacle crossing during walking.

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4. Contribution 2: Obstacle crossing task during walking and body mass index: a scoping review of Brazilian studies

Chardon M., Barbieri FA., Petit P., & Vuillerme N. Obstacle avoidance task during walking and body mass index: a scoping review of Brazilian studies (submitted)

Abstract

Background: Being overweight is a major public health issue that represents a worldwide pandemic of increasing incidence, in particular in Brazil. In addition to its well-documented adverse effects on the cardiovascular system, overweight, defined as a body mass index (BMI) $\geq 25.0 \text{ kg/m}^2$, also leads to functional deficits related to mobility. In particular, obstacle avoidance while walking, such as stepping over a curb, becomes more challenging for overweight individuals and could lead to obstacle-related trips and falls.

Aim: This scoping review examined existing research to describe the BMI of Brazilian participants included in published studies on obstacle avoidance during walking.

Method: A scoping review was conducted using the Web of Science database. Only records examining Brazilian adults performing obstacle avoidance while walking were included. BMI distributions were studied using either individual participant data when provided or by generating pseudo-BMI distributions based on reported summary statistics (i.e., arithmetic mean and standard deviation).

Results: Thirty-five studies, including a total of 1253 Brazilian participants, were identified and analyzed. A diverse range of populations were studied, with 76 subgroups, such as people with Parkinson's disease or older adults. BMI was never part of the inclusion/exclusion criteria and was very rarely reported (4 studies, 11%). Individual participant data was provided in 4 studies (11%), while only summary statistics were reported in 33 studies (%). Overall, most subgroups ($n=64$, 84%) reported a mean BMI greater than 25.0 kg/m^2 .

Conclusion: Our results emphasize the importance of considering body mass and height in future studies examining obstacle avoidance during walking, as overweight can impact functional mobility.

1. Introduction

Overweight, including obesity, is defined by the World Health Organization (WHO) as “abnormal or excessive fat deposits that can impair health” [1]. Overweight is typically assessed using the body mass index (BMI), calculated by dividing an individual's body mass (kg) by the square of their height. According to WHO standards, adults are considered overweight when their BMI ranges from 25.0-29.9 kg/m² and obese when it exceeds 30 kg/m² [2]. Overweight is a major global concern because of its rising prevalence and incidence [3], with approximately 43% of the adult worldwide population being overweight, including 16% being obese in 2022 [1].

Overweight is associated with several comorbidities, including coronary heart disease [4], respiratory sleep disorder [5,6], type II diabetes mellitus [7,8], and knee osteoarthritis [9]. It can even lead to sudden death [10]. Overweight is also linked to functional impairments [11], particularly those affecting static and dynamic balance [12,13], as well as gait behaviors [12,14], which place overweight individuals at a higher risk of falling during daily activities such as obstacle avoidance [15,16].

Avoiding an obstacle is a routine task [17] that increases neuromuscular [18] and cognitive demands [19]. Effective execution of obstacle avoidance tasks is crucial, as falling often occurs during this activity. Indeed, more than half of falls in healthy older adults occur while avoiding an obstacle [20], predominantly due to tripping during this task. Obstacle avoidance performance has thus been assessed across various populations, including for instance older adults [20,21], people with Parkinson's disease [22–24], knee osteoarthritis [25,26], and multiple sclerosis [27]. Previous studies reported that overweight and obesity also impact gait behavior during obstacle avoidance [28,29]. More precisely, overweight and obese individuals have reduced gait speed and cadence and increased step width while crossing obstacle compared to their normal-weight counterparts [28,29].

To the best of our knowledge, no study has reviewed and comprehensively summarized available data regarding how and to what extent overweight has been considered in the context of obstacle avoidance while walking, particularly with respect to Brazilian populations. Brazil has one of the highest prevalence rates of overweight and obesity [30] with 37.1% of the people in the overweight class and 24.3% in the obese class in 2023 [31]. Additionally, the projected prevalences by 2030 are estimated to be 38.5% for overweight class, and 29.6% for obesity [32]. To contribute to this effort, this scoping review was specifically designed to examine

existing research to describe the BMI of Brazilian participants included in studies on obstacle avoidance during walking.

2. Methods

The literature search was conducted in accordance with PRISMA-ScR (Preferred Reporting Items for Scoping Reviews) guidelines [33] (supplementary materials). The protocol of this study was not registered.

2.1 Eligibility criteria

This review included only original peer-reviewed articles published in English-language. Editorials, abstracts, letters to the editor, opinions, perspectives, case reports, case studies, books, chapters, reviews, meta-analyses, or other gray literature materials (i.e., government reports, policy statements, issue papers, conference proceedings, preprinted articles, theses, and dissertations) were excluded. Studies investigating obstacle avoidance during walking in Brazilian adults were included.

2.2 Data sources and search strategy

The Web of Science database was searched from inception onwards to March 6, 2024, to identify studies satisfying the search criteria. The search focused on keywords related to the obstacle avoidance task, namely "obstacle avoidance", "obstacle negotiation", "obstacle crossing" or "obstructed walking", as previously done in recent systematic reviews on this topic [34,35]. The search fields were restricted to the abstract, title, and keywords (i.e., topic search). The search was restricted to "Brazil" (country/region filter).

2.3 Study selection

The selection process was performed by two independent reviewers (MC and NV). Titles, abstracts, and keywords were first screened for all studies found to identify potentially relevant articles. The same two reviewers then screened full-length text articles and assessed their eligibility. In cases of discrepancies or disagreements between the two reviewers, a consensus meeting was held until these disagreements were resolved.

2.4 Data extraction

A standardized data extraction form was used by the two reviewers (MC and NV). The following metadata were retrieved: (1) study characteristics; (2) criteria for the inclusion and exclusion of participants; (3) participant characteristics (sample size, sex, age, health status, body mass, body height, and BMI); and (4) description of the obstacle avoidance protocols used.

2.5 BMI calculation

To go beyond a simple synthesis of reported summary statistics regarding BMI and delve into population characteristics (e.g., prevalence proportion of obesity), BMI distributions were studied. When individual BMI data was available, it was extracted and used for analysis. When individual BMI data was not reported but individual data for both body mass and body height was provided, it was used to estimate the corresponding individual BMI distribution by calculating the ratio of body mass (in kilograms) to the square of the associated body height (in meters). If individual data was not provided, pseudo-BMI distributions were generated based on the available summary statistics (i.e., arithmetic mean and standard deviation) reported in the articles using either BMI summary statistics, or as a last resort, both body mass and body height summary statistics [36]. For this latter case, the pseudo-distributions of body mass and body height were randomly generated first, and then the pseudo-BMI distribution was estimated as the ratio of body mass (in kilograms) to the square of the associated body height (in meters). The BMI distributions, in particular the proportions of overweight participants, were compared to data from the general population that were obtained from the WHO [1].

All calculations were carried out using R software 4.3.1® (R Core Team, Vienna, Austria) for Windows 10©. For the pseudo-distribution generation, the body mass, body height, and BMI were considered to follow a normal distribution with an arithmetic mean and standard deviation extracted from the original studies. For each study, participant group (e.g., Parkinson's disease patients), and anthropometric parameter (e.g., body mass), a total of 100,000 random values were generated using the `rnorm` function and the following seed generator: 1234. To prevent abnormal or impossible values, the generated values were restricted (i.e., truncated) to plausible ranges. For body mass, plausible boundaries were defined as 40 kg and 150 kg, while for body height, they were set at 1.40 meters and 2.20 meters, and for BMI, they were defined at 15 kg/m² and 45 kg/m². These choices were made to encompass realistic ranges of anthropometric characteristics.

3. Results

3.1. Study Selection

The database search of Web of Science resulted in 200 potentially relevant records (Fig. 1). One hundred and sixty articles were excluded based on the eligibility criteria after reading abstract, titles and keywords. Forty full-texts articles were read, with 5 records that were excluded, including two conference papers [37,38], one including non-Brazilian participants [39], and two with no obstacle avoidance task performed (i.e., not a physical obstacle placed in a pathway) [40,41].

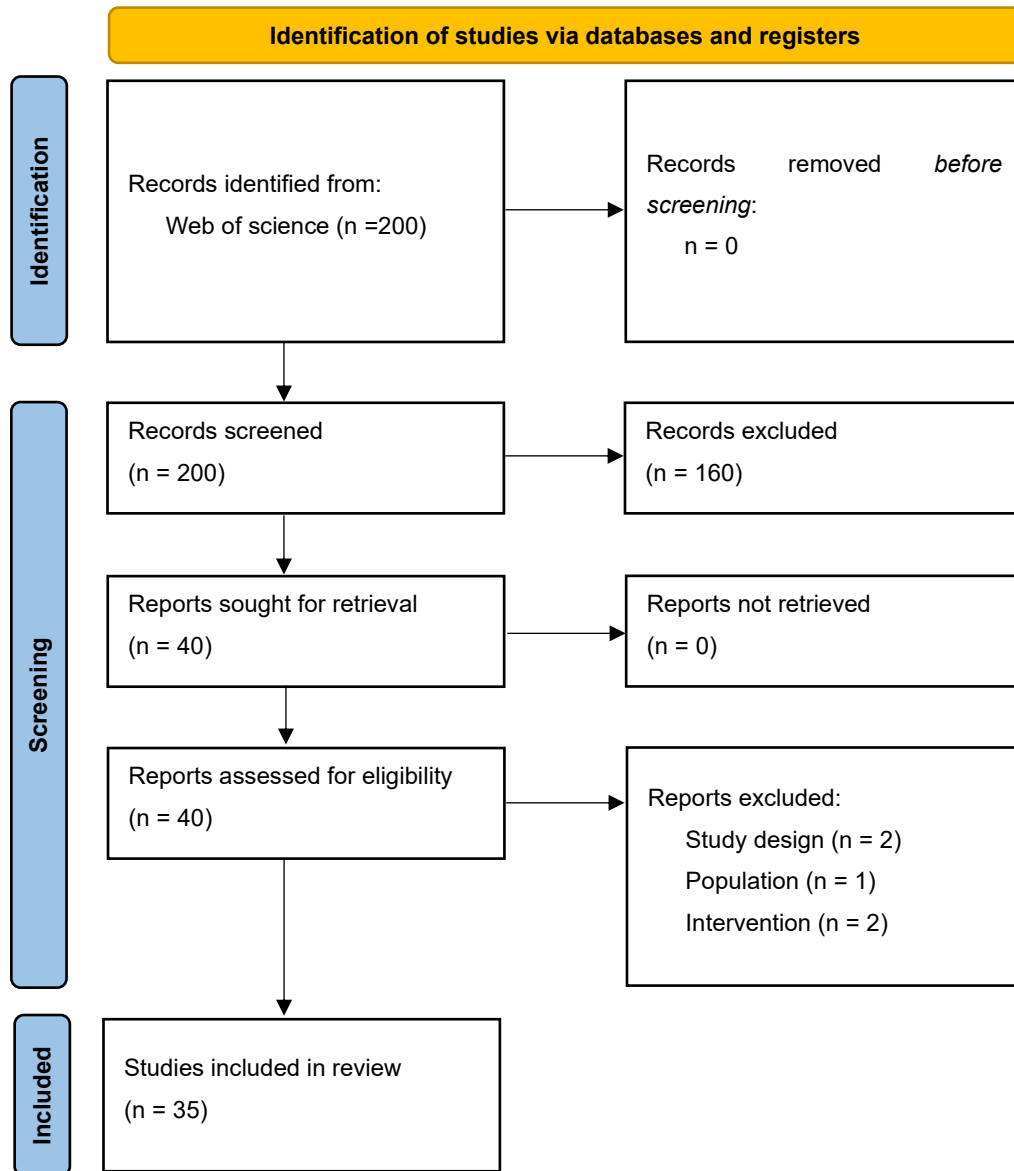


Figure 2. Flow-Diagram of the studies selection. The number of original articles is indicated at each stage of the search.

3.2. Study characteristics

Information about the study characteristics is presented in Table 1. All included studies had a cross-sectional or case-control design.

3.2.1 Publication year

Papers were published between 2009 [42] and 2023 [43,44], with between 0 (2016) to 5 (2018 and 2021) publications per year (Figure 2).

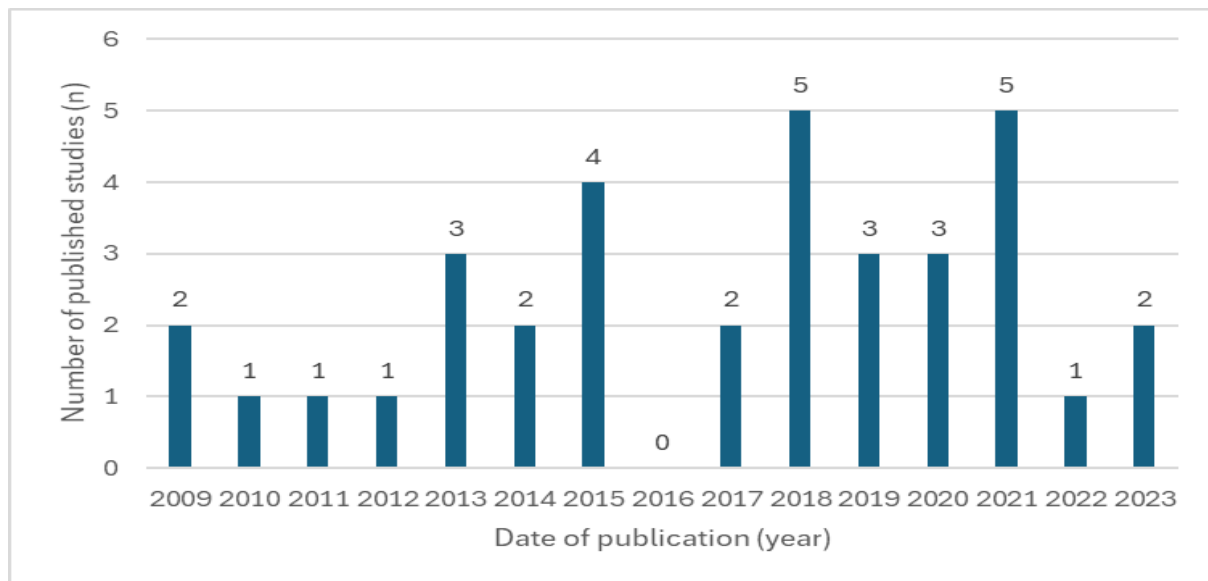


Fig. 2: Number of included studies published per year.

3.2.2 Journal

The studies were published in 21 different journals, with no study published in Brazilian journals. Most studies were published in *Gait & Posture* ($n = 10$, 28.6%) [27,45–53], while other journals published between one or two studies.

3.2.3 Sample size

A total of 1253 participants were analyzed across the 35 studies. The mean participant sample size was 35.8 ± 25.01 and ranged from 7 [42] to 120 [49]. The overall population consisted of 665 healthy individuals (53%) and 588 individuals diagnosed with a disease or with fall risk. Nine studies (25.7%) included only healthy individual groups [42,48–50,53–57], accounting for a total of 314 participants, with between 7 [42] to 120 [49] participants per study.

Most studies ($n = 25$, 71.4%) included a group of individuals diagnosed with a disease. For these studies, the number of participants ranged from 7 (blind participants) [58] to 65 (Parkinson's disease participants) [52], accounting for a total of 573 participants, with a mean of 22.92 ± 14.75 participants per study. The most investigated pathologies or populations were Parkinson's disease patients ($n = 19$ studies, 54.3%, 472 participants) [22–24,43–47,51,52,59–67], Alzheimer's disease patients ($n = 2$, 5.7%, 33 participants) [68,69], people with multiple sclerosis ($n = 2$, 5.7%, 37 participants) [27,70], knee osteoarthritis ($n = 1$, 2.9%, 24 participants) [71], blind individuals ($n = 1$, 2.9%, 7 participants) [58]. One study (2.9%) investigated a group of older females at risk of falling ($n = 1$, 2.9%, 15 participants) [72]. Of the 26 studies that

included groups of participants diagnosed with a disease or at risk of falling, 21 studies (60%) also included a group of healthy individuals (i.e., not diagnosed with a disease, or without a fall risk).

The number of participants in healthy groups accounted for 351 participants, ranging from 7 [58] to 45 participants [52], with a mean of 16.71 ± 7.93 participants. In most studies (85.7%), there was a group including only healthy individuals. Overall, the number of healthy participants accounted for a total of 665 participants ranging from 7 [58] to 120 [49], with a mean of 22.17 ± 23.76 participants.

Table 1. Study characteristics in a chronological order of publication

Author, year	Country	Title	Journal	Conflict of interest	Funding
Gobbi et al., 2009 [42]		Obstacle stepping and body scale modulating parameters	Perceptual and Motor Skills	Not reported	FUNDUNESP (#006-13/09-DFP)
Rodrigues et al., 2009 [58]		Sensitivity of toe clearance to leg joint angles during obstacle crossing: Effects of unavailability of visual information	Journal of Sport and Exercise Psychology	Not reported	Not reported
Vitorio et al., 2010 [45]		Effects of obstacle height on obstacle crossing in mild Parkinson's disease	Gait & Posture	The authors have no conflicts of interest to disclose	FAPESP (#2005/00775-6)
Da Silva et al., 2011 [54]		Adaptive locomotion for Crossing a moving obstacle	Motor Control	Not reported	Not reported
Menuchi et al., 2012 [55]		Optic flow contribution to locomotion adjustments in obstacle avoidance	Motor Control	Not reported	Not reported
Vitorio et al., 2013 [46]		Influence of visual feedback sampling on obstacle crossing behavior in people with Parkinson's disease	Gait & Posture	The authors have no conflicts of interest to disclose. All authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) our work and manuscript	FAPESP (#2007/06261-0)
Pieruccini-Faria et al., 2013 [59]		Evaluating the acute contributions of dopaminergic replacement to gait with obstacles in Parkinson's disease	Journal of Motor Behavior	Not reported	FUNDUNESP, CNPq, FAPESP (#2005/00775-6)

Author, year	Country	Title	Journal	Conflict of interest	Funding	
Barbieri et al., 2013 [48]		Effect of muscle fatigue and physical activity level in motor control of the gait of young adults	Gait & Posture	The authors have no conflicts of interest to disclose. All authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) our work and manuscript.	FAPESP (# 2009/51272-5); CAPES	Effect of muscle fatigue and physical activity level in motor control of the gait of young adults
Barbieri et al., 2014 [49]		Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing	Gait & Posture	None declared	CAPES	Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing
Vitorio et al., 2014 [47]		Disease severity affects obstacle crossing in people with Parkinson's disease	Gait & Posture	The authors have no conflicts of interest to disclose. All authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) our work and manuscript	FAPESP (#2010/07040-0)	Disease severity affects obstacle crossing in people with Parkinson's disease
Simieli et al., 2015 [68]		Obstacle crossing with dual tasking is a danger for individuals with Alzheimer's disease and for healthy older people	Journal of Alzheimer's Disease	Nothing to disclose for all authors	FAPESP (#2009/54275-5)	Obstacle crossing with dual tasking is a danger for individuals with Alzheimer's disease and for healthy older people
Pegoretti et al., 2015 [71]		Additional sensory input improves the strategy of stepping over obstacle in individuals with knee osteoarthritis	Journal of Back and Musculoskeletal Rehabilitation	Not reported	Not reported	Additional sensory input improves the strategy of stepping over obstacle in individuals with knee osteoarthritis

Author, year	Country	Title	Journal	Conflict of interest	Funding
Barbieri et al., 2015 [69]	Variability in obstacle clearance may (not) indicate cognitive disorders in Alzheimer disease	Alzheimer Disease & Associated Disorders	The authors declare no conflicts of interest	FAPESP (#2009/54275-5; #2011/00414-4); FUNDUNESP (#0412/011/14)	Variability in obstacle clearance may (not) indicate cognitive disorders in Alzheimer disease
Guadagnin et al., 2015 [50]	Effects of regular exercise and dual tasking on spatial and temporal parameters of obstacle negotiation in elderly women	Gait & Posture	The authors declare that they have no conflict of interest concerning the content of the paper	CAPES	Effects of regular exercise and dual tasking on spatial and temporal parameters of obstacle negotiation in elderly women
Simieli et al., 2017 [61]	The variability of the steps preceding obstacle avoidance (approach phase) is dependent on the height of the obstacle in people with Parkinson's disease	Plos One	The authors have declared that no competing interests exist	FAPESP (# 2013-21841-3)	The variability of the steps preceding obstacle avoidance (approach phase) is dependent on the height of the obstacle in people with Parkinson's disease
Orcioli-Silva et al., 2017 [51]	Walking behavior over multiple obstacles in people with Parkinson's disease	Gait & Posture	None	FAPESP (# 2013/27032-0)	Walking behavior over multiple obstacles in people with Parkinson's disease
Barbieri et al., 2018 [22]	Obstacle avoidance increases asymmetry of crossing step in individuals with Parkinson's disease and neurologically healthy individuals	Journal of Motor Behavior	Not reported	FAPESP (#2013/00925-4)	Obstacle avoidance increases asymmetry of crossing step in individuals with Parkinson's disease and neurologically healthy individuals
Orcioli-Silva et al., 2018 [52]	Objective measures of unobstructed walking and obstacle avoidance in Parkinson's disease subtypes	Gait & Posture	The authors have no conflicts of interest to disclose	FAPESP (#2010/07040-0; #2013/27032-0; #2014/22308-0)	Objective measures of unobstructed walking and obstacle avoidance in Parkinson's disease subtypes
Costa et al., 2018 [56]	Effect of a cognitive task on online adjustments when avoiding stepping on an obstacle and stepping on a target during walking in young adults	Experimental Brain Research	The authors declare that they have no conflict of interest	FAPESP (#2016/02202-8)	Effect of a cognitive task on online adjustments when avoiding stepping on an obstacle and stepping on a target during walking in young adults
Simieli et al., 2018 [60]	Variability of crossing phase in older people with Parkinson's disease is dependent of obstacle height	Scientific Reports	The authors declare no competing interests	FAPESP (#2014/20549-0)	Variability of crossing phase in older people with Parkinson's disease is dependent of obstacle height

Author, year	Country	Title	Journal	Conflict of interest	Funding	
Penedo et al., 2018 [23]		Influence of obstacle color on locomotor and gaze behaviors during obstacle avoidance in people with Parkinson's disease	Experimental Brain Research	The authors declare that they have no conflict of interest	Not reported	Influence of obstacle color on locomotor and gaze behaviors during obstacle avoidance in people with Parkinson's disease
Guadagnin et al., 2019 [53]		Correlation between lower limb isometric strength and muscle structure with normal and challenged gait performance in older adults	Gait & Posture	Not reported	CAPES; CNPq	Correlation between lower limb isometric strength and muscle structure with normal and challenged gait performance in older adults
Nobrega-Sousa et al., 2019 [62]		Usual walking and obstacle avoidance are influenced by depressive and anxiety symptoms in patients with Parkinson's disease	Geriatrics Gerontology International	The authors declare no conflict of interest	FAPESP (#2010/07040-0; #2014/22308-0); CAPES	Usual walking and obstacle avoidance are influenced by depressive and anxiety symptoms in patients with Parkinson's disease
Conceicao et al., 2019 [63]		Utility of center of pressure measures during obstacle crossing in prediction of fall risk in people with Parkinson's disease	Human Movement Science	Not reported	FAPESP (#2010/07040-0; #2014/22308-0); CAPES	Utility of center of pressure measures during obstacle crossing in prediction of fall risk in people with Parkinson's disease
Orcioli-Silva et al., 2020 [64]		Double obstacles increase gait asymmetry during obstacle crossing in people with Parkinson's disease and healthy older adults: A pilot study	Scientific Reports	The authors declare no competing interests	FAPESP (#2013/27032- 0); CNPq (#309045/2017-7), CAPES	Double obstacles increase gait asymmetry during obstacle crossing in people with Parkinson's disease and healthy older adults: A pilot study
Nobrega-Sousa et al., 2020 [57]		Prefrontal cortex activity during walking: effects of aging and associations with gait and executive function	Neurorehabilitation and Neural Repair	The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.	CNPq (#166467/ 2017-0); FAPESP (#2014/22308-0; 2016/21499-1); CAPES	Prefrontal cortex activity during walking: effects of aging and associations with gait and executive function
Ceccon et al., 2020 [72]		Relationship between performance in the timed up & go and foot clearances during obstacle crossing in older women	Topics in Geriatric Rehabilitation	The authors declare that they do not have conflicts of interest concerning the content of this manuscript	CNPq; FAPERGS; CAPES	Relationship between performance in the timed up & go and foot clearances during obstacle crossing in older women

Author, year	Country	Title	Journal	Conflict of interest	Funding
Orcioli-silva et al., 2021a [66]	Cortical activity underlying gait improvements achieved with dopaminergic medication during usual walking and obstacle avoidance in Parkinson disease	Neurorehabilitation and Neural Repair	The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article	CAPES; FAPESP (#2017/19845-1; #2016/21499-1; #2014/22308-0); CNPq (#429549/2018-0)	Cortical activity underlying gait improvements achieved with dopaminergic medication during usual walking and obstacle avoidance in Parkinson disease
Santinelli et al., 2021 [27]	Cortical activity and gait parameter characteristics in people with multiple sclerosis during unobstructed gait and obstacle avoidance	Gait & Posture	The authors report no declarations of interest	FAPESP (#2018/18078-0); CAPES	Cortical activity and gait parameter characteristics in people with multiple sclerosis during unobstructed gait and obstacle avoidance
Orcioli-silva et al., 2021b [65]	Is cortical activation during walking different between Parkinson’s disease motor subtypes?	Journal of Gerontology: Biological Science	None declared	CAPES; FAPESP (#2017/19845-1; #2016/214991; #2014/22308-0); CNPq (#429549/2018-0)	Is cortical activation during walking different between Parkinson’s disease motor subtypes?
Santos et al., 2021 [24]	Being physically active minimizes the effects of leg muscle fatigue on obstacle negotiation in people with Parkinson’s disease	Journal of Biomechanics	The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper	CAPES; CNPq (#142057/2017-7; 309045/2017-7); FAPESP (#2011/05144-5)	Being physically active minimizes the effects of leg muscle fatigue on obstacle negotiation in people with Parkinson’s disease

Author, year	Country	Title	Journal	Conflict of interest	Funding
Casal et al., 2021 [67]		Postural adjustments and biomechanics during gait initiation and obstacle negotiation: a comparison between akinetic-rigid and hyperkinetic Parkinson's disease	Frontiers in Physiology	The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest	FAPERGS; CAPES
Santinelli et al., 2022 [70]		Is BDNF related to spatial-temporal gait parameters in people with multiple sclerosis? An observational study	Multiple Sclerosis and Related Disorders	The Authors declare that there is no financial/personal interest which could impact in this manuscript	FAPESP (#2018/18078-0); CAPES
Vitorio et al., 2023 [43]		Electrocortical dynamics of usual walking and the planning to step over obstacles in Parkinson's disease	Sensors	The authors declare no conflict of interest	FAPESP (#2014/22308-0; 2017/19845-1); CAPES
Faria et al., 2023 [44]		(A)symmetry during gait initiation in people with Parkinson's disease: A motor and cortical activity exploratory study	Frontiers in Aging Neuroscience	The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest	FAPESP (#2018/21870-7; #2019/24752-8; #2016/14950-6; and #2022/02971-2); CAPES

CAPES: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CNDq: Conselho Nacional de Desenvolvimento Científico e Tecnológico, FAPERGS: Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul, FAPESP: Sao Paulo Research Foundation, FUNDUNESP: Fundação para o Desenvolvimento da UNESP.

3.3. Participant characteristics

Basic information regarding participants' demographic and anthropometric parameters is reported in Table 3.

3.3.1. Inclusion/exclusion criteria

Table 2 presents the inclusion and exclusion criteria considered in each study. BMI, body height and body mass were never used as an inclusion and/or exclusion criteria. The main exclusion criteria reported were either any factors that could interfere with gait (n = 9, 25.7%) [22,48–50,52,65,66,68,69], neuromuscular/osteoarthritic impairments (n = 4, 11.4%) [47,55,56,59], or musculoskeletal diseases other than the disorder investigated (n = 3, 8.6%) [43,45,46].

Table 2. Inclusion and exclusion criteria

Author, year	Inclusion/Exclusion criteria
Gobbi et al., 2009	No known problems of motor and sensory functions
Rodrigues et al., 2009	Blind: Classified as type B1 in accordance to the International Blind Sport Federation (IBSA) criteria
Vitorio et al., 2010	Inclusion criteria: older than 60 years of age, independent walker and no cognitive impairment as judged by the MEMS. Older individuals without neurological, musculoskeletal or cardiorespiratory impairments were included in the control group. People with PD without other neurological, musculoskeletal or cardiorespiratory diseases and classified in Stages I–III of the H&Y were included Exclusion criteria: any history of orthopedic, cardiovascular, or psychiatric disorders
Da Silva et al., 2011	Normal or corrected-to-normal vision and without any known neurological or musculoskeletal system impairment or sensory-motor disorders that might make accomplishing the task difficult
Menuchi et al., 2012	No neuromuscular impairments or visual limitations that were not corrected by corrective lenses and without history of convulsion or dizziness in stroboscopic environments
Vitorio et al., 2013	PD: Inclusion criteria: independent walker and no cognitive impairment, classified into Stages 1–2.5 of the H&Y, did not have other neurological, musculoskeletal, or cardiorespiratory diseases, and were taking regular PD medication Healthy: no neurological, musculoskeletal, or cardiorespiratory impairments

Author, year	Inclusion/Exclusion criteria
Pieruccini-Faria et al., 2013	PD: only taking levodopa or carbidopa as their anti- Parkinsonian dopaminergic replacement therapy. The specialist also excluded participants experiencing freezing of gait. Only participants between stages 1.5 and 3 of the Hoehn and Yahr scale were included in the study. Participants with any osteoarthritic issue, dementia, visual problems that could not be corrected for lenses, or any other non-PD neurological comorbidities were excluded Healthy: no musculoskeletal or visual impairment (not corrected by lens) or history of neurological diseases
Barbieri et al., 2013	Exclusion criteria: factors that could interfere with gait and other experimental procedures, such as medication use, presence of osteomyoarticular, neuromuscular or cardio-respiratory diseases and balance and vision disorders
Barbieri et al., 2014	Exclusion criteria: factors that could interfere with gait (such as using an assistive devices), diabetes, medication use, presence of lower limb musculoskeletal, neuromuscular or cardio-respiratory diseases and balance and vision disorders
Vitorio et al., 2014	Inclusion criteria: independent walker, no cognitive impairment, and no musculoskeletal or cardiorespiratory impairments
Simieli et al., 2015	AD: participants with musculoskeletal, orthopedic, or neurological disorders that affected walking, other than those characteristic of AD, were excluded from the study. Individuals with stage three or higher AD or did not understand the task were excluded Healthy: any complications, such as musculoskeletal, orthopedic, or neurological disorder were excluded
Pegoretti et al., 2015	The volunteers were excluded if they had performed physical therapy for the affected knee in the previous six months or if they had a history of lower limb arthroplasty; knee surgery in the previous three months; intra-articular injection of corticosteroids in the previous six months; previous use of external sensory devices, such as tape and/or a brace; or any other clinical condition which might affect gait or cognitive function, as in other associated musculoskeletal conditions, neurological diseases and fracture. Also, eventual concomitant metabolic diseases must be controlled for the participant to take part in the study
Barbieri et al., 2015	Exclusion criteria: musculoskeletal, orthopedic, or neurological disorders other than AD that affect walking
Guadagnin et al., 2015	Inclusion criteria for both groups: able to walk independently; and no auditory, vestibular, visual and/or musculoskeletal impairments that could influence locomotion or communication with the researchers
Simieli et al., 2017	Exclusion criteria for both groups: age under 60, cognitive decline, history of orthopedic problems, use of any walking aid, vision deficits (glaucoma, cataract) and vestibular problems (dizziness, labyrinthitis) that prevented performance of the experimental protocol. Participants with diabetes mellitus were also excluded, since plantar sensitivity may be altered and thereby, impair gait. No individuals wore bifocal glasses, and all individuals that wore glasses that corrected their visual deficits, such as myopia, farsightedness, astigmatism, were included in the sample. In addition, for older people with PD, the individual was required to be under dopaminergic medication treatment and in a stage of PD up to III according to the H&Y disability scale
Orcioli-Silva et al., 2017	Inclusion criteria: over 60 years of age, able to walk without the use of any aids, not presenting cognitive decline, and not presenting musculoskeletal, orthopedic and/or visual impairments. In addition, an inclusion criterion was that the people with PD had to be taking PD medication and be classified in stages I–III of the H&Y Scale

Author, year	Inclusion/Exclusion criteria
Barbieri et al., 2018	The exclusion criteria comprised (a) suspected parkinsonism before the onset of the study, (b) significant memory impairment (defined as MMSE score < 24), (c) presentation of other parkinsonism syndromes, (d) not presenting independent living in the community, (e) not able to walk without the use of any aids, and (f) disorders that impaired locomotion. In addition, for people with PD, individuals were included in the study if their stage on the H&Y was ≤ 3 and they were under dopaminergic medication treatment
Orcioli-Silva et al., 2018	Patients with PD were included if they were: (a) diagnosed with idiopathic PD (b) H&Y stages I-III; and (c) taking PD medication. Participants were excluded if they had a diagnosis of dementia or co-morbidities likely to affect gait
Costa et al., 2018	Exclusion criteria: visual problems not corrected by glasses, musculoskeletal injuries, vestibular or somatosensory problems and left lower limb dominance.
Simieli et al., 2018	Exclusion criteria for both groups: age under 60, cognitive decline, history of orthopedic problems, use of any walking aid, vision deficits (glaucoma, cataract) and vestibular problems (dizziness, labyrinthitis) that prevented performance of the experimental protocol. Participants with diabetes mellitus were also excluded, since plantar sensitivity may be altered and thereby, impair gait. No individuals wore bifocal glasses, and all individuals that wore glasses that corrected their visual deficits, such as myopia, farsightedness, astigmatism, were included in the sample. In addition, for older people with PD, the individual was required to be under dopaminergic medication treatment and in a stage of PD up to III according to the H&Y disability scale
Penedo et al., 2018	Both groups: (a) inclusion criteria: aged below 50 years, able to walk without assistance, and presenting normal hearing capabilities; (b) exclusion criteria: inadequate visual acuity [20/20 scale through the Snellen chart, with or without the use of corrective lenses as needed], cognitive decline [below 24 points in the MMSE according to years of schooling], history of orthopedic problems, such as acute lower back or lower extremity pain, and history of stroke or traumatic brain injury or other neurological disorders (different than PD) PD exclusion criteria: H&Y scale above stage 3, and taking stable anti-Parkinsonian medication for the past 1 month
Guadagnin et al., 2019	Inclusion criteria: ability to walk independently; no severe auditory, vestibular, visual, and/or neuromusculoskeletal impairments that could prevent them performing one or more tests, not participating in regular physical exercise, and no severe cognitive impairments (the MMSE mean score was above the 23 cutoff point)
Nobrega-Sousa et al., 2019	The exclusion criteria were: aged <60 years, dementia, a history of orthopedic problems that made it impossible to carry out the experimental protocol and a stage >3 on the Hoehn and Yahr scale.
Conceicao et al., 2019	Exclusion criteria: disease at a stage higher than 3 on the H&Y, cognitive decline detected by the MMSE – score < 24, use of walking aids (e.g., cane, walkers, etc.), and a history of orthopedic problems that made it impossible to complete the experimental protocol
Orcioli-Silva et al., 2020	The following exclusion criteria were used: cognitive decline (MMSE score < 24) and musculoskeletal, orthopedic, and/or visual impairments that prevent the subject from performing the required tasks. Patients were included if they were diagnosed with PD according to the UK Brain Bank criteria, classified in stages I-III of the H&Y scale, and were taking PD medication
Nobrega-Sousa et al., 2020	Exclusion criteria: history of orthopedic problems that made it impossible to comply with the experimental protocol and diagnosis of dementia (Montreal Cognitive Assessment score ≤ 17)

Author, year	Inclusion/Exclusion criteria
Ceccon et al., 2020	Inclusion criteria: 65 years of age or older, able to walk independently, without neurodegenerative disease clinically confirmed, without use of prosthesis, and in the case of visual limitation, they should make use of corrective lens. Exclusion criteria: inability to perform the tasks during the experiments.
Orcioli-silva et al., 2021	All participants were >60 years of age, independent walkers, and free of cognitive impairment (MMSE >24), neurological disorders (other than PD), and musculoskeletal, orthopedic, and/or visual impairments that could affect their performance. People with PD had a clinical diagnosis of idiopathic PD, according to the UK Brain Bank criteria, at H&Y stage I to III, and were taking PD medication (levodopa)
Santinelli et al., 2021	Inclusion criteria: no cognitive decline (≥ 24 cut-off points on the MMSE). PwMS were required to report no relapse in the previous three months, not to have taken fampridine medicine, and present a score lower than 4.5 on the EDSS, allowing the participants to walk at least 300 m without assistance. Participants with poor visual acuity or other neurological, orthopedic, cerebellar, oculomotor, cardiac, or respiratory disorders that could impact the experimental protocol were excluded
Orcioli-silva et al., 2021	Exclusion criteria were cognitive impairment (MMSE score <24), neurological disorders (other than PD), and musculoskeletal, orthopedic, and/or visual impairments that could affect performance
Santos et al., 2021	Exclusion criteria were: diagnosis of additional neurological disorders, inability to walk safely and independently, uncontrolled diabetes, hypertension, and cardio-respiratory diseases, PD Stage > 3 on H&Y scale
Casal et al., 2021	Inclusion criteria: They should be on regular drug treatment and have the ability to understand verbal instructions to perform tests. Also, they did not participate in any exercise program in the last 3 months Exclusion criteria: having cognitive impairment, with Montreal Cognitive Assessment reaching at least 21 points, deep brain stimulation surgery, history of vertigo, surgeries in lower limbs during the last year, use of prostheses in the lower limbs, severe heart diseases or other associated neurological diseases and not having conditions of ambulation
Santinelli et al., 2022	Common inclusion criteria included: a) age between 18 and 55 years; b) no cognitive decline (> 24 points in the MMSE); and c) no orthopedic, cerebellar, cardiac, and oculomotor disabilities not corrected by glasses. For PwMS, an additional set of inclusion criteria was used, including d) clinically definitive diagnosis of relapsing-remitting MS (McDonald criteria); e) EDSS score lower than 4.5 and 4 in the Patient Determined Disease Steps; f) relapse-free in the three months prior to data collection, and g) not using fampridine
Vitorio et al., 2023	The participants of both groups were included if they were able to walk unaided and were community-dwelling. Exclusion criteria included the following: diagnosed major depressive disorder; clinical diagnosis of dementia or other severe cognitive impairment (according to recommendations for utilization of the Mini-Mental State Examination—MMSE—in Brazil; cut-off = 20/24 points for illiterates and those who attended formal education, respectively); chronic musculoskeletal or neurological disease (other than PD)

Author, year	Inclusion/Exclusion criteria
Faria et al., 2023	Inclusion criteria for PD: (i) diagnosis from a neurologist indicating the presence of Parkinson's disease determined by the London's Brain Bank, (ii) stage 3 or less on the Hoehn & Yahr scale and (iii) be under drug Parkinson's disease treatment for more than 3-months. The following exclusion criteria were established for both groups: age below 50 years, cognitive decline assessed through the Mini Mental State Examination—MMSE [score below 24pts corrected according to the years of schooling], and orthopedic (such prosthesis), vision (assessed through the Snellen chart test or vestibular (such dizziness) problems that made it impossible to carry out the experimental protocol

Note: AD: Alzheimer's disease, EDSS: Expanded Disability Status Scale, H&Y: Hoehn and Yahr, MMSE: Mini Mental State Exam, PD: Parkinson's disease, PwMS: participants diagnosed with multiple sclerosis

3.3.2 Age

Only one study (2.9%) did not report the participants' age [59]. For this study, the authors reported the age of the Parkinson's disease group ($n = 12$, mean age: 67 ± 6.24 years old), and the "healthy elderly control participants were matched by age, sex, height, body mass, and right lower limb length relative to those participants in the PD group" ($n = 12$, participants) [59]. Participants age ranged from 22.4 ± 2.07 [42] to 78.33 ± 5.23 [68,69] years old. There were 101 aged 20-29 years old (8.1%) [42,48,49,54–57], 120 aged 30-39 years old (9.6%) [27,49,57,58,70], 35 aged 40-49 years-old [49,57], 35 aged 50-59 years old (2.8%) [49,57], 454 aged 60-69 years old (36.2%) [23,24,44–47,49,50,52,57,59,63,65–67,71], and 496 aged 70+ years old (39.6%) [22,24,43,47,49–51,53,57,60–62,64–66,68,69,72]. Two studies (5.7%) specifically examined obstacle avoidance task based on participants' age classified into 6 aged decade groups [49,57].

3.3.3 Sex

Two studies (5.7%) did not report the sex of their included participants [58]. Three studies (8.6%) included only males [24,47,48], while two studies (5.7%) included only females [50,72]. Twenty-one studies (60%) included both male and female participants and reported the number of males and females analyzed, Menuchi and colleagues were contacted and provided the number of males and females in their study group (5 males and 5 females). For four studies (11.4%), the sex repartition of the non-healthy group (i.e., Parkinson's disease and Alzheimer's disease groups) was clearly reported, whereas the healthy/control group was "sex/gender matched" [45,46,59,69]. Finally, for two studies (5.7%), the sex of the healthy/control participants' group was not reported [27,68]. Even though the sex repartition was provided, anthropometric parameters were never provided specifically for each sex.

Table 3. Participant characteristics

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Gobbi et al., 2009	1: undergraduate students	7	F: 6; M: 1	22.4 (2.07)	1.64 (0.07)	64.9 (14.9)	23.9 (3.1) ^[I]	Overall: NW NW: <i>n</i> = 5 (71.4%) OW: <i>n</i> = 1 (14.3%) OB: <i>n</i> = 1 (14.3%)
Rodrigues et al., 2009 ^[I]	2: Blind Normal vision	Blind: 7 Normal vision: 7	Not reported	Blind: 39.3 (11.7) Normal vision: 39.3 (11.5)	Blind: 1.721 (0.08) Normal vision: 1.738 (0.049)	Blind: 79.4 (15.1) Normal vision: 76.4 (10.7)	Blind: 26.8 ^[M] ; 27.1 ^[X] Median: 26.8 [23.2-30.73] Normal vision: 25.3 ^[M] ; 25.4 ^[X] Median: 25.3 [22.93-26.7]	Blind: Overall: OW UW: 5% NW: 31.8% OW: 34.2% OB: 29% Normal Vision: Overall: OW UW: 2.7% NW: 43.8% OW: 43.4% OB: 10.1%
Vitorio et al., 2010	2: PD: Healthy:	PD: 12 Healthy: 12	PD: F: 4; M: 8 Healthy: sex- matched with PD	PD: 67 (6.24) Healthy: 67 (6.44)	PD: 1.64 (0.09) Healthy: 1.62 (0.09)	PD: 65.26 (8.83) Healthy: 66.11 (10.67)	PD: 24.5 (3.5) ^[I] Healthy: mean: 25.2 ^[M] ; 25.5 ^[X] Median: 25.2 [22.1-28.5]	PD: Overall: NW NW: <i>n</i> = 7 (58.3%) OW: <i>n</i> = 4 (33.3%) OB: <i>n</i> = 1 (8.3%) Healthy: Overall: OW UW: 6.2% NW: 42.2% OW: 34.5% OB: 17.2%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Da Silva et al., 2011	1: young adults	10	F: 5; M: 5	22.8 (1.8)	1.70 (0.068)	64.3 (10.1)	Mean: 22.2 ^[M] ; 22.6 ^[X] Median: 22.4 [19.87-25]	Overall: NW UW: 14.2% NW: 60.9% OW: 21.6% OB: 3.3%
Menuchi et al., 2012	1: young adults	10	F: 5; M: 5	23.4 (1.3)	1.6455 (0.0531)	57.83 (8.82)	21.4 ^[M] ; 21.7 ^[X] Median: 21.5 [19.27-23.87]	Overall: NW UW: 17.9% NW: 65.9% OW: 15.1% OB: 1.1%
Vitorio et al., 2013	2: PD: Healthy:	PD: 12 Healthy: 12	PD: F: 4, M: 8* Healthy: Sex matched with PD	PD: 69.8 (5.72)* Healthy: 69.6 (6.04)*	PD: 1.636 (0.0725)* Healthy: 1.621 (0.0669)*	PD: 69.8 (10.75)* Healthy: 68.8 (8.27)*	PD: 26.1 ^[M] ; 25.5 ^[X] Median: 25.2 [22.32-28.3] Healthy: 26.2 ^[M] ; 26.3 ^[X] Median: 26.2 [23.64-28.83]	PD: Overall: OW UW: 5% NW: 42.8% OW: 37.1% OB: 15.1% Healthy: Overall: OW UW: 1.5% NW: 36.6% OW: 45% OB: 17%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Pieruccini-Faria et al., 2013	2: PD and Healthy	PD: 12 Healthy: 12	PD: F: 4; M: 8 Healthy: sex- matched with PD	PD: 67 (6.24) Healthy: age- matched with PD	PD: 1.64 (0.09) Healthy: 1.62 (0.09)	PD: 65.26 (8.83) Healthy: 66.11 (10.67)	PD: 24.5 (3.5) ^[I] Healthy: mean: 25.2 ^[M] ; 25.5 ^[X] Median: 25.2 [22.1-28.5]	PD: Overall: NW NW: <i>n</i> = 7 (58.3%) OW: <i>n</i> = 4 (33.3%) OB: <i>n</i> = 1 (8.3%) Healthy: Overall: OW UW: 6.2% NW: 42.2% OW: 34.5% OB: 17.2%
Barbieri et al., 2013	2: Active young male, inactive young male	Active: 10 Inactive: 10	M: 20	Active: 24.63 (2.85) Inactive: 22.49 (2.95)	Active: 1.787 (0.101) Inactive: 1.788 (0.056)	Active: 73.2 (4.4) Inactive: 82.7 (17.6)	Active: 22.9 ^[M] ; 23.2 ^[X] Median: 22.91 [21.05-25] Inactive: 25.8 ^[M] ; 26.3 ^[X] Median: 26.1 [22.37-29.86]	Active: Overall: NW UW: 4.3% NW: 70.8% OW: 22.8% OB: 2.1% Inactive: Overall: OW UW: 7.2% NW: 35.3% OW: 33.3% OB: 24.2%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Barbieri et al., 2014	6: G20 (20-29 years old), G30 (30-39 years old), G40 (40-49 years old), G50 (50-59 years old), G60 (60-69 years old) and G70 (+70 years old)	G20: 20 G30: 20 G40: 20 G50: 20 G60: 20 G70: 20	M: 120	G20: 24 (2.88) G30: 32.5 (2.74) G40: 44 (2.98) G50: 54.5 (2.25) G60: 64 (2.68) G70: 75.5 (4.5)	G20: 1.78 (0.04) G30: 1.74 (0.06) G40: 1.75 (0.06) G50: 1.71 (0.07) G60: 1.71 (0.06) G70: 1.65 (0.06)	G20: 77.96 (14.74) G30: 79.26 (14.23) G40: 84.83 (15.51) G50: 82.17 (13.4) G60: 77.99 (12.61) G70: 73 (12.26)	G20: 24.6 ^[M] ; 24.9 ^[X] Median: 24.7 [21.65-27.91] G30: 26.2 ^[M] ; 26.4 ^[X] Median: 26.2 [22.94-29.62] G40: 27.6 ^[M] ; 27.9 ^[X] Median: 27.7 [24.18-31.38] G50: 28.1 ^[M] ; 28.3 ^[X] Median: 28.1 [24.72-31.60] G60: 26.7 ^[M] ; 26.8 ^[X] Median: 26.7 [23.59-29.89] G70: 26.8 ^[M] ; 27 ^[X] Median: 26.8 [23.61-30.17]	G20: Overall: NW UW: 8% NW: 44.3% OW: 34.4% OB: 13.3% G30: Overall: OW UW: 4.9% NW: 35.4% OW: 37.1% OB: 22.7% G40: Overall: OW UW: 2% NW: 24.8% OW: 37.8% OB: 35.3% G50: Overall: OW UW: 8% NW: 44.3% OW: 34.4% OB: 13.3% G60: Overall: OW UW: 3.1% NW: 32.8% OW: 39.9% OB: 24.3% G70: Overall: OW UW: 3.3% NW: 32% OW: 38.7% OB: 26.1%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Vitorio et al., 2014	3: Mild PD, moderate PD, Healthy	Mild PD: 15 Moderate PD: 15 Healthy: 15	Mild PD: F: 8; M: 7 Moderate PD: F: 8; M: 7 Healthy: F: 8; M: 7	Mild PD: 69.4 (5.3) Moderate PD: 70.8 (6.9) Healthy: 70.7 (5.1)	Mild PD: 1.598 (0.089) Moderate PD: 1.602 (0.099) Healthy: 1.62 (0.072)	Mild PD: 70.2 (8.9) Moderate PD: 70.9 (15) Healthy: 67 (12.1)	Mild PD: 27.5 ^[M] ; 27.6 ^[X] Median: 27.4 [24.42-30.58] Moderate PD: 27.6 ^[M] ; 27.9 ^[X] Median: 27.6 [23.49-31.96] Healthy: 25.5 ^[M] ; 25.9 ^[X] Median: 25.6 [22.29-29.08]	Mild PD: Overall: OW UW: 1.3% NW: 28.3% OW: 41.6% OB: 28.8% Moderate PD: Overall: OW UW: 5.1% NW: 28.7% OW: 31.1% OB: 35.1% Healthy: Overall: OW UW: 6.1% NW: 39.1% OW: 19.9% OB: 34.9%
Simieli et al., 2015	2: AD, Healthy	AD: 18 Healthy: 16	AD: F: 14; M: 4 Healthy: Not reported	AD: 78.33 (5.23) Healthy: 77.44 (6.19)	AD: 1.53 (0.07) Healthy: 1.52 (0.06)	AD: 62.92 (12.52) Healthy: 62.9 (12.68)	AD: 26.9 ^[M] ; 27.2 ^[X] Median: 26.9 [23.30-30.79] Healthy: 27.2 ^[M] ; 27.6 ^[X] Median: 27.3 [23.67-31.21]	AD: Overall: OW UW: 3.9% NW: 32.4% OW: 34.2% OB: 29.4% Healthy: Overall: OW UW: 3.1% NW: 30.4% OW: 34.4% OB: 32.1%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Pegoretti et al., 2015	1: Individuals with knee OA	24	F: 16; M: 8	60.7 (6.5)	1.6 (0.07)	75.1 (14.4)	28.6 (5.1)	Overall: OW
Barbieri et al., 2015	2: AD and Healthy	AD: 15 Healthy: 15	AD: F: 12; M: 3 Healthy: Sex- matched	AD: 78.33 (5.23) Healthy: 77.44 (6.19)	AD: 1.53 (0.07) Healthy: 1.52 (0.06)	AD: 62.92 (12.52) Healthy: 62.9 (12.68)	AD: 26.9 ^[M] ; 27.2 ^[X] Median: 26.9 [23.30-30.79] Healthy: 27.2 ^[M] ; 27.6 ^[X] Median: 27.3 [23.67-31.21]	AD: Overall: OW UW: 3.9% NW: 32.4% OW: 34.2% OB: 29.4% Healthy: Overall: OW UW: 3.1% NW: 30.4% OW: 34.4% OB: 32.1%
Guadagnin et al., 2015	2: Sedentary and active groups	Sedentary: 12 Active: 12	F: 24	Sedentary: 63 (3) Active: 71 (8)	Sedentary: 1.53 (0.07) Active: 1.55 (0.04)	Sedentary: 68 (15) Active: 63 (6)	Sedentary: 29 ^[M] ; 29.2 ^[X] Median: 29 [24-86- 33.25] Active: 26.2 ^[M] ; 26.2 ^[X] Median: 26.2 [24.88-27.48]	Sedentary: Overall: OW UW: 2.8% NW: 22.9% OW: 30.4% OB: 43.9% Active: Overall: OW UW: 0.1% NW: 26.7% OW: 67.2% OB: 6%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Simieli et al., 2017	2: PD and Healthy	PD: 15 Healthy: 13	PD: F: 7; M: 8 Healthy: F: 6; M: 7	PD: 70.66 (6.55) Healthy: 71.53 (5.42)	PD: 1.63 (0.07) Healthy: 1.59 (0.08)	PD: 70.61 (9.82) Healthy: 70.5 (15.49)	PD: 26.6 ^[M] ; 26.7 ^[X] Median: 26.6 [23.73-29.57] Healthy: 27.9 ^[M] ; 28.2 ^[X] Median: 27.9 [23.74-32.4]	PD: Overall: OW UW: 2.1% NW: 33.6% OW: 42.2% OB: 22.1% Healthy: Overall: OW UW: 4.7% NW: 27.3% OW: 30.4% OB: 37.6%
Orcioli-Silva et al., 2017	2: PD and Healthy	PD: 19 Healthy: 19	PD: F: 9; M: 10 Healthy: F: 9; M: 10	PD: 71.53 (6.39) Healthy: 70.37 (6.25)	PD: 1.6172 (0.0813) Healthy: 1.6104 (0.0712)	PD: 67.38 (9.44) Healthy: 72.82 (14.86)	PD: 25.8 ^[M] ; 26 ^[X] Median: 25.7 [22.87-28.79] Healthy: 28.1 ^[M] ; 28.3 ^[X] Median: 28.1 [24.13-32.26]	PD: Overall: OW UW: 3.4% NW: 40.1% OW: 38.9% OB: 17.7% Healthy: Overall: OW UW: 3.9% NW: 26.1% OW: 32.2% OB: 37.8%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Barbieri et al., 2018	2: PD and Healthy	PD: 13 Healthy: 13	PD: Not reported Healthy: Not reported	PD: 70.33 (6.02) Healthy: 70.77 (7.56)	PD: 1.62 (0.08) Healthy: 1.6 (0.06)	PD: 68.2 (12.48) Healthy: 70.15 (10.32)	PD: 26 ^[M] ; 26.3 ^[X] Median: 26 [22.6- 29.71] Healthy: 27.4 ^[M] ; 27.5 ^[X] Median: 27.4 [24.4-30.5]	PD: Overall: OW UW: 5.7% NW: 36.4% OW: 34.5% OB: 23.4% Healthy: Overall: OW UW: 1.6% NW: 27.9% OW: 42% OB: 28.5%
Orcioli-Silva et al., 2018	3: PD-TD, PD- PIGD, Healthy	PD-TD: 30 PD-PIGD: 35 Healthy: 45	PD-TD: F: 10; M: 20 PD-PIGD: F 18; M: 17 Healthy: F: 24; M: 21	PD-TD: 69.86 (6.97) PD-PIGD: 67.66 (9.38) Healthy: 66.51 (8.64)	PD-TD: 1.635 (0.0815) PD-PIGD: 1.589 (0.0911) Healthy: 1.6098 (0.0752)	PD-TD: 73.43 (10.61) PD-PIGD: 67.5 (14.8) Healthy: 69.9 (13.02)	PD-TD: 27.5 ^[M] ; 27.7 ^[X] Median: 27.4 [24.32-30.72] PD-PIGD: 26.7 ^[M] ; 27.2 ^[X] Median: 26.8 [22.81-31.18] Healthy: 27 ^[M] ; 27.2 ^[X] Median: 27 [23.38- 30.82]	PD-TD: Overall: OW UW: 1.9% NW: 28.1% OW: 40.1% OB: 29.8% PD-PIGD: Overall: OW UW: 6.1% NW: 32.2% OW: 30.7% OB: 31.0% Healthy: Overall: OW UW: 4.4% NW: 31.3% OW: 34.6% OB: 29.8%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Costa et al., 2018	1 : Healthy young adults	20	F: 7; M: 13	23.3 (3.6)	1.733 (0.096)	73.9 (14.6)	24.6 ^[M] ; 25.2 ^[X] Median: 24.8 [21.30-28.55]	Overall: NW ^[M] or OW ^[X] UW: 9.8% NW: 42% OW: 30.3% OB: 17.9%
Simieli et al., 2018	2: PD and Healthy	PD: 15 Healthy: 13	PD: F: 7; M: 8 Healthy: F: 6; M: 7	PD: 70.66 (6.55) Healthy: 71.53 (5.42)	PD: 1.63 (0.07) Healthy: 1.59 (0.08)	PD: 70.61 (9.82) Healthy: 70.5 (15.49)	PD: 26.6 ^[M] ; 26.7 ^[X] Median: 26.6 [23.73-29.57] Healthy: 27.9 ^[M] ; 28.2 ^[X] Median: 27.9 [23.74-32.4]	PD: Overall: OW UW: 2.1% NW: 33.6% OW: 42.2% OB: 22.1% Healthy: Overall: OW UW: 4.7% NW: 27.3% OW: 30.4% OB: 37.6%
Penedo et al., 2018	2: PD and Healthy	PD: 13 Healthy: 11	PD: F: 6; M: 7 Healthy: F: 7; M: 4	PD: 63.67 (5.96) Healthy: 67.75 (6.78)	PD: 1.65 (0.09) Healthy: 1.59 (0.08)	PD: 75.61 (15.32) Healthy: 70.75 (17.87)	PD: 27.8 ^[M] ; 28.1 ^[X] Median: 27.8 [23.73-32.1] Healthy: 28 ^[M] ; 28.5 ^[X] Median: 28.2 [23.56-33.09]	PD: Overall: OW UW: 4.6% NW: 27.9% OW: 31.3% OB: 36.1% Healthy: Overall: OW UW: 5.6% NW: 26.7% OW: 27.9% OB: 39.8%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Guadagnin et al., 2019	1: Older adults	15	F: 9; M: 6	75.4 (5)	1.57 (0.11)	68.6 (14.8)	27.8 ^[M] ; 27.9 ^[X] Median: 27.5 [23.28-32.10]	Overall: OW UW: 5.5% NW: 29.4% OW: 29.8% OB: 35.4%
Nobrega-Sousa et al., 2019	3: PD-WDAS, PD-DS, PD-DAS	PD-WDAS: 28 PD-DS: 15 PD-DAS: 19	PD-WDAS: F: 14; M: 14 PD-DS: F: 4; M: 11 PD-DAS: F: 13; M: 6	PD-WDAS: 72.71 (5.17) PD-DS: 71 (5.07) PD-DAS: 71.47 (5.28)	PD-WDAS: 1.6104 (0.0884) PD-DS: 1.5926 (0.0842) PD-DAS: 1.5757 (0.0882)	PD-WDAS: 69.35 (7.87) PD-DS: 68.7 (10.19) PD-DAS: 65.68 (10.63)	PD-WDAS: 26.7 ^[M] ; 26.9 ^[X] Median: 26.7 [23.95-29.60] PD-DS: 27.1 ^[M] ; 27.3 ^[X] Median: 27 [23.83-30.39] PD-DAS: 26.5 ^[M] ; 26.6 ^[X] Median: 26.3 [23.03-29.87]	PD-WDAS: Overall: OW UW: 1.2% NW: 33% OW: 43.5% OB: 22.3% PD-DS: Overall: OW UW: 2.5% NW: 31.1% OW: 38.9% OB: 27.5% PD-DAS: Overall: OW UW: 4% NW: 35.6% OW: 36.2% OB: 24.2%
Conceicao et al., 2019	1: PD	42	F: 19; M: 23	65.59 (9.22)	1.6186 (0.0954)	72.02 (11.43)	27.5 ^[M] ; 27.7 ^[X] Median: 27.4 [23.92-31.15]	Overall: OW UW: 3% NW: 29.4% OW: 35.9% OB: 31.8%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Orcioli-Silva et al., 2020	2: PD, Healthy	PD: 19 Healthy: 19	PD: F: 9; M: 10 Healthy: F: 9; M: 10	PD: 71.53 (6.39) Healthy: 70.37 (6.25)	PD: 1.6172 (0.0813) Healthy: 1.6104 (0.0712)	PD: 67.38 (9.44) Healthy: 72.82 (14.86)	PD: 25.8 ^[M] ; 26 ^[X] Median: 25.7 [22.87-28.79] Healthy: 28.1 ^[M] ; 28.3 ^[X] Median: 28.1 [24.13-32.26]	PD: Overall: OW UW: 3.4% NW: 40.1% OW: 38.9% OB: 17.7% Healthy: Overall: OW UW: 3.9% NW: 26.1% OW: 32.2% OB: 37.8%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Nobrega-Sousa et al., 2020	6: Healthy individuals: G20 (20-25 years old), G30 (30-35 years old), G40 (40-45 years old), G50 (50-55 years old), G60 (60-65 years old), G70 (70-75 years old)	G20: 14 G30: 15 G40: 15 G50: 15 G60: 15 G70: 14	G20: F: 7. M: 7 G30: F: 7. M: 8 G40: F: 8. M: 7 G50: F: 7. M: 8 G60: F: 8. M: 7 G70: F: 7. M: 7	G20: 22.4 (1.3) G30: 31.5 (1.8) G40: 42.5 (1.6) G50: 52.7 (1.4) G60: 62.3 (2) G70: 71.7 (1.4)	G20: 1.694 (0.072) G30: 1.706 (0.099) G40: 1.665 (0.101) G50: 1.674 (0.077) G60: 1.642 (0.078) G70: 1.633 (0.101)	G20: 68.8 (7.3) G30: 70.5 (16.3) G40: 68.1 (9) G50: 79.9 (18.3) G60: 76.3 (12.5) G70: 78 (15.4)	G20: 24 ^[M] ; 24.1 ^[X] Median: 24 [22.14- 25.87] G30: 24.2 ^[M] ; 25.1 ^[X] Median: 24.63 [20.85-28.8] G40: 24.6 ^[M] ; 24.9 ^[X] Median: 24.5 [21.74-27.61] G50: 28.5 ^[M] ; 28.8 ^[X] Median: 28.5 [24.09-33.17] G60: 28.3 ^[M] ; 28.5 ^[X] Median: 28.3 [24.8-31.9] G70: 29.2 ^[M] ; 29.3 ^[X] Median: 29 [24.78- 33.56]	G20: Overall: NW UW: 3% NW: 64% OW: 29.1% OB: 3.9% G30: Overall: OW ^[X] UW: 11.9% NW: 40.5% OW: 28.1% OB: 19.5% G40: Overall: NW UW: 6% NW: 48.4% OW: 33.3% OB: 12.4% G50: Overall: OW UW: 4.9% NW: 24.8% OW: 28.8% OB: 41.5% G60: Overall: OW UW: 2.1% NW: 24.2% OW: 36.7% OB: 37% G70: Overall: OW UW: 3.3% NW: 22.9% OW: 29.7%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Ceccon et al., 2020	2: older women with risk of fall and without risk of fall (control)	Fall risk: 15 Control: 15	F: 30	Fall risk: 74 (6) Control: 77 (8)	Fall risk: 1.51 (0.07) Control: 1.52 (0.06)	Fall risk: 67 (14) Control: 66 (11)	Fall risk: 29 (4.6) Control: 28.6 (6)	Fall risk: Overall: OW Control: Overall: OW
Orcioli-silva et al., 2021	2: PD, Healthy	PD: 23 Healthy: 30	PD: F: 5; M: 18 Healthy: F: 15; M: 15	PD: 70.55 (6.03) Healthy: 67.99 (5.61)	PD: 1.6624 (0.1017) Healthy: 1.6344 (0.0894)	PD: 74.1 (10.34) Healthy: 78.68 (13.89)	PD: 26.8 ^[M] ; 27.1 ^[X] Median: 26.7 [23.58-30.18] Healthy: 28.7 ^[M] ; 29.5 ^[X] Median: 29.3 [25.40-33.45]	PD: Overall: OW UW: 2.8% NW: 32.9% OW: 38.2% OB: 26.1% Healthy: Overall: OW UW: 2.1% NW: 20.6% OW: 31.8% OB: 45.5%
Santinelli et al., 2021	2: PwMS, Healthy	PwMS: 15 Healthy: 15	PwMS: F: 11; M: 4 Healthy: Not reported	PwMS: 33 (7) Healthy: 31 (5)	PwMS: 1.67 (0.08) Healthy: 1.68 (0.08)	PwMS: 75.6 (13.5) Healthy: 69.4 (10.5)	PwMS: 27.1 ^[M] ; 27.4 ^[X] Median: 27.1 [23.58-30.87] Healthy: 24.6 ^[M] ; 24.8 ^[X]	PwMS: Overall: OW UW: 4% NW: 30.6% OW: 35.4% OB: 30% Healthy: Overall: NW UW: 4% NW: 35.6% OW: 36.2% OB: 24.2%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Orcioli-silva et al., 2021	2 : PD-TD, PD-PIGD	PD-TD: 19 PD-PIGD: 17	PD-TD: F: 7; M: 12 PD-PIGD: F: 6; M: 11	PD-TD: 70.8 (6.8) PD-PIGD: 69.4	PD-TD: 1.648 (0.11) PD-PIGD: 1.668 (0.1)	PD-TD: 71.5 (13.5) PD-PIGD: 73.2 (10.9)	PD-TD: 26.3 ^[M] ; 26.7 ^[X] Median: 26.3 [22.53-30.45] PD-PIGD: 26.3 ^[M] ; 26.6 ^[X] Median: 26.3 [23.05-29.74]	PD-TD: Overall: OW UW: 6.4% NW: 34.7% OW: 31.6% OB: 27.3% PD-PIGD: Overall: OW UW: 3.9% NW: 35.9% OW: 36.7% OB: 23.6%

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Santos et al., 2021	4 : PD active and inactive, Healthy active and inactive	PD active: 10 PD inactive: 10 Healthy active: 10 Healthy inactive: 10	M: 40	PD active: 67 (5.2) PD inactive: 71.7 (5) Healthy active: 67.5 (6.5) Healthy inactive: 71.4 (6.4)	PD active: 1.7 (0.09) PD inactive: 1.7 (0.06) Healthy active: 1.7 (0.07) Healthy inactive: 1.7 (0.07)	PD active: 72.6 (7.6) PD inactive: 73.1 (10.1) Healthy active: 68.6 (9.4) Healthy inactive: 78.7 (12.8)	PD active: 25.1 ^[M] ; 25.3 ^[X] Median: 25.1 [22.69-27.71] PD inactive: 25.3 ^[M] ; 25.4 ^[X] Median: 25.3 [22.72-27.96] Healthy active: 23.7 ^[M] ; 23.9 ^[X] Median: 23.7 [21.26-26.35] Healthy inactive: 27.2 ^[M] ; 27.4 ^[X] Median: 27.2 [23.97-30.61]	PD active: Overall: OW UW: 2.3% NW: 46.5% OW: 39.9% OB: 11.2% PD inactive: Overall: OW UW: 3.2% NW: 44% OW: 40.5% OB: 12.2% Healthy active: Overall: NW UW: 6.8% NW: 56.1% OW: 31% OB: 6.1% Healthy inactive: Overall: OW UW: 2.7% NW: 29.6% OW: 38.8% OB: 28.9%
Casal et al., 2021	2: PD akinetic, PD hyperkinetic	PD akinetic: 16 PD hyperkinetic: 17	PD akinetic: F: 4; M: 12 PD hyperkinetic: F: 5; M: 12	PD akinetic: 61.4 (10.2) PD hyperkinetic: 69.2 (9.1)	PD akinetic: 1.72 (0.1) PD hyperkinetic: 1.67 (0.1)	PD akinetic: 80.5 (10.6) PD hyperkinetic: 74.7 (15.7)	PD akinetic: 27.1 (3.6) PD hyperkinetic: 26.5 (4.2)	PD akinetic: Overall: OW PD hyperkinetic: Overall: OW

Author, year	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ² , Median [IQR]	BMI category
Santinelli et al., 2022	2 : PwMS, Healthy	PwMS: 22 Healthy: 19	PwMS: F: 13; M: 9 Healthy: F: 10; M: 9	PwMS: 33.1 (7.5) Healthy: 35.5 (5.9)	PwMS: 1.67 (0.1) Healthy: 1.67 (0.08)	PwMS: 73.5 (13.5) Healthy: 67.9 (10.8)	PwMS: 26.04 (4.06) Healthy: 24.06 (3.12)	PwMS: Overall: OW Healthy: Overall: NW
Vitorio et al., 2023	2 : PD, Healthy	PD: 15 Healthy: 14	PD: F: 9; M: 6 Healthy: F: 9; M: 6	PD: 70.8 (10.5) Healthy: 70.9 (10.5)	PD: 1.622 (0.075) Healthy: 1.608 (0.086)	PD: 69.6 (12.4) Healthy: 69.4 (12.1)	PD: 26.5 ^[M] ; 26.7 ^[X] Median: [23.08- 30.11] Healthy: 26.8 ^[M] ; 27.1 ^[X] Median: 26.8 [23.42-30.4]	PD: Overall: OW UW: 4.6% NW: 34.1% OW: 35.7% OB: 25.6% Healthy: Overall: OW UW: 4% NW: 32% OW: 36.7% OB: 27.2%
Faria et al., 2023	2 : PD, Healthy	PD: 16 Healthy: 16	PD: F: 8; M: 8 Healthy: F: 8; M: 8	PD: 66 (8) Healthy: 66 (5.9)	PD: 1.64 (0.09) Healthy: 1.63 (0.09)	PD: 68.3 (9.7) Healthy: 70.7 (17.2)	PD: 26.53 (3.60) ^[I] Healthy: 26.55 (5.36) ^[I]	PD: Overall: OW NW: <i>n</i> = 4 (25%) OW: <i>n</i> = 9 (56.3%) OB: <i>n</i> = 3 (18.8%) Healthy: Overall: OW NW: <i>n</i> = 7 (43.8%) OW: <i>n</i> = 7 (43.8%) OB: <i>n</i> = 2 (12.5%)

Note: AD: Alzheimer's disease, NW: normal weight, OA: osteoarthritis, OB: obese, OW: overweight, PD: Parkinson's disease, PD-DAS: Parkinson's disease with depressive and anxiety symptoms, PD-DS: PD with depressive symptoms, PD-PIDG: Parkinson Disease with postural instability and gait disorder, PD-TD: Parkinson's disease with tremor dominant, PD-WDAS: Parkinson's disease without depressive and anxiety symptoms, PwMS: people with multiple sclerosis, UW: underweight [I]: individual data provided, [M]: calculated using mean body mass and height provided, [X]: calculated using summary statistics (mean and standard deviation of body mass and height) provided, [1]: only

data from experiment 1 were extracted, *: Data were extracted from: *Vitório R, Lirani-Silva E, Barbieri FA, Raile V, Batistela RA, Stella F, Gobbi LT. The role of vision in Parkinson's disease locomotion control: free walking task. Gait Posture. 2012 Feb;35(2):175-9. doi: 10.1016/j.gaitpost.2011.09.002. Epub 2011 Oct 1. PMID: 21962407.*

3.3.5 Body height and body mass

Individual participant data of both body height and mass were reported in 4 studies [42,44,45,59] but provided for 63 (72%) out of 87 participants. These 63 participants were divided into 5 groups: one group of undergraduate students [42], three groups of people with Parkinson's disease [44,45,59] and one healthy group [44]. In two comparative studies, indeed, individual data of both body height and body mass was reported for the Parkinson's disease group only [45,59]. For the remaining 24 participants, the summary statistics of body height and body mass were either provided in the article [45], or provided after contacting the authors. For the other studies ($n = 31$, 89%), both arithmetic mean of body height and body mass data were provided for all groups.

Of the 76 groups of participants included in the 35 included studies, the mean body height ranged from 1.51 ± 0.07 [72] to 1.79 ± 0.06 m [48], with a median body height of 1.64 m. The mean body mass ranged from 57.83 ± 8.82 [72] to 84.83 ± 15.51 kg [49], with a median body mass of 70.5 kg.

3.3.6 BMI

Individual participant data of both body height and mass was provided in 4 studies (11%) [42,44,45,59], including a total of 87 participants (6.9%) divided into 7 groups. However, individual data was provided for 63 (72%) participants included in the studies who were divided into 5 groups. Overall, 30 participants had a normal-weight BMI (48%), 25 (40%) had a BMI between 25.0 and 29.9 kg/m², and 8 (13%) above 30 kg/m². Mean BMI ranged from 23.9 (i.e., healthy young adults [42]) to 26.55 kg/m² (i.e., Parkinson's disease group from Faria and colleagues' study [44]). Two groups out of 5 had a mean BMI greater than 25.0 kg/m², including a group of 16 patients with Parkinson's disease (26.53 ± 3.60 kg/m²) and a control group of 16 older adults neurologically healthy (26.55 ± 5.36 kg/m²) [44].

The summary statistics of BMI were reported in 4 studies (11%) [67,70–72], for a total of 128 participants (10.2%) divided into 7 groups. For these 4 studies, the mean BMI ranged from 24.1 ± 3.1 [70] to 29 ± 4.6 kg/m² [72]. Of the 7 groups of participants included in these 4 studies, 6 had a mean BMI greater than 25 kg/m², with one group of individuals with knee osteoarthritis [71], one group of older females with fall risk, one group of older females without fall risk [72], two groups of people with Parkinson's disease (one akinetic and one hyperkinetic) [Casal et al., 2021], one group of people with multiple sclerosis and one healthy-matched control group (by age, body height and body mass) [70].

Regarding the remaining 64 groups of participants included in 29 studies, the summary statistics of both body height and mass data was available, either reported in the article (n=63 groups, [22–24,27,43,45–58,60–66,68,69] or obtained after contacting the authors (n=1 group, [59]). Of the 64 groups of participants included in these 29 studies, 56 (87.5%) had a mean BMI greater than 25.0 kg/m².

All in all, of the 76 groups of participants included in the 35 articles, 64 (84%) had a mean BMI greater than 25.0 kg/m².

3.4. Obstacle crossing task

The description of the obstacle crossing task performed in each included study is described in Table 4.

3.4.1 Pathway and starting point

The pathway length ranged from 5 [58] to 26.8m (i.e., cone circuit) [57,65,66]. Most studies (n = 21, 60%) used an 8m-long pathway. For two studies (5.7%), the pathway length was not reported [42,67].

Several methods were used for defining the starting point. For fixed starting point (i.e., starting point defined by a metric, n = 12, 34.3%), it ranged from 3 [58] to 5 m [55]. Two studies (5.7%) set the starting point according to the participant anthropometric characteristics, with one study using lower limb and half lower limb length [42] and for the other study, the obstacle was placed in front of the participant's feet at 10% of the participant's height [44]. For several studies (n = 4, 11.4%), the starting point was adjusted to ensure that the obstacle was crossed first with the desired leg and that at least two strides were completed prior to obstacle avoidance [22,24,48,49], or to ensure comfortable avoidance with the right leg (n = 3, 8.6%) (with no information about step/strides before the obstacle) [23,51,61]. For one study (2.7%), the starting point was one step away from the obstacle [71]. For another study, the starting point was adjusted within an amplitude of 10-cm to avoid accommodation [56] across trials. For another study, practice trials were used to define the starting point to guarantee the avoidance with the right limb as leading limb [54]. Regarding studies using a cone circuit pathway with four obstacles evenly spaced (n = 4, 11.4%), the starting point from the first obstacle was not reported [43,57,65,66]. Finally, three studies (8.6%) did not report information regarding the starting point [27,67,70].

3.4.2 Obstacle height

More than half of the studies used a fixed obstacle height (i.e., obstacle height designed with a metric, $n = 18$, 51.4%) [22–24,27,43,44,48,49,51,57,58,64–67,70–72]. Most of those studies ($n = 14$, 40%) used a 15-cm high obstacle [23,24,27,44,48,49,51,57,65,66,71,72], two studies (5.7%) used a 10-cm high obstacle [43,67], one study (2.9%) used two obstacles (15-cm and a 3-cm high obstacle) [72], and one study used a 26-cm high obstacle [58]. For the studies performed on a cone-circuit with 4 obstacles evenly spaced ($n = 4$, 11.4%), all obstacles were either 15-cm high [57,65,66] or 10cm high [43].

For sixteen studies (45.7%), the obstacle height was set according to the participant anthropometric characteristics [42,45–47,50,52–55,59–63,68,69]. Obstacle heights were set either at the knee height ($n = 3$, 8.6%) [42,54,55], half knee height ($n = 10$, 28.6%) [42,45–47,52,59,62,63,68,69], ankle height ($n = 4$, 11.4%) [45,46,55,59], 20% of the participant's leg length ($n = 1$, 2.9%) [50], or 30% ($n = 1$, 2.9%) [53] of the participant's leg length. For two studies (5.7%) [60,61] a low obstacle was set at 5 or 10-cm when the participant's height ankle was lower or higher than 7cm, respectively [61], or the low obstacle was set at ankle height [60]. The high obstacle was set at 20 or 25cm when the participant's knee height was lower or higher than 48.5cm, respectively [61], or obstacle height was set at half-knee height [60]. The intermediate obstacle height was the average of low and high obstacle height [60,61]. For one study (2.9%), the obstacle was a projected planar (30-cm long * 15-cm wide) [56].

3.4.3 Experimental conditions

For all studies except one, obstacle crossing protocols were performed in one session. The only exception was for Orcioli-Silva and colleagues' for which Parkinson's disease participants performed 2 sessions in OFF and ON medication state [66].

The number of trials performed by participants ranged from 3 [24,46,48,49,51,52,62,71] to 120 trials [56] per obstacle conditions. One study (2.7%) did not report the number of trials performed [67].

Almost all studies ($n = 31$, 88.6%) performed a single walking speed condition [22–24,27,42,43,45–52,55–66,68–72]. The instruction was either to walk at preferred velocity/speed [42,43,45–47,55,60–62,64,69,72], self-selected/paced [22,24,27,48,49,51–53,56,58,59,62,63,65,66,70,71], “their own speed” [68], “as fast as possible at their preferred speed” [23], or « normal and comfortable speed » [57]. One study (2.9%) used two walking

speed conditions, with walking at both preferred and maximal speed [53]. For 3 studies (8.6%), no information about the walking speed was provided [44,54,67].

For one study (2.9%), the obstacle avoidance was performed in both single and dual task conditions [50]. The dual task was a variation of the Stroop task in which the participant was required to answer verbal commands [50]. For another study, obstacle avoidance was always performed in dual-task condition [68]. The dual tasking consisted of the participant counting backward from twenty to 1 [68]. All other studies performed obstacle avoidance protocols in single-task condition.

For eight studies (22.9%), practice/familiarization information were reported [23,46,50,54,56,59,67,72]. The participants performed either 3 trials in each condition [54], were allowed to familiarize themselves with each condition over three to five trials [46], had one practice trial per condition [59], or had five trials of self-paced walking on the GaitRite [56]. For the other studies, the exact number of practice trial was not reported. The participants had, some trials performed before the test [23], some familiarization trials [50], a few familiarization trials walking around the laboratory [72], or were familiarized with the gait initiation and obstacle negotiation tests [67].

Table 4. Obstacle crossing tasks.

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Gobbi et al., 2009	Take a step with the left limb and using the right limb to step over the obstacle	Length: 60cm Depth: 3cm Low obstacle: Half of knee height High obstacle: Knee height	Not reported	Expected	Far: Lower's limb length Close: Half lower's limb length	1	4: Low obstacle (half of knee height), starting distance "Far" and "Close" High obstacle: Knee height, starting distance "Far" and "Close"	5	Preferred velocity	Single task	Not reported
Rodrigues et al., 2009*	Barefoot walking along a five meter flat pathway with an obstacle of 0.26 m height located at 3 m from the starting point.	Height: 26 cm	5-m	Expected and Unexpected	3-m from the obstacle	1	2 for control (with and without vision) 1 for blindfolded group	30	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Vitorio et al., 2010	Walking at preferred speed, step over an obstacle, and keep walking until they reached the end of the pathway. The obstacle was placed in the middle of the pathway	Low obstacle: ankle height High obstacle: half of knee height	8-m long and 1.4-m wide, covered with a black rubber carpet 3 mm thick	Expected	The starting position was modified for each participant to ensure a comfortable cross with the right limb. All participants performed at least five steps before obstacle avoidance.	1	3 No obstacle and no visual cue Low obstacle High obstacle Conditions were randomized	5	Preferred speed	Single task	Not reported

Author, year	Task	Obstacle	Pathway Expected/ Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Da Silva et al., 2011	Walking an 8 m long × 0.5 m wide rubberized mat walkway and cross the obstacle with the right leg leading exactly when the obstacle crossed the walkway. The walkway width limited the avoidance area.	0.5 m wide *8-m long Expected 50cm long wood obstacle Height: knee height (49 ± 3.5 in average)		During practice trials, the departure point was defined to guarantee the right limb as leading limb	1	3 Control (stationary obstacle) Obstacle avoidance the path perpendicularly to the participant's direction in <i>slow</i> speed (1.07 m/s) and <i>fast</i> speed (1.71 m/s)	50 condition. Fifteen trials in five-attempt blocks were recorded for each participant in each condition (150 trials per participants). Blocks were randomized Out of the trials 20% were repeated at the end of each block of trials. Among them, 12% were with the moving obstacle, 55.5% of which were in <i>slow</i> obstacle speed and 44.5% in <i>fast</i> obstacle speed. For stationary obstacle, 8% were repeated	perNot reported	Single task	Participants performed three trials in each condition for familiarization purposes

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Menuchi et al., 2012	Walking distance of 5 m at preferred speed, step over an obstacle and continue walking for three more meters.	aLow obstacle: 8-m * 1.4-m High obstacle: knee height	8-m * 1.4-m walkway	Expected	5-m	1	6 Low obstacle: The trials were with static visual sampling (2 samples/s and 4 samples/s) and constituted the dynamic visual sampling High obstacle: randomized only for obstacle height (10 trials). The second set constituted the static sampling trials that were randomized for frequency and obstacle (20 trials). This division of trials into two blocks was performed to avoid constant changes in camera focus and also for the comfort of participants.	5	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Vitorio et al., 2013	Walking along a pathway (8 m long by 1.4 m wide) and step over an obstacle, under three visual conditions. The obstacle for each condition was positioned in the middle of a pathway.	Low obstacle: 8-m ankle height High obstacle: 1.4-m knee height	8-m * 1.4-m walkway	Expected	4-m	1	6 Low obstacle with dynamic presentation (normal vision), order of the static visual conditions was sample (at 3Hz, randomized. sample duration: 0.016s) and according to voluntary visual obstacle height sampling also were randomized in each block of visual condition. High obstacle with dynamic presentation (normal vision), static visual sample (at 3Hz, sample duration: 0.016s) and voluntary visual sampling (subjects were allowed to choose when and where to take a visual sample of the environment)	3	Preferred	Single task	Participants were allowed to familiarize themselves with each condition (and the equipment) over three to five unrecorded trials.

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Pieruccini-Faria et al., 2013	Walking toward the obstacle at their self-selected velocity, step over it, and keep walking until the end of the walkway.	The obstacles dimensions were 0.3 m thick, 60 cm wide, and were made of wood. Low obstacle: ankle height High obstacle: half-knee height	8-m length *	Expected	The starting point was set at ~4.5 m from obstacle.	1	3 Without obstacle Low obstacle High obstacle Conditions were randomized	5 Conditions blocks were randomized	Self-selected	Single task	One practice trial per block
Barbieri et al., 2013	Walking over an 8 m pathway, at self-selected speed. The participant was instructed to avoid contact with the obstacle, which was positioned between two force platforms.	15 cm high, 80 cm wide and 2 cm thick	8-m length	Expected	Adjusted to ensure that the obstacle was crossed with the right leg and that at least two strides were completed prior to obstacle avoidance.	1 for gait trials	4 Without obstacle pre and post fatigue With obstacle pre and post fatigue	3 Conditions pre and post were randomized	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Barbieri et al., 2014	Barefoot walking over an 8 m wooden pathway. The participant was instructed to avoid an obstacle (15 cm high, 80 cm wide and 2 cm thick), which was positioned between two force platforms, midway down the pathway.	15 cm high, 80 cm wide and 2 cm thick	8-m length	Expected	Adjusted to ensure that the obstacle was crossed with the right leg and that at least two strides were completed prior to obstacle avoidance	1	4 Without obstacle pre and post fatigue With obstacle pre and post fatigue	3 The order of posttrials was randomized	Self-selected	Single task	Not reported
Vitorio et al., 2014	Walking along a pathway at preferred speed step over an obstacle. The obstacle was positioned in the middle of a pathway.	Half of knee height * 60 cm * 30 cm	8 m long * 1.4 m wide	Expected	4-m	1	1	3	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Simieli et al., 2015	Barefoot walking at own speed along an 8m long pathway. The participants were instructed to avoid contact with the obstacle. The obstacle was positioned midway along the pathway	The obstacle (width: 50 cm; depth: 2 cm) was made of wood and was collapsible to ensure the safety of the participant. The obstacle height was set at half knee height	8-m long	Expected	The starting position was adjusted for each participant to ensure comfortable obstacle avoidance with the right limb	1	3 unobstructed walking unobstructed walking dual tasking obstacle avoidance during walking with dual tasking (The dual tasking consisted of the participant counting backward from twenty)	5 Trials conditions were randomized	Their own speed	Dual task for obstacle avoidance trials	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Pegoretti et al., 2015	The first task began with the volunteers in a standing position facing the force plate and with the limb with knee OA being moved forward. This limb was designated as the “trailing leg”. The second task began from a standing position in front of the obstacle, and the limb affected by knee OA being moved forward. The volunteers were instructed to perform the task safely and at a self-selected (comfortable) speed.	A cylindrical obstacle with a 15-cm diameter (obstacle height) was affixed to the force plate	Not reported	Expected	1 step	1	4 Leading and trailing leg condition with and without bandage	3	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Barbieri et al., 2015	Barefoot walking at preferred velocity along an 8m pathway. The participants were instructed to avoid contact with the obstacle, which was positioned midway down the pathway.	The obstacle (width: 50 cm; depth: 2 cm) was made of wood and was collapsible for safety. The height was adjusted to half-knee height	8-m	Expected	The starting position was adjusted for each participant to ensure comfortable avoidance of the obstacle with the right limb, regarded as the leading limb, whereas the left limb was considered the trailing limb. The obstacle was positioned nearly 4m of the starting position.	1	2 Walking without obstacle avoidance Walking with obstacle avoidance	5 The trial order was randomized	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Guadagnin et al., 2015	Barefoot walking and obstacle avoidance at self-selected speeds. A dual task was added for half of the obstacle avoidance trials.	The obstacle was made of polystyrene (length * width: 80 cm * 20 cm, height defined as 20% of participant's leg length)	8-m	Expected	Different distances from the obstacle In order to record avoidances for both legs as the leading limb	1	5 Overground walking Obstacle avoidance single and dual task (The dual task was a variation of the Stroop task in which the participant was required to answer verbal commands) with preferred or non-preferred leg as leading limb Conditions were randomized	10	Self-selected	Single and dual task	Some familiarization trials

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Simieli et al., 2017	Walking at preferred speed until the end of the walkway. The obstacle was placed in the center of the walkway, 4 m from the start position, which was adjusted to ensure comfortable avoidance with the right leg.	The height of the low obstacle was 5 or 10cm when participant's height ankle was lower or higher than 7cm, respectively. The height of high obstacle was 20 or 25cm when participant's height knee was lower or higher than 48.5cm, respectively. The height of the intermediate was the ratio of low obstacle and high obstacle sum. The other dimensions of the obstacle were 60cm long and 3cm wide.	8-m	Expected	Adjusted to ensure comfortable avoidance with the right leg.	1	4 Unobstructed walking Low obstacle Intermediate obstacle High obstacle	10 The trials were performed in blocks. The order of blocks started, for all participants, with the unobstructed walking, and then, the other conditions were randomized for each participant.	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Orcioli-Silva et al., 2017	Walking over an 8 m wooden pathway at a self-selected speed. Each participant performed three trials for each condition: (i) unobstructed walking; (ii) walking with one obstacle avoidance; (iii) walking with two obstacles avoidance. In the Double condition, the second obstacle (Second Double) was placed in the travel pathway 108 cm distant from the first obstacle	The obstacles were made of foam and were 15 cm in height, 3 cm thick, and 60 cm wide	8-m	Expected	Adjusted for each participant to ensure comfortable obstacle avoidance with the right limb	1	3 Unobstructed walking Single obstacle Double obstacle	3 The trials were randomized for each participant	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Barbieri et al., 2018	Walking over a 10 m wooden pathway at a self-selected speed. The participants were also instructed to avoid contact with the obstacle, which was positioned in the middle of the pathway	15 cm high, 80 cm wide and 2 cm thick	10-m	Expected	The starting point 1 (~5 m from the obstacle) was adjusted according to the leg that the participant needed to cross the obstacle and to ensure that at least two strides (walking acceleration phase) were completed prior to obstacle avoidance	1	3 Unobstructed walking Obstacle avoidance with dominant limb as leading limb Obstacle avoidance with non-dominant limb as leading limb	5 The trial order was randomly defined	Self-selected	Single task	Not reported
Orcioli-Silva et al., 2018	Walking at self-selected pace on a 8-m long pathway. The obstacle was positioned in the middle of the pathway.	The obstacle was set up at half knee height×60 cm width×3 cm depth	8-m	Expected	4-m	1	3 Unobstructed walking Obstacle avoidance with dominant limb as leading limb Obstacle avoidance with non-dominant limb as leading limb	3 Results with dominant and non-dominant leg as leading limb were pooled	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Costa et al., 2018	Walking at self-paced speed on a 7-m long walkway, always starting with the right lower limb. They performed two tasks: stepping on a target and obstacle avoidance. In the obstacle avoidance task, the obstacle position was initially projected on the ground at one of the four extremities relative to the normal foot landing area. Participants had to avoid stepping on the obstacle even if it changed position. They could freely choose where to step to avoid the obstacle.	A projected planar 30-cm long × 15-cm wide obstacle	7-m	Expected	The starting point was constantly altered within an amplitude of 10 cm to avoid accommodation. To define the location of the starting point and the target/obstacle, participants performed five trials of self-paced walking on the GaitRite to measure the average step length and width.	3	Stepping on a target Obstacle avoidance Trials without projection	Obstacle avoidance: 120 trials: 40 trials in which the obstacle moved from the extremities to the normal foot landing area and another 40 trials at which the obstacle remained at the initial position 20 trials where the obstacle moved from one extremity to another. Additionally, in each block of trials, participants performed 20 trials without any projection. Trials were completely randomized within each block for each participant.	Self-paced	Single task	Five trials of self-paced walking on the GaitRite

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Simieli et al., 2018	Walking at preferred speed until the end of the walkway (8 m). The following walking conditions were performed by participants: low obstacle avoidance, intermediate obstacle avoidance and high obstacle avoidance.	High obstacle: 8-m half of knee height Low obstacle: ankle height Intermediate obstacle: half the sum of the high obstacle height and low obstacle height All obstacle width and length were 60 cm and 3 cm, respectively		Expected	4-m	1	3 Low obstacle Intermediate obstacle High obstacle	10 The trials were performed in blocks in a randomized order for all participants	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/ Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Penedo et al., 2018	Walking at self-selected pace for a distance of 8.5 m on a walkway. In all 20 trials, an obstacle was positioned nearly 4 m from the beginning and in the center of the walkway. Participants avoided the obstacle with the right lower limb. Participants were required to keep their eyes closed at the beginning of each attempt	15 cm height * 60 cm width * 5 cm depth	8.5m	Expected	Nearly 4-m. The starting position was adjusted for each participant to ensure comfortable avoidance with the right limb	1	4 White obstacle Black obstacle Red obstacle Blue obstacle	5 The trials were their completely preferred randomized for speed each participant	As fast as possible at	Single task	Some trials performed before the test

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Guadagnin et al., 2019	Walking with flat casual shoes, along an 8 m walkway. Ten trials (five with each lower limb as the leading limb) at each speed were registered for obstacle avoidance. Participants were not told which limb to use to cross the obstacle first. The obstacle was positioned halfway on the walkway	An obstacle made of polystyrene (length * width: 80 cm * 20 cm), with height adjusted to 30% of each participant's lower limb length	8-m	Expected	4-m	1 for gait evaluations	6 Overground at preferred speed Overground at maximal speed Obstacle avoidance at preferred speed with right and left limb as leading limb Obstacle avoidance at maximal speed with right and left limb as leading limb	Overground conditions: 3 Obstacle avoidance conditions: 5 Results with right or left limb as leading limb were pooled The conditions (overground gait and gait with obstacle avoidance) were randomized and the trials at a preferred speed were always registered first	Preferred Maximal	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Nobrega-Sousa et al., 2019	Walking at preferred speed, along a pathway (8-m long by 1.4-m wide). Three trials for each of two experimental conditions were carried out (fully randomized): (i) usual walking; and (ii) obstacle avoidance. The obstacle was positioned in the middle of the pathway. In the obstacle avoidance condition, participants were instructed to step over the obstacle, avoiding contact with it.	Height: half of knee height * * 60-cm width * 3-cm depth	8-m long * 1.4-m wide	Expected	4-m	1	2 Usual walking Obstacle avoidance	3 Conditions were fully randomized	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Conceicao et al., 2019	Walking at self-selected pace along a pathway (8m long by 1.4m wide) and cross an obstacle positioned in the middle of the pathway. Participants were instructed to cross the obstacle using the less affected limb as the leading limb	The obstacle was made of foam (3 cm depth×60 cm width), and the height was determined for each participant using half knee height	8m long * 1.4m wide	Expected	4-m	1	1 Obstacle avoidance	3	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Orcioli-Silva et al., 2020	Walking at preferred speed on a pathway 8 m long by 0.8 m wide. Three conditions were tested: (i) walking with one obstacle; (ii) walking with two obstacles with a 50 cm distance between them; (iii) walking with two obstacles with a 108 cm distance between them	the obstacles were made of foam and were 15 cm high * 3 cm thick * 60 cm wide	8 m long * 0.8 m	Expected	4-m		6 Single obstacle (3 for each limb as leading limb) Double obstacle spaced 50-cm (3 for each limb as leading limb) Double obstacle spaced 108-cm (3 for each limb as leading limb)	6 Results with right or left limb as leading limb were pooled	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/ Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Nobrega-Sousa et al., 2020	Overground walking was tested in 3 experimental conditions: usual walking, obstacle avoidance, and dual-task walking. In all conditions, participants walked at their normal and comfortable pace on a cone circuit (total distance = 26.8 m) with 2 parallel 7-m long straights. In the obstacle avoidance condition, 4 foam obstacles were positioned every 6.7 m (an obstacle was positioned immediately at the end of the GAITRite registration area)	4 foam obstacle depth $\times$ width $\times$ height = $3 \times 60 \times 15$ cm	26.8 m	Expected	Not reported for the first obstacle to cross	1	3 Usual Walking Obstacle avoidance Dual task walking	5 Walking trials were randomized	Normal and comfortable	Single task for obstacle avoidance	Not reported for walking task

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice
Ceccon et al., 2020	Walking at preferred pace and wearing their casual flat shoes along an 8-m walkway, and cross an obstacle placed exactly at mid distance (4 m).	Foam obstacles with width and length of 34 * 11 cm, and 2 different heights of 3 and 15 cm were utilized	8-m	Expected	4-m	1	2 3-cm high obstacle 15-cm high obstacle	12 Trials were randomized	Preferred	Single task	Participants performed a few familiarization trials walking around the laboratory

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Orcioli-silva et al., 2021	Participants started with 30 s in a quiet stance, during which participants were required to look straight ahead and think about nothing. A verbal sign indicated the participant should start walking along a 26.8-m circuit for 30 s, with two 7-m parallel straights. In the obstacle avoidance condition, 4 foam obstacles were evenly spaced along the walking path	4 foam obstacle Height * width * depth: 15-cm * 60-cm * 5-cm	26.8-m	Expected	Not reported for the first obstacle	2 (1 week apart) for people with PD were tested in off and on state 1 for control group	2 Unobstructed walking Obstacle avoidance	5	Self-paced	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Santinelli et al., 2021	Walking at self-selected velocity on a walkway (8.5 m length x 1.5 m width). For the obstacle avoidance, participants were instructed to avoid the obstacle without making contact with it. No instruction was given about which limb to use to avoid the obstacle	Foam material- 15 cm high and 2 cm deep	8.5-m length * 1.5-m width)	Expected	Not reported	1	2 Unobstructed walking Obstacle avoidance	10 The trials were randomized	Self-selected	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Orcioli-silva et al., 2021	Gait and cortical activation were assessed during 2 conditions (at self-selected speed): (i) unobstructed walking and (ii) obstacle avoidance. Four foam obstacles were evenly spaced along the walking path during the obstacle conditions.	4 foam obstacle, 60 cm width * 5 cm depth * 15 cm height	26.6-m	Expected	Not reported for the first obstacle	1	2 Unobstructed walking Obstacle avoidance	5 Trials were fully randomized	Self-selected	Single task	Not reported
Santos et al., 2021	Walking at self-selected speed over an 8 m long wooden walkway and stepped over an obstacle placed in the middle of the walkway	15 cm high * 80 cm wide * 2 cm thick obstacle	8-m	Expected	Adjusted so that individuals crossed the obstacle with the right leg, with at least two strides before the avoidance	1 for obstacle avoidance task	2: 1. Rested 2. After fatigue	3	Self-selected	Single task	Not mentioned

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Casal et al., 2021	Participants walked over an obstacle 10 cm high.	10-cm high	Not reported	Expected	Not reported	1 for obstacle avoidance task	2 Gait initiation Obstacle avoidance	Not reported	Not reported	Single task.	The participants were familiarized with the gait initiation and obstacle negotiation tests.
Santinelli et al., 2022	Barefoot walking at self-selected speed across a walkway 8.5m long and 3.5m wide.	A foam obstacle of 15-cm high	8.5-m long * 3.5-m wide	Expected	Not reported	1	2 Unobstructed walking Obstacle avoidance	The conditions were randomized	Self-selected	Single task	Not reported for unobstructed and obstacle avoidance tasks

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Vitorio et al., 2023	Walking at self-preferred pace for 60 s around a 25.8 m oval circuit (with two 6.5 m parallel straights). Two walking conditions were tested: usual walking and obstacle avoidance. For the obstacle condition, participants were instructed to step over four foam obstacles evenly spaced along the walking path	4 foam obstacles 60 cm width * 3 cm depth * 10 cm height	25.8-m	Expected	Not reported for the first obstacle	1	2 Usual walking Obstacle avoidance	4 Trials were randomized	Preferred	Single task	Not reported

Author, year	Task	Obstacle	Pathway length	Expected/Unexpected	Starting point	Number of Sessions	Number of conditions	Trial per condition (n)	Walking speed	Experimental condition	Practice condition
Faria et al., 2023	Participants were instructed to keep their eyes closed until the command to start the trial, and walk until the end of walkway (~10 m). The obstacle was positioned in front of participant's feet at a distance equivalent to 10% of the participant's height. The participants were instructed to avoid contact with the obstacle	15 cm high × 60 cm wide × 5 cm long	~10 m	Expected	Obstacle was placed in from of participants' feet at 10% of participants height	1	4 Gait initiation starting with right of left foot Obstacle avoidance starting with right or left foot	5 The order of the conditions was randomized by blocks.	Not reported	Single task	Not reported

Note: OA: osteoarthritis, PD: Parkinson's disease. *: Only experiment 1 was reported

4. Discussion

This study reviewed existing research to describe the BMI of Brazilian participants included in studies examining obstacle avoidance during walking.

On the whole, our findings suggest that BMI was rarely reported ($n = 4$, 11.4%) and was never part as inclusion/exclusion criteria. Participants had a wide range of BMI, including a large proportion of overweight individuals. In addition, almost half of the studies ($n = 16$, 46%) used anthropometric characteristics to define obstacle height, aiming to "offer the same relative challenge to all participants" [47]. To that end, anthropometric measures such as knee height, half-knee height, and ankle height were commonly employed. Additionally, some studies used a percentage of the participant's leg length (e.g., 20% or 30%) to determine the obstacle height.

4.1 BMI, evolution across the years

For most studies ($n = 29$, 82.9%), at least one group of participants had a mean BMI exceeding 25 kg/m^2 —the threshold for overweight [1]. Studies published in recent years tended to include a higher proportion of overweight participants than older ones. For instance, in Gobbi et al.'s study published in 2009, the distribution was 71.4% normal weight, 14.3% overweight class, and 14.3% obesity [42], while in the most recent study published in 2023, the distribution was 43.8% normal weight, 43.8% overweight class, and 12.5% obesity [44]. One possible explanation for this trend is the general increase in overweight in the Brazilian population, which rose from 46% in 2009 to 61.4% in 2023 (Fig. 3) [31]. The proportion of overweight participants in the included studies is fairly comparable to that in the general population, while the proportion of obese individuals was generally higher (Fig. 3). There were a few exceptions, in particular for the years 2011 and 2012, where the proportion of overweight individuals was below that of the general population. This discrepancy could be because the studies published in those years only included young adults and were therefore not representative of the general population [54,55]. However, when examining the proportions of each study individually, it was found that they varied substantially. Normal weight proportions ranged from 20.6% [66] to 70.8% [48], overweight proportions ranged from 15.1% [55] to 67.2% [50], and obesity proportions ranged from 1.1% [55] to 45.5% [59]. Since BMI was not a criterion for inclusion in any of the included studies, it is not surprising that a greater proportion of overweight class participants were included in more recent studies because of the increased of overweight in the general Brazilian population.

4.2 BMI, gait behavior and health status

The distribution of BMI by health status is detailed in Figure 4. Previous studies have shown that being overweight affects motor functions across the lifespan by altering brain functions and the musculoskeletal system [73], and impacting gait patterns during flat ground walking [14,74]. In addition, obstacle avoidance is also affected by overweight and obesity [28,29,75,76] in both adults and children/adolescent individuals. Being overweight is known to increase the risk of conditions such as knee osteoarthritis [77], which may explain the predominance of overweight individuals in groups with this condition. Similarly, being obese early in life is strongly associated with the later development of multiple sclerosis [78], which could explain the high overweight proportion of individuals found in these groups. No differences in BMI were observed between females with and without falling risk, even though overweight older adults are more prone to falls [16]. The proportion of overweight participants was higher among people with Parkinson's disease compared to healthy individuals, aligning with previous findings that overweight is more prevalent among individuals with Parkinson's disease [79]. Other conditions such as Alzheimer's disease [68,69] and multiple sclerosis [27,70] were investigated in fewer studies ($n = 2$ studies each, 5.7%), but were consistently associated with overweight BMI categories, while control groups included in numerous sclerosis studies were normal weight [27,70]. Conditions such as blindness [58] and fall risk in older females [72] were each explored in individual studies (2.9%). These groups exhibited overweight BMIs, consistent with previous research linking excessive weight to the exacerbation of symptoms and the risk of further health complications.

Examination of healthy groups ($n = 42$ groups) revealed that a large majority ($n = 32$ groups, 76.2%) had an overweight mean BMI [22–24,43–53,56–58,60,61,64,66,68,69,72], probably reflecting the general trend of increasing obesity and overweight rates in Brazil (Fig. 3) [31]. These studies reported differences in obstacle avoidance behavior based on participants' health status. However, previous research on adults has shown that both overweight [28] and obesity [28,29] also impact obstacle avoidance performance. Therefore, BMI may have influenced gait behavior during obstacle avoidance, particularly in studies comparing groups with different mean BMI categories (i.e., normal weight and overweight) [27,45,48,49,57,59,70].

4.3. BMI and age

The distribution of BMI per age decade is illustrated in Figure 5, revealing a wide age range among participants across the studies. Interestingly, all age decades exhibited a median BMI categorized as overweight, except for the 20-29 age group, which had a median BMI of 23.7 kg/m², placing it within the normal-weight range. Two studies included several age groups spanning from the 20s to the 70+ years [49,57]. In these studies, most groups (n = 9, 75%) had a mean BMI indicating overweight. Notably, the youngest group (20-29) was within the normal weight range, as well as a middle-aged adult group (40-49) in Nobrega-Sousa et al.'s study [57].

In contrast, for the 20-29 age group, 4 out of 6 groups (66.7%) were classified as normal-weight [42,48,54,55], while 2 groups were categorized as overweight [48,56]. Notably, one of these groups consisted of "inactive young males" [48], aligning with studies showing that a lack of physical activity is a major contributor to overweight and obesity [80–82]. For the 30-39 decade, 2 out of 6 groups (33.3%) were identified as normal-weight [27,70], and 4 (66%) were classified as overweight ([49,57,58,70]). No studies except those of Barbieri et al. [49] and Nobrega-Sousa et al. [57] investigated the 40-49 and 50-59 age decades. In the 60-69 age group, only 3 out of 22 groups (13.6%) were classified as normal-weight [24,45,59]. Remarkably, for the 70+ age group, all groups (n = 30, 100%) were overweight. Globally, the older the participants, the higher the proportion of overweight groups, which is consistent with reports from the World Obesity Federation Global Obesity Observatory [83] that indicate an increasing prevalence of overweight with age in Brazil: 23% among 18-24-year-olds, 33.9% among 25-39 year-olds, 35.9% among 40-59 year-olds, and 39.6% among those 60 and older in 2019 (see Fig. 6). Thus, it is not surprising that studies involving older individuals included more overweight participants.

4.4. BMI and sex

The distribution of BMI by sex is detailed in Figure 7, while the prevalence of overweight and obesity by age and sex among Brazilian adults is shown in Figure 6. For studies that included both sexes, only overall data were provided, prevailing us from examining BMI distributions for each sex. Three studies included only male participants [24,48,49], and two studies included only female participants [50,72]. Among studies with male-only groups, only 3 out of 12 groups (25%) were normal-weight, including an "active young male" group [48], a group of young males in their 20s [49], and a group of "healthy active" older adults [24]. For female-only studies, all groups (100%) were overweight, encompassing both active and inactive older females [50,72]. The comparison between the two sex-specific groups of older active

adults—one male (normal-weight) [24] and one female (overweight) [24,50]—illustrates an interesting trend. Although overweight prevalence is typically higher among Brazilian males (35.7%) compared to females (33.1%) (see Figures 8-11), especially in older adults over 60 years (42.1% in males vs. 37.8% in females) (see Figure 6), the specific male group studied exhibited a lower BMI compared to the corresponding female group. This could be due to the small sample size in these studies, comprising only 10 males [24] and 12 females [50], which may not represent broader population dynamics accurately.

Study strength, limitations and perspectives

This study had several strengths and limitations that open up new and interesting research perspectives. To the best of our knowledge, this is the first study to retrospectively analyze the BMI characteristics of individuals during obstacle avoidance tasks and assess whether and to what extent the BMI status had been reported and studied. The present study highlights the need for explicit consideration to control for body weight and mass in studies related to health and mobility [84]. This study also reveals that the necessary data to compare individuals across different BMI categories have already been collected in the analyzed studies, which could facilitate future retrospective analyses from both economic and temporal perspectives, avoiding the costs and time associated with new data collection if the data are FAIR. Implementing specific inclusion/exclusion criteria regarding body mass and height or controlling for both body mass and height in statistical analyses could help clarify the specific impacts of overweight and obesity class on gait outcomes. One of the main limitations of the included studies is the poor reporting of BMI, forcing us to reconstruct most of the BMI distributions.

This approach, while useful, is not without flaws. For instance, the method of generating random values assumed an unimodal normal distribution, which might not accurately reflect the true underlying distribution, especially when considering variables such as age, sex, and health status that can influence BMI. We had to assume that body height, body mass and BMI followed a normal distribution because only the arithmetic mean and standard deviation were reported. However, studies have shown that these anthropometric parameters rather follow a lognormal distribution [85,86]. The geometric mean and standard deviation of BMI, body mass and height were never reported, preventing us from using lognormal distributions to generate pseudo-BMI distributions. Alternative methods using mean statistics and prevalence proportions also exist, but the data provided in the identified articles did not allow us to use

them [87]. In addition, since the range of body height, body mass, and BMI was not reported in many studies, truncations had to be made, which could lead to imperfect BMI estimates. A second limitation is that only one database was searched (Web of Science), potentially omitting relevant articles. This choice was made due to the ease of filtering electronic search results by country/region on Web of Science compared to PubMed, for example.

Given these strengths and limitations, future research should aim to provide a more comprehensive reporting of anthropometric data. Researchers are encouraged to report not only mean and standard deviation but also the range of participants' characteristics, the prevalence proportions of each BMI class, as well as the median, geometric mean and geometric standard deviation. In a FAIR framework, the best practice would be to report all individual participant data. This would allow for more accurate re-analyses of published data and better replication of studies.

Finally, it is noteworthy that a significant number of studies ($n=9$, 26%) [22,48–50,52,65,66,68,69] excluded participants based on any factors that could interfere with gait. However, as previously mentioned, a non-healthy BMI (overweight and/or obese) affects both flat-ground walking [14,74] and obstacle-avoidance behavior [28,29,75,76]. Therefore, we recommend that BMI should be systematically reported and considered, particularly in Brazil, where projections for 2030 indicate that approximately 7 out of 10 people will be overweight, including 3 out of 10 obese people [32].

5. Conclusion

The characteristics of participants highly varied across studies. However, BMI was rarely reported and was not used as an inclusion/exclusion criterion or analyzed. Our results highlighted that the participant groups encompassed a broad range of BMI categories, potentially reflecting the diversity of the general population in Brazil. Future studies are needed to explore the potential impact of overweight and obesity on obstacle avoidance performance, as it is known to affect motor skills and gait behavior.

Finally, our results highlight the need to consider the body mass and height in future studies examining obstacle avoidance tasks during walking since being overweight affects functional mobility and could impact obstacle avoidance tasks while walking.

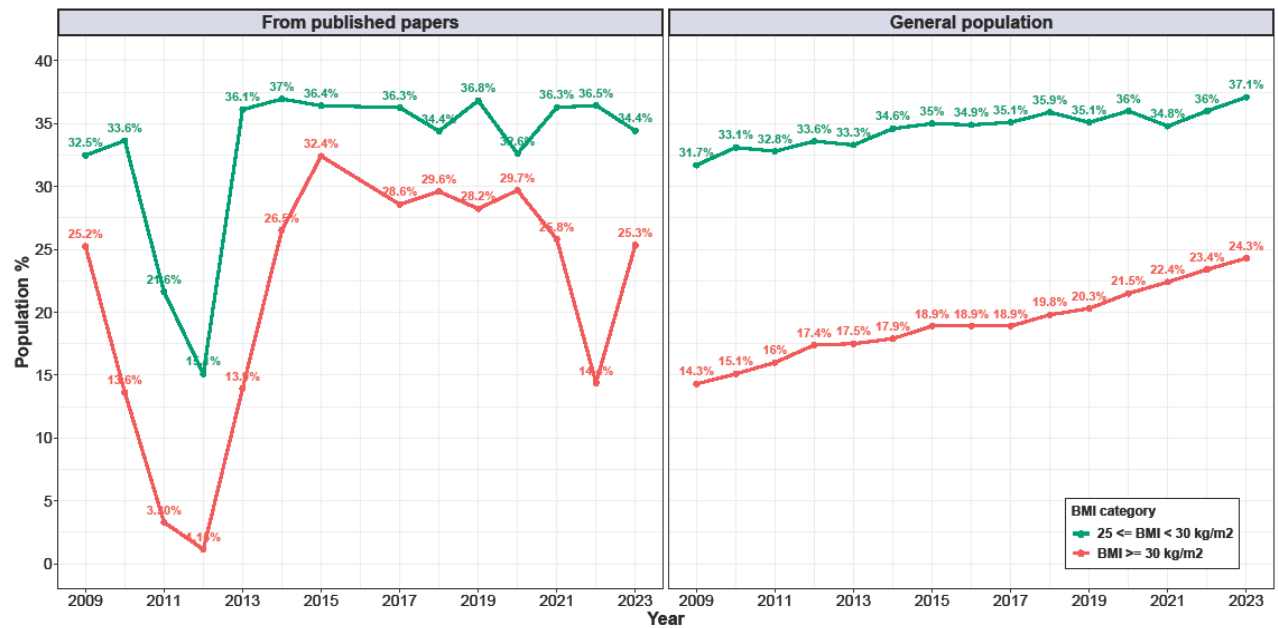


Figure 3. Estimated proportion of overweight and obese individuals from published papers compared to the proportion of the general population [31].

Note: No data were available for the general population in 2022. The value provided was the ratio of 2021 and 2023 sum values. No included study was published in 2016.

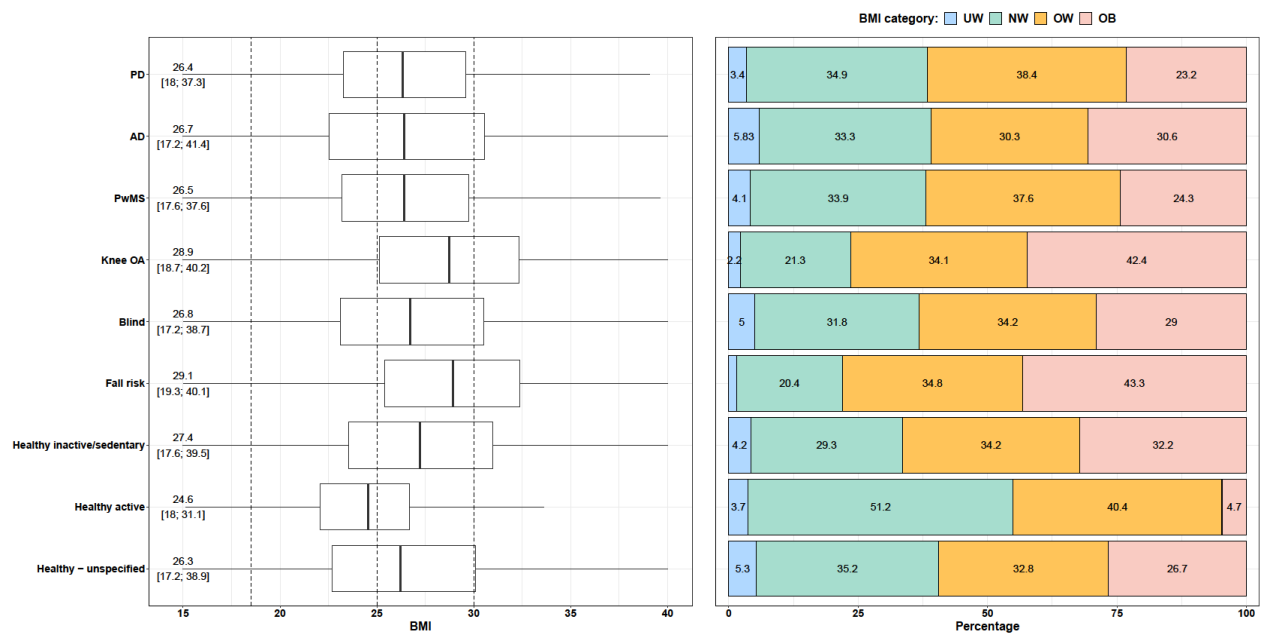


Figure 4. Estimated BMI distribution per health status.

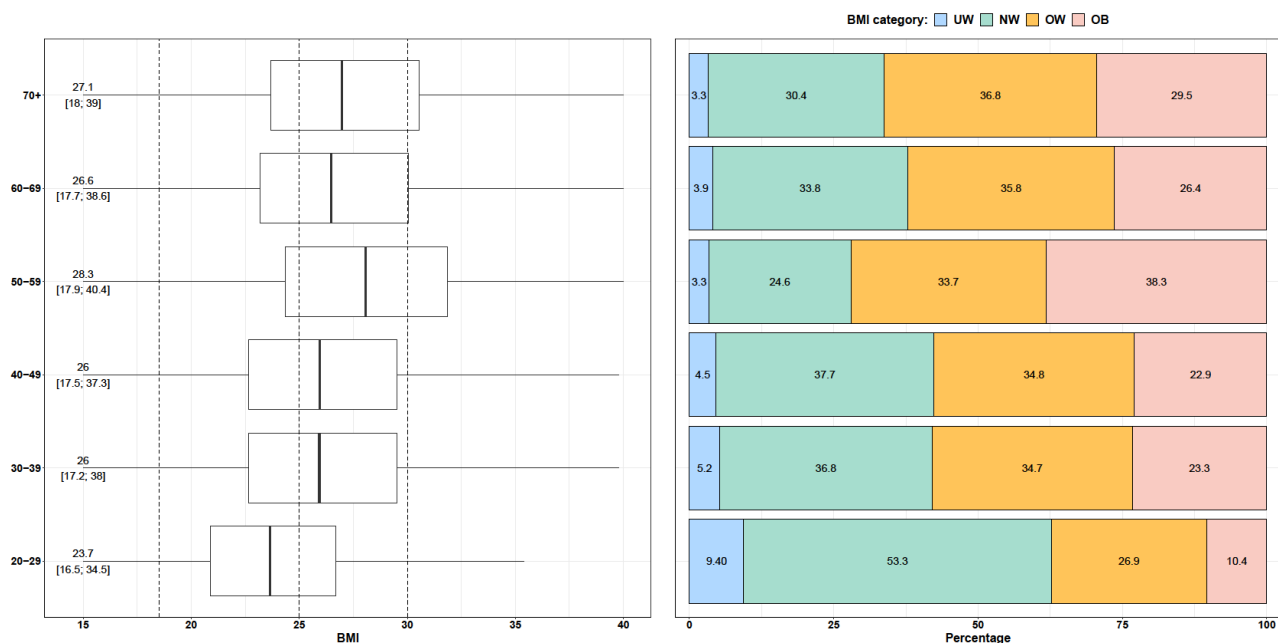


Figure 5. Estimated BMI distribution per age decade

Brazil: Overweight/obesity by age

Adults, 2019

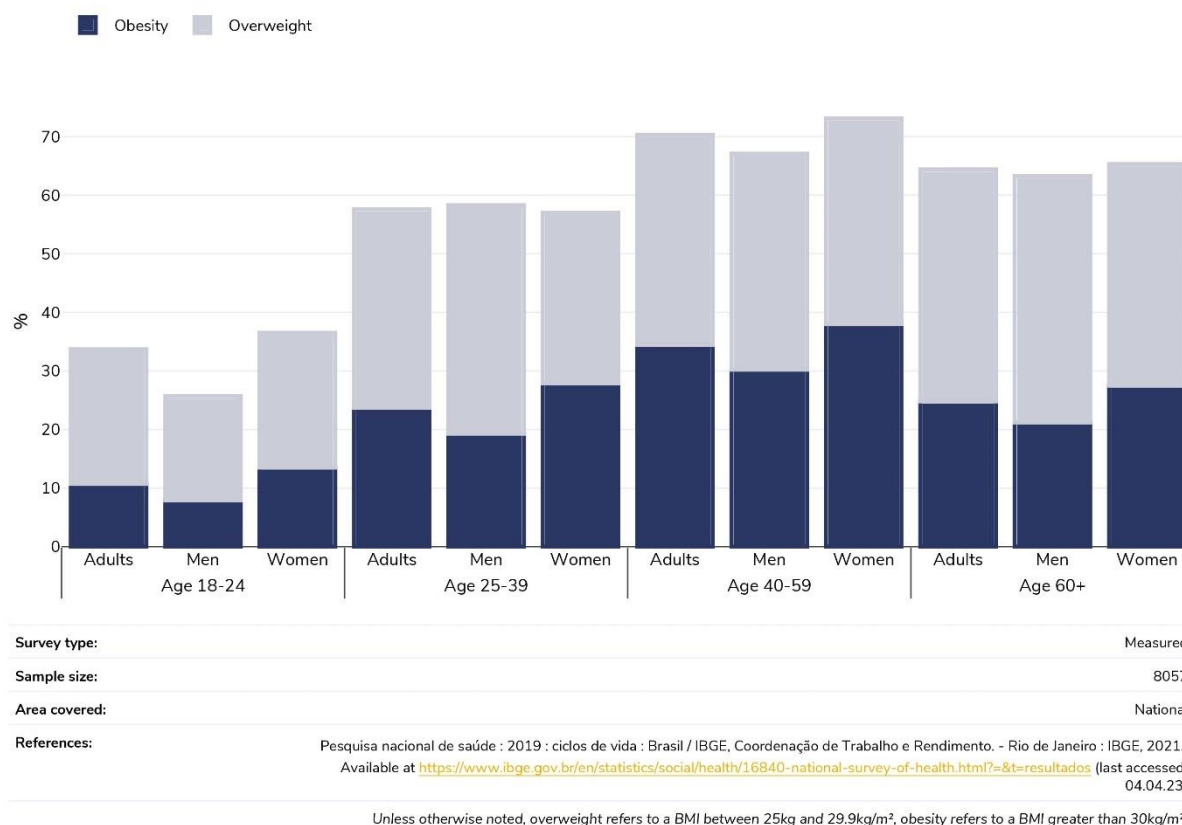


Figure 6. Overweight and obesity prevalence by age in Brazilian adults in 2019 [88].

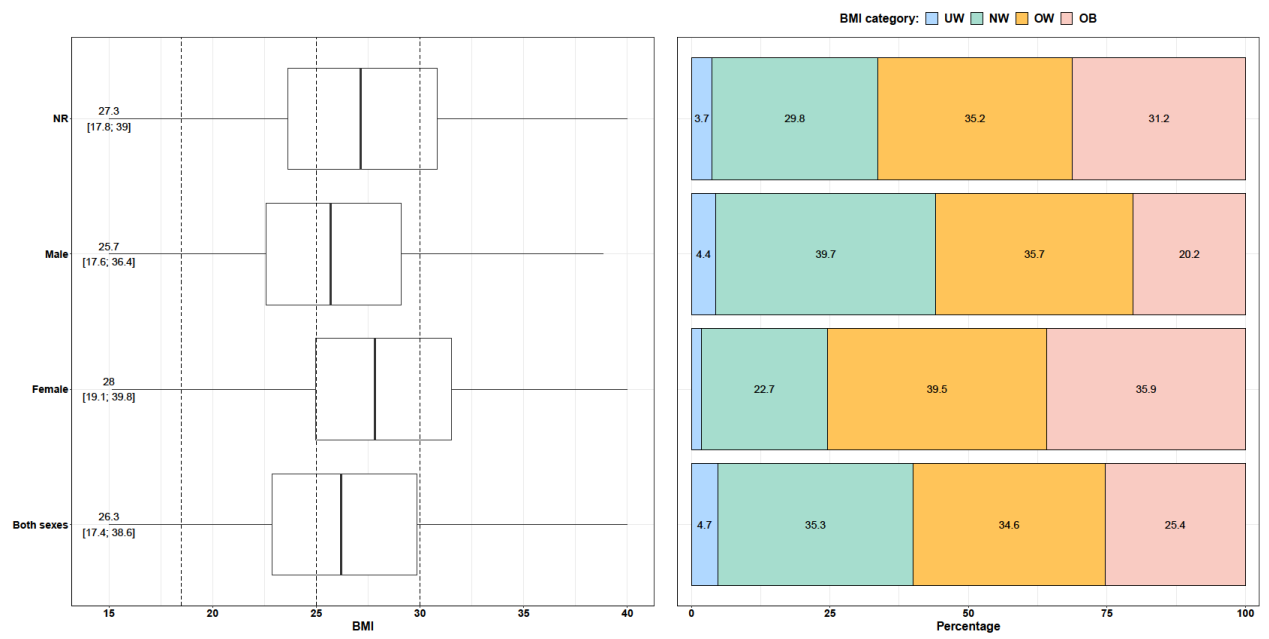
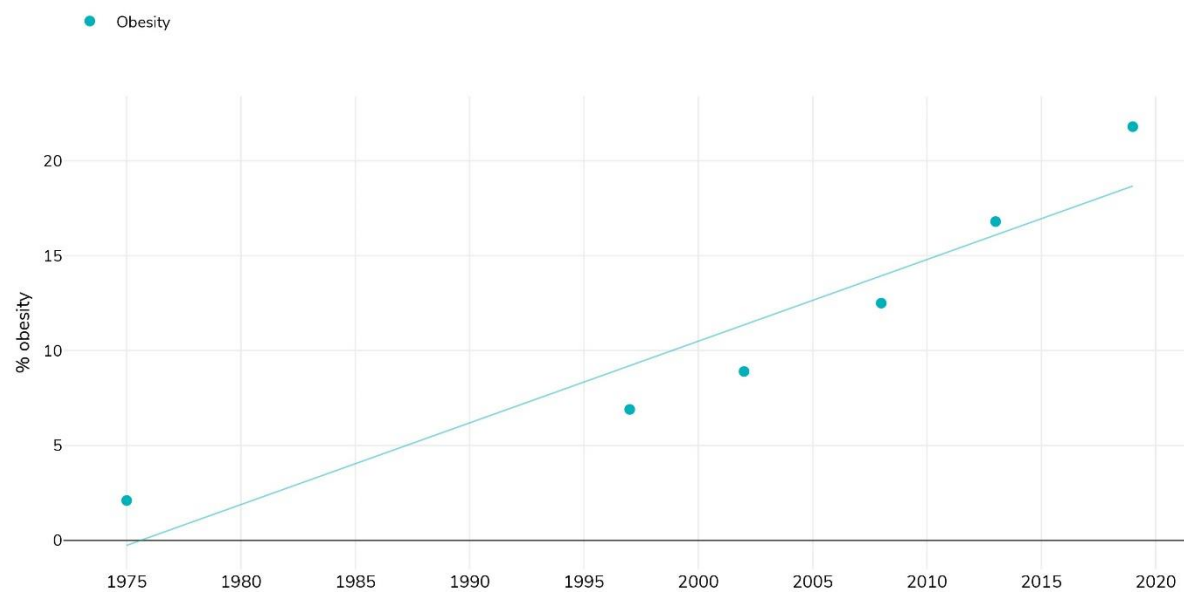


Figure 7. Estimated BMI distribution per sex.

Brazil: % Adults living with obesity, 1975-2019



Men



Survey type:

Measured

References:

For full details of references visit <https://data.worldobesity.org/>

Unless otherwise noted, overweight refers to a BMI between 25kg and 29.9kg/m², obesity refers to a BMI greater than 30kg/m².

Different methodologies may have been used to collect this data and so data from different surveys may not be strictly comparable. Please check with original data sources for methodologies used.

Figure 8. Trends in Obesity Prevalence among Brazilian Men: 1975-2019 [88].

Brazil: % Adults living with obesity, 1975-2019



Women

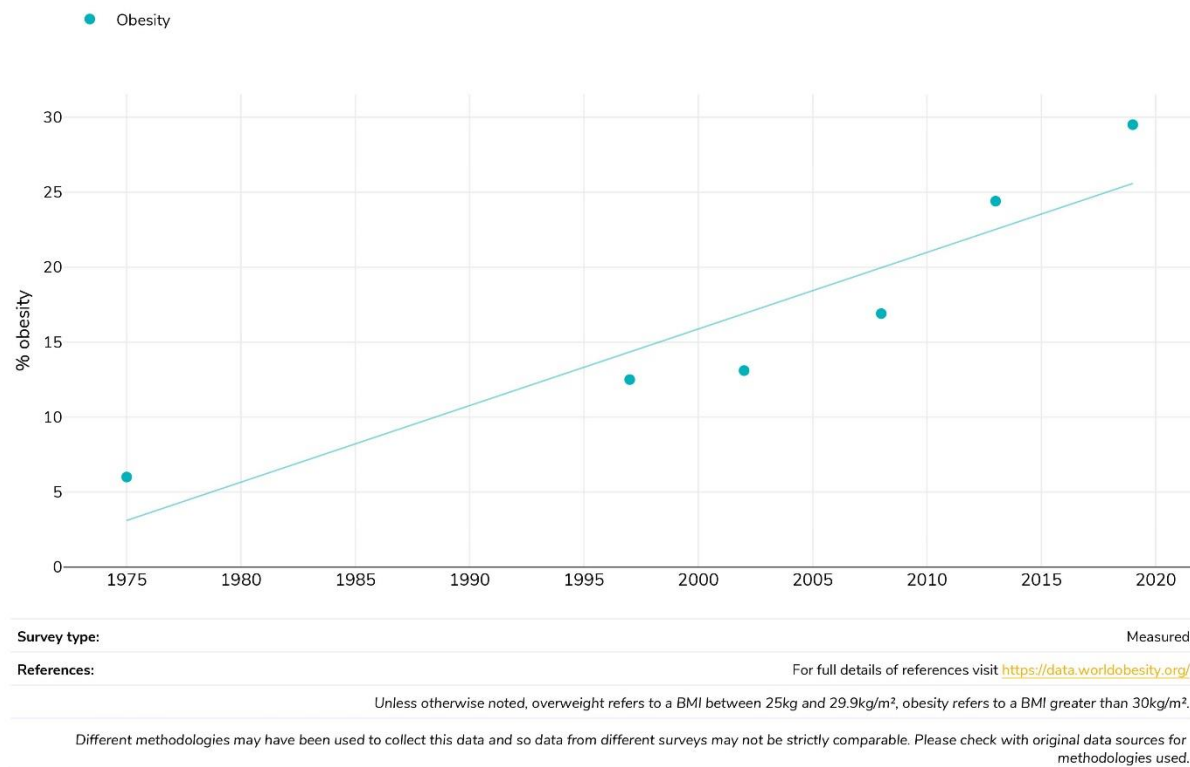


Figure 9. Trends in Obesity Prevalence among Brazilian Women: 1975-2019 [88].

Brazil: % Adults living with overweight or obesity, 1975-2019



Men

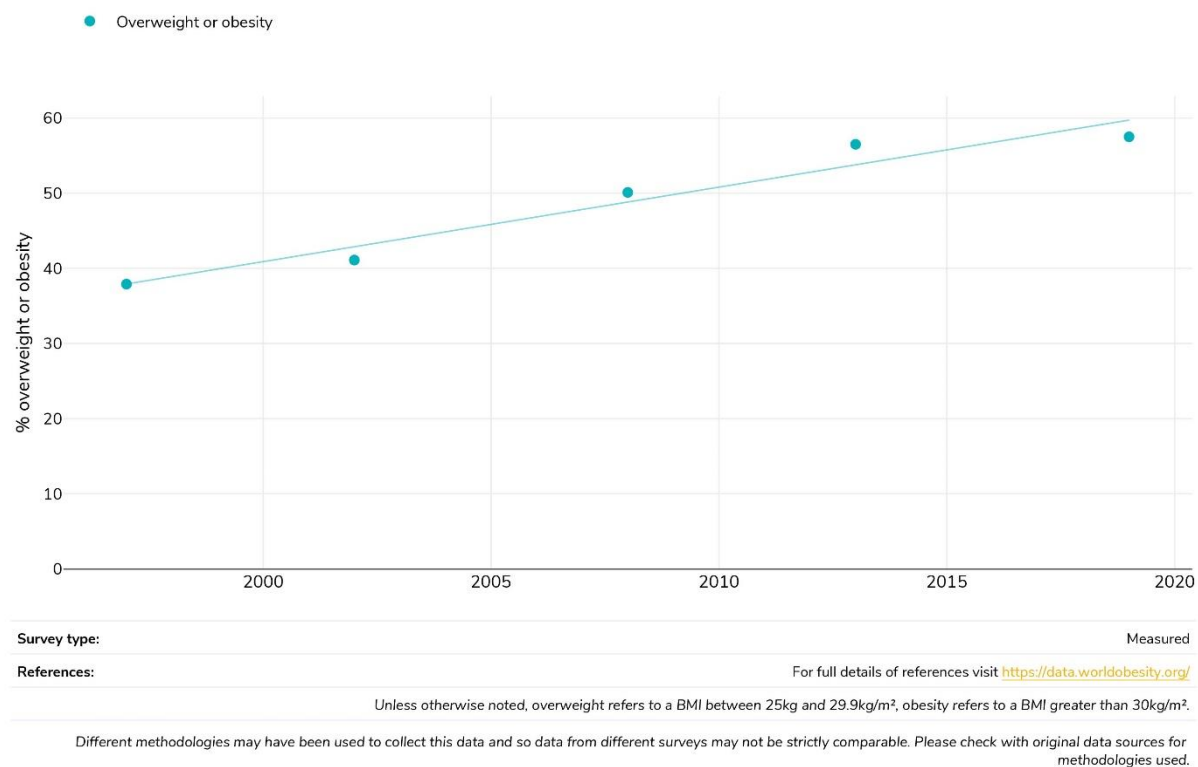


Figure 10. Trends in Overweight and Obesity Prevalence among Brazilian Men: 1975-2019 [88].

Brazil: % Adults living with overweight or obesity, 1975-2019



Women

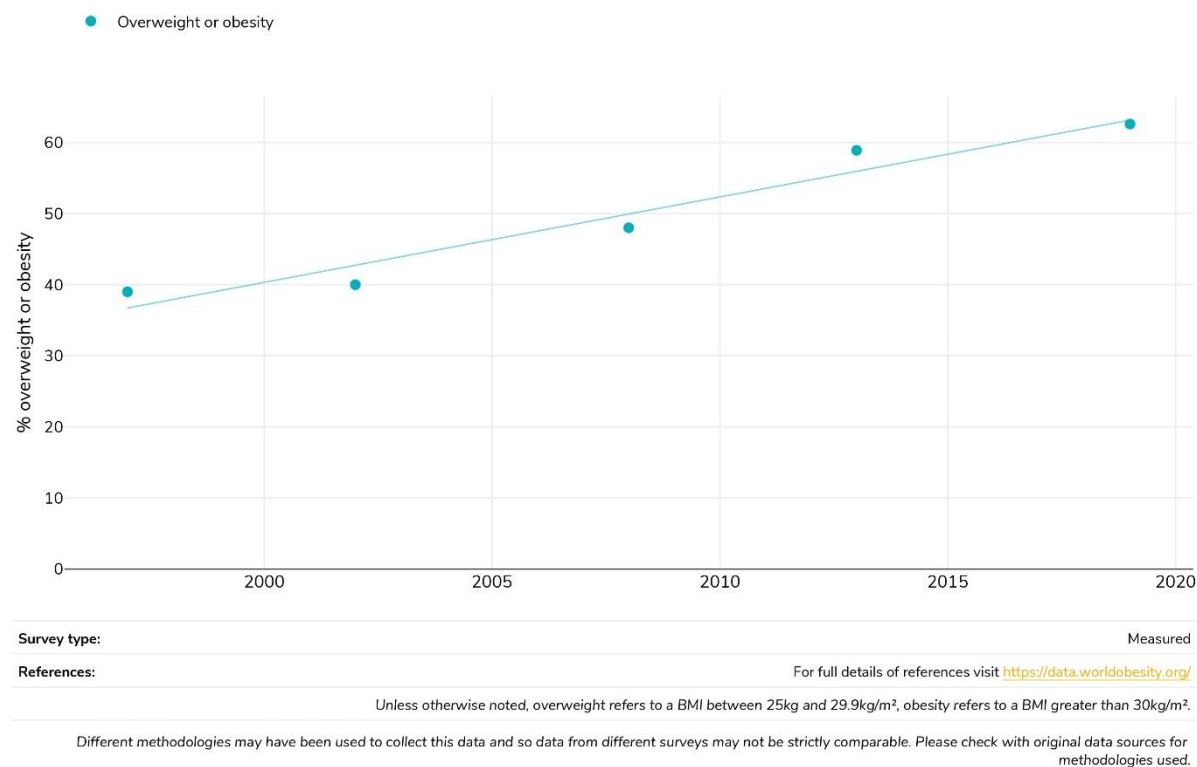


Figure 11. Trends in Overweight and Obesity Prevalence among Brazilian Women: 1975-2019 [88].

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The results of the first review demonstrated that certain parameters considered most important for assessing the risk of tripping over obstacles, such as horizontal and vertical clearances, have not yet been specifically analyzed in overweight or obese adults. The results of the second review revealed that a significant proportion of the Brazilian participants included in the published studies on obstacle crossing during walking were overweight or obese. These two key findings led us to compare a group of overweight and normal-weight individuals during an obstacle-crossing task, focusing on spatiotemporal gait parameters and clearances relative to the obstacle.

There were two main reasons for focusing on the Brazilian population. First, the Brazilian population is significantly impacted by overweight and obesity. Second, through this international collaboration, we had the opportunity to reanalyze data previously collected from a Brazilian cohort. To further explore how overweight affects obstacle crossing during walking, three research sub-objectives were pursued:

- To assess the intra-session reproducibility of spatiotemporal gait parameters and horizontal and vertical clearances in young healthy adults during an obstacle-crossing task.

- To compare these parameters between young adults of normal weight and those overweight.

- To assess the correlations between anthropometric characteristics and obstacle clearance performance in the same group of young adults.

5. Contribution 3: Reliability of Obstacle-Crossing Parameters during Overground Walking in Young Adults

Chardon, M., Barbieri, F. A., Petit, P., & Vuillerme, N. (2024). *Reliability of Obstacle-Crossing Parameters during Overground Walking in Young Adults*. *Sensors (Basel, Switzerland)*, 24(11), 3387. <https://doi.org/10.3390/s24113387>

Abstract: We aimed to evaluate the intra-session relative and absolute reliability of obstacle-crossing parameters during overground walking in young adults, and to determine the number of trials required to ensure reliable assessment. We analysed data from 43 young male adults who were instructed to walk at a self-selected velocity on a pathway and to step over an obstacle (height = 15 cm; width = 80 cm, thickness = 2 cm) three times. Spatial–temporal gait parameters of the approaching and crossing phases (i.e., before and after the obstacle) and obstacle clearance parameters (i.e., vertical and horizontal distance between the foot and the obstacle during crossing) were computed using a three-dimensional motion analysis system. Intraclass correlation coefficients were used to compute the relative reliability, while standard error of measurement and minimal detectable change were used to assess the absolute reliability for all possible combinations between trials. Results showed that most spatial–temporal gait parameters and obstacle clearance parameters are reliable using the average of three trials. However, the mean of the second and third trials ensures the best relative and absolute reliabilities of most obstacle-crossing parameters. Further works are needed to generalize these results in more realistic conditions and in other populations.

Keywords: reliability; obstacle-crossing; gait

1. Introduction

Reliability does represent a crucial consideration as a methodology for application in gait analysis. Indeed, if gait analysis is intended to serve as an outcome measure for diagnostic, monitoring, or therapeutic purposes, the level of reliability for each computed gait parameter has to be established.

This is certainly one of the reasons that has prompted scientists and researchers to focus on the reliability assessment of gait measurements in both healthy [1,2,3,4,5] and pathological [3,6,7,8,9,10,11] populations. In previous studies conducted on overground/flat conditions in healthy patients [2] and stroke individuals [6,7], speed and stride length [2,6,7], as well as cadence and gait cycle time [7], showed good reliability. In addition, knee, hip, and ankle angles showed good to excellent reliability in healthy individuals [1] and adults with spinal cord injury [6].

However, few studies have investigated the number of trials needed to ensure reliable intra-session gait assessment [2,9,12]. For instance, Soulard et al. (2021) [2] showed that three trials were enough to ensure reliable gait assessment during the 10 m walk test in both single and dual-task conditions in healthy adults [2]. Interestingly, the common feature of the above-mentioned gait reliability studies is the assessment of unobstructed level walking tasks. However, not much is known about the reliability of gait parameters under more challenging conditions, such as crossing physical obstacles while overground walking (obstructed walking task). This observation is somewhat surprising since obstacle-crossing performance during walking has been widely studied using vision/camera-based systems in various populations, including children [13,14], older healthy adults [15,16], obese individuals [17], and people with Parkinson's disease [18,19,20,21], multiple sclerosis [22], traumatic brain injuries [23], or stroke [24,25]. This observation is also of great concern since obstacles are likely encountered during community ambulation in an everyday environment (e.g., obstacles on sidewalks or in corridors of railway or subway stations [26]). In addition, it is widely agreed that measuring clearance parameters during the performance of the obstacle-crossing task is of significant clinical importance, assuming that lower toe clearances [27] and horizontal distances [28] could result in a high probability of foot contact and hence an increased risk of stumbles, trips, and falls.

To our knowledge, no study has yet investigated the reliability of these widely used gait and clearance parameters during obstacle-crossing in young healthy adults, whereas the reliability of gait parameters computed using vision/camera-based systems has previously been

assessed during unobstructed walking in healthy adults (e.g., [29,30,31,32]). To address some of the aforementioned limitations, the purpose of the present work was to evaluate the reliability, relative and absolute, of obstacle-crossing parameters during overground walking in young adults. We further aimed to determine the number of trials required to ensure reliable obstacle-crossing measurements. Indeed, determining the number of trials required to ensure reliable measurement is a prerequisite to allow comparisons between groups at a single time point [33]. Note that this question has been the subjects of a number of studies in a variety of applications fields, including human movement, sport, and health, to name a few (e.g., [2,34,35,36,37,38,39,40,41,42,43,44,45,46,47]). In particular, intra-session reliability can favourably be used to assess the number of trials to ensure reliable measurements [2,9,38,48] to optimize gait assessments in clinical practice.

2. Materials and Methods

This study is a secondary analysis of previously published obstacle-crossing studies [22,49,50].

2.1. Participants

Data from 43 Brazilian males (age = 29.1 ± 5.91 years old, body mass = 76.3 ± 9.97 kg, body height = 1.77 ± 0.06 cm, BMI = 24.4 ± 2.72 kg/m², mean $\pm$ SD) were analysed. Participants had no diagnosis of muscular or neurodegenerative disease. Participants were informed about the experimental procedures and signed informed consent. The study was approved by the University Institution Review Board (authorization number: CAAE#99191318.0.0000.5398). This study and all methods were performed in accordance with the Declaration of Helsinki.

2.2. Experimental Protocol

Participants were instructed to walk barefoot at a self-selected velocity on an 8.5 m long pathway and to step over a physical obstacle (height = 15 cm; width = 80 cm, thickness = 2 cm) placed in the middle of the pathway. To ensure that participants crossed the obstacle with the right leg as the leading limb, the starting point of each trial was adjusted, and at least two strides were completed before crossing the obstacle. Participants completed three trials.

2.3. Gait Assessment

Kinematic data were recorded using ten infrared cameras (Vicon Motion System[®], Oxford, UK, 200 Hz). Two markers were positioned at the top of the obstacle. Also, four markers were placed on the lateral aspect of the calcaneus and head of the second metatarsus of the right limb and the medial aspect of the calcaneus and head of the second metatarsus of the left limb. Conventional labelling of the limbs was used: the leading foot crossed the obstacle first, and the trailing foot crossed second. Signals were filtered with a low-pass (6 Hz) Butterworth filter of fifth-order (zero-lag). These pre-processed signals were used to compute the following parameters:

Spatial–temporal gait parameters (length, width, duration, velocity, and double-support time) of the approaching phase (stride before the obstacle) and of the crossing phase (step over the obstacle);

Leading and trailing foot placement prior to the obstacle (horizontal distance from the second metatarsal marker to the obstacle);

Leading and trailing vertical toe foot clearance during obstacle-crossing (vertical distance at the moment that the second metatarsal marker was above the obstacle);

Leading and trailing foot placement after the obstacle (horizontal distance from the heel marker to the obstacle).

2.4. Statistical Analysis

To examine the potential difference between trials for each obstacle-crossing parameter, a repeated measures analysis of variance (RM-ANOVA) was first carried out. In cases where a difference was observed (type I error rate set at $\alpha = 0.05$), a pairwise comparison post hoc test was performed to compare differences between pairs of trials, using the Benjamini–Hochberg approach to account for multiple testing.

To assess relative reliability across the three trials, the intraclass correlation coefficient (ICC) based on a two-way random effects model (absolute agreement, ICC(2.1)) was calculated. ICC(2.1) values inferior to 0 were considered ‘poor’, between 0.01 and 0.20 as ‘slight’, between 0.21–0.40 as ‘fair’, between 0.41–0.60 as ‘moderate’, between 0.61–0.80 as ‘substantial’, and 0.80–1.00 as ‘almost perfect’ relative reliability [51].

To assess absolute reliability across the three trials, the standard error of measurement (SEM) and the minimum detectable change (MDC) were computed. SEM, with the same unit as obstacle-crossing parameters, corresponds to the absolute measure of the variability of the

errors of measurements and informs on the precision of obstacle-crossing parameters of individual participants [52]. SEM was calculated using the following formula [53]: $SEM = SD\sqrt{(1-ICC(2.1))}$, where SD is the standard deviation of the obstacle-crossing parameters from all participants and ICC(2.1) is the relative reliability. MDC is the minimum value for which a difference can be considered “real”. MDC was calculated using the following formula [54]: $MDC = SEM \times 1.96 \times \sqrt{2}$. The SEM% and MDC% were also expressed as a percentage of the mean for each obstacle-crossing parameter. Lower values for SEM% and MDC% indicate higher absolute reliability. Precisely, SEM% values were considered ‘low’ ($SEM\% \leq 10\%$) or ‘high’ ($SEM\% > 10\%$) [55], while MDC% values were considered ‘low’ ($MDC\% \leq 20\%$), ‘acceptable’ ($20\% < MDC\% < 40\%$), or ‘high’ ($MDC\% \geq 40\%$) [56].

To quantify the agreement between pairs of trials for each of the 16 obstacle-crossing parameters, Lin’s concordance correlation coefficient (CCC) and associated 95% confidence intervals [57,58], as well as the Shieh exact test for agreement [59], were used. The CCC indicates how close the measurement pairs fall to the 45-degree line (perfect agreement). Hence, the CCC is a measure of the reproducibility of measurements. The CCC ranges from -1 to 1 , with perfect agreement at 1 and perfect discordance at -1 . Agreement was considered ‘poor’ for CCC values < 0.40 , ‘moderate’ for CCC values ranging from 0.40 to 0.70 , and ‘good’ for CCC values > 0.70 [60].

Limits of agreement (LOA) and Bland–Altman plots of the differences between trials and their arithmetic mean were used to assess the magnitude of disagreement between trials for each obstacle-crossing parameter. LOA allows the quantification of bias and the determination of a range of agreement, within which 95% of the differences between one measurement and the other are included. The bias is significant when the line of equality is not within the 95% CI of the mean difference. The smallest worthwhile change (SWC) was used to determine the maximum allowed difference between trials presented in Bland–Altman plots [61]. The SWC provides a method to evaluate a real change in performance between trials. If the SWC is low and included in the LOA or Shieh 95% CI, it indicates a low variation between trials. Two trials are considered in agreement if the LOA or Shieh exact test does not exceed the maximum allowed difference between trials (SWC).

All statistical analyses were performed using R software 4.3.1[®] (R Core Team, Vienna, Austria) for Windows 10©. The list of all R packages used is provided in the Supplementary Materials.

3. Results

3.1. Difference between Trials

Most obstacle-crossing parameters exhibited no significant differences between trials. The only three exceptions were observed for the stride width and the double support time ($p=0.04$, eta-squared = 0.01) during the approaching phase, and for the trailing foot horizontal distance after the obstacle ($p=0.02$, eta-squared = 0.02). For these three parameters, pairwise t -tests showed that trial 1 (T1) differed from trials 2 and 3. Stride width was lower in T1 compared to T2 and T3 ($p=0.02$ for T1–T2, $p=0.04$ for T1–T3), double support time was greater for T1 compared to T2 and T3 ($p=0.05$ for T1–T2, $p=0.03$ for T1–T3), while for the trailing foot horizontal distance after obstacle, T3 was higher compared to T1 and T2 ($p=0.03$).

Table 1 provides the arithmetic mean and standard deviation of obstacle-crossing parameters for each trial and the mean of the three trials.

Table 1: Arithmetic mean and standard deviation of obstacle crossing parameters for each trial and for their mean

Condition	Parameter	T1	T2	T3	T123
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Approaching phase	Stride double support time (s)	0.36 (0.05)	0.35 (0.06)	0.35 (0.05)	0.36 (0.05)
	Stride duration (s)	1.10 (0.13)	1.09 (0.11)	1.09 (0.10)	1.09 (0.11)
	Stride length (cm)	131 (11.4)	131 (11.5)	132 (11.2)	131 (11.3)
	Stride velocity (cm/s)	120 (17.2)	122 (15.5)	122 (15.4)	121 (15.9)
	Stride width (cm)	10.6 (2.49)	11.3 (2.74)	11.2 (2.86)	11.0 (2.70)
Crossing phase	Step double support time (s)	0.22 (0.04)	0.20 (0.05)	0.21 (0.04)	0.21 (0.04)
	Step duration (s)	0.64 (0.08)	0.62 (0.07)	0.63 (0.07)	0.63 (0.07)
	Step length (cm)	72.7 (9.49)	73.4 (9.78)	73.6 (9.33)	73.2 (9.47)
	Step velocity (cm/s)	115 (20.8)	119 (21.5)	118 (19.0)	118 (20.4)
	Step width (cm)	10.2 (3.40)	10.4 (3.80)	10.1 (3.79)	10.2 (3.64)
Obstacle clearance	Leading foot horizontal distance prior to obstacle (cm)	108 (13.0)	108 (10.4)	108 (10.1)	108 (11.1)
	Trailing foot horizontal distance prior to obstacle (cm)	43.0 (10.3)	44.1 (8.77)	42.9 (10.1)	43.3 (9.71)
	Leading foot horizontal distance after obstacle (cm)	25.7 (6.61)	25.0 (6.63)	26.8 (7.75)	25.8 (7.00)
	Trailing foot horizontal distance after obstacle (cm)	91.6 (11.5)	91.8 (10.4)	95.0 (12.1)	92.8 (11.4)
	Leading foot toe clearance (cm)	9.93 (4.21)	9.99 (4.37)	10.8 (5.19)	10.2 (4.59)
	Trailing foot toe clearance (cm)	31.4 (8.68)	32.2 (8.01)	32.0 (6.53)	31.9 (7.74)

Note: SD: arithmetic standard deviation, T1: trial 1, T2: trial 2, T3: trial 3, T123: arithmetic mean of the three trials.

3.2. Absolute and Relative Reliabilities

Figure 1 and Table 2 present the ICC(2.1) values for each obstacle-crossing parameter for all comparisons of trials. Table 2 also provides the SEM, SEM%, MDC, and MDC%.

Figure 1. Mean ICC(2.1) for the means of trial 1–2, 1–3, 2–3 and 1–2–3 calculated for each obstacle-crossing parameter.

Relative reliability:					
	slight (0.00 < ICC ≤ 0.20)	fair (0.20 < ICC ≤ 0.40)	moderate (0.40 < ICC ≤ 0.60)		
	substantial (0.60 < ICC ≤ 0.80)	almost perfect (ICC > 0.80)			
Stride width (cm)	0.741	0.739	0.764	0.748	Approaching phase
Stride velocity (cm/s)	0.825	0.819	0.9	0.846	
Stride length (cm)	0.745	0.763	0.859	0.789	
Stride duration (s)	0.868	0.84	0.874	0.861	
Stride double support time (s)	0.764	0.774	0.814	0.784	
Step width (cm)	0.349	0.317	0.709	0.466	Avoidance phase
Step velocity (cm/s)	0.719	0.771	0.816	0.767	
Step length (cm)	0.835	0.811	0.869	0.839	
Step duration (s)	0.6	0.778	0.763	0.711	
Step double support time (s)	0.188	0.443	0.648	0.416	
Vertical distance: toe clearance — trailing limb (cm)	0.673	0.576	0.728	0.657	Obstacle clearance
Vertical distance: toe clearance — leading limb (cm)	0.841	0.78	0.886	0.836	
Horizontal distance: obstacle foot — trailing limb (cm)	0.722	0.713	0.634	0.689	
Horizontal distance: obstacle foot — leading limb (cm)	0.712	0.605	0.696	0.669	
Horizontal distance: foot obstacle — trailing limb (cm)	0.744	0.699	0.804	0.746	
Horizontal distance: foot obstacle — leading limb (cm)	0.511	0.506	0.688	0.558	
	T1-T2	T1-T3	T2-T3	T1-T2-T3	Trial

Table 2: Relative and absolute reliability for each obstacle crossing parameter between the mean of the first and second trials (T1-T2), the first and third trials (T1-T3), the second and third trials (T2-T3), and the means of the three consecutive trials (T1-T2-T3).

Condition	Parameter	T1-T2					T1-T3					T2-T3					T1-T2-T3				
		ICC(2.1) [95%CI]	MDC	MDC%	SEM	SEM%	ICC [95%CI]	MDC	MDC%	SEM	SEM%	ICC(2.1) [95%CI]	MDC	MDC%	SEM	SEM%	ICC(2.1) [95%CI]	MDC	MDC%	SEM	SEM%
Approaching phase	Stride length (cm)	0.75 [0.58 ; 0.85]	15.9	12.2	5.75	4.40	0.76 [0.60 ; 0.86]	15.2	11.6	5.48	4.18	0.86 [0.76 ; 0.92]	11.7	8.94	4.23	3.23	0.79 [0.68 ; 0.87]	14.4	11.0	5.19	3.96
	Stride width (cm)	0.74 [0.55 ; 0.85]	3.71	34.0	1.34	12.3	0.74 [0.56 ; 0.85]	3.81	35.0	1.37	12.6	0.76 [0.61 ; 0.87]	3.75	33.4	1.35	12.1	0.75 [0.62 ; 0.84]	3.76	34.2	1.35	12.3
	Stride double support time (s)	0.76 [0.60 ; 0.87]	0.07	20.4	0.03	7.36	0.77 [0.61 ; 0.87]	0.07	18.8	0.02	6.78	0.81 [0.68 ; 0.89]	0.06	18.3	0.02	6.60	0.78 [0.67 ; 0.87]	0.07	19.2	0.02	6.92
	Stride duration (s)	0.87 [0.77 ; 0.93]	0.12	10.9	0.04	3.95	0.84 [0.72 ; 0.91]	0.13	11.5	0.05	4.15	0.87 [0.78 ; 0.93]	0.11	9.73	0.04	3.51	0.86 [0.78 ; 0.92]	0.12	10.7	0.04	3.88
	Stride velocity (cm/s)	0.83 [0.70 ; 0.90]	18.9	15.6	6.82	5.64	0.82 [0.69 ; 0.90]	19.2	15.8	6.92	5.71	0.90 [0.82 ; 0.95]	13.4	11.0	4.85	3.98	0.85 [0.76 ; 0.91]	17.3	14.3	6.26	5.16
Crossing phase	Step length (cm)	0.84 [0.72 ; 0.91]	10.8	14.8	3.89	5.33	0.81 [0.68 ; 0.89]	11.3	15.4	4.07	5.57	0.87 [0.77 ; 0.93]	9.52	13.0	3.44	4.67	0.84 [0.75 ; 0.90]	10.5	14.4	3.80	5.19
	Step width (cm)	0.35 [0.06 ; 0.59]	8.02	77.9	2.89	28.1	0.32 [0.02 ; 0.56]	8.20	80.8	2.96	29.2	0.71 [0.52 ; 0.83]	5.64	54.8	2.03	19.8	0.47 [0.28 ; 0.64]	7.37	72.0	2.66	26.0
	Step double support time (s)	0.19 [-0.10 ; 0.45]	0.11	53.5	0.04	19.3	0.44 [0.18 ; 0.65]	0.09	40.9	0.03	14.8	0.65 [0.44 ; 0.79]	0.07	34.4	0.03	12.4	0.42 [0.23 ; 0.60]	0.09	43.9	0.03	15.8
	Step duration (s)	0.60 [0.37 ; 0.76]	0.13	20.3	0.05	7.34	0.78 [0.63 ; 0.87]	0.09	14.9	0.03	5.38	0.76 [0.61 ; 0.86]	0.09	14.8	0.03	5.34	0.71 [0.58 ; 0.82]	0.11	16.9	0.04	6.09
	Step velocity (cm/s)	0.72 [0.54 ; 0.84]	31.0	26.5	11.2	9.54	0.77 [0.62 ; 0.87]	26.3	22.5	9.49	8.14	0.82 [0.69 ; 0.90]	24.0	20.2	8.65	7.29	0.77 [0.65 ; 0.86]	27.3	23.2	9.83	8.36
Obstacle clearance	Trailing foot horizontal distance prior to obstacle (cm)	0.74 [0.58 ; 0.85]	13.4	30.8	4.83	11.1	0.70 [0.51 ; 0.82]	15.5	36.0	5.58	13.0	0.80 [0.67 ; 0.89]	11.6	26.6	4.18	9.60	0.75 [0.62 ; 0.84]	13.6	31.3	4.89	11.3
	Trailing foot horizontal distance after obstacle (cm)	0.72 [0.54 ; 0.84]	15.9	17.4	5.74	6.26	0.71 [0.51 ; 0.84]	17.6	18.9	6.35	6.81	0.63 [0.41 ; 0.79]	18.9	20.3	6.83	7.32	0.69 [0.54 ; 0.80]	17.6	18.9	6.33	6.82
	Trailing foot toe clearance (cm)	0.67 [0.47 ; 0.81]	13.2	41.4	4.76	15.0	0.58 [0.34 ; 0.75]	13.8	43.5	4.98	15.7	0.73 [0.55 ; 0.84]	10.5	32.7	3.79	11.8	0.66 [0.51 ; 0.78]	12.6	39.4	4.53	14.2
	Leading foot horizontal distance prior to obstacle (cm)	0.51 [0.25 ; 0.70]	22.6	21.0	8.17	7.57	0.51 [0.25 ; 0.70]	22.5	20.9	8.12	7.55	0.69 [0.49 ; 0.82]	15.8	14.6	5.70	5.28	0.56 [0.39 ; 0.71]	20.5	19.1	7.41	6.88
	Leading foot horizontal distance after obstacle (cm)	0.71 [0.53 ; 0.83]	9.80	38.6	3.54	13.9	0.61 [0.38 ; 0.76]	12.5	47.6	4.51	17.2	0.70 [0.50 ; 0.82]	11.0	42.6	3.98	15.4	0.67 [0.52 ; 0.79]	11.2	43.2	4.03	15.6
	Leading foot toe clearance (cm)	0.84 [0.73 ; 0.91]	4.72	47.4	1.70	17.1	0.78 [0.63 ; 0.88]	6.14	59.3	2.21	21.4	0.89 [0.79 ; 0.94]	4.47	43.0	1.61	15.5	0.84 [0.75 ; 0.90]	5.16	50.4	1.86	18.2

Note: ICC: intraclass correlation coefficient, MDC: minimal detectable change, SEM: standard error of measurement, T1: trial 1, T2: trial 2, T3: trial 3.

Mean relative reliability legend: slight (gray: $0.00 < \text{ICC}(2.1) < 0.20$), fair (red: $0.21 < \text{ICC}(2.1) < 0.40$), moderate (orange: $0.41 < \text{ICC}(2.1) < 0.60$), substantial (yellow: $0.61 < \text{ICC}(2.1) < 0.80$), and almost perfect (green: $0.81 < \text{ICC}(2.1) < 1.00$).

MDC% legend: low (yellow: $\text{MDC} \% \leq 20\%$), acceptable (orange: $20\% < \text{MDC} \% < 40\%$), and high (red: $\text{MDC} \% \geq 40\%$).

SEM% legend: low (green: $\text{SEM} \% \leq 10\%$), and high ($\text{SEM} \% > 10\%$).

Overall, when pooling the values of the three trials, the relative reliability ranged from moderate to practically perfect, whereas the absolute reliability was good for nine out of the sixteen parameters. Furthermore, the highest relative and absolute reliabilities were found when pooling values from T2–T3, followed by T1–T2–T3, T1–T3, and T1–T2.

3.2.1. Spatial–Temporal Gait Parameters during the Approaching Phase

Relative reliability: Regardless of the comparison of trials considered, spatial–temporal gait parameters during the approaching phase showed either substantial or almost perfect reliability. Indeed, ICC(2.1) ranged from 0.61 to 0.80 for stride width for all trial comparisons, for stride length, and double support time for T1–T2, T1–T3, and T1–T2–T3, while ICC(2.1) ranged from 0.81 to 1.00 for stride duration and stride velocity for all trial comparisons, and for stride length and double support time for T2–T3.

Absolute reliability: Regardless of the comparison of trials considered, SEM% and MDC% values were low for most of the spatial–temporal gait parameters during the approaching phase ($\text{SEM}\% < 10$ and $\text{MDC}\% < 20\%$), with the exception of the stride width ($\text{SEM}\% > 10\%$ and $20\% < \text{MDC}\% < 40\%$, for all trial comparisons), and MDC% of the double support time ($\text{MDC}\% = 20.4\%$, for T1–T2).

Number of trials to ensure reliable measurements: The comparisons of means of ICC(2.1) between trials showed that, for all spatial–temporal gait parameters during the approaching phase, slightly higher ICC(2.1) and lower SEM% and MDC% were obtained when pooling the second and third trials, compared to the first and second trials, the first and third trials, or the three trials.

3.2.2. Spatial–Temporal Gait Parameters during the Crossing Phase

Relative reliability: Regardless of the comparison of trials considered, step length, step duration, and step velocity showed either substantial or almost perfect relative reliability. Indeed, ICC(2.1) ranged from 0.61 to 0.80, for step duration for all trial comparisons and for step velocity for T1–T2, T1–T3, and T1–T2–T3, while ICC(2.1) ranged from 0.81 to 1.00, for step length for all trial comparisons and for step velocity for T2–T3. Furthermore, step width and double support time showed slight relative reliability ($\text{ICC}(2.1) = 0.19$ for double support time for T1–T2), fair relative reliability ($\text{ICC}(2.1)$ ranged from 0.21 to 0.40, for step width for T1–T2 and T1–T3), moderate relative reliability ($\text{ICC}(2.1)$ ranged from 0.41 to 0.60 for step width for T1–T2–T3, and for double support time for T1–T3 and T1–T2–T3), or substantial

relative reliability (ICC(2.1) ranged from 0.61 to 0.80 for step width and double support time for T2–T3 only).

Absolute reliability: Regardless of the comparison of trials considered, SEM% and MDC% were low or acceptable ($\text{SEM}\% < 10\%$ and $\text{MDC}\% < 40\%$) for step length, duration, and velocity. Step width and double support time showed high SEM% and MDC% values ($\text{SEM}\% > 10\%$ and $\text{MDC}\% > 40\%$), except for double support time when pooling the second and third trials with an acceptable MDC% ($\text{MDC}\% = 34.4\%$).

Number of trials to ensure reliable measurements: The comparisons of means of ICC(2.1) between trials showed that, for almost all spatial–temporal gait parameters during the crossing phase, slightly higher ICC(2.1) (except for step duration, the best relative reliability was found for T1–T3, $\text{ICC}(2.1) = 0.78$) and lower SEM% (all parameters) and MDC% (all parameters) were obtained when pooling the second and third trials, compared to the first and second trials, the first and third trials, or the three trials.

3.2.3. Obstacle Clearance Parameters

Relative reliability: Regardless of the comparison of trials considered, obstacle clearance parameters showed either moderate, substantial, or almost perfect mean relative reliability. The highest ICC(2.1) values were found for leading toe clearance with substantial to almost perfect reliability ($0.78 \leq \text{ICC}(2.1) \leq 0.89$ for all trial comparisons), followed by trailing foot horizontal distance prior to the obstacle, and leading and trailing foot horizontal distance after the obstacle with substantial reliability ($0.61 \leq \text{ICC}(2.1) \leq 0.80$ for all trial comparisons). The lowest ICC values were found for the trailing foot toe clearance (moderate reliability, $\text{ICC}(2.1) = 0.58$, for T1–T3) and for the leading foot horizontal distance prior to an obstacle (moderate reliability, $0.51 \leq \text{ICC}(2.1) \leq 0.56$, for T1–T2, T1–T3, and T1–T2–T3).

Absolute reliability: Regardless of the comparison of trials considered, SEM% and MDC% were low or acceptable for leading foot horizontal distance prior to the obstacle and trailing foot horizontal distance after the obstacle ($\text{SEM}\% < 10\%$ and $\text{MDC}\% < 40\%$). Regardless of the comparison of trials considered, high SEM% values were found for leading and trailing foot toe clearance, leading foot horizontal distance after the obstacle, and trailing foot horizontal distance prior to the obstacle (for T1–T2, T1–T3, and T1–T2–T3). High MDC% ($\text{MDC}\% > 40\%$) values were observed for the leading (all trial comparisons) and trailing (T1–T2, T1–T3) limb toe clearances, as well as for the horizontal distance after the obstacle for the leading limb (T1–T3, T2–T3, T1–T2–T3).

Number of trials to ensure reliable measurements. The comparisons of means of ICC(2.1) between trials showed that, for almost all clearance parameters, slightly higher ICC(2.1) and lower SEM% and MDC% were obtained when pooling the second and third trials, compared to the first and second trials, the first and the third trials, or the three trials.

3.3. Agreement between Trials

When considering the maximum allowed difference between trials (SWC), regardless of the obstacle-crossing parameter, all pairs of trials were considered in agreement because the SWC was always within the LOA and Shieh ranges.

3.3.1. Spatial–Temporal Gait Parameters during the Approaching Phase

Good agreement ($CCC > 0.70$) between each pair of trials was found for all spatial–temporal gait parameters during the approaching phase.

The best results were found for T2–T3 for all parameters, followed by T1–T2 and T1–T3 for stride width, stride duration, and stride velocity, or followed by T1–T3 and T1–T2 for stride length and double support time.

3.3.2. Spatial–Temporal Gait Parameters during the Crossing Phase

Moderate ($0.40 < CCC < 0.70$) and good ($CCC > 0.70$) agreements between each pair of trials were found for all spatial–temporal gait parameters during the crossing phase, with the exception of the step width for T1–T2 ($CCC = 0.34$) and T1–T3 ($CCC = 0.31$), and of the double support time for T1–T2 ($CCC = 0.19$) with poor agreement between trials.

The best results were found when pooling values from T2–T3 for step length, step width, step velocity, and double support time (except for step duration, agreements between trials were better for T1–T3, $CCC = 0.77$ vs. $CCC = 0.76$ for T2–T3), followed by T1–T2 and T1–T3 for step length and step width, or followed by T1–T3 and T1–T2 for step velocity and double support time.

3.3.3. Obstacle Clearance Parameters

Moderate ($0.40 < CCC < 0.70$) and good ($CCC > 0.70$) agreements between each pair of trials were found for all obstacle clearance parameters.

The best results were found when pooling values from T2–T3 for leading and trailing foot toe clearance and foot horizontal distance prior to the obstacle. However, for leading and trailing

foot horizontal distance after obstacle, agreements between trials were better for T1–T2 (CCC = 0.71 vs. CCC = 0.69 for T2–T3 for leading horizontal distance after obstacle, and CCC = 0.72 vs. CCC = 0.63 for T2–T3 for trailing foot distance after obstacle), followed by T1–T2 and T1–T3.

Table 3 presents the CCC, LOA, Shieh exact test agreement, and SWC. Figure 2 presents the Bland–Altman of each gait and obstacle-crossing parameter.

Table 3: Agreement between the mean of the first and second trials (T1-T2), the first and third trials (T1-T3), the second and third trials (T2-T3), for each obstacle crossing parameter.

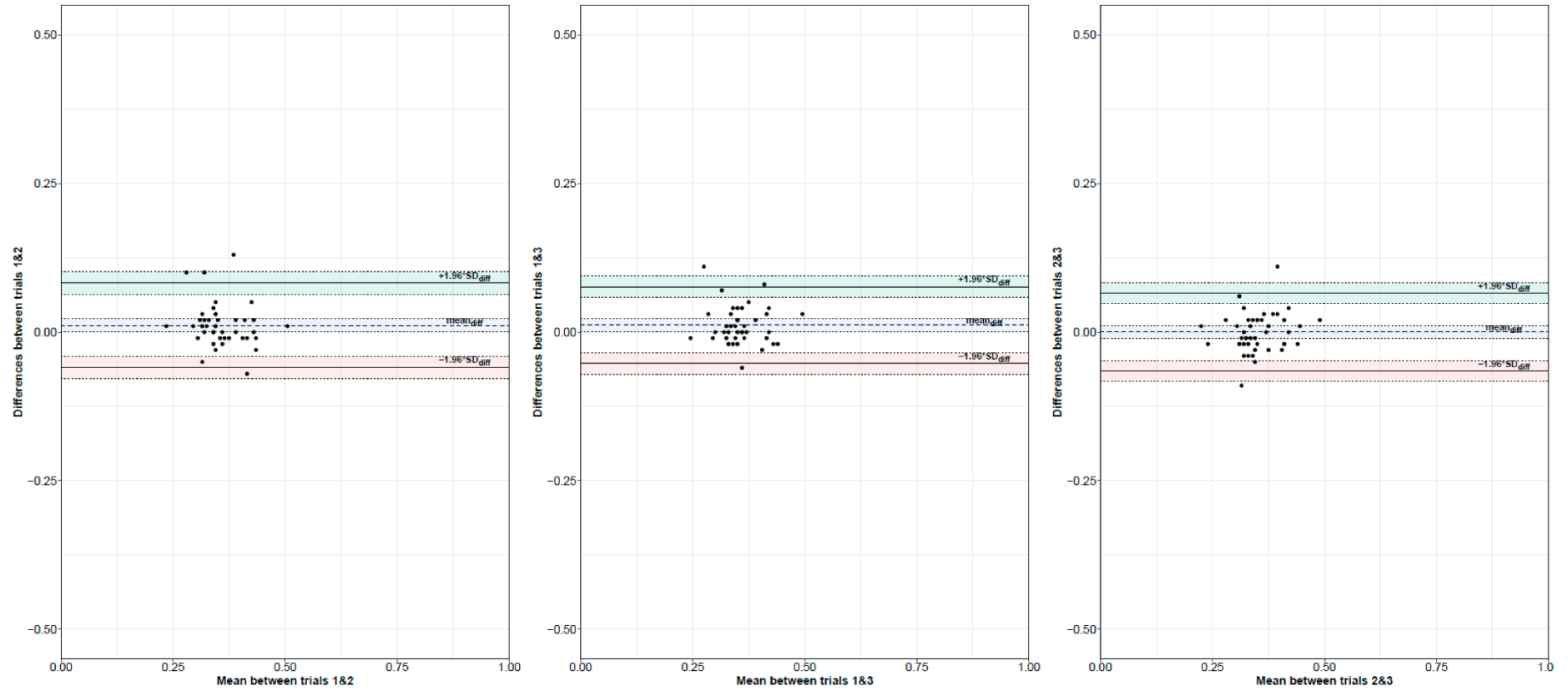
Condition	Parameter	T1-T2				T1-T3				T2-T3			
		CCC [95%CI]	LOA [95%CI]	Shieh test [95%CI]	SWC	CCC [95%CI]	LOA [95%CI]	Shieh test [95%CI]	SWC	CCC [95%CI]	LOA [95%CI]	Shieh test [95%CI]	SWC
Approaching phase	Stride length (cm)	0.74 [0.57 ; 0.85]	[-16.1 ; 16.3]	[-18.7 ; 18.9]	2.14	0.76 [0.60 ; 0.86]	[-16.3 ; 14.3]	[-18.8 ; 16.8]	2.12	0.86 [0.75 ; 0.92]	[-12.8 ; 10.6]	[-14.7 ; 12.5]	2.19
	Stride width (cm)	0.74 [0.57 ; 0.84]	[-4.23 ; 2.85]	[-4.80 ; 3.42]	0.49	0.73 [0.57 ; 0.84]	[-4.30 ; 3.09]	[-4.90 ; 3.68]	0.50	0.76 [0.60 ; 0.86]	[-3.73 ; 3.89]	[-4.34 ; 4.50]	0.53
	Stride double support time (s)	0.76 [0.60 ; 0.86]	[-0.06 ; 0.08]	[-0.07 ; 0.09]	0.01	0.77 [0.62 ; 0.87]	[-0.05 ; 0.08]	[-0.06 ; 0.09]	0.01	0.81 [0.68 ; 0.89]	[-0.07 ; 0.07]	[-0.08 ; 0.08]	0.01
	Stride duration (s)	0.87 [0.77 ; 0.92]	[-0.10 ; 0.13]	[-0.12 ; 0.15]	0.02	0.84 [0.73 ; 0.90]	[-0.11 ; 0.14]	[-0.13 ; 0.16]	0.02	0.87 [0.78 ; 0.93]	[-0.11 ; 0.11]	[-0.13 ; 0.12]	0.02
	Stride velocity (cm/s)	0.82 [0.70 ; 0.90]	[-20.5 ; 17.5]	[-23.6 ; 20.5]	3.13	0.82 [0.69 ; 0.89]	[-21.2 ; 16.9]	[-24.3 ; 19.9]	3.11	0.90 [0.82 ; 0.94]	[-14.3 ; 13.0]	[-16.4 ; 15.2]	3.01
Crossing phase	Step length (cm)	0.83 [0.71 ; 0.91]	[-11.6 ; 10.1]	[-13.4 ; 11.9]	1.85	0.81 [0.67 ; 0.89]	[-12.2 ; 10.4]	[-14.1 ; 12.2]	1.79	0.87 [0.77 ; 0.93]	[-9.83 ; 9.53]	[-11.4 ; 11.1]	1.85
	Step width (cm)	0.34 [0.05 ; 0.58]	[-8.39 ; 7.85]	[-9.70 ; 9.15]	0.59	0.31 [0.01 ; 0.55]	[-8.29 ; 8.34]	[-9.63 ; 9.68]	0.58	0.70 [0.52 ; 0.83]	[-5.40 ; 6.00]	[-6.32 ; 6.92]	0.70
	Step double support time (s)	0.19 [-0.10 ; 0.44]	[-0.09 ; 0.13]	[-0.11 ; 0.14]	0.01	0.44 [0.17 ; 0.64]	[-0.07 ; 0.10]	[-0.09 ; 0.11]	0.01	0.64 [0.43 ; 0.79]	[-0.08 ; 0.06]	[-0.09 ; 0.08]	0.01
	Step duration (s)	0.59 [0.37 ; 0.75]	[-0.11 ; 0.14]	[-0.13 ; 0.16]	0.01	0.77 [0.62 ; 0.87]	[-0.09 ; 0.10]	[-0.10 ; 0.12]	0.01	0.76 [0.60 ; 0.86]	[-0.10 ; 0.09]	[-0.12 ; 0.10]	0.01
	Step velocity (cm/s)	0.71 [0.53 ; 0.83]	[-34.6 ; 26.7]	[-39.5 ; 31.7]	3.93	0.77 [0.61 ; 0.87]	[-28.9 ; 23.7]	[-33.1 ; 27.9]	3.75	0.81 [0.68 ; 0.89]	[-22.9 ; 25.6]	[-26.8 ; 29.5]	3.86
Obstacle clearance	Trailing foot horizontal distance prior to obstacle (cm)	0.74 [0.57 ; 0.85]	[-14.5 ; 12.3]	[-16.7 ; 14.5]	1.79	0.69 [0.50 ; 0.82]	[-15.6 ; 15.8]	[-18.2 ; 18.4]	1.88	0.80 [0.67 ; 0.88]	[-10.3 ; 12.7]	[-12.2 ; 14.6]	1.80
	Trailing foot horizontal distance after obstacle (cm)	0.72 [0.54 ; 0.83]	[-16.3 ; 16.1]	[-18.9 ; 18.7]	2.03	0.71 [0.53 ; 0.83]	[-20.1 ; 13.4]	[-22.8 ; 16.1]	2.20	0.63 [0.42 ; 0.77]	[-21.5 ; 15.1]	[-24.5 ; 18.0]	2.05
	Trailing foot toe clearance (cm)	0.67 [0.46 ; 0.80]	[-14.1 ; 12.4]	[-16.3 ; 14.6]	1.53	0.57 [0.34 ; 0.73]	[-14.6 ; 13.3]	[-16.8 ; 15.6]	1.36	0.72 [0.55 ; 0.84]	[-10.4 ; 10.9]	[-12.2 ; 12.6]	1.36
	Leading foot horizontal distance prior to obstacle (cm)	0.50 [0.25 ; 0.69]	[-23.4 ; 22.5]	[-27.1 ; 26.2]	2.04	0.50 [0.25 ; 0.69]	[-22.7 ; 23.0]	[-26.4 ; 26.7]	2.01	0.68 [0.48 ; 0.81]	[-15.4 ; 16.6]	[-18.0 ; 19.2]	1.88
	Leading foot horizontal distance after obstacle (cm)	0.71 [0.52 ; 0.83]	[-9.14 ; 10.6]	[-10.7 ; 12.2]	1.22	0.60 [0.38 ; 0.76]	[-13.6 ; 11.5]	[-15.6 ; 13.5]	1.29	0.69 [0.51 ; 0.82]	[-12.5 ; 9.02]	[-14.2 ; 10.7]	1.33
	Leading foot toe clearance (cm)	0.84 [0.72 ; 0.91]	[-4.86 ; 4.73]	[-5.63 ; 5.51]	0.82	0.78 [0.64 ; 0.87]	[-6.88 ; 5.18]	[-7.85 ; 6.15]	0.89	0.88 [0.81 ; 0.93]	[-5.07 ; 3.50]	[-5.76 ; 4.19]	0.93

Note: CCC: Lin's concordance correlation coefficient, LOA: limits of agreement, SWC: smallest worthwhile change, T1: trial 1, T2: trial 2, T3: trial 3.

CCC legend: poor agreement (red: $CCC \leq 0.40$), moderate (yellow: $0.40 < CCC < 0.70$), and good (green: $CCC \geq 0.70$).

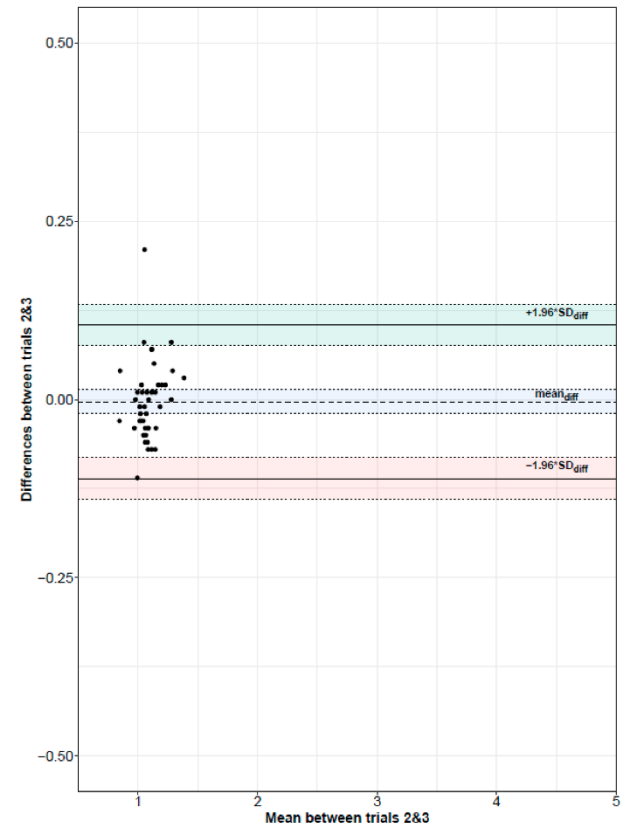
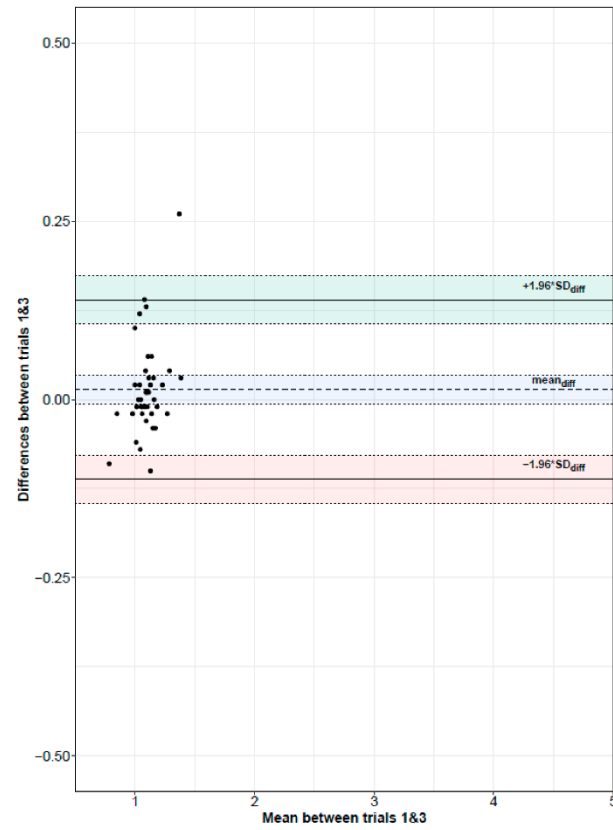
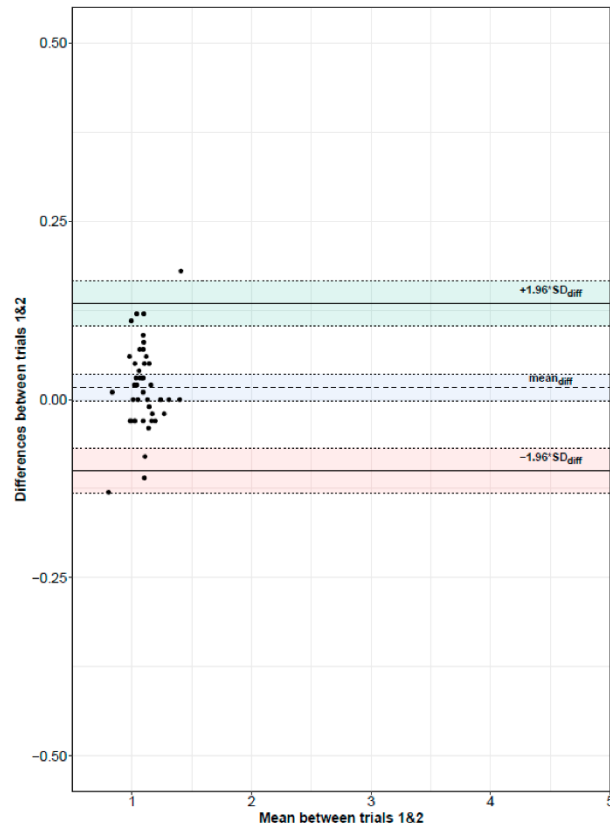
(A)

Approaching phase – stride double support time (s)



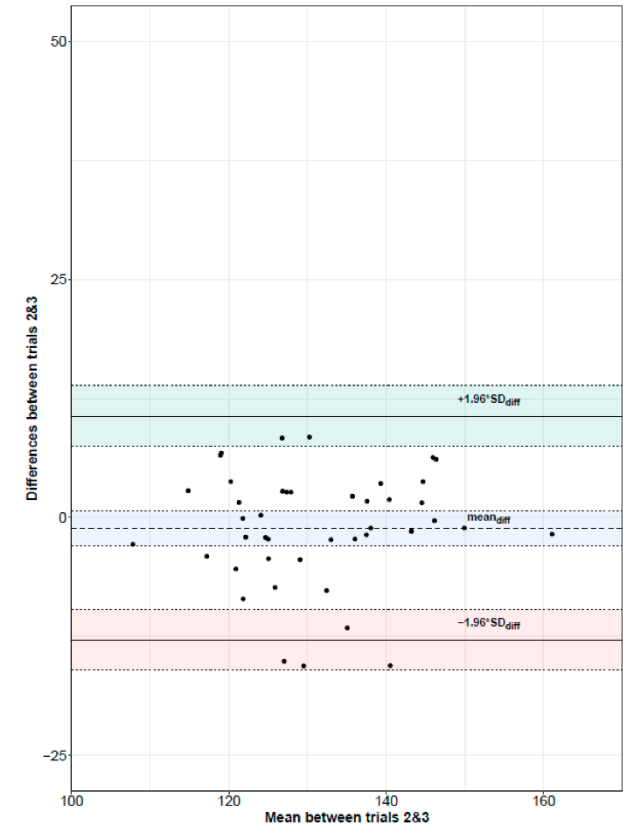
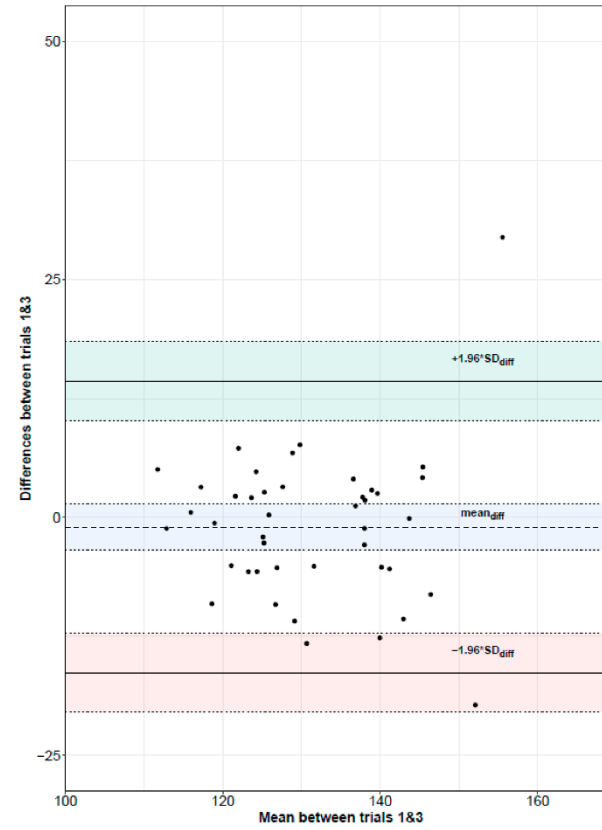
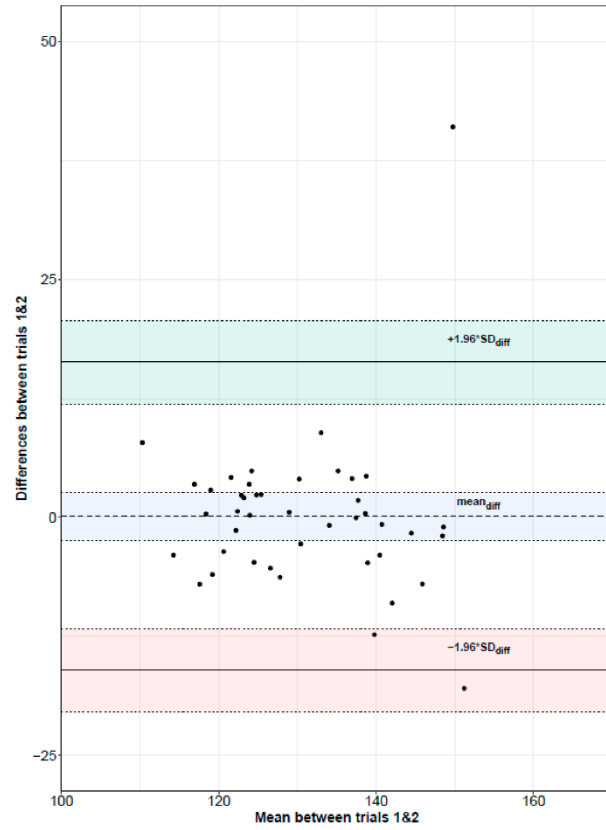
(B)

Approaching phase – stride duration (s)



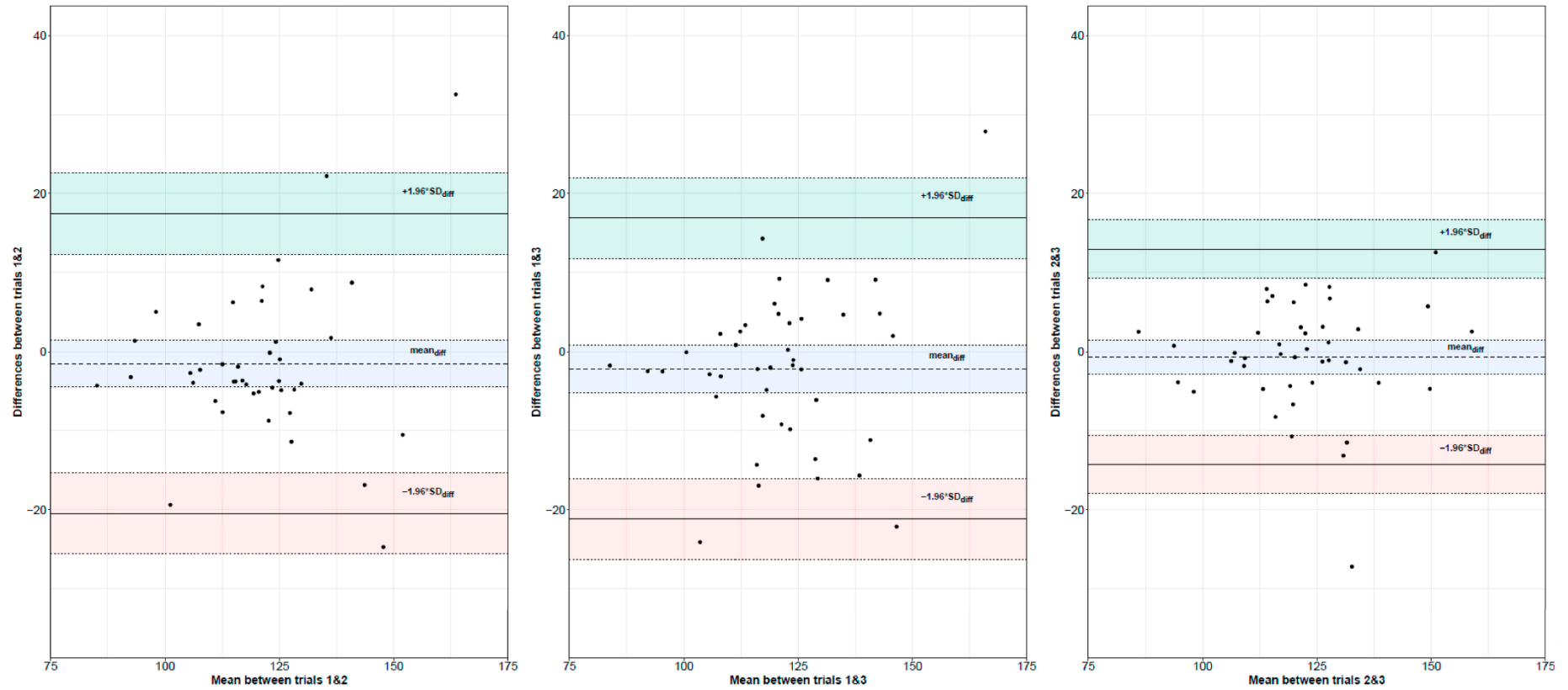
(C)

Approaching phase – stride length (cm)



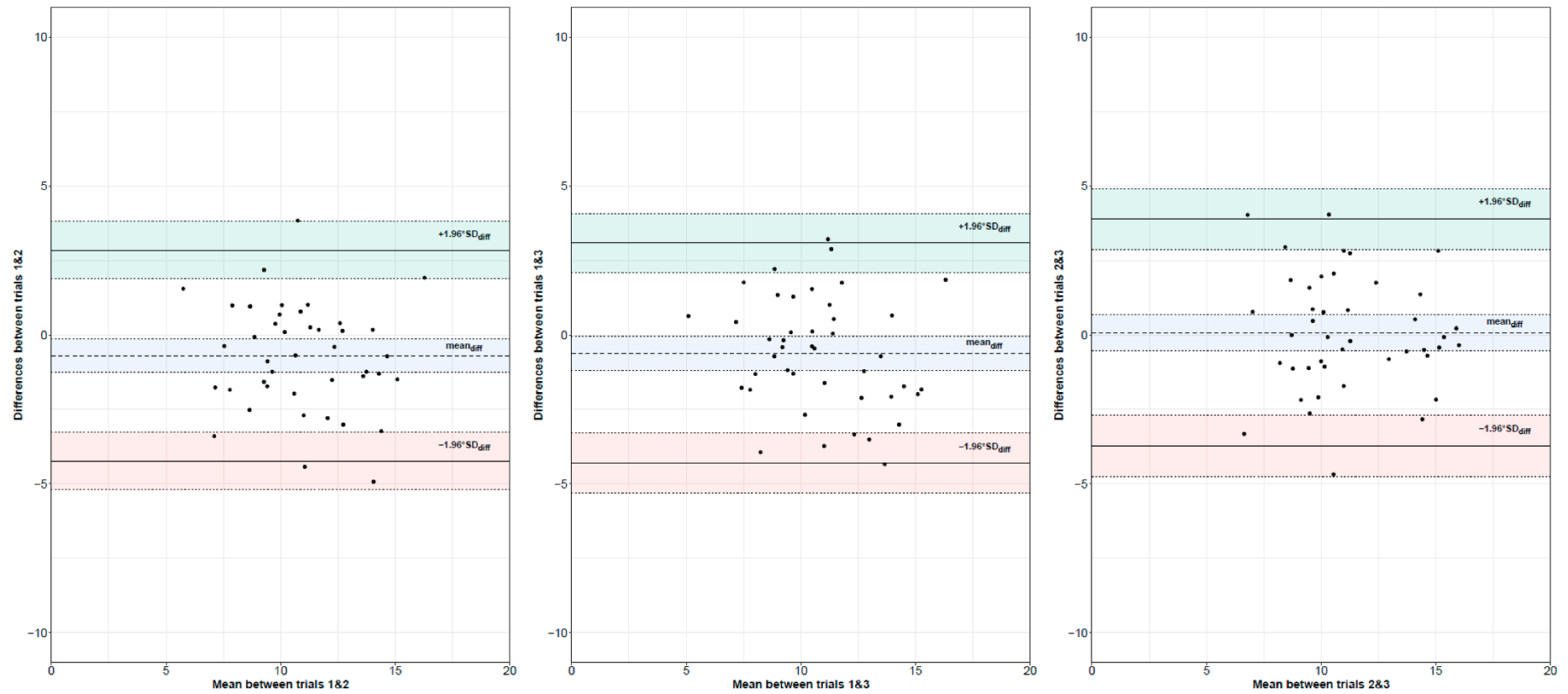
(D)

Approaching phase - stride velocity (cm/s)



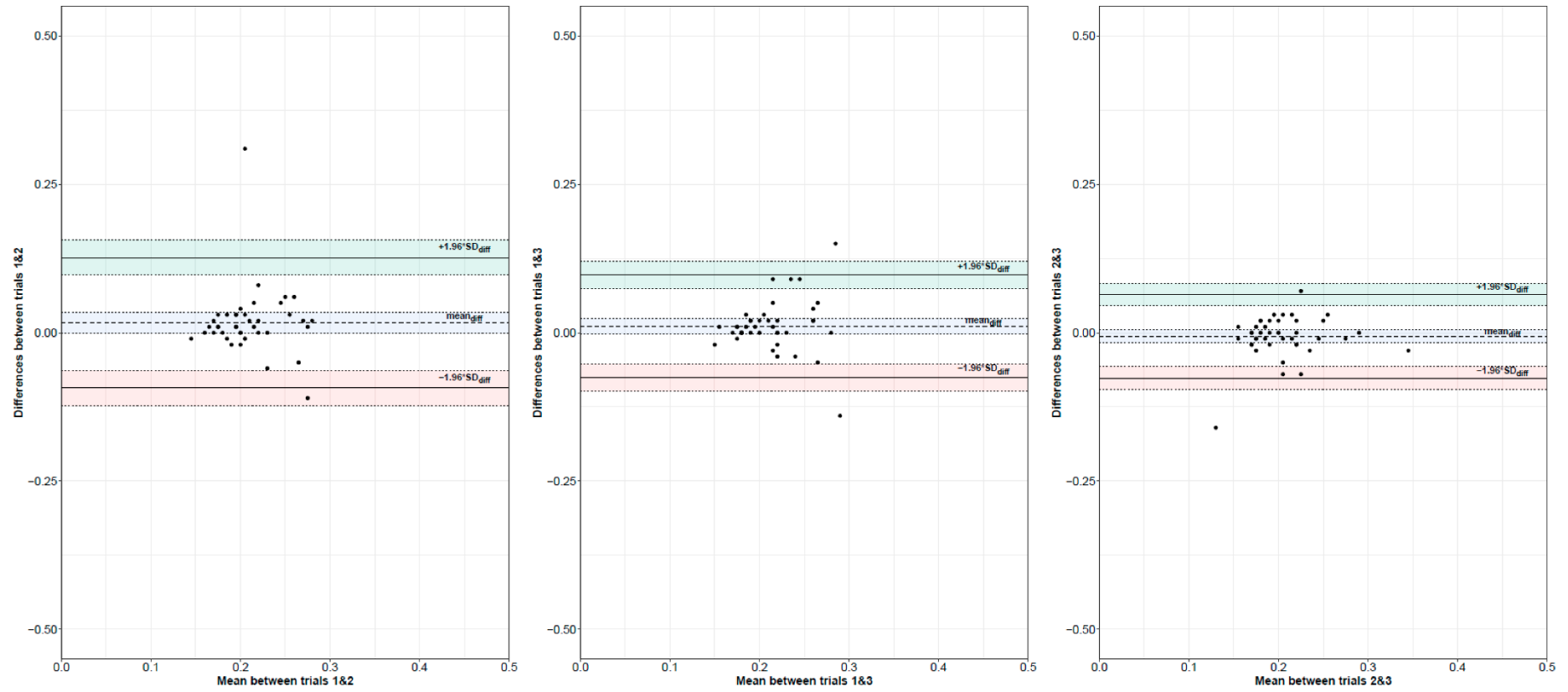
(E)

Approaching phase – stride width (cm)



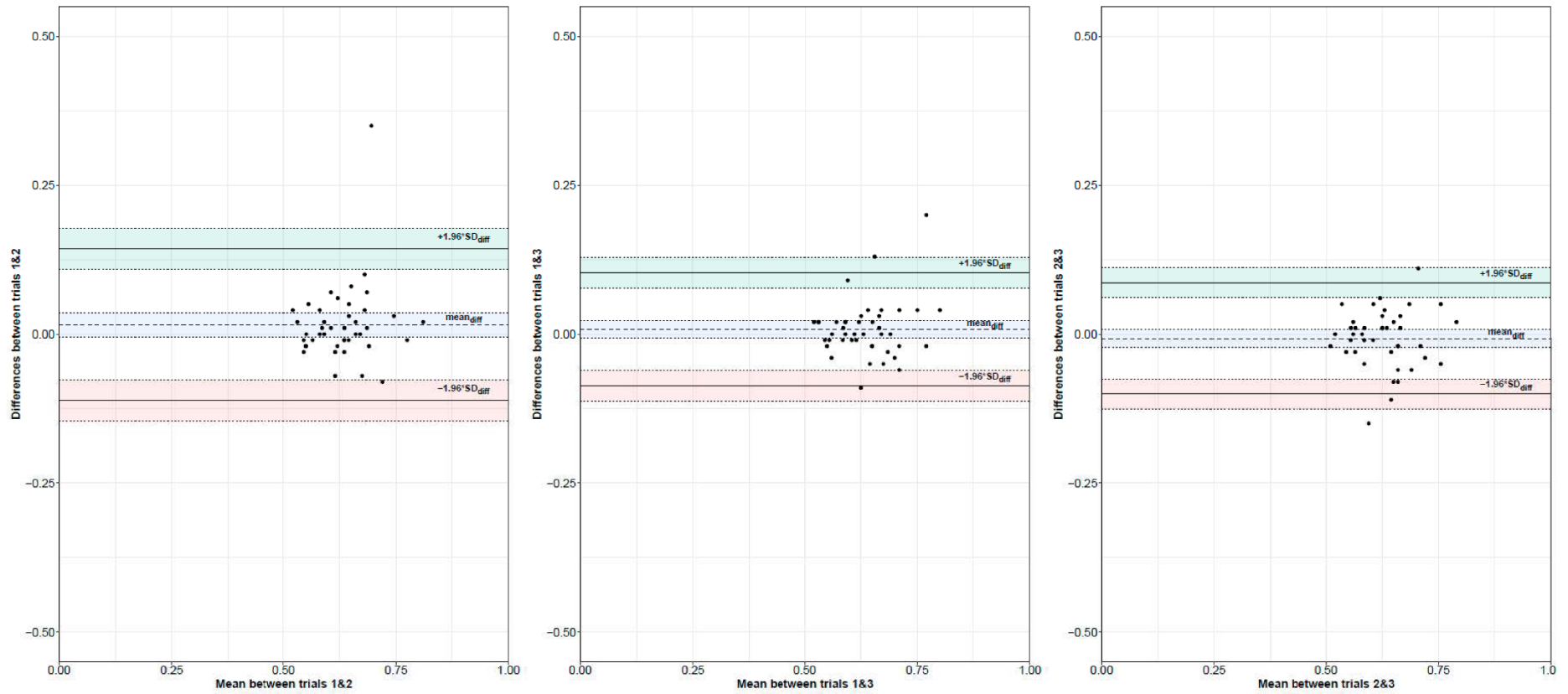
(F)

Crossing phase – step double support time (s)



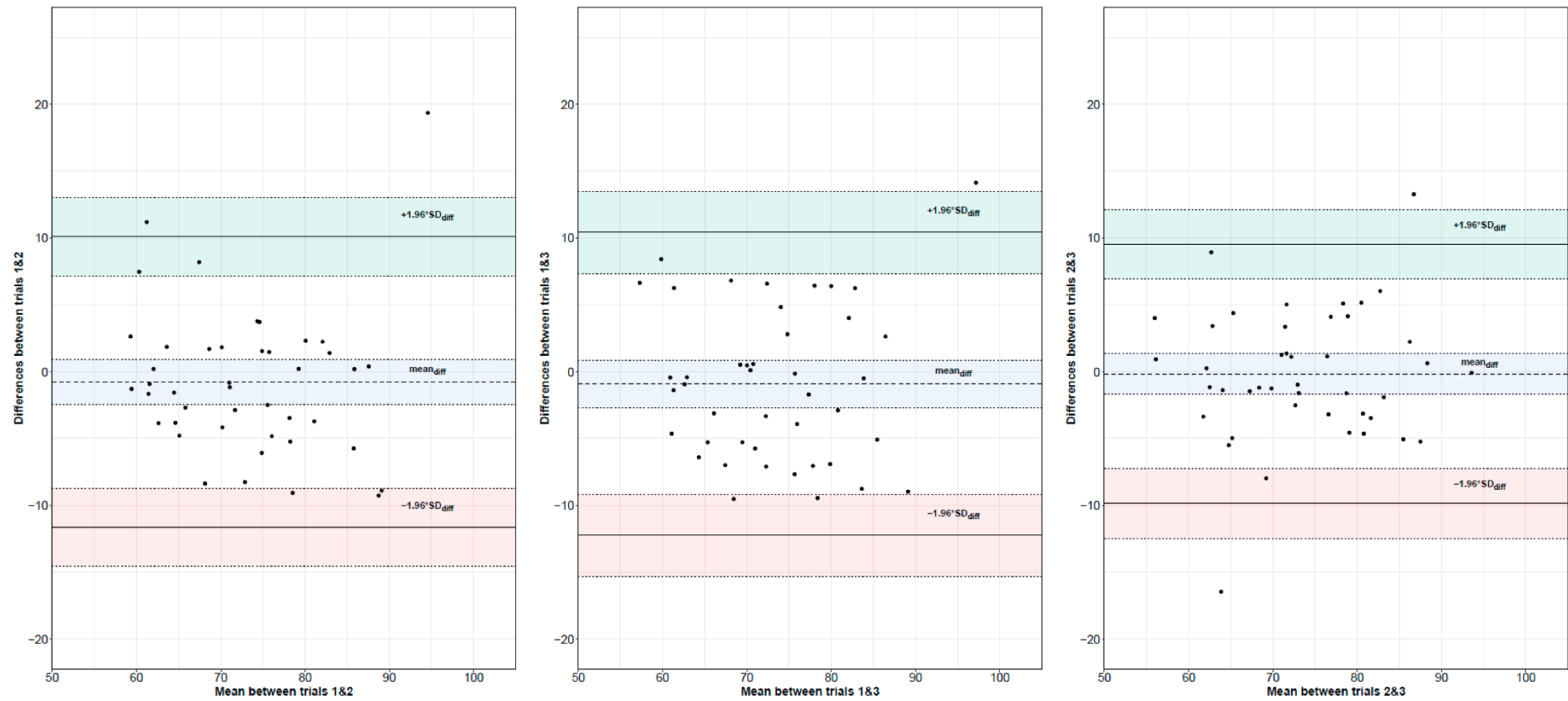
(G)

Crossing phase – step duration (s)



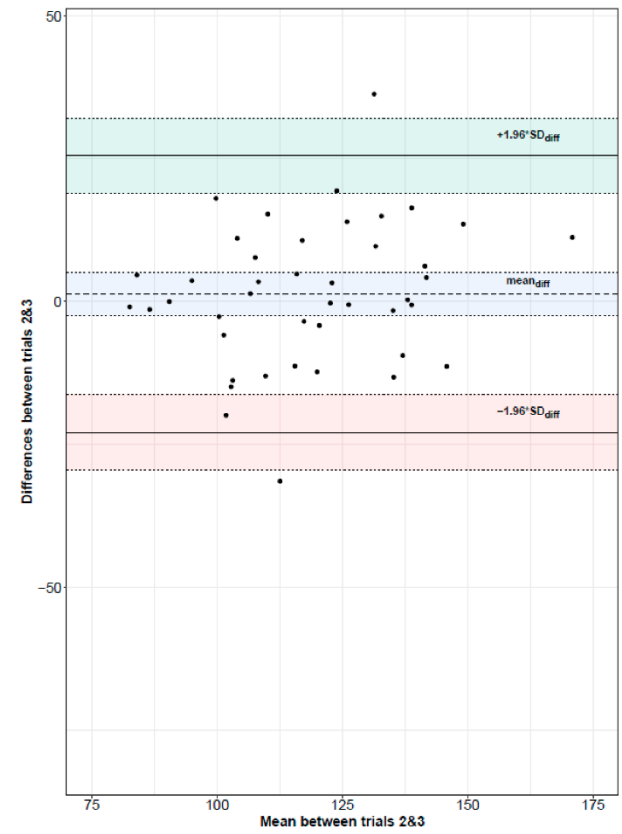
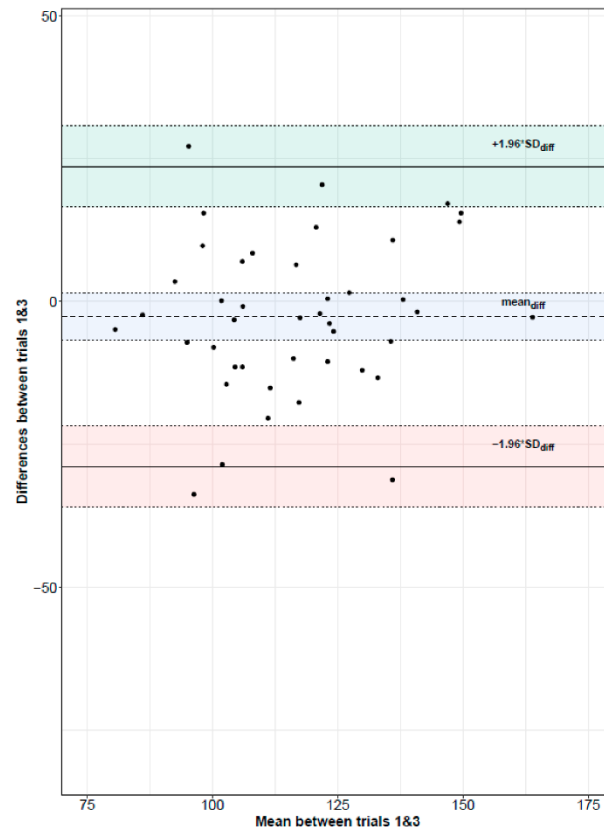
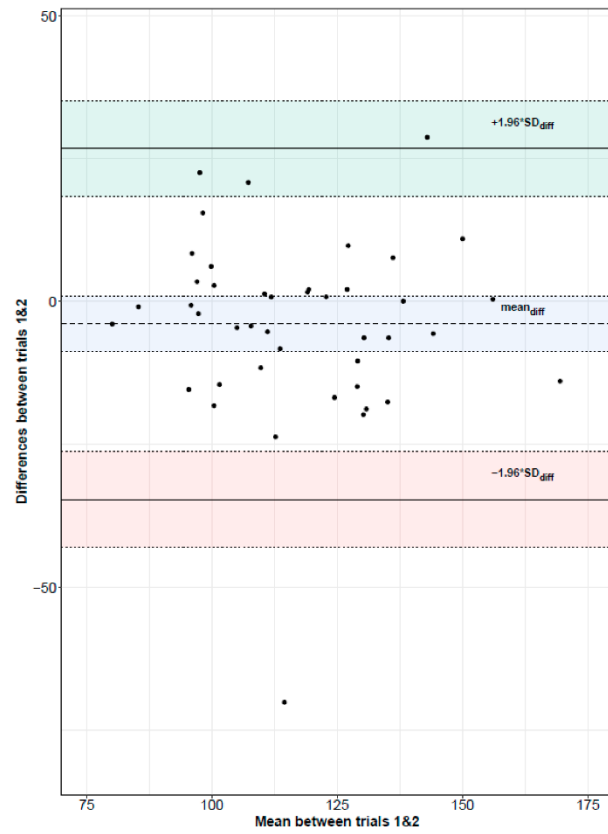
(H)

Crossing phase – step length (cm)



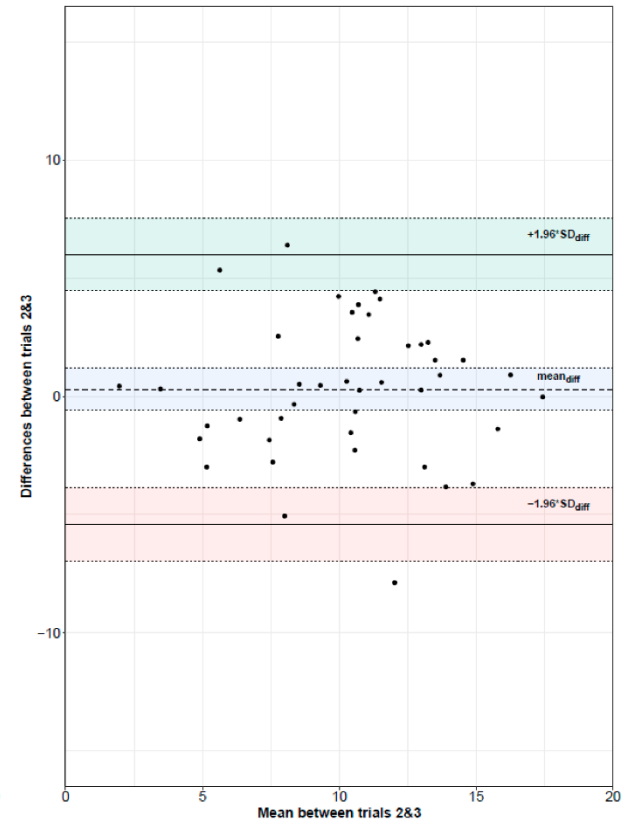
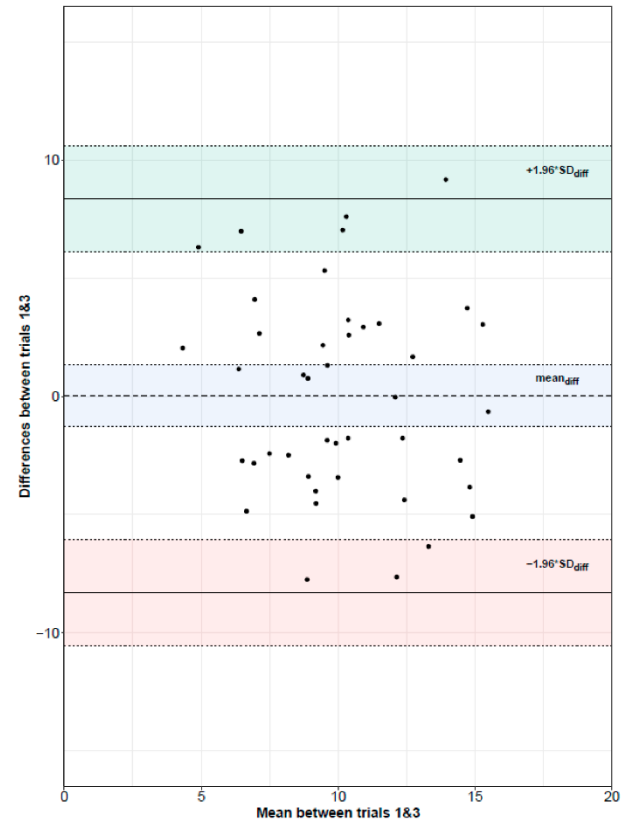
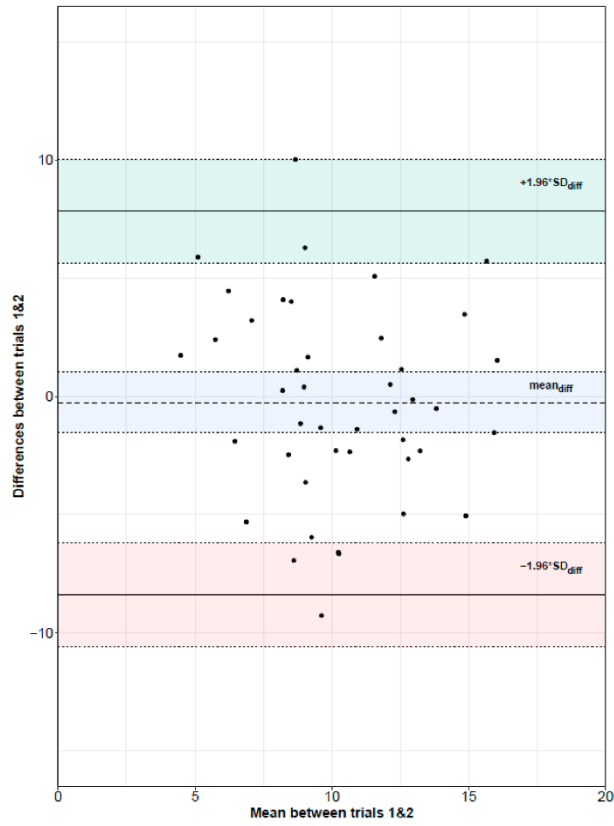
(I)

Crossing phase – step velocity (cm/s)



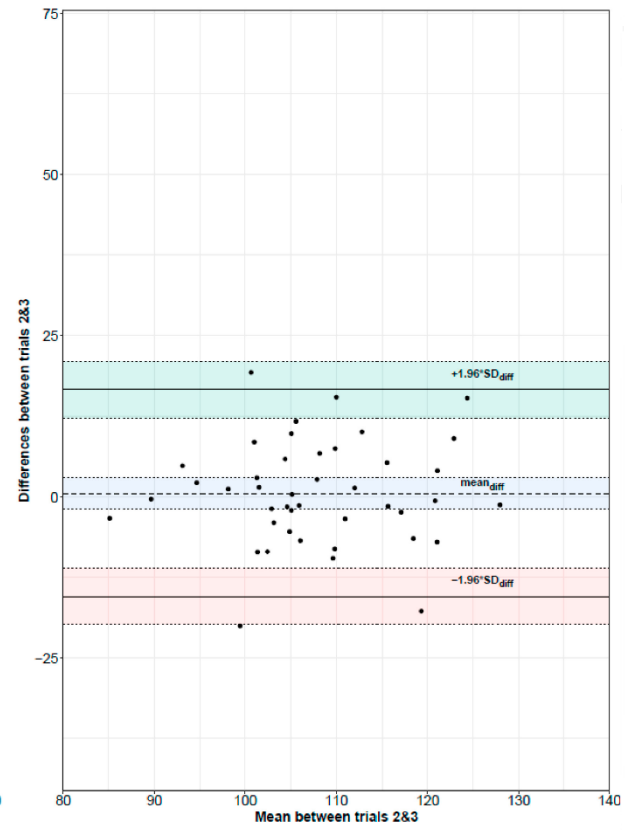
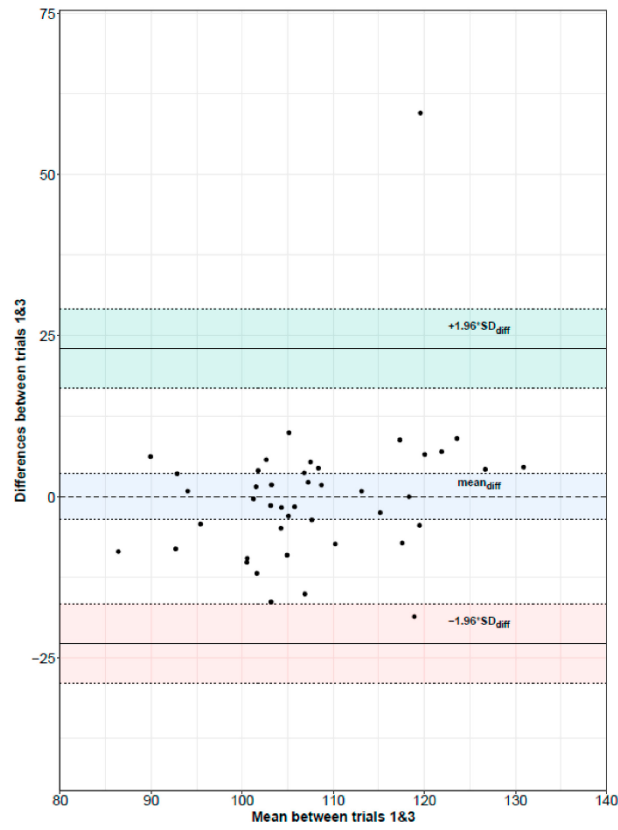
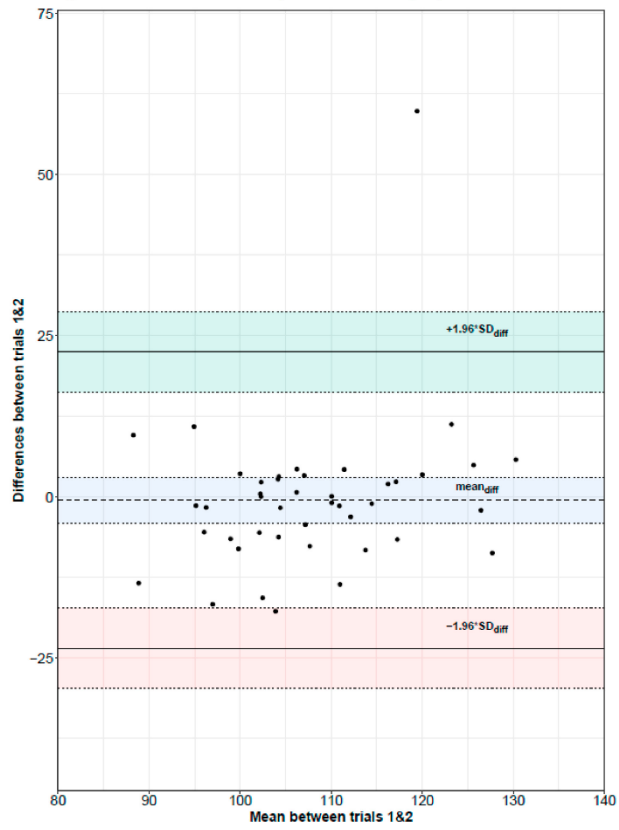
(J)

Crossing phase – step width (cm)



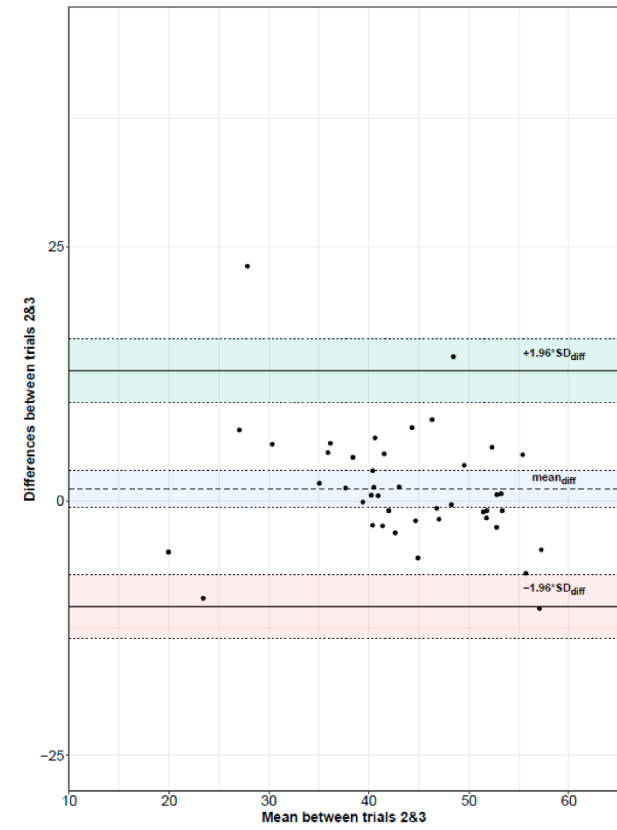
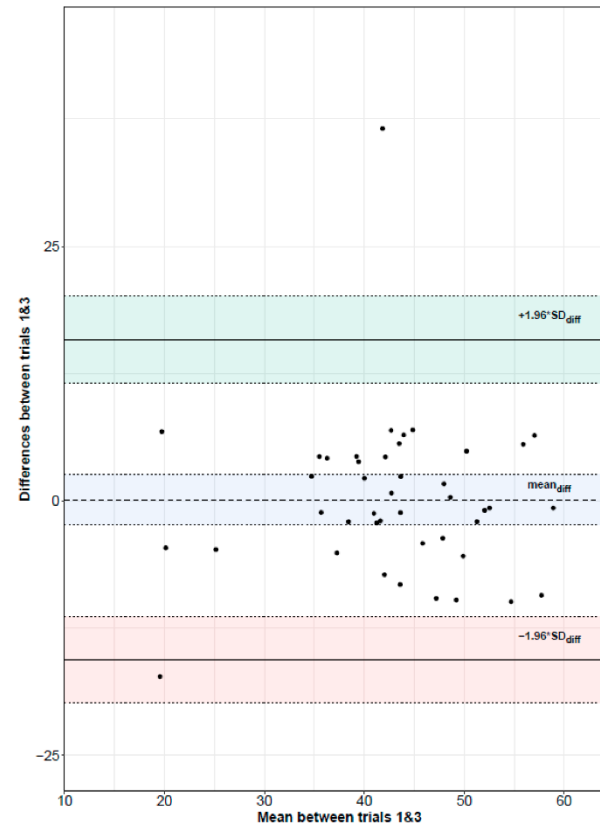
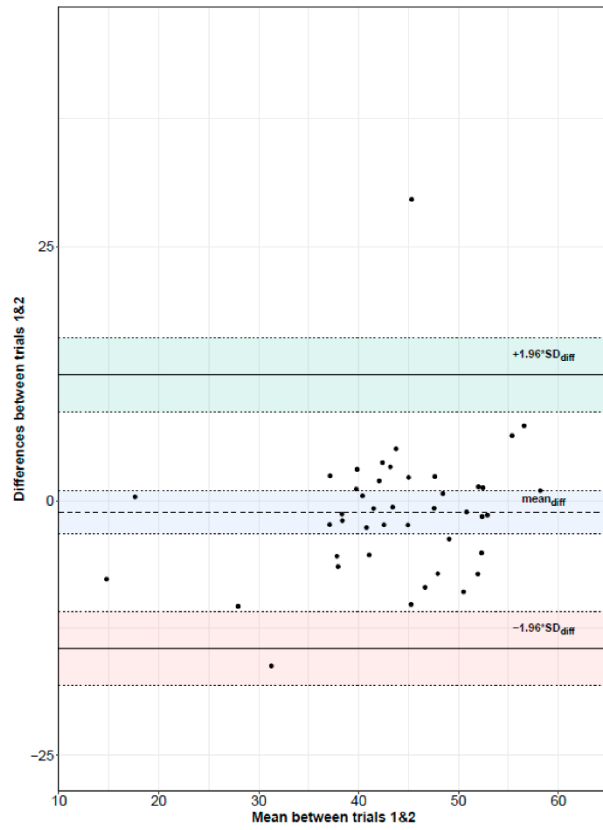
(K)

Leading foot – horizontal distance prior to obstacle (cm)



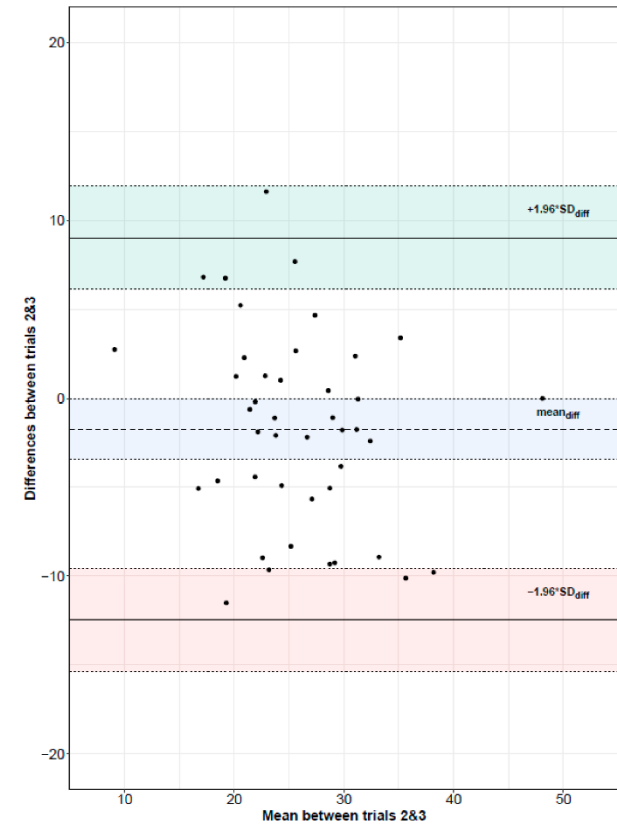
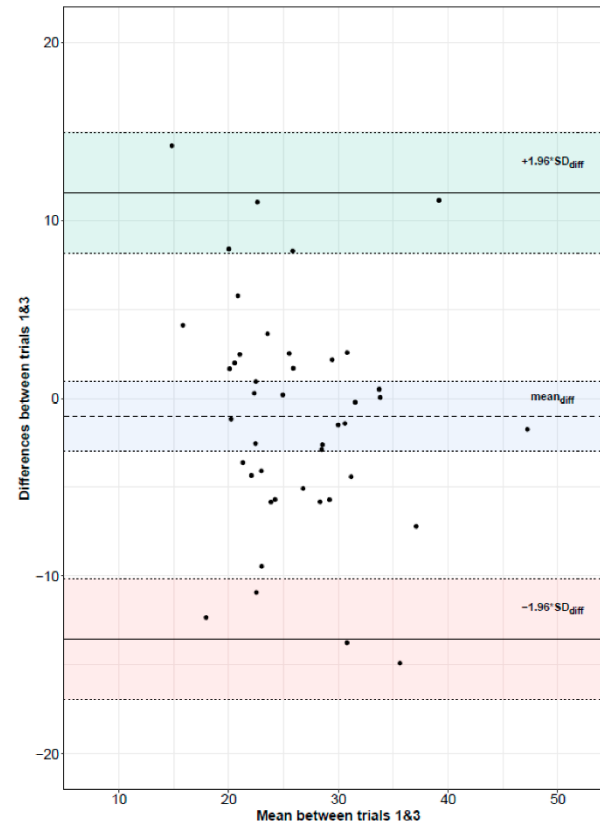
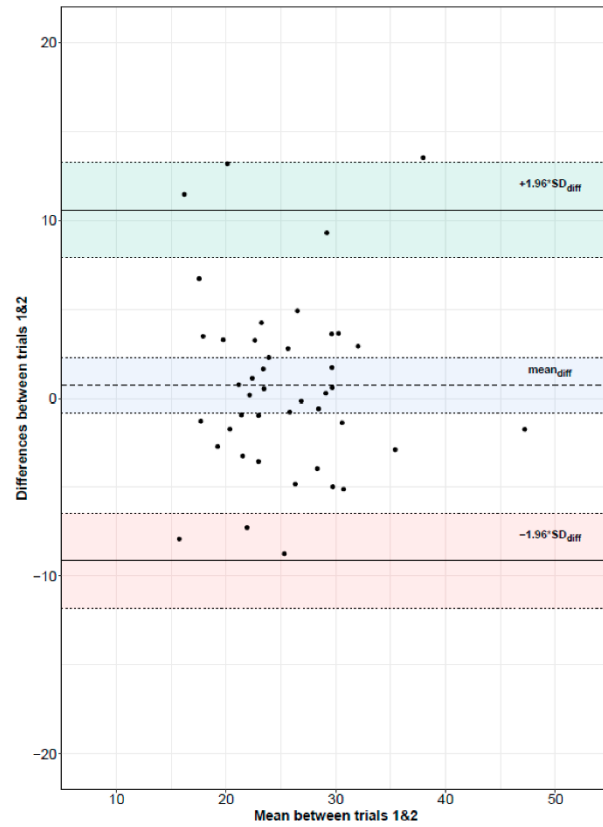
(L)

Trailing foot – horizontal distance prior to obstacle (cm)



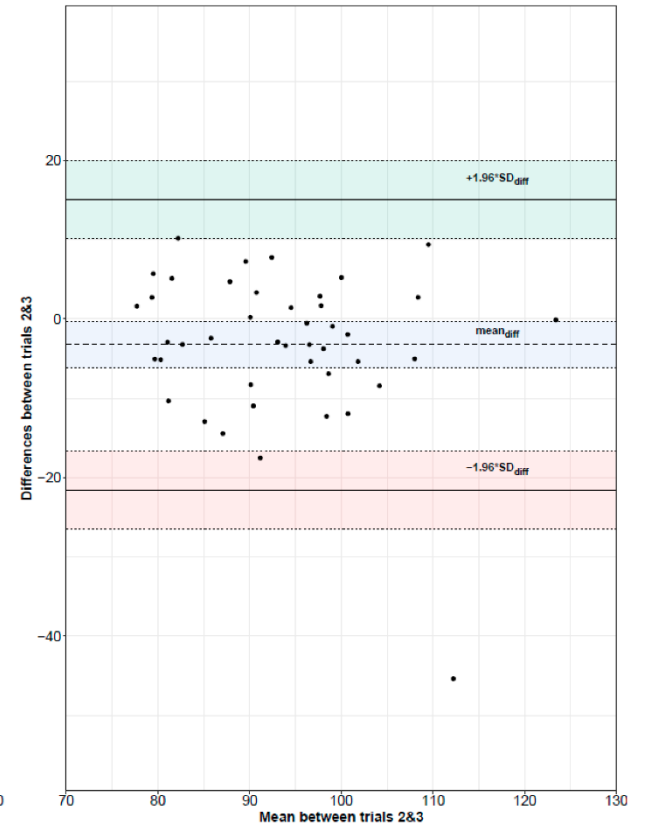
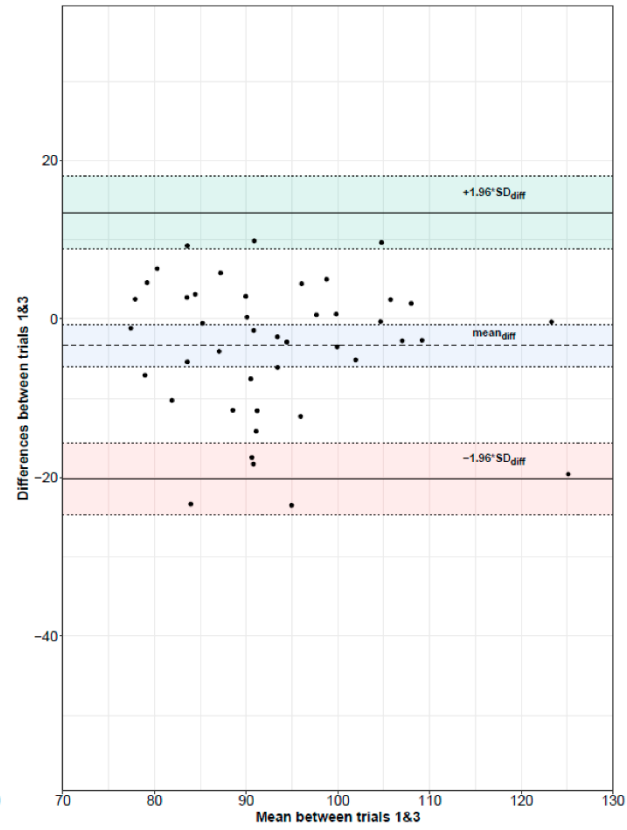
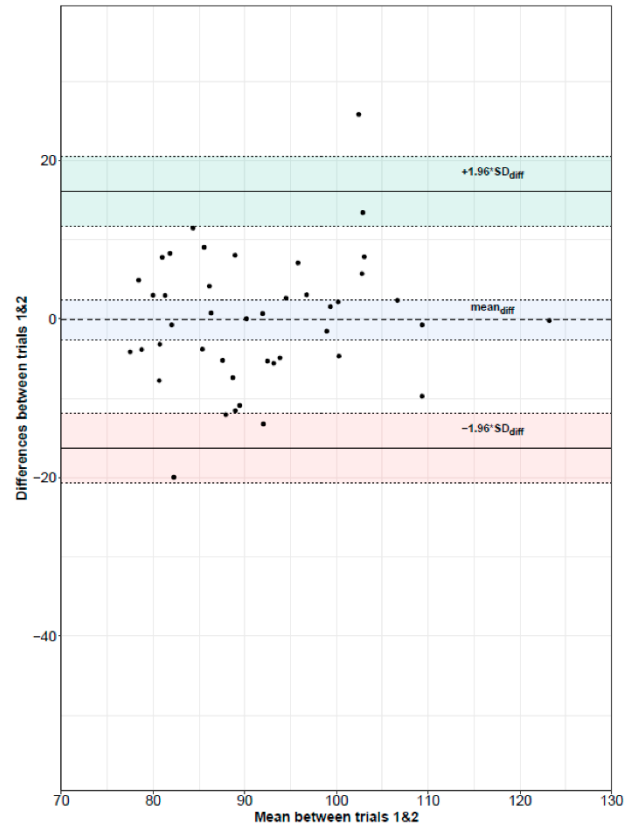
(M)

Leading foot – horizontal distance after obstacle (cm)



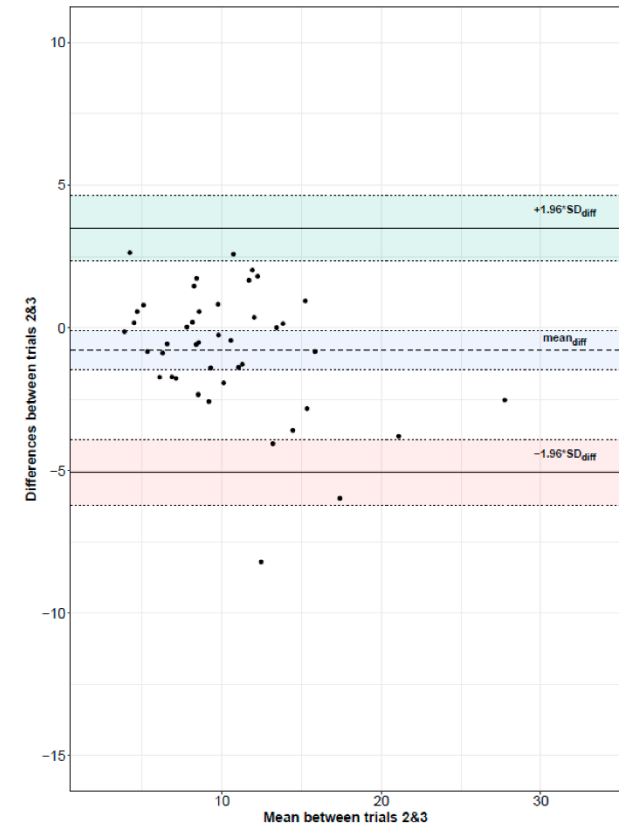
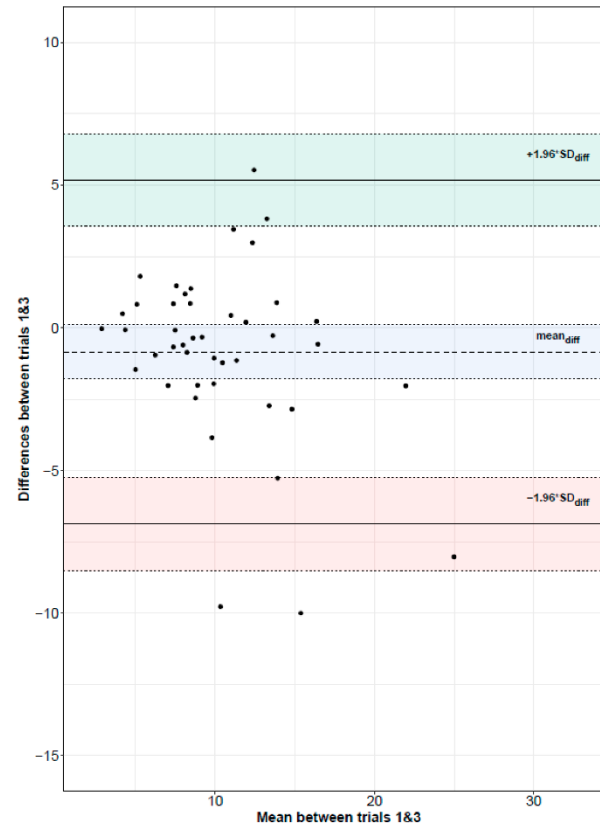
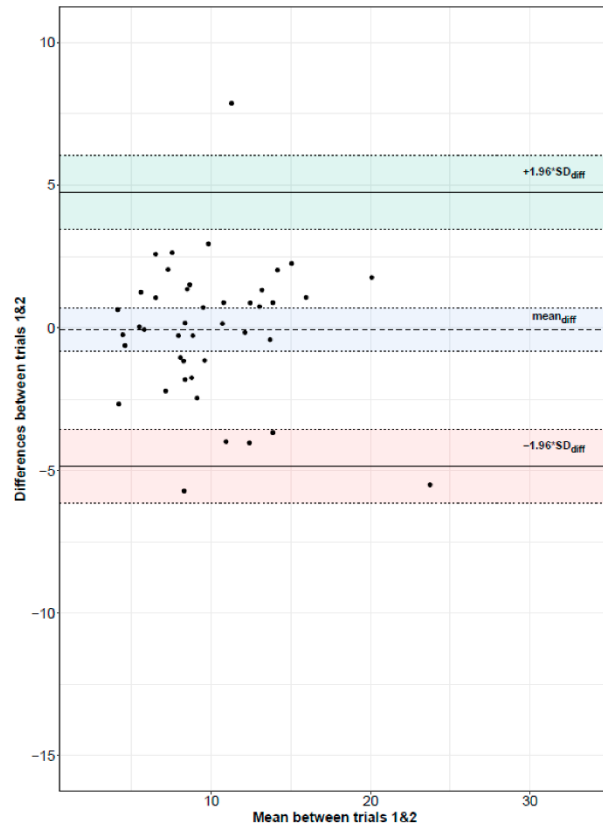
(N)

Trailing foot – horizontal distance after obstacle (cm)



(O)

Leading foot – toe clearance (cm)



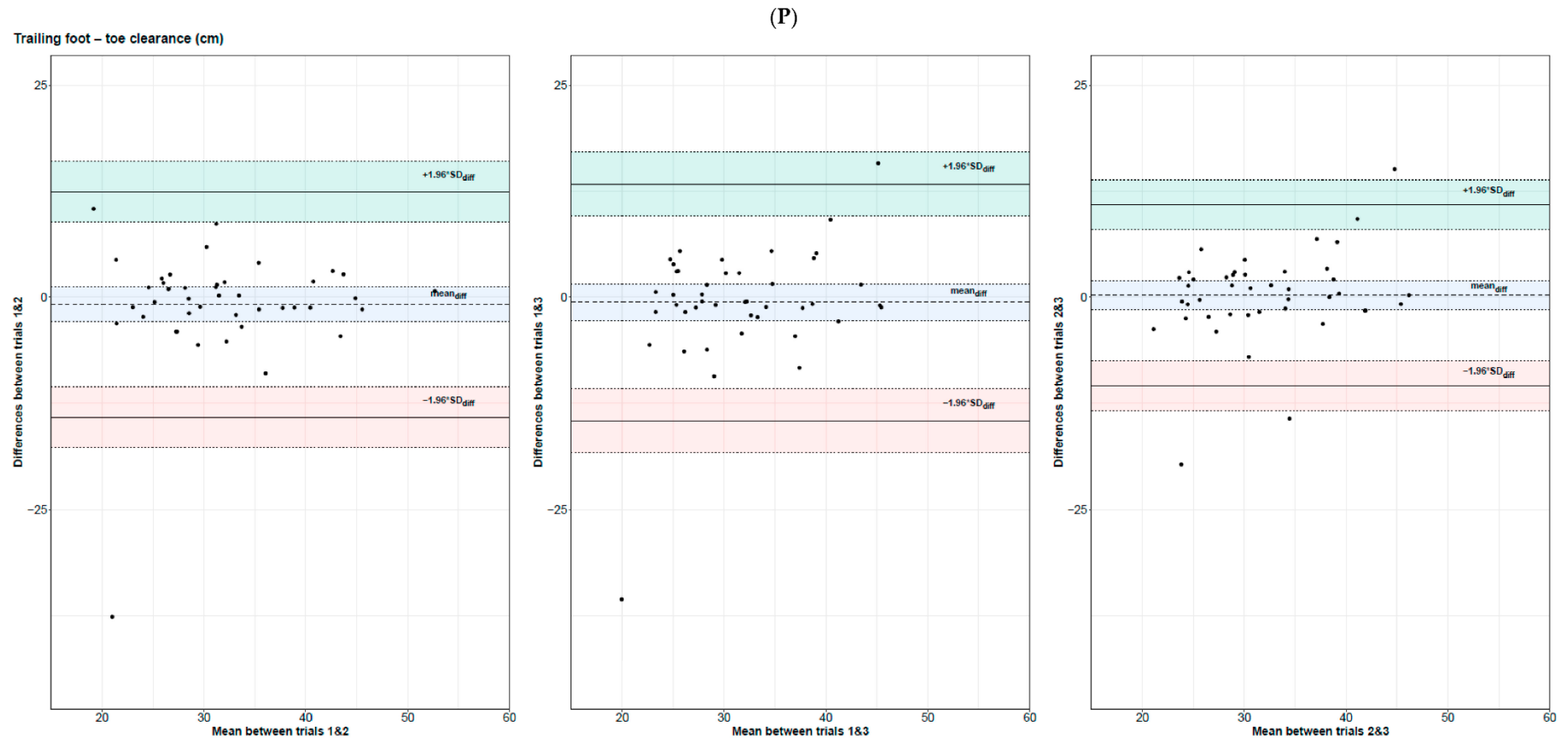


Figure 2. Bland–Altman plots for trial 1 and 2, 1 and 3, and 2 and 3 for gait parameters during the approaching phase (A–E), the crossing phase (F–J), and obstacle clearance parameters (K–P).

4. Discussion

The aim of this study was to evaluate the intra-session relative and absolute reliability of obstacle-crossing parameters during overground walking in young adults and to determine the number of trials required to ensure reliable assessment.

Overall, our results showed for the first time that spatial–temporal gait parameters and clearance parameters were reliable, except for the step width (between T1–T2 and T1–T3) and double support time (between T1–T2) during the crossing phase. In addition, for most spatial–temporal gait and clearance parameters, the reliability and agreement were better when pooling trials 2 and 3 than when the first trial was used for comparison. This suggests that when conducting an obstacle-crossing task in young adults—under the specific experimental conditions used in the present study, at least—a first practice trial should be performed before the experimental trials to enhance the reliability of the parameters studied, or that the first experimental trial should be discarded from data analysis.

4.1. Intra-Session Reliability during Obstacle-Crossing

4.1.1. Approaching Phase

Relative reliability for all spatial–temporal gait parameters measured in young adults during the approaching phase was always either substantial or almost perfect. Regarding absolute reliability, all parameters except step width ($SEM\% \geq 10\%$) exhibited good absolute reliability in all trial comparisons, and MDC% was low or acceptable for all gait parameters in all trial comparisons. Comparisons between trials showed that participants had a higher step width in the last two trials compared to the first one. Perhaps after the first trial, the strategy chosen was to increase their pre-crossing base of support after the trial to ensure more stability before the crossing phase. Regarding agreements between trials, results were considered good for all spatial–temporal gait parameters in all trial comparisons. Hence, young male adults had almost identical gait patterns during all trials during the approaching phase. In addition, for all spatial–temporal gait parameters, relative and absolute reliabilities and agreement between trials were better when using the mean of the second and third trials, compared to the first and second trials, to the first and third trials, or to the three trials. This could suggest that participants adapted a more stable/consistent gait pattern after the execution of the first trial, which could have been used as a learning/warming-up trial. These results are similar to those recently reported in healthy adults during unobstructed level walking [2]. In that study, 20 healthy participants performed three trials of a 10-m walking test, and spatial–temporal gait parameters

were computed using inertial motor units (Physilog® 5, 200Hz GaitUp, Lausanne, Switzerland). Results showed that speed, double support, and stride length had almost perfect relative reliability ($0.81 < ICC(2.1)$). In addition, absolute reliability was good, with low SEM% ($1.74\% \leq SEM\% \leq 6.58\%$ in all trial comparisons) and low MDC% ($4.82\% \leq MDC\% \leq 18.25\%$ for all trial comparisons) for these three spatial–temporal gait parameters [2].

4.1.2. Crossing Phase

Contrary to what was observed for the approaching phase, not all spatial–temporal gait parameters were found to have substantial or almost perfect relative reliability, good absolute reliability, or good agreement between trials.

The relative reliability of step length, duration, and velocity was substantial to almost perfect regardless of the trial comparisons considered. Conversely, step width and double support time showed slight to moderate relative reliability ($0.19 \leq ICC(2.1) \leq 0.47$), with the worst results when the first trial was included. Regarding absolute reliability, both step width and double support time showed poor reliability in all trial comparisons, except the MDC% of double support time, which was acceptable for the T2–T3 comparison ($MDC\% = 34.4$). In addition, agreements between trials were poor for step width (T1–T2 and T1–T3) and double support time (T1–T2), compared to the other spatial–temporal parameters (moderate or good) between each pair of trials. Comparison between trials showed no differences in step width or double support time during the crossing phase ($p < 0.05$). One hypothesis is that the lower reliability found for step width and double support time parameters during the crossing phase compared to the approaching phase could be explained by the more unusual nature of this step compared to the approaching phase (i.e., walking on flat ground) and due to the higher demand of the task in neuromuscular [62] and cognitive resources [63] than flat ground walking. Also, medial lateral dynamic balance during the crossing phase might be harder to maintain, so it is difficult for the participants to maintain a stable behaviour for crossing step width. However, it is worth noting that agreements between trials were better for all spatial–temporal gait parameters, with the exception of step duration (for which the best value was obtained for T1–T3) when pooling values from the second and third trials.

4.1.3. Obstacle Clearance

Relative reliability for all clearance parameters measured in young adults was either moderate to almost perfect ($0.51 \leq \text{ICC}(2.1) \leq 0.89$), and the reliability was enhanced from substantial to almost perfect when pooling the second and third trials ($0.63 \leq \text{ICC}(2.1) \leq 0.89$). However, the absolute reliability was low for four clearance parameters (leading and trailing foot horizontal distance after obstacle, trailing foot horizontal distance after obstacle, and leading foot toe clearance) for T1–T2, T1–T3, and T1–T2–T3, and three clearance parameters for T2–T3 (leading and trailing foot toe clearance and leading foot horizontal distance after obstacle). In addition, MDC% was high (i.e., $40\% \leq \text{MDC}\%$) for two clearance parameters for T1–T2 (leading and trailing foot clearance), T2–T3 (leading foot toe clearance and horizontal distance after obstacle), and T1–T2–T3 (leading foot toe clearance and horizontal distance after obstacle), and for three clearance parameters for T1–T3 (leading and trailing foot toe clearance and leading foot horizontal distance after obstacle).

On the one hand, in general, clearance parameters were less reliable than spatial–temporal gait parameters measured during the approaching and crossing phases (with the exception of stride width and double support time during the crossing phase). As mentioned, the more unusual nature of this step compared to flat ground walking might have played a role in individuals' behaviour and clearance strategy. In addition, it is possible that the higher cognitive load and precise motor control during obstacle-crossing compared to unobstructed walking [63] may contribute to the reduced reliability of clearance parameters. On the other hand, similar to what was observed for spatial–temporal gait parameters computed before and after the obstacle, for most obstacle clearance parameters, both relative and absolute reliabilities were better when using the mean of the second and third trials, compared to the first and second trials, to the first and third trials, or to the three trials. This reinforces the idea of a learning/warming-up effect after the first trial for individuals when they perform an obstacle-crossing task. However, comparisons between trials showed that trailing foot horizontal distance after the obstacle was higher in the third trial compared to the first and second. Together, these results suggest that, contrary to spatial–temporal parameters, individuals might need more than three trials to have reliable behaviour. Regarding agreements between trials, moderate to good agreement was found for all parameters between each pair of trials. Similarly to relative and absolute reliabilities, the best results were found for four out of six clearance parameters (leading and trailing toe clearance and distance prior to obstacle) when pooling the second and third trials. However, agreements between trials were better for T1–T2 for both leading and trailing foot distances after the obstacle.

As shown by measures of agreement (CCC and Bland–Altman, see Figure 2), there should not be any systematic bias in measurements since no obvious relation existed between the difference and the mean of any pair of two trials. In addition, the LOA were relatively small, with few to no outliers depending on the obstacle clearance parameter considered.

Having high absolute reliability ($10\% < \text{SEM}\%$) indicates that there were intra-individual variabilities between trials.

4.2. Study Limitations, Strengths, and Perspectives

To the authors' best knowledge, this is the first study that assessed the reliability, both relative and absolute, and agreements between trials of spatial–temporal gait parameters and obstacle clearance parameters in young adults. It should be noted that although previous studies have reported either the absolute or relative reliability of these parameters (e.g., [64,65,66]), none of them addressed our specific research questions. Indeed, we aimed to evaluate the intra-session relative and absolute reliability of obstacle-crossing parameters during overground walking in young healthy adults, and to determine the number of trials required to ensure reliable assessment. Contrary to us, the study from Punt et al. (2017) assessed virtual obstacle-crossing task during treadmill walking in stroke survivors [64], while Grinberg et al. (2021) did not assess obstacle-crossing parameters during overground walking [66], and Said et al. (2009) did not involve young healthy adults [65]. In addition, the sample size of the present study is relatively high ($n = 43$), compared to previously conducted gait reliability studies [1,2,3,5,8,11,38]. At this point, it is important to mention that, fully in line with the scientific roadmap we have set up to assess the intra-session reliability of the 10 m walk test [2], we focused on young healthy adults as a first step to provide normative reference values for a young healthy population (e.g., see [67,68,69]). Naturally, the reliability must now be further tested in other populations with different socio-demographic, anthropometric, clinical, and lifestyle characteristics, including individuals who are overweight or obese (e.g., see [70] for a review), children, adolescents, middle age, and the elderly (e.g., see [71] for a review), and pathological populations (e.g., see [72,73,74] for reviews) who may also present different levels of fatigue (e.g., see [75] for a review) or physical fitness (e.g., see [76] for a review).

Finally, the present findings highlighted that most spatial–temporal and obstacle clearance parameters were reliable across the three trials and that better relative and absolute reliabilities, as well as agreements between trials, were found when pooling the second and

third trials. Nevertheless, several limitations warrant further consideration and caution regarding the interpretation of the results.

The reliability and agreement were assessed during a single experimental session, which prevented us from studying the inter-session reliability. In addition, only young healthy males aged between 20–40 years old were included, and only one experimental condition (15 cm height obstacle; self-selected walking speed; single-task condition) was assessed. In other words, strictly speaking, our conclusion applies only to the population tested and the experimental conditions used in the present study. These experimental conditions could be considered as relatively mild and easy in that the task consisted of crossing a physical obstacle 15 centimeters high at a comfortable speed without any other particular constraint. Further works are thus needed to generalize them in more realistic conditions. For instance, it could be interesting to replicate this reliability study while walking over different and challenging obstacle paradigms that may predispose the participants to an increased risk of foot contact with the obstacle [77,78,79] and/or with individuals with balance and gait disorders for whom the consequences of imbalance and tripping over obstacles could be more dramatic [80,81]. Hence, these specific issues deserve investigations, which are included in our immediate plans. Another potential future investigation would be to perform more than three trials of obstacle-crossing. This would probably enhance the reliability of all parameters, especially the clearances with the obstacle. This might enable us to determine the minimum number of trials to be carried out, and the number of trials from which data analysis should begin in order to obtain reliable and valid data.

5. Conclusions

Most spatial–temporal gait parameters and obstacle clearance parameters computed using a three-dimensional motion analysis system in young adults during an obstacle-crossing task are reliable using the average of three trials. Our findings further suggest using the mean of the second and third trials to ensure the best relative and absolute reliabilities of most obstacle-crossing parameters. However, our findings only apply to the population tested and to the relatively mild and easy experimental conditions used in the present study. Further works are thus needed to generalize them in more realistic conditions and in other populations.

Supplementary Materials

The following supporting information can be downloaded at:
<https://www.mdpi.com/article/10.3390/s24113387/s1>.

S1: List of R packages used for statistical analysis

The tidyverse package version 2.0.0 (including ggplot2) was used to handle, analyze, and present data (tables and graphics) [82]. The rstatix package version 0.7.2 was used to conduct the RM-ANOVA and the pairwise comparison post hoc test [83]. The psych package version 2.4.3 was used to compute the ICC(2.1) [84]. The psr package version 0.1.0 was used to determine the MDC, SEM, and SWC [85]. The SimplyAgree package version 0.2.0 was used to calculate the LOA, CCC and performed the Shieh exact test [86]. The blandr package version 0.5.1 was used to generate the Bland–Altman plots and compute the LOA [87].

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Most gait and obstacle clearance parameters during both the approaching and the crossing phases are reliable when using the mean of the three trials. However, both relative and absolute reliability improved when pooling only the second and third trials. This result suggests that including a practice trial before the experimental trials in future studies could enhance the reliability of all obstacle crossing parameters. Taken together, these findings on the reliability of gait and obstacle clearance parameters enabled us to conduct a comparative analysis between normal weight and overweight subjects included in this dataset using the mean of the three trials.

6. Contribution 4: Impact of overweight on spatial-temporal gait parameters during obstacle crossing in young adults: a cross-sectional study

Chardon M. Barbieri FA. Petit P. Hansen C. Vuillerme, N. Obstacle avoidance has minimum impact on spatial-temporal parameters in young overweight adults (submitted)

Abstract

Background: Overweight may present an additional challenge when crossing obstacles. More specifically it may affect adequate foot clearance to reduce the risk of obstacle contact. Thus, the objective of this study was to compare obstacle clearance and spatial-temporal gait parameters during obstacle crossing in young adults with normal body weight and overweight.

Methods: Twenty-eight and fifteen individuals were categorized in normal body mass index ($18.5\text{-}25\text{kg/m}^2$) and overweight ($25\text{-}30\text{kg/m}^2$), respectively. The participants walked along a walkway at their preferred speed and stepped over an obstacle. Spatial-temporal parameters were calculated during the approaching (stride before obstacle), and the crossing (step over the obstacle) phases. Additionally, the leading and trailing foot placements prior to and after the obstacle and toe clearance were calculated.

Results: No significant differences were found for the approach, the crossing phases, and leading and trailing toe clearance. Analysis of foot placements distance prior to and after the obstacle showed that, compared to the individuals with normal body weight, overweight individuals significantly increased the leading foot placement distance prior to the obstacle and increased the trailing foot placement distance after the obstacle.

Conclusion: Our findings indicated that overweight individuals have a different obstacle crossing behavior regarding foot placement distance prior to and after the obstacle compared to normal-weight individuals without differences in spatial-temporal gait parameters nor toe clearances. However, the results did not suggest that participant with overweight show a higher risk of tripping

Keywords: Overweight, obstacle crossing, gait, clearance

1. Introduction

Overweight and obesity have become a significant problem worldwide, with the obesity prevalence nearly tripled in the last 50 years [1]. The body mass index (BMI) is commonly used to assess overweight (BMI between 25 and 29.9 kg/m²) and obesity (BMI $\geq$ 30 kg/m²). Overweight and obesity impose functional limitations by the additional loading of the increased body mass to the locomotor system, resulting in gait alterations and aberrant mechanism in posture and balance [2, 3]. Although the question of whether and how overweight and obesity could affect gait during unobstructed walking in adults has received a large interest in the past decades [4–6], not much is reported about how overweight and obesity could impact gait under more challenging conditions, such as crossing an obstacle while walking. However, it is probable that excess body weight may present an additional challenge when crossing obstacles and ensuring adequate foot clearance. A systematic review on the influence of overweight and obesity on obstacle crossing performance [7] identified a small number of published studies that have specifically compared obstacle crossing during walking in adults with overweight or obesity to those with normal body weight ($n=3$) [8–10]. Despite this small number of published studies and their heterogeneity, results of this re-view suggested that overweight and obesity significantly impacted gait patterns during obstacle crossing in adults.

Compared to normal body weight adults; overweight or obese adults exhibit lower velocity [8, 10], shorter step length, lower cadence, larger step width, lesser time spent in single-limb support, more time spent in double support [8] and a reduced swing time (as percentage of gait cycle) [10] during obstacle crossing. At this point, however, the three studies that investigated the effects of overweight or obesity on gait behavior during obstacle crossing have certain limitations; we were particularly concerned about two of them.

First, none of the studies examined the distance from the foot to the obstacle, which is called “horizontal and vertical foot–obstacle clearance distances” or “toe/heel clearance”. These parameters are usually considered as a critical parameter in a variety of obstacle crossing task (e.g., see for reviews [11, 12]). More largely, it is further recognized that since the foot clearance is the safety margin in the obstacle crossing task, decreasing the clearance might lead to the higher risk of tripping over an obstacle (e.g., [13–15]). In addition, foot placement prior to and after the obstacles may be fundamental, since errors may result in a misstep [16]. An optimal foot placement to the obstacle allows enough time to flex the limb and clear the obstacle [16], especially when body limitations are present as in obese.

Second, none of the above-mentioned studies specifically compared obstacle crossing during walking between normal body weight (BMI of 18.5 – 24.9 kg/m²) versus overweight individuals (BMI of 25.0 - 29.9 kg/m²). Therefore, potential differences in obstacle clearance and spatial-temporal gait parameters during obstacle crossing among overweight individuals remain unknown, even though differences compared to normal weight individuals have been demonstrated during flat ground walking [17].

Silva et al (2017) [9] and Desrochers et al. (2021) [8] compared a group of normal body weight participants to a group of obese participants (BMI ≥ 27 [9] or 30 kg/m² [8]) which according to the WHO classification combines both overweight and obese individuals (mean BMI: 29.9 ± 2.5 kg/m²) [18]. Gill (2019) [10] included the so-called “Overweight/ Class I obesity” group (BMI of 25 - 34.9 kg/m²) that hence brought together individuals with overweight (BMI of 25.0 - 29.9 kg/m²) and individuals with obesity (BMI of 30.0 - 34.9 kg/m²). All of the studies highlighted group differences in the spatial-temporal parameters when comparing the overweight and normal body-weight participants.

Consequently, the aim of the present study is to compare obstacle clearance and spatial-temporal gait parameters, during an obstacle crossing task in normal body weight and overweight young adults. We hypothesized that overweight impacts gait behavior during obstacle crossing, particularly on obstacle clearance parameters by reducing foot clearances which might lead to an increased risk of tripping.

2. Methods

This study is a secondary analysis of previous studies performing obstacle crossing task [19–21]. Data from forty-three participants in these studies were analyzed. Only healthy participants aged 20-39 years were included in this analysis [19], specifically those in the healthy control group, excluding participants with multiple sclerosis [20, 21]. No new data were collected for this specific analysis.

2.1 Participants

Based on the classifications for BMI recommended by the World Health Organization (WHO) [22], the 43 participants were categorized in two groups of (1) 28 (65%) individuals with normal body weight (BMI of 18.5 to < 24.9 kg/m²) and (2) 15 (35%) individuals with overweight (BMI of 25 to < 29.9 kg/m²). Apart from their weight status, participants were considered healthy (i.e., no participant with multiple sclerosis was included). The subjects were

informed about the experimental procedures (University Institution Review Board CAAE#99191318.0.0000.5398) and signed informed consent. Also, the experiment was performed in accordance with Declaration of Helsinki and Brazilian ethical regulations.

2.2 Obstacle crossing task

Participants were instructed to walk barefoot at self-selected speed along a 8.5 m long * 1.5 m [20] or 3.5m [21] width wooden pathway and to step over an obstacle (high = 15 cm; width = 80 cm, thickness= 2 cm, foam material [20]) without making contact, positioned in the middle of the pathway. The pathway was covered with a 3 mm thick black rubber carpet [19]. Three trials were performed. The starting point of each trial was adjusted to ensure that the obstacle was crossed with the right leg as leading limb and that two strides were completed prior to the obstacle crossing.

2.3 Data collection

Kinematic data were recorded using ten-infrared cameras (Vicon Motion Sys-tem®, 200 Hz). Two markers were positioned at the top of the obstacle. Also, markers were placed lateral aspect of calcaneus and head of the second metatarsus of the right limb, and medial aspect of calcaneus and head of the second metatarsus of the left limb. Conventional labelling of the limbs was used: the leading foot crossed the obstacle first; the trailing foot crossed second. Gait signals were filtered with a low-pass (6 Hz) Butterworth filter of fifth-order (zero-lag).

Fig 1 illustrates the obstacle clearance outcomes assessed. The following parameters were computed:

- Spatial-temporal gait parameters (length, width, duration, velocity and double-support time) of the approach phase (stride before obstacle) and of the crossing phase (step over the obstacle),
- Leading and trailing foot placement prior to the obstacle (horizontal distance from second metatarsal marker to the obstacle),
- Leading and trailing vertical toe foot clearance during obstacle crossing (vertical distance at the moment that second metatarsal marker was above the obstacle),
- Leading and trailing foot placement after the obstacle horizontal distance from the heel marker to the obstacle).

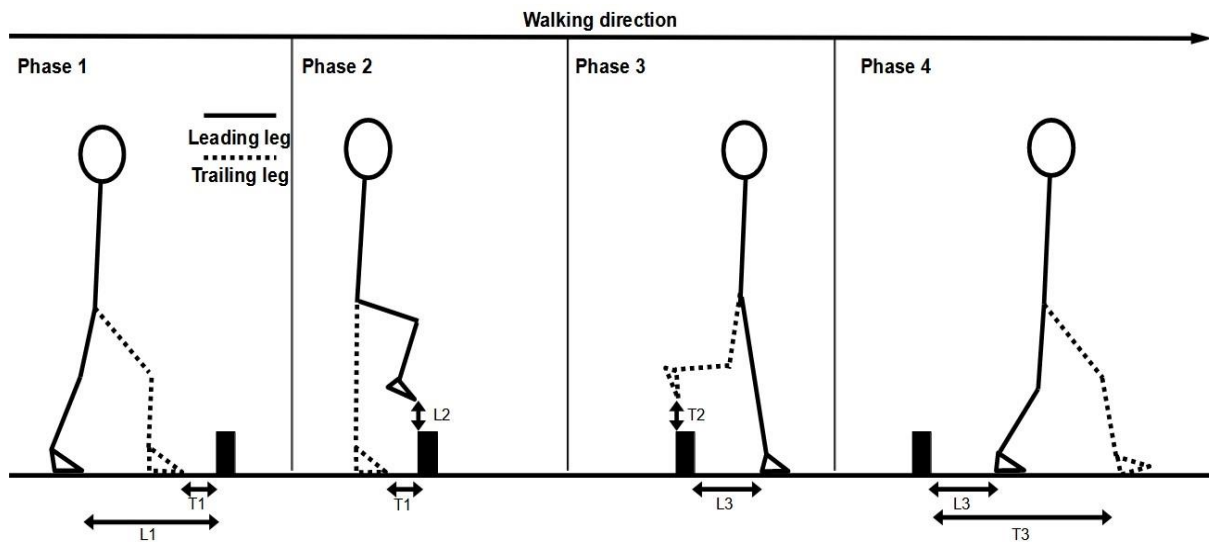


Figure 1. Description of the different phases of the obstacle crossing task and the obstacle clearance parameters.

Note: L1: Leading foot horizontal distance prior to the obstacle (cm); L2: Leading foot toe clearance (vertical distance between the foot marker and the obstacle) (cm); L3: Leading foot horizontal distance after the obstacle (cm); T1: Trailing foot horizontal distance prior to the obstacle (cm); T2: Trailing foot toe clearance (cm); T3: Trailing foot horizontal distance after the obstacle (cm).

2.4 Statistical analysis

All statistical analyses were performed using R software 4.2.2® (R Core Team, Vienna, Austria) for Windows 10©. Vargha and Delaney's A (VDA) was calculated using the effect size package [23]. For each participant, the mean trial value of each gait parameter was used. In a previous analysis, we demonstrated that gait and clearance parameters were reliable across three trials [24]. In addition, for data analysis previous studies commonly used the mean of the three trials of gait outcomes in obstacle cross-ing tasks [25–29].

Due to skewed, non-normal or multimodal distributions, the outcomes were evaluated with nonparametric methods [30]. Wilcoxon Mann-Whitney rank sum test was used to test whether there were differences in socio-demographics, anthropometrics, and gait parameters between the two groups. The Wilcoxon effect size (ES) and its 95% confidence interval were computed to quantify the difference between the two groups beyond p-value interpretation. To that end, the Vargha and Delaney's A statistic (VDA) was used. VDA is a standardized quantification of the difference between the two groups. VDA reports the probability that a value from one group will be greater than a value from the other group. A value of 0.50 indicates that the two groups are stochastically equal. A value of 1 indicates that the first group (individuals with normal body weight) shows complete stochastic domination over the other

group (over-weight individuals). A value of 0 indicates the complete stochastic domination by the second group (overweight individuals). Vargha and Delaney (2000) suggested an ES of 0.45-0.55 as a negligible effect, 0.56-0.63 (or 0.35-0.44) as a small effect, 0.64-0.70 (or 0.30-0.34) as a medium effect, and >0.70 (or <0.30) as a large effect [31]. The type I error rate was set at $\alpha=0.05$.

3. Results

Table 1 presents the results from the Wilcoxon Mann-Whitney rank sum tests examining differences between the two groups.

3.1. Socio-demographic and anthropometric characteristics

Age and the body height did not significantly differ between the two groups ($p>0.05$), while body mass and BMI did. Overweight individuals had significantly higher body mass ($p<0.01$) and BMI ($p<0.01$) than individuals with normal body weight.

3.2. Spatial-temporal gait parameters during the approaching and crossing phases

There were no significant differences between the two groups in any of the spatial-temporal step parameters studied in both approaching and crossing phases ($p>0.05$). Fig 2 presents as raincloud plot the distributions of horizontal and vertical foot clearance parameters measured in normal body weight (in grey) and overweight young adults (in green).

3.3. Leading and trailing foot placements to the obstacle

The leading foot horizontal distance prior to the obstacle and trailing foot horizontal distance after the obstacle were significantly longer in overweight individuals than in individuals normal body weight ($p=0.03$; and $p=0.02$, respectively).

There was no significant difference between the two groups in the trailing foot horizontal distance prior to the obstacle and leading foot horizontal distance after the obstacle ($p>0.05$) (Table 1 and Figure 2).

3.4. Leading and trailing vertical toe clearance during obstacle crossing

There were no significant differences between the two groups in the leading and trailing vertical toe clearance during obstacle crossing ($p>0.05$).

3.5. Obstacle contacts

There was no contact with the obstacle on all trials in both groups.

Table 1. Results of the Wilcoxon rank sum tests examining differences between the two groups regarding socio-demographic and anthropometric characteristics, spatiotemporal gait parameters measured during the approaching and the crossing phases, and obstacle clearance parameters.

Condition	Parameter	18.5 <= BMI < 25 kg/m ²			25 <= BMI < 30 kg/m ²			W	p	Effect size (VDA)
		n	mean ± SD	median [IQR]	n	mean ± SD	median [IQR]			
Socio-demographic	Age (years)	28	28.3 ± 6.12	27.9 [8.25]	15	30.6 ± 5.39	31 [6]	154	0.156	0.367 [0.218; 0.546]
Anthropometric	Body height (m)	28	1.76 ± 0.0666	1.77 [0.113]	15	1.78 ± 0.0618	1.77 [0.09]	187	0.566	0.445 [0.278; 0.625]
Anthropometric	Body mass (kg)	28	70.8 ± 6.78	70.8 [9.41]	15	86.5 ± 6.15	87.9 [5.3]	13	5.51e-07	0.031 [0.0151; 0.0623]
Anthropometric	BMI (kg/m²)	28	22.8 ± 1.72	23.5 [1.55]	15	27.4 ± 1.41	26.9 [2.4]	0	9.22e-08	0 [0; 0]
Spatial-temporal gait parameters	Stride length (cm)	28	129 ± 9.85	127 [15.2]	15	135 ± 10.8	139 [16.9]	141	0.0808	0.336 [0.195; 0.513]
Approaching phase	Stride width (cm)	28	10.5 ± 2.49	10.2 [2.41]	15	11.8 ± 2.28	11.6 [3.46]	147	0.112	0.35 [0.206; 0.528]
	Stride double support time (s)	28	0.361 ± 0.0512	0.35 [0.0567]	15	0.344 ± 0.0447	0.333 [0.0533]	263.5	0.177	0.627 [0.447; 0.778]
	Stride duration (s)	28	1.1 ± 0.116	1.09 [0.0742]	15	1.09 ± 0.0986	1.05 [0.12]	240	0.452	0.571 [0.391; 0.735]
	Stride velocity (cm/s)	28	119 ± 14.6	119 [14.1]	15	125 ± 15.8	123 [18.3]	160	0.21	0.381 [0.228; 0.561]
	Step length (cm)	28	72.1 ± 9.18	71.7 [12.7]	15	75.3 ± 8.59	78.4 [13.4]	160	0.21	0.381 [0.228; 0.561]
Spatial-temporal gait parameters	Step width (cm)	28	10.1 ± 2.7	9.45 [3.32]	15	10.6 ± 3.4	11.1 [3.37]	175	0.384	0.417 [0.256; 0.598]
Crossing phase	Step double support time (s)	28	0.211 ± 0.033	0.207 [0.0317]	15	0.204 ± 0.0359	0.2 [0.0483]	235.5	0.524	0.561 [0.38; 0.726]
	Step duration (s)	28	0.636 ± 0.0547	0.645 [0.0683]	15	0.623 ± 0.0813	0.59 [0.0933]	249.5	0.32	0.594 [0.413; 0.753]
	Step velocity (cm/s)	28	115 ± 17	113 [22.6]	15	123 ± 21.3	125 [26.5]	158	0.192	0.376 [0.225; 0.556]
Obstacle clearance parameters	Trailing foot - horizontal distance prior to obstacle (cm)	28	42.4 ± 8.77	42.7 [10.4]	15	45 ± 9.19	47.5 [9.54]	163	0.239	0.388 [0.234; 0.569]
	Trailing foot - horizontal distance after obstacle (cm)	28	90 ± 8.21	89.6 [11.9]	15	98.1 ± 11.6	95.7 [15.5]	122	0.0245	0.29 [0.164; 0.46]
	Trailing foot - toe clearance (cm)	28	32 ± 7.07	31.1 [11.6]	15	31.7 ± 6.61	30 [7.51]	208	0.97	0.495 [0.32; 0.671]
	Leading foot - horizontal distance prior to obstacle (cm)	28	105 ± 8.91	106 [9.28]	15	112 ± 8.88	110 [13.4]	123	0.0263	0.293 [0.166; 0.463]
	Leading foot - horizontal distance after obstacle (cm)	28	25.1 ± 5.75	24.8 [8.3]	15	27.3 ± 6.95	24.2 [7.01]	172	0.343	0.41 [0.25; 0.591]
	Leading foot - toe clearance (cm)	28	10.1 ± 4.27	9.38 [4.04]	15	10.4 ± 4.67	10.9 [5.18]	195	0.715	0.464 [0.294; 0.643]

Note: IQR: interquartile range, SD: arithmetic standard deviation, VDA: Vargha and Delaney's A statistic.

Blue background: negligible effect size, green background: small effect size, yellow background: moderate/medium effect size, red background: large effect size.

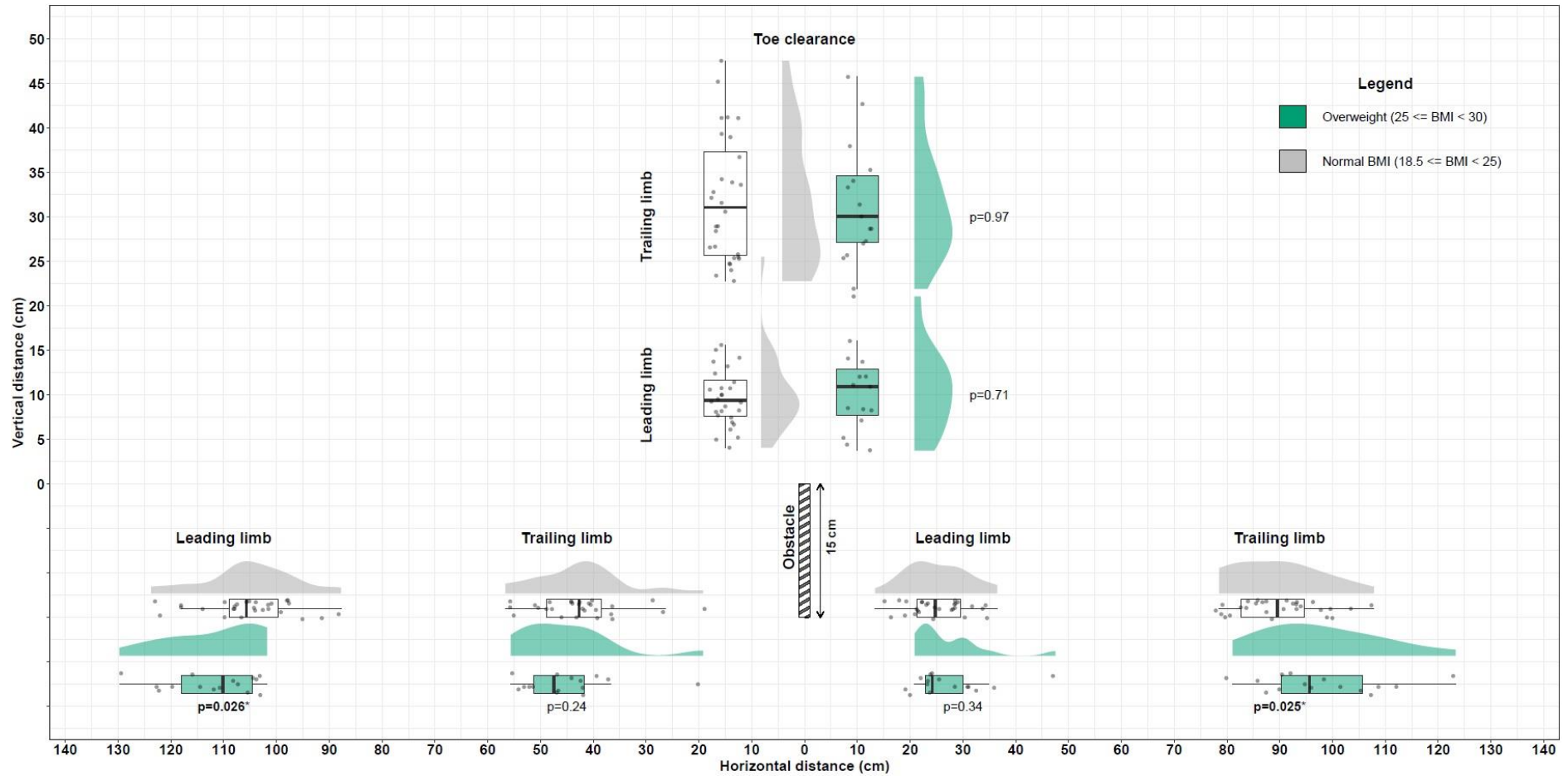


Figure 2 - Raincloud plot of the distributions of obstacle clearance parameters measured in individuals with normal body weight (in grey) and overweight individuals (in green), with the p-value of the Wilcoxon rank sum tests

Note: p: p-value of the Wilcoxon rank sum tests; *: $p \leq 0.05$

4. Discussion

The aim of this study was to compare spatial-temporal gait parameters, during an obstacle crossing task in normal body weight and overweight young adults. Our hypothesis that overweight impacts gait behavior during obstacle crossing, was partially confirmed as only leading foot horizontal distance prior to the obstacle and trailing foot horizontal distance after the obstacle were impacted and no trips occurred. No changes were observed in the spatial-temporal parameters during both the approach-ing and crossing phase.

Compared to the individuals with normal body weight, overweight individuals significantly increased the leading foot placement distance prior to the obstacle and the trailing foot placement distance after the obstacle crossing. Considering that vertical clearance parameters are critical outcomes to assess the risk of tripping over an obstacle (e.g., [13, 14, 32–34]), our results suggest that overweight young male adults do not seem to have an increased risk of trips during the obstacle task compared to their normal-weight peers in those specific experimental conditions (crossing an expected 15-cm high obstacle at self-selected speed).

This foot placement behavior observed in overweight young adults could represent an adaptive, effective and safe obstacle crossing behavior. Considering the vertical foot clearance as the safety margin in the obstacle crossing task, an unchanged clearance does not lead at the higher risk of tripping [34]. Moreover, no participants touched the obstacle during the experimental trials, suggesting that the behavior of overweight individuals is safe when avoiding obstacles. Potentially increasing horizontal distances is a behavior in overweight individuals to maintain dynamic balance (as no difference were observed in double-support time). It could be of interest for future studies to assess the foot trajectory while crossing the obstacle to identify potential differences between overweight and normal body weight participants regarding their strategies to maintain toe clearance [35] at different obstacle heights.

Our results revealed no significant group differences in the spatial-temporal gait parameters measured during the approaching and the crossing phase. In other words, both normal body weight and overweight young adults had a similar step velocity, length, width and duration and double support time during the two steps before the obstacle and crossing step. Previous studies reported that step crossing velocity was reduced in obese individuals compared to normal body weight individuals. Moreover, the higher the BMI the lower their velocity during obstacle crossing (reduction of 15.5%, 26.9%, and 31.7% for overweight/Class I obesity, Class II obesity, and Class III obesity respectively [10]). In addition the studies showed

reductions of leading leg step length (14%), cadence (13.6%), and single-limb support (relative to a single gait cycle, 6.1%), while leading step width (37.4%), and double-limb support increased (relative to a single gait cycle, 24.5%) were reported in obese individuals compared to normal body weight individuals [8]. When looking at gait phases, Gill. 2019 [10] showed that step crossing swing phase was reduced in all overweight/obesity class compared to normal body weight individuals (9.7%, 11.4%, and 12.7% for overweight/Class I obesity, Class II obesity, and Class II obesity respectively).

One may argue that the gait adaptations observed in obese individuals are caused by higher body mass [2], hence individuals with obesity need to increase their base of support for a greater amount of time relative to a single gait cycle [8] and reduce step velocity and length to successfully complete the gait task. A shorter single-limb support during the crossing phase might enhance the risk of tripping over the obstacle, to cross it “more quickly and with less assurance” [8] even if step crossing speed was reduced. However, in the specific context of crossing a 15-cm high obstacle in laboratory settings, the results of our study showed that overweight individuals do not adopt a similar spatial-temporal gait behavior compared to those with class I, class II, and class III obesity. The functional and balance impairments associated with being overweight are probably less deleterious than those associated with obesity [36, 37].

Our study investigated overweight individuals, with lower body mass and BMI compared to obese individuals and overweight individuals are able to adapt their gait behavior when crossing a 15 cm high obstacle at self-selected pace which simulates crossing a typical curb height in Brazil [38]. It is possible that the experimental obstacle crossing task was insufficiently demanding to reveal BMI-related changes in foot clearance parameters in overweight individuals due to their lower functional and balance impairments, as well as the likelihood that they perform this task very routinely. As previously mentioned the obstacle height represents an typical curb height in Brazil [38]. Further studies should consider various task-related factors that have previously shown to significantly impact foot clearances parameters. These obstacle crossing conditions that also resemble real-life situations, could include crossing one or multiple obstacles [39, 40] of different heights [34, 39, 41–43] at different walking speed [44], under various lighting conditions [45, 46], while wearing different footwear [41, 47] or orthotic bracing [48], during single-task (obstacle crossing only) and dual-task conditions (obstacle crossing with concurrent cognitive or motor task) [49–53].

To the best of our knowledge, this is the first work that compared obstacle crossing during walking in normal body weight and overweight young adults. Also, this study is the first to assess BMI influence through obstacle clearance parameters, critical parameters of fall risk during obstacle crossing [11, 12]. However, these changes do not seem to increase overweight individuals' risk of trips and falls when crossing an obstacle. The present findings per se may not reflect what was experienced by individuals with more excessive body weight, such as obese individuals ($\text{BMI} > 30.0 \text{ kg/m}^2$). It is furthermore probable that the excess body weight would have a greater impact in older adults as previously reported in other gait tasks [54, 55].

The present findings indicate that increased BMI (overweight) may have minimum impact on obstacle crossing in male adults, suggesting that overweight young male adults have not a higher the risk of tripping. Indeed, even if overweight individuals placed their leading limb further prior to crossing the obstacle, and their trailing limb further after crossing the obstacle, toe clearances remained unchanged compared to normal body weight individuals. The changes in horizontal clearance could be due to overweight individuals' willingness to ensure more space to cross the obstacle without reducing their vertical clearance. Additionally, the changes in foot placement without a change in vertical clearance imply a different foot motion over the obstacle. Overweight individuals might have a lower foot elevation during the beginning of the swing phase of the leading foot during the crossing step. Nevertheless, this interpretation remains speculative, and it would be of interest for future studies to investigate not only foot horizontal and vertical clearances relative to the obstacle, but also the entire foot trajectory during the crossing steps, as was done in a recent study [34]. Finally, a relevant aspect that has not been addressed in this or previous studies is the investigation of muscle parameters. Obstacle crossing requires greater neuromuscular activation (e.g., increased knee flexor activation) compared to walking on flat ground [56], and obese individuals have reduced strength normalized by body mass compared to normal weight individuals [57]. As a result, it seems essential for future studies to couple spatial-temporal and clearance data during obstacle crossing with muscular data in order to better interpret potential limitations in this population when performing this task. However, the limits stated above should caution readers to not draw conclusions too easily or to misinterpret the results.

To better understand whether and how excess body weight impact obstacle crossing during walking, future studies are necessary to investigate different BMI, age, and sex (as women exhibit different gait behavior on flat ground [58] and inclined walking [59]) groups of participants. Studying the influence of BMI on obstacle crossing behavior across various

demographic groups would provide a more comprehensive understanding of how BMI affects the functional capacities of these distinct demographic groups.

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Our findings showed that being overweight had only a slight impact on gait behavior while crossing a 15-cm high obstacle. Specifically, only two horizontal obstacle clearances were increased in overweight individuals compared to their normal weight peers. This result suggests that a slight spatial strategy was adopted by overweight individuals, possibly to maintain vertical clearance similar to that of normal weight individuals. Therefore, in this specific context (i.e., the population studied and the obstacle crossing protocol performed), overweight individuals do not appear to have an increased risk of tripping on the obstacle. To move beyond this dichotomous analysis, a correlation analysis between anthropometric characteristics and age is described in the following contribution, aiming to conduct a linear analysis of the potential impacts of these characteristics, particularly BMI.

7. Contribution 5: Determinants of obstacle crossing performance in young male adults: do anthropometrics and age matter?

Chardon, M. Barbieri FA. Petit P. Vuillerme N. Determinants of obstacle crossing performance in young male adults: do anthropometrics and age matter? (submitted)

Abstract

Background: Striking an obstacle while walking can be dangerous and can sometimes lead to falling. Not everyone is equal regarding the risk of falling, which can differ depending on age and anthropometric factors.

Goal: To study the influence of anthropometric factors and age on gait parameters during obstacle crossing in young male adults.

Methods: Forty-three male adults between 20 and 40 years were included. Participants performed three trials of obstacle crossing (15 cm high) while walking on an 8m walkway at a self-selected speed. Spatial-temporal gait parameters were measured using a three-dimensional camera system. Pearson correlation analyses were first undertaken to investigate the association between age, body height, body mass, body mass index (BMI) and spatial-temporal gait parameters during obstacle crossing (approaching and crossing phases, and obstacle clearances). In order to go beyond the analysis of more than one single factor, multiple regression analyses were further conducted to examine the linear relationship between participants' age and anthropometric characteristics with several gait parameters during obstacle crossing.

Results: Correlation analysis showed that during the approaching phase, the body height was positively correlated with stride length ($r=0.34$, $p=0.03$), stride double support time ($r=0.34$, $p=0.03$), and stride duration ($r=0.37$, $p=0.02$). The body mass was positively correlated with the stride length ($r=0.34$, $p=0.03$). During the crossing phase, the body height was positively correlated with the step length ($r=0.36$, $p=0.02$). Regarding obstacle clearances, correlation analysis showed that the body height was moderately and positively correlated with the leading foot horizontal distance prior to the obstacle ($r=0.30$, $p=0.05$), while the body mass was moderately and positively correlated with the leading foot horizontal prior to the obstacle ($r=0.32$, $p=0.03$) and the trailing foot horizontal distance after the obstacle ($r=0.38$, $p=0.01$). Age was positively correlated with leading ($r=0.30$, $p=0.05$) and trailing ($r=0.38$, $p=0.01$) foot horizontal distance after the obstacle, but negatively correlated with trailing foot horizontal distance prior to the obstacle ($r=-0.31$, $p=0.04$).

Multiple regression analysis showed that linear combinations of age and/or anthropometric factors were usually found to explain the variability of gait parameters better than single factors for all phases of obstacle crossing and obstacle clearances, with R^2 ranging from 5 to 14%, from 5 to 13%, and from 9 to 25% for the approaching, crossing and obstacle clearance phases, respectively. The variability of both toe clearances (the vertical distance between the obstacle and each foot at the point of obstacle crossing) was not explained by age or any anthropometric factors.

Conclusion: The present findings suggest that age and anthropometric factors are low to moderate determinant factors of gait parameters during obstacle crossing in young, normal-weight and overweight male adults. These factors are thus not sufficient to fully explain gait parameters during both the approaching and crossing phases. Further studies are required to identify predictors of obstacle clearances, in particular for toe clearances that reflect the risk of falling.

Keywords: Obstacle crossing, height, weight, BMI, age

1. Introduction

Walking is a fundamental human activity [1]. During their daily activities, individuals walk and need to cope with their physical environment [2]. Daily walking tasks include, among others, stair walking [3], dual task walking [4], and negotiating with obstacles in the travel path [5], all of which change motor patterns. Crossing an obstacle while walking can be dangerous due to trips leading to falls, with more than half of falls occurring while tripping on an obstacle for healthy older adults [6]. Obstacle crossing is a task where falls occur frequently, notably due to reductions in clearances with the obstacle [7,8] (i.e., the distance between the feet and obstacle while crossing it), leading to trips. Moreover, obstacle crossing is a more demanding task than flat-ground walking regarding neuromuscular demand [9] and sensory resources (e.g., integration of proprioceptive information) [10]. In addition, sociodemographic (e.g., age) and anthropometric factors, in particular the body mass index (BMI), might induce modifications in an individual's walking behavior [11,12].

Overweight and obesity are defined by the World Health Organization as “abnormal or excessive fat accumulation that may impair health” [13]. They represent one of the major worldwide health issues due to their increasing prevalence [14]. BMI, which is calculated as $\text{body mass (kg)} / \text{height}^2 (\text{m}^2)$ (i.e., two basic anthropometric parameters used to characterize a study population), is commonly used to categorize individuals as overweight ($\text{BMI} \geq 25$) or obese ($\text{BMI} \geq 30$). Obesity affects gait behaviors and dynamic balance during unobstructed [15,16] and obstructed walking [17,18]. These changes are linked with an increased risk of injuries during daily living [19], and fall risk [20]. Incidentally, a previous study showed that BMI affects gait behavior, with a negative correlation between BMI and stride length and walking speed [21] during flat-ground walking. Age also influence obstacle crossing behavior. A systematic review showed that older adults used a more “conservative strategy” than younger adults by reducing walking velocity and step length and with reduced horizontal distance between the feet and the obstacle before and after the crossing step [22]. This study also highlighted that obstacle contacts were more frequent for older [22]. The short step strategy might enhance the risk of stepping onto the obstacle.

Even though gait behavior during obstacle crossing has been widely studied in the past in several health status populations (e.g., obese [17,18], Parkinson's disease [23,24], older adults [6,25], and multiple sclerosis [26,27]), to the best of our knowledge, no studies specifically focused on the possible relation between sociodemographic and anthropometric parameters and obstacle crossing behavior. In a previous study on the same population that

aimed to compare spatial-temporal gait and obstacle clearance parameters in normal body weight and overweight young adults. We showed that an overweight BMI had a minimal influence on obstacle crossing behavior in young adults. Spatial temporal outcomes were not affected in either the approaching and crossing phase. However, the leading foot placement prior to the obstacle and the trailing foot placement after the obstacle crossing were higher in overweight individuals (Chardon et al., submitted). We believed that this adaptive strategy was effective and safe as vertical toe clearance remained unchanged, overweight individuals might need more space to maintain a safe toe clearance (Chardon et al. submitted). To complement the first analysis, this study aimed to investigate the influence of basic anthropometric factors and age on gait spatial-temporal and obstacle clearance parameters during obstacle crossing in young normal weight and overweight male adults.

2. Materials and methods

This study is a secondary analysis of previous published research on obstacle crossing tasks [26–28]. Also, this is the second analysis on this specific dataset. (Chardon et al., submitted)

2.1 Participants

Forty-three Brazilian male participants were included. Participants were free of any muscular or neurodegenerative disease. Participants were informed about the experimental procedures (University Institution Review Board CAAE#99191318.0.0000.5398) and signed informed consent.

2.2. Experimental protocol

Participants walked barefoot on an 8.5m long walkway at a self-selected pace and stepped over an obstacle (high = 15 cm, width = 80 cm, thickness = 2 cm) placed in the middle of the walkway three times. The starting point of each trial was adjusted to ensure that participants crossed the obstacle with the right leg as the leading foot. A minimum of two strides were completed before crossing the obstacle.

2.3. Gait assessment

Kinematic data were recorded using ten-infrared cameras (Vicon Motion System®, 200 Hz). Two markers were positioned at the top of the obstacle. Also, markers were placed on the lateral

aspect of the calcaneus and head of the second metatarsus of the right foot and the medial aspect of the calcaneus and head of the second metatarsus of the left foot. Conventional labelling of the feet was used: the leading foot crossed the obstacle first; the trailing foot crossed second. Signals were filtered with a low-pass (6 Hz) Butterworth filter of fifth-order (zero-lag).

The following parameters were computed:

- Spatial-temporal gait parameters (length, width, duration, velocity, and double-support time) of the approaching phase (stride before the obstacle) and the crossing phase (step over the obstacle),

- Obstacle clearance: leading and trailing foot placement prior to and after the obstacle (horizontal distance from the second metatarsal marker and from the heel marker to the obstacle, respectively), and – leading and trailing vertical toe foot clearance during obstacle crossing (vertical distance at the moment that the second metatarsal marker was above the obstacle).

2.4. Statistical analysis

For each participant, the mean value of the three trials for each spatial-temporal gait parameter was used. A descriptive analysis of the population studied was conducted, with the calculation for each anthropometric, socio-demographic, and spatial-temporal gait parameter of the arithmetic mean, the standard deviation (SD), the median, the interquartile range (IQR), the minimum, the maximum, and the coefficient of variation (CV), defined as $CV = SD/\text{mean} \times 100$.

Pearson's correlation analyses were undertaken to determine the relationship between age, body height, body weight, body mass index (BMI), and all spatial-temporal gait parameters during the three phases of obstacle crossing, namely the approaching, avoidance, and obstacle clearance phases. Correlation quantifies the strength and direction of the linear relationship between a pair of variables.

In order to go beyond the analysis of more than one factor, multiple linear regression analyses were further conducted to examine the effects of several participants' characteristics (age, body height, and body weight) on gait parameters during obstacle crossing. BMI was not included in the multiple linear regression analysis because it is highly correlated with body mass, which was preferred over BMI because it is a modifiable factor. Multiple linear regression analysis consists of finding the more parsimonious linear combination of predictors (participants' characteristics) that best explains the gait parameter variance. To that end, a bi-directional stepwise procedure was undertaken to select the explanatory variables to be used in

a multiple linear regression model. Linear regression analyses were applied to the data to determine the best combination of anthropometric factors (body height, and body mass) and age that explained the most variability of gait parameters computed during each step of obstacle crossing (approaching, avoidance, and obstacle clearance phases). For each regression model, the Breusch-Pagan test, Durbin-Watson test and Shapiro-Wilk test were performed to assess the variance homogeneity, independence, and normality of residuals, respectively. In addition, the F statistic and its associated p-value, the residual standard error (RSE), the R-squared (R^2), the adjusted R^2 , and the t-value and its associated p-value were provided for each model.

The type I error rate was set at $\alpha=0.05$. All statistical analyses were performed using R software 4.2.3® (R Core Team, Vienna, Austria) for Windows 10©.

3. Results

3.1 Population characteristics

Socio-demographic and anthropometric characteristics of the studied population are presented in Table 1. There were 43 males included in this study, who were on average 29.1 ± 5.91 years, weighted 76.3 ± 9.97 kg, were 1.77 ± 0.06 cm in height and had an average BMI of 24.4 ± 2.72 kg/m². Overall, 28 participants (65%) were considered to have a normal weight ($18.5 \leq \text{BMI} < 25$ kg/m²), and 15 (35%) were considered overweight ($25 \leq \text{BMI} < 30$ kg/m²). The body weight was much more variable (CV=13.1%) than the body height (CV=3.66%).

Table 1. Socio-demographic and anthropometric characteristics of the studied population (n=43 males).

Variable	mean $\pm$ SD	median [IQR]	min-max	CV (%)
Age (years)	29.1 ± 5.91	29.6 [9.00]	20.0 – 40.0	20.3
Body height (m)	1.77 ± 0.06	1.77 [0.11]	1.61 – 1.89	3.66
Body weight (kg)	76.3 ± 9.97	75.5 [14.5]	56.3 – 99.4	13.1
BMI (kg/m ²)	24.4 ± 2.72	23.9 [3.10]	18.9 – 29.4	11.1

Note: BMI: body mass index, CV: coefficient of variation, IQR: interquartile range, min: minimum, max: maximum, SD: arithmetic standard deviation.

The main spatial-temporal gait parameter characteristics of the studied population during obstacle crossing are presented in Table 2. During the approaching phase, the stride width was the most variable gait parameter (CV=23%), which was 1.4, 1.6, 1.6, and 2.7 times higher than the variability of the stride duration, stride double support time, stride velocity, and

stride length, respectively. During the crossing phase, the step width was also the most variable gait parameter (CV=28%), which was 1.4, 1.5, 2.3, and 2.4 times higher than the variability of the step double support time, step velocity, step length, and step duration, respectively. Regarding obstacle clearances, the leading limb toe clearance was the most variable gait parameter (CV=42%), which was 1.7, 2.0, 2.1, 3.9 and 4.3 times higher than the variability of the leading foot horizontal distance after the obstacle, trailing foot toe clearance, trailing foot horizontal distance before the obstacle, trailing foot horizontal distance after the obstacle, and leading foot horizontal distance before the obstacle, respectively.

Table 2. Characteristics of the gait parameters observed in the overall studied population during obstacle crossing.

Phase	Parameters	mean $\pm$ SD	median [IQR]	min-max	CV (%)
Approaching phase (stride parameters)	Stride length (cm)	131 $\pm$ 10.5	128 [15.0]	110 – 155	8.02
	Stride width (cm)	11.0 $\pm$ 2.48	10.5 [3.85]	6.33 – 16	22.5
	Stride double support time (s)	0.36 $\pm$ 0.05	0.34 [0.06]	0.24 – 0.50	13.9
	Stride duration (s)	1.09 $\pm$ 0.11	1.09 [0.09]	0.81 – 1.39	10.0
	Stride velocity (cm/s)	121 $\pm$ 15.2	121 [14.0]	85 – 160	12.6
Crossing phase (step parameters)	Step length (cm)	73.2 $\pm$ 9.01	73.0 [13.8]	57.5 – 93.1	12.3
	Step width (cm)	10.2 $\pm$ 2.93	9.97 [4.12]	3.99 – 15.9	28.7
	Step double support time (s)	0.21 $\pm$ 0.03	0.20 [0.04]	0.15 – 0.30	16.2
	Step duration (s)	0.63 $\pm$ 0.06	0.63 [0.08]	0.52 – 0.80	10.2
	Step velocity (cm/s)	118 $\pm$ 18.8	116 [29.0]	81.1 – 168	15.9
Obstacle clearance	Leading foot – horizontal distance prior to the obstacle (cm)	108 $\pm$ 9.40	106 [11.0]	87.8 – 130	8.70
	Leading foot – toe clearance (cm)	10.2 $\pm$ 4.36	9.50 [4.63]	3.76 – 25.5	42.7
	Leading foot – horizontal distance after the obstacle (cm)	25.8 $\pm$ 6.21	24.6 [8.00]	13.4 – 47.5	24.1
	Trailing foot – horizontal distance prior to the obstacle (cm)	43.3 $\pm$ 8.90	43.1 [11.3]	19.2 – 56.7	20.6
	Trailing foot – toe clearance (cm)	31.9 $\pm$ 6.83	30.6 [9.80]	21.9 – 47.5	21.4
	Trailing foot – horizontal distance after the obstacle (cm)	92.8 $\pm$ 10.2	91.7 [13.7]	78.5 – 123	11.0

Note: CV: coefficient of variation, IQR: interquartile range, min: minimum, max: maximum, SD: arithmetic standard deviation.

3.2 Pearson's correlation analysis

3.2.1 Age and anthropometric parameters

Fig. 1 presents Pearson's correlations between anthropometric factors and age. Age was not correlated with any of the three anthropometric parameters. The body mass was positively correlated with body height ($r=0.52$, $p=3.3e-4$), and BMI ($r=0.83$, $p=6.1e-12$).

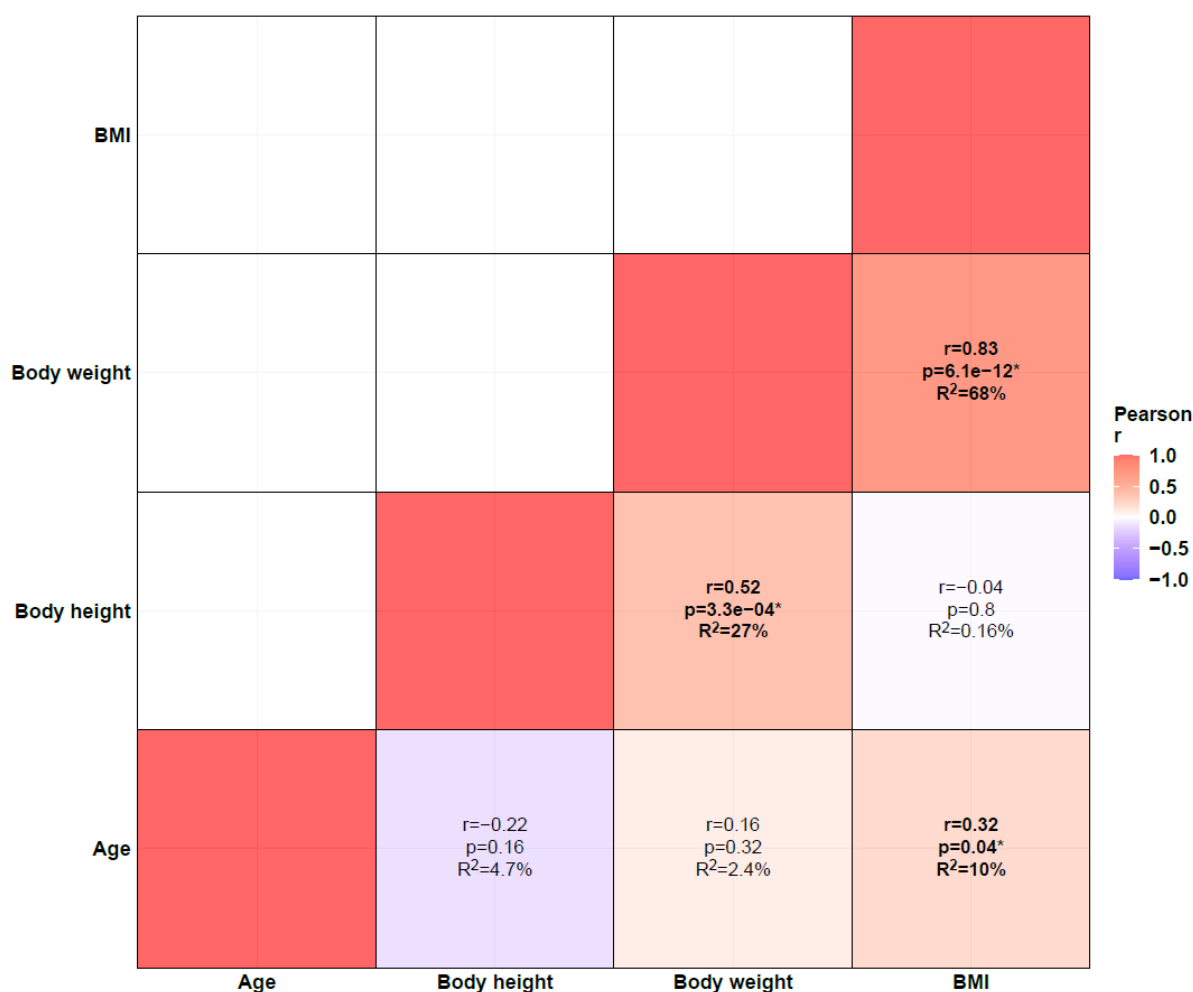


Fig.1. Pearson's correlation matrix between anthropometrics and age

* p -value <0.05 . Red color indicates positive correlation ($r \geq 0$), while blue color refers to negative correlation ($r < 0$). Darker the color, stronger the correlation.

3.2.2 Approaching phase

Fig.2 presents Pearson's correlations between participants' characteristics and spatial-temporal gait parameters during the approaching phase of obstacle crossing. Age and BMI were not correlated with any gait parameters ($p>0.05$). The body height was positively correlated with stride length ($r=0.34$, $p=0.03$), stride double support time ($r=0.34$, $p=0.03$), and stride

duration ($r=0.37$, $p=0.02$). The body mass was positively correlated with the stride length ($r=0.34$, $p=0.03$).

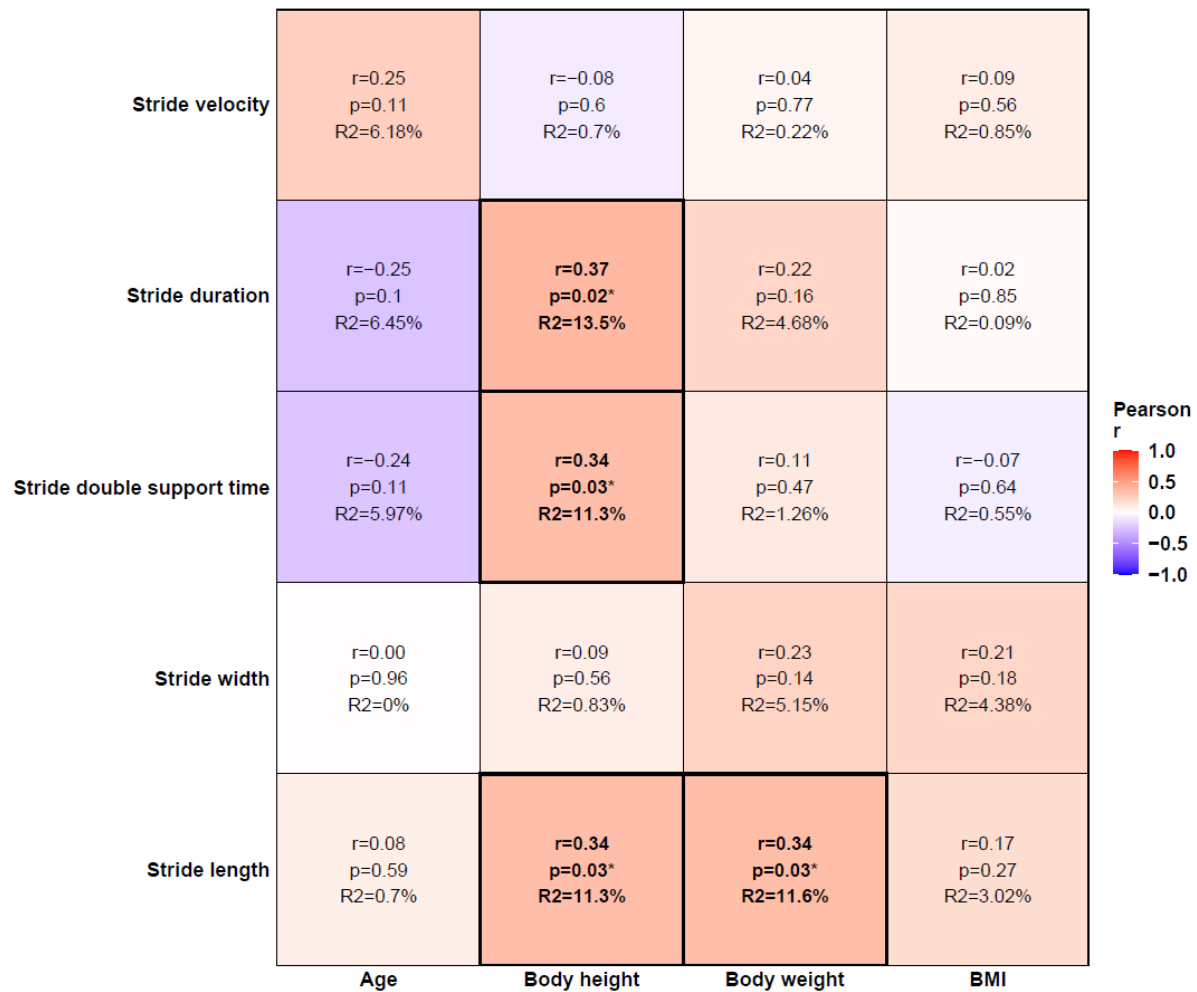


Fig.2. Pearson's correlation matrix between age, anthropometric and spatial-temporal gait parameters measured during the approaching phase of obstacle crossing

* p -value <0.05 . Red color indicates positive correlation ($r \geq 0$), while blue color refers to negative correlation ($r < 0$). Darker the color, stronger the correlation.

3.2.3 Crossing phase

Fig.3 presents Pearson's correlations between participants' characteristics and spatial-temporal gait parameters during the crossing phase. Age, body mass, and BMI were not correlated with any gait parameters ($p > 0.05$). The body height was positively correlated with the step length ($r=0.36$, $p=0.02$).



Fig.3. Pearson's correlation matrix between age, anthropometric and spatial-temporal gait parameters measured during the crossing phase of obstacle crossing

*p-value<0.05. Red color indicates positive correlation ($r \geq 0$), while blue color refers to negative correlation ($r < 0$). Darker the color, stronger the correlation.

3.2.4 Obstacle clearance

Fig.4 presents Pearson's correlations between participants' characteristics and obstacle crossing clearance parameters. Age was negatively correlated with the trailing foot horizontal distance prior to the obstacle ($r=-0.31$, $p=0.04$). Age was positively correlated with both the leading ($r=0.30$, $p=0.05$) and trailing ($r=0.38$, $p=0.01$) foot horizontal distance after the obstacle. The body height ($r=0.29$, $p=0.05$) and body mass ($r=0.32$, $p=0.03$) were positively correlated with the leading foot horizontal distance prior to the obstacle. Body mass ($r=0.38$, $p=0.01$) and BMI ($r=0.34$, $p=0.03$) were positively correlated with the trailing foot horizontal distance after the obstacle. No participant's characteristic was correlated with both toe clearances.

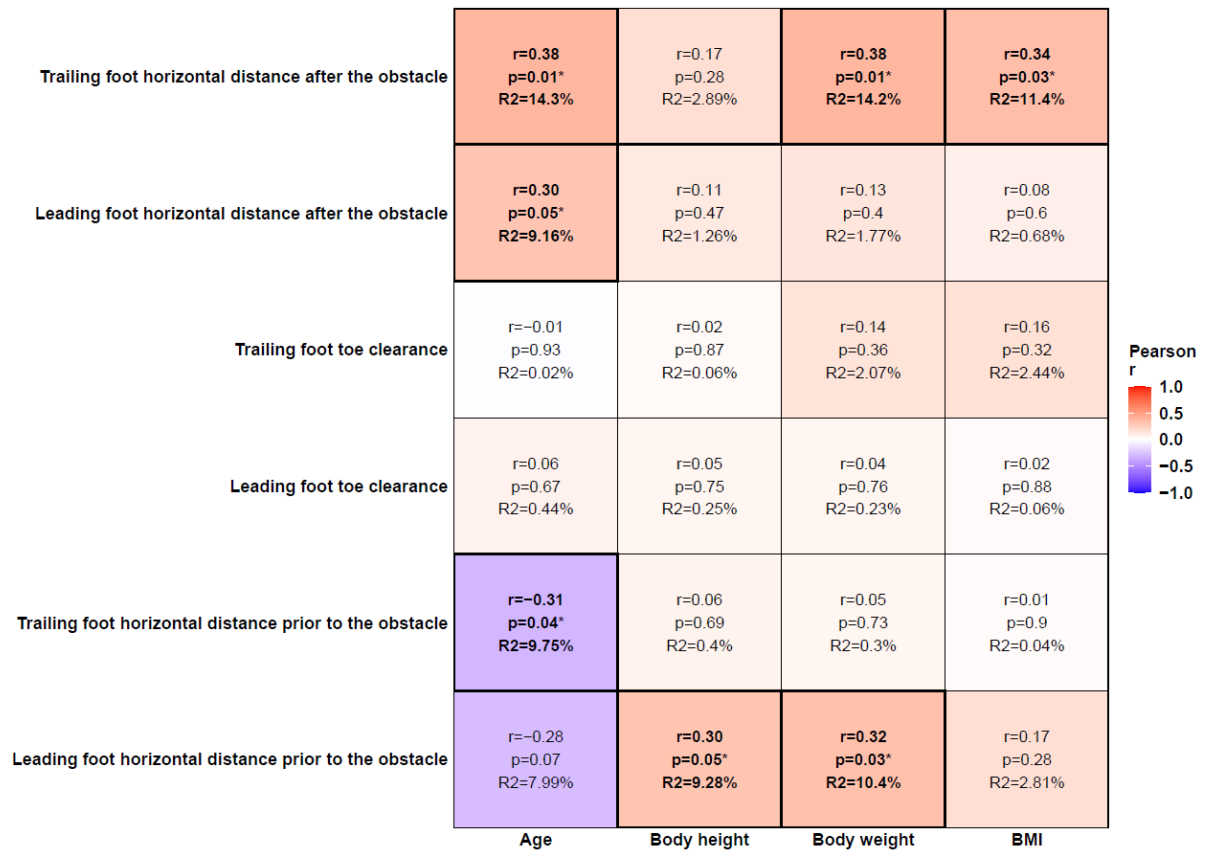


Fig.4. Pearson's correlation matrix between age, anthropometric and obstacle clearance parameters

* p -value <0.05 . Red color indicates positive correlation ($r \geq 0$), while blue color refers to negative correlation ($r < 0$). Darker the color, stronger the correlation.

3.3 Multiple linear regression analysis

Table 3 presents the results of the bi-directional stepwise multiple regression analysis examining the effect of age, body height, and body mass on spatial-temporal gait parameters during all stages of obstacle crossing.

3.3.1 Approaching phase

Overall, there were between 0 and 1 out of 3 anthropometric and socio-demographic factors that were selected in the final model. Body height and body mass were selected twice in the final model, whereas age was selected once.

Age, body height, and body mass explained between 5 and 14% of the gait parameter variance (Table 3). The best results were found for stride duration ($R^2=14\%$), followed by stride length ($R^2=12\%$), and stride double support time ($R^2=11\%$).

Regardless of the model considered, anthropometric factors and age always had a positive impact on the gait parameters for which they were selected.

More specifically:

- the taller the participant, the longer the stride duration and stride double support time,
- the heavier the participant, the greater the stride length and stride width,
- the older the participant, the higher the stride velocity.

3.3.2 Crossing phase

Overall, there were between 0 and 1 out of the 3 anthropometric and socio-demographic factors that were selected in the final model. Regardless of the model considered, body mass was never among the best combinations of factors that explained the most variability in gait parameters. Conversely, body height was selected twice in the final model, whereas age was selected once. No anthropometric factor was found to explain the variabilities of the step width and step double support time. For the other three remaining gait parameters (step length, duration, and velocity), body height and age explained between 5 and 13% of the gait parameter variance (Table 3). The best result was found for the step length ($R^2=13\%$). Regardless of the model considered, age and body height always had a positive impact on the gait parameters for which they were selected.

More specifically:

- the taller the participant, the longer the step length and step duration,
- the older the participant, the greater the step velocity.

3.3.3 Obstacle clearances

Fig.5 presents the best models for each obstacle crossing clearance parameter. Overall, there were between 0 and 2 out of the 3 anthropometric and socio-demographic factors that were selected in the final model. Regardless of the model considered, body height was among the best combinations of factors that explained the most variability in gait parameters. Conversely, body mass was selected twice in the final model, whereas age was selected four times.

No anthropometric factor was found to explain the variability of both toe clearances (Fig.5). For the four remaining gait parameters (horizontal distances prior to and after the obstacle for both feet), anthropometric factors and age explained between 9 and 25% of the gait

parameter variance (Table 3). The best results were found for the trailing foot horizontal distance after the obstacle ($R^2=25\%$), followed by the leading foot horizontal distance prior to the obstacle ($R^2=22\%$), the trailing foot horizontal distance prior to the obstacle ($R^2=10\%$), and the leading foot horizontal distance after the obstacle ($R^2=9\%$). Regardless of the model considered, anthropometric factors and age always had a positive impact on the gait parameters for which they were selected, with the exception of age for the horizontal distances prior to the obstacle for both the leading and trailing feet.

More specifically:

- the older the participant, the higher the horizontal distance after the obstacle of the leading and trailing feet, but the lower the horizontal distances prior to the obstacle with both feet,

- the heavier the participant, the higher the leading foot horizontal distance prior to the obstacle and the trailing foot horizontal distance after the obstacle.

Table 3. Results of the bi-directional stepwise multiple regression analysis examining the effect of anthropometric factors and age on spatial-temporal gait parameters during the approaching and crossing phases of obstacle crossing and obstacle clearance parameters

Phase	Parameter	Final model equation	Selected variable	t	P(> t)	R ²	R ² adj.	F	P(> F)	RSE	DW test	BP test	SW test
Approaching phase (stride parameters)	Stride length (cm)	y = 2.32 x body weight + 8.68	Intercept	8.68	7.8e-11	0.12	0.09	5.38	0.0254	10.0	0.17	0.35	0.36
			Body weight	2.32	0.03								
	Stride width (cm)	y = 1.49 x body weight + 2.30	Intercept	2.30	0.03	0.05	0.03	2.22	0.143	2.44	0.36	0.66	0.15
			Body weight	1.49	0.14								
	Stride velocity (cm/s)	y = 1.64 x age + 8.90	Intercept	8.90	4.0e-11	0.06	0.04	2.70	0.108	14.9	0.31	0.24	0.61
			Age	1.64	0.11								
	Stride double support time (s)	y = 2.29 x body height - 0.49	Intercept	-0.49	0.63	0.11	0.09	5.24	0.0272	0.05	0.56	0.50	0.08
			Body height	2.29	0.03								
	Stride duration (s)	y = 2.53 x body height – 5.0e-3	Intercept	5.0e-3	0.99	0.14	0.11	6.40	0.0154	8.51	0.11	0.89	0.54
			Body height	2.53	0.02								
Avoidance phase (step parameters)	Step length (cm)	y = 2.45 x body height – 0.41	Intercept	-0.41	0.69	0.13	0.11	6.00	0.0186	8.51	0.11	0.89	0.54
			Body height	2.45	0.02								
	Step width (cm)	/	Intercept	22.9	2.4e-25	0	0	/	/	/	/	/	/
	Step double support time (s)	/	Intercept	40.5	2.9e-35	0	0	/	/	/	/	/	/
	Step duration (s)	y = 1.97 x body height + 0.43	Intercept	0.43	0.67	0.09	0.06	3.90	0.06	0.06	0.39	0.36	0.33
			Body height	1.97	0.06								
	Step velocity (cm/s)	y = 1.47 x age + 6.74	Intercept	6.74	3.8e-8	0.05	0.03	2.15	0.15	18.6	0.49	0.69	0.35
			Age	1.47	0.15								
Obstacle clearance	Leading foot – horizontal	y = -2.41 x age + 2.66 x body weight + 8.55	Intercept	8.55	1.5e-10	0.22	0.18	5.58	0.007	8.52	0.18	0.77	0.38

Phase	Parameter	Final model equation	Selected variable	t	P(> t)	R ²	R ² adj.	F	P(> F)	RSE	DW test	BP test	SW test
(distances from the obstacle)	distance prior to the obstacle		Age Body weight	-2.41 2.66	0.02 0.01								
	Leading foot – toe clearance	/	Intercept	15.4	7.1e-19	0	0	/	/	/	/	/	/
	Leading foot – horizontal	y = 2.03 x age + 3.58	Intercept	3.58	9.0e-4	0.09	0.07	4.14	0.049	5.99	0.79	0.36	0.04
	distance after the obstacle		Age	2.03	0.05								
	Trailing foot – horizontal	y = - 2.10 x age + 8.60	Intercept	8.60	1.0e-10	0.10	0.08	4.43	0.042	8.56	0	0.40	0.02
	distance prior to the obstacle		Age	2.10	0.04								
	Trailing foot – toe clearance	/	Intercept	30.6	2.5e-30	0	0	/	/	/	/	/	/
	Trailing foot – horizontal	y = 2.35 x age + 2.34 x body weight + 4.27	Intercept	4.27	1.2e-4	0.25	0.21	6.53	0.003	9.04	0.74	0.76	0.20
	distance after the obstacle		Age Body weight	2.35 2.34	0.02 0.02								

Note: BP test: Breusch-Pagan test for testing the homoscedasticity of the residuals, DW: Durbin-Watson test for testing the independence of the residuals, F: F statistic, NS: not selected, P: probability, RSE: residual standard error, SW: Shapiro-Wilk test for testing the linearity of the residual, t: t value. *At least one assumption regarding the model residuals is not met.

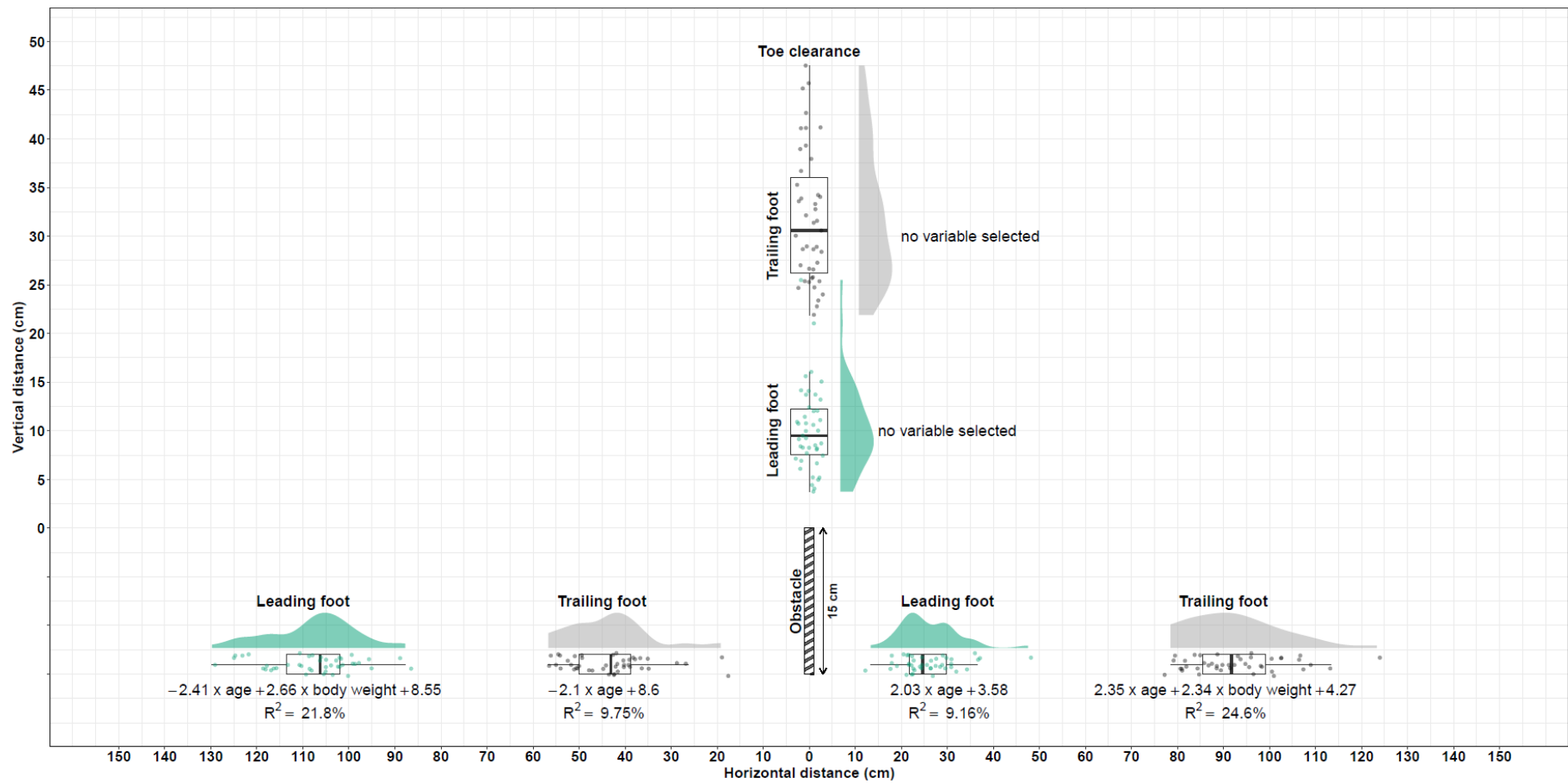


Fig.5 – Raincloud plot of the distributions of obstacle clearance parameters during obstacle crossing, along with the participants' characteristics, that explained the most of their variability. In green: leading limb, in gray: trailing limb.

4. Discussion

The aim of this study was to investigate the influence of age and anthropometric factors on gait parameters during obstacle crossing in young normal weight and overweight male adults. Results showed that for almost all parameters, Pearson's correlation and multiple regression analysis yielded similar results. A linear combination of age and anthropometric factors was usually found to explain the variability of gait parameters better than single factors for all stages of obstacle crossing (approaching and crossing phases, and specifically obstacle clearance parameters). However, no combination of these parameters explained the toe clearance variance of both feet. To date, to our knowledge, no studies have investigated the possible association between sociodemographic and anthropometric gait parameters during obstacle crossing.

4.1. Approaching phase

In a previous study, no difference was found between normal weight and overweight individuals on spatial-temporal parameters during the approaching phase of obstacle crossing (Chardon et al., submitted). However, in the present study, several anthropometric parameters were associated with gait outcomes during the approaching phase. The body height of individuals was positively associated with their stride length, as shown in a previous study [29] on flat-ground walking. However, Mikos and colleagues showed that normalization of these parameters successfully de-correlated the influence of body height [29]. It could be interesting for future studies to investigate the specific influence of leg length or the body height/leg length ratio. Perhaps surprisingly, BMI was not associated with any gait parameters during the approaching phase, and a positive association between body weight and stride length was found. Previous studies have shown that a high BMI (obese category) is associated with increased step width, and lower step length during flat-ground walking compared to normal-weight individuals [17,30]. Because of the high correlation between BMI and body weight in our dataset, we could have expected a decreased stride length with higher body weight mass or BMI. Another study showed that BMI was negatively associated with stride length and gait speed [21]. However, our dataset included only normal weight and overweight individuals compared to the above-mentioned studies (i.e., obese [17,30] or overweight and obese individuals [21]). We could have expected that a higher body mass led to lower stride length and a negative association between BMI and stride length and speed if our dataset included individuals in all BMI categories. In addition, another potential explanation could be that

individuals have different behaviors during flat-ground walking compared to the approaching phase of obstacle crossing.

The influence of age on walking patterns has been widely studied [31–34]. Older adults have decreased speed [31,33], and stride length [33] compared to young adults. However, we found that age was never associated with any gait parameters during the approaching phase. The absence of association between age and gait parameters is probably due to the relatively small age range of the individuals included in our study (20-40 years old). This is in line with a previous study comparing age (from 20 to 70+ years old) groups during an obstacle crossing task [28]. No difference in gait and obstacle clearance parameters were found between the 20-29 and the 30-39 years old groups. Also, a previous study showed that physical declines in function were much greater during late adulthood than during the younger years [35]. Therefore, adults younger than 40 years old might be able to compensate the deleterious effect of higher body mass and BMI on obstacle crossing performance. Future studies should include a larger range of age groups to better appreciate the influence of age during the approaching phase of obstacle crossing. This will perhaps help to identify when adults start to use proactive strategies, also called conservative strategies, such as reducing velocity during the approaching phase compared to the step crossing speed [36] for older adults.

Similarly to Pearson's correlation analysis, regression models revealed that a higher body height increased stride duration and double support time. The body height was not selected to explain the variability of stride length or stride velocity. With increased stride duration we could have expected that one of these two parameters could also be affected (e.g., increased stride length or decreased stride velocity) by body height. However, as above mentioned, with Pearson's correlation analysis, both body height and weight were positively correlated with stride length (R^2 was greater with body weight than height: 11.6% vs. 11.3%), but not with stride velocity. This could mean that body height does have an influence on stride length, or that its influence was lower than that of body mass, or the combination of body height and mass. In addition to stride length, body mass had a positive impact on stride width. However, its influence was very slight ($R^2=5\%$).

4.2. Crossing phase

In a previous study, no difference was found between normal weight and overweight individuals on spatial-temporal outcomes during the approaching phase of obstacle crossing (Chardon et al., submitted). In this study, we showed that the only anthropometric parameter

correlated to gait parameter during the crossing phase was body height, which was correlated with step length. Similarly to the approaching phase, body height had a positive impact on step length when crossing the obstacle. The absence of influence of BMI or body weight is perhaps surprising, as previous studies reported a decreased step crossing velocity in obese adults [17,18], as well as reduced step length and increased step width [17]. This could suggest that BMI is not associated with changes in kinematic behavior to cross a 15cm-high obstacle in our study population (normal and overweight individuals), contrary to obese individuals.

Age and body height were the only factors selected in the final regression analysis models during the crossing phase. Age had a positive impact on step velocity. A systematic review showed that eight studies found reduced velocity in older adults compared to young adults while crossing an obstacle [22]. As mentioned for the approaching phase, our dataset did not include older adults, so our results could suggest that this strategy is not already being used by the oldest adults in our study population.

Body height had a positive impact on both step length and duration. This is not surprising, as body height was not associated with step velocity. Therefore, individuals with higher body height crossed the obstacle with a higher step length but with a similar velocity, increasing the stride duration. When using a fixed obstacle height, the difficulty of the task is different for individuals with different body heights (the higher the body height, the lower the obstacle as a percentage of body height). Future studies should investigate the influence of obstacle height (i.e., several obstacle heights or an adjustable obstacle height according to a percentage of body height or leg length) to better appreciate the relation between body height and gait parameters during the obstacle crossing phase.

4.3. Obstacle clearances

Age, body height, mass, and BMI were significantly correlated with horizontal obstacle distance parameters but not with toe clearances. Age was positively correlated with both foot distances after the obstacle and negatively correlated with both foot horizontal distances prior to the obstacle. Body height and mass were both positively correlated with leading foot horizontal distance prior to the obstacle and body mass and BMI were also positively correlated with trailing foot horizontal distance after the obstacle. This is in line with the results of our previous study which showed that overweight individuals increased leading foot horizontal distance prior to the obstacle, and trailing foot horizontal distance after the obstacle (Chardon et al., submitted).

Age and body mass were the only factors selected in the regression analysis model for clearance parameters. Similarly to Pearson's correlation analysis, age and anthropometric parameters did not explain the variance of both toe clearances. The regression analysis showed that age also influenced trailing foot horizontal distance after the obstacle. Being older reduced both foot horizontal distances prior to the obstacle, while it increased both foot horizontal distances after the obstacle. This could mean that the oldest adults in the studied population (up to around 40 years old) adopt a strategy consisting of starting by crossing the obstacle closer but then landing their foot further to the obstacle. However, as toe clearance was not affected by these factors, the risk of tripping did not seem to be affected by this strategy [37,38]. Nevertheless, by starting to cross the obstacle closer without changes in toe clearance, the whole foot trajectory might have changed with a greater elevation of the feet for the oldest adults during the first part of the swinging phase. Perhaps these individuals are beginning to experience difficulties controlling dynamic balance and choose to pass above the obstacle earlier in their swing phase, which is a more stable strategy than the latter phase of swing because the center of mass "is quickly thrust into a position between stance foot heel and toe" [39]. In our study, vertical clearance was only assessed with the toe. Assessing the minimal distance between the foot and the obstacle during its whole trajectory (i.e., not only the vertical distance when the toe is above the obstacle) should be interesting for future studies to confirm that this strategy is not riskier by reducing the distance between the foot and the obstacle during the whole swinging phase, thus increasing the risk of tripping on it. Future studies with a wider range of ages are needed to better appreciate the influence of age on clearance parameters throughout the lifespan. As in Pearson's correlation analysis, higher body weight resulted in an increase in leading foot horizontal distance prior to the obstacle and trailing foot horizontal distance after the obstacle. Individuals with a higher body weight strategy appeared to start the step crossing further from the obstacle. However, anthropometric parameters did not explain vertical clearance variability, so the possible impact of these parameters on the risk of tripping remains unknown.

Limitations and future directions

The results of this study have to be carefully taken into account because the sample size was relatively small (n=43) and individuals were aged between 20 and 40 years old. In addition, only three anthropometric factors and one sociodemographic factor were considered. Further studies on the largest populations with additional sociodemographic and anthropometric factors

are needed. Among other anthropometric parameters of interest for future investigations are leg length, foot size, and foot dominance. Also studying gender differences in obstacle crossing behavior could be of interest to future studies.

There might be a selection bias in our study because females were not included in this work. However, this choice was made because previous works showed that it was better to consider females and males separately, as females and males exhibit different gait behaviors during flat-ground walking [40]. In addition, the absence of obese individuals might have played a role in the small number of significant correlations between BMI and gait outcomes. The impact of obesity (i.e., high BMI) on gait parameters during obstacle crossing such as lower velocity [17,18], shorter step length [17], lower cadence [17], larger step width [17], less time spent in single-limb support [17], more time spent in double support [17] and a reduced swing time (as a percentage of gait cycle) [18] suggests that BMI does have an influence on obstacle crossing performance. Therefore, future studies should include a large sample of individuals in several BMI categories to better appreciate the impact of a higher BMI on gait and obstacle clearance outcomes.

Finally, the height of the obstacle (i.e., 15cm high, corresponding to a typical sidewalk height in Brazil [41]) and crossing it at a self-selected pace might not be constrained enough to highlight the impact of anthropometric parameters on all phases of obstacle crossing. Future studies could use obstacles of various heights, give several walking conditions (i.e., slow, fast speed) and use dual-tasking to increase the challenge of the obstacle crossing task and reproduce a task more similar to everyday life.

5. Conclusion

The present findings suggest that age, body height, body mass, can help in predicting gait and clearance parameters during obstacle crossing. However, these factors were low to moderate determinants, thus do not sufficient to fully explain gait parameters during both the approaching and crossing phases, especially regarding vertical toe clearances. Other anthropometric parameters such as foot size, leg length, waist circumference, weight trajectory, and measures of adiposity (fat) would be interesting to consider. Further studies are required to identify predictors of obstacle clearances, in particular for vertical clearances, which are essential to identifying people at risk of falling when crossing an obstacle.

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8. General discussion

The objective of this PhD thesis was to explore the effect of overweight on gait characteristics during an obstacle crossing task. To address this, first was conducted a systematic review to consolidate existing knowledge on the topic. Subsequently, a second review focused on how and to what extent Brazilian studies have examined BMI status in the context of obstacle crossing tasks. Based on these reviews, we opted to conduct a retrospective analysis of previously published data from three Brazilian studies identified in the second review. This analysis comprised three parts: assessing the relative and absolute reliability of gait and obstacle crossing parameters, comparing these parameters between normal-weight and overweight individuals, and using correlation and linear regression analyses to explore associations between age, anthropometric factors, and gait parameters.

The following sections will detail the work completed in this PhD thesis, discussing its findings, implications, and future research directions.

8.1. Scientific Contributions of the PhD thesis

8.1.1. The literature on the influence of overweight during obstacle crossing is limited

This thesis includes a systematic review aimed at identifying potential differences in obstacle crossing tasks between individuals of normal weight and those who are overweight or obese. A comprehensive search yielded only five studies meeting our eligibility criteria, highlighting the scarcity of research in this area. This systematic review's protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) (CRD#42021269949) and published in May 2022 [130]. The full article can be found in annex 1. Figure 10 illustrates the synthesis of these studies.

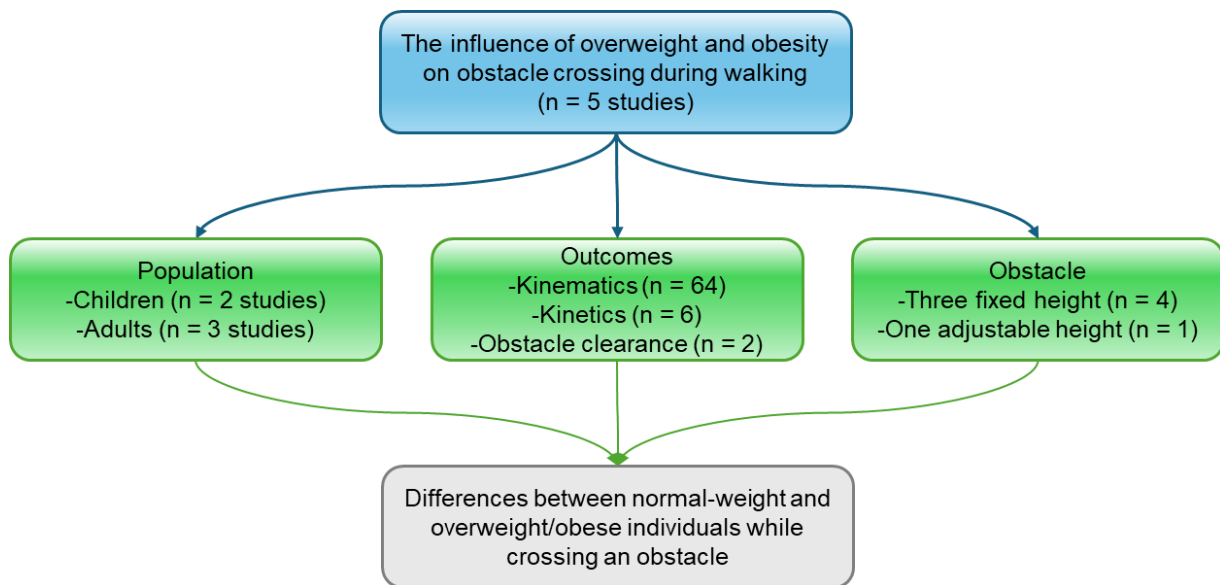


Figure 10. Synthesis of the characteristics of the studies investigating the influence of overweight and obesity during obstacle crossing.

The methodologies and participant demographics varied across studies. Key findings included a decrease in gait velocity attributed to overweight and obesity [68], with a more pronounced reduction observed in individuals with a BMI over 35 kg/m² [63]. Additionally, it was noted that obese adults exhibited an increased step width and a longer double-stance duration, alongside decreased cadence, step length, and swing time [68]. Interestingly, overweight children were found to adopt a more dorsiflexed (heel-toe) landing strategy compared to their normal-weight counterparts who preferred a flat-foot strategy [131], though such differences were not noted in post-menopausal women [117]. Remarkably, only one study, focused on children, investigated obstacle vertical clearance parameters [132], revealing that both overweight/obesity and obstacle height influenced vertical clearance, overweight children demonstrating reduced clearance over higher obstacles, potentially increasing tripping risk. Overall, the collected data indicate that observed kinematic changes reflect adaptive behaviors in response to postural imbalances, overweight or obese individuals modifying their gait to increase base support and reduce time in the swing phase.

Kinetic parameters were specifically explored in a study involving children [132]. The analysis of ground reaction forces further confirmed the stability challenges in gait control previously noted in kinematic assessments. Notable differences in ground force reactions—in terms of anterior/posterior, medial/lateral, and vertical forces—were identified between normal weight and obese children, as well as across various obstacle heights [132]. Such disparities in gait mechanics may exacerbate balance issues [133] and contribute to the development of

musculoskeletal disorders [71], potentially due to increased hip abduction angles and elevated medial/lateral and vertical ground reaction forces.

This review has highlighted several key implications and directions for future research:

- The performance in obstacle crossing tasks appears to be influenced by the height of the obstacle in young adult. We presume that the performance is thus also influenced by the participant's body height and leg length. We advocate for the systematic documentation of participants' body height and leg length in obstacle crossing studies.

- A systematic approach to recording vertical obstacle clearance and instances of obstacle contact (errors) is recommended to better identify individuals at higher risk of falls during these tasks. This aligns with previous findings emphasizing the importance of these measures in assessing fall risk during obstacle crossing [80,90,108].

- Remarkably, none of the reviewed studies exclusively focused on a specific group of overweight individuals by BMI criteria. While Gill (2019) did examine a mixed group of overweight and obese participants ($25 < \text{BMI} < 35 \text{ kg/m}^2$) [63], future research could benefit from exploring the nuances of obstacle crossing performance across different levels of overweight, especially given evidence suggesting greater reductions in gait speed among more severely obese individuals.

- Additionally, the literature lacks studies assessing the reliability of gait parameters during obstacle crossing within the demographic of individuals with different BMI status.

In conclusion, although the existing literature is scarce, our systematic review has underscored the significant impact of overweight and obesity on obstacle crossing abilities across both child and adult populations. A notable gap in the current body of research is the dearth of detailed analyses on kinetic, muscular, and specific obstacle clearance parameters. While kinematic parameters have been a focus across all included studies, gait speed was the only parameter consistently examined in more than one study, limiting our ability to conduct comparative analyses. The reduced gait speed observed is probably due to the lower cadence and step length observed in the obese individuals. The variability in participant demographics (i.e., children, adults, mixed gender group or not), measured outcomes, and the design of obstacle crossing tasks further complicates the ability to draw broad, generalizable conclusions about the effects of overweight on obstacle crossing performance. The database search was repeated on August 28, 2024. Eleven new potential articles were identified; however, none of

these records fulfilled the eligibility criteria and therefore could not be included to update the review.

Our findings emphasize the need for the systematic documentation of participants' body height and leg length in future obstacle crossing studies, as well as the recording of vertical obstacle clearance and instances of obstacle contacts, and the study of different BMI subgroups. To that end, several challenges will have to be overtaken, in particular using standardized equipment to assess gait and clearance parameters and including comparable group of participants from different BMI categories (i.e., same age, sex, body height etc.).

8.1.2. Body mass index and obstacle crossing: a review of Brazilian studies

Building upon our initial systematic review, we conducted an analysis of Brazilian research focusing on obstacle crossing tasks. The aim of this second review was to identify the anthropometric characteristics of height, weight and BMI of Brazilian adults included in published studies on obstacle crossing. This review was limited to studies involving adult participants aged 18 and above, without regard to their health status. A total of 35 studies met our inclusion criteria for this analysis. The characteristics of these studies are synthesized in Figure 11, offering a comprehensive overview of how BMI has been integrated into obstacle crossing research in Brazil.

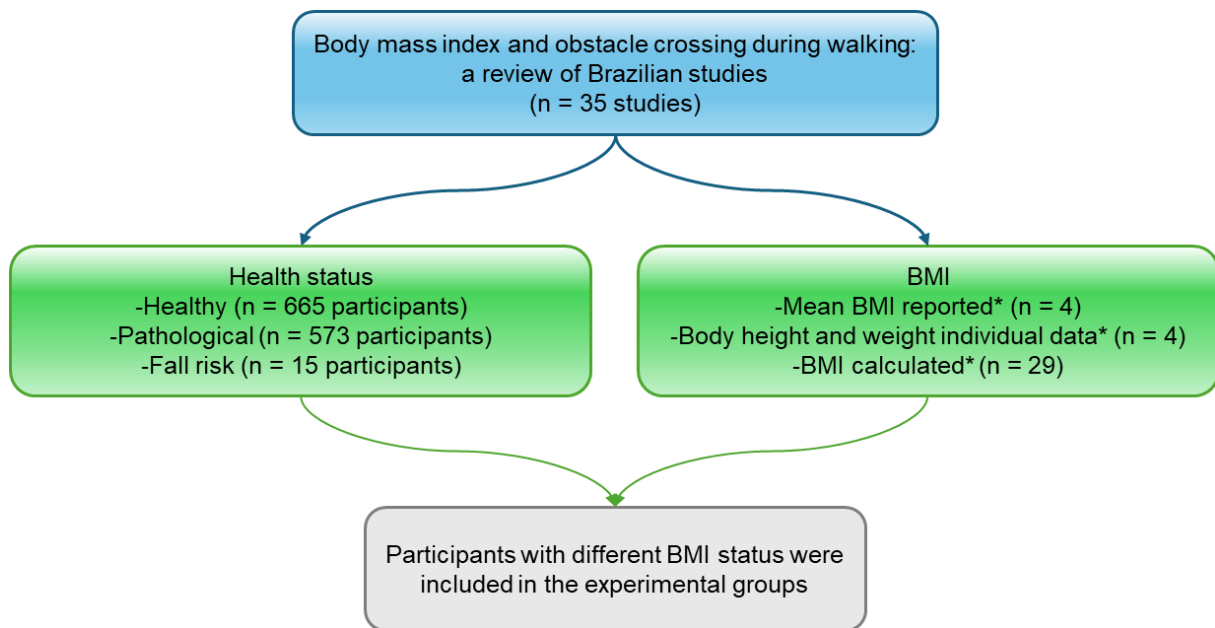


Figure 11. Synthesis of the Brazilian studies included in the review.

Note: *: indicates that the information was reported/calculated for at least one study group.

The 35 studies analyzed encompassed a total of 1253 participants, with more than half being healthy (665 participants, 53.1%), while the remainder included individuals with various diseases, such as Parkinson's disease (472 participants, 37.7%), multiple sclerosis (37 participants, 3%), Alzheimer's disease (33 participants, 2.6%), knee osteoarthritis (24 participants, 2%), and blindness (7 participants, >1%). The age range of participants spanned from 20 to over 70 years, with a significant majority being older adults over 60 years of age (950 participants, 75.8%). Reporting on participants' BMI was inconsistent, with only four studies providing mean group BMI, and four studies provided individual body height and body mass data, sufficient for precise BMI calculation. In contrast, 29 studies offered only average and standard deviation values for body height and body mass, necessitating the estimation of BMI through bounded random value generation. Among the reports on mean group BMI, six out of seven participant groups presented an average BMI above the overweight threshold of 25 kg/m². Detailed BMI breakdown showed 30 individuals classified as normal weight (47.6%), 25 as overweight (39.7%), and 8 as obese (12.7%), among 63 participants with individual data. When estimating the BMI for 64 participant groups, a notable distribution emerged: 8 groups fell into the normal-weight category (12.5%), while the overwhelming majority, 56 groups, were categorized as overweight (87.5%). The results of the present analysis showed that in the Brazilian studies, participants' groups commonly included adults in different BMI categories. One explanation is that BMI status was never used as an inclusion/exclusion criterion. Moreover, the studies reporting mean group BMI did not include BMI as a co-founding factor

for their analysis. Interestingly, the distribution of BMI categories closely mirrors the prevalence rates of overweight and obesity in the broader Brazilian population, indicating a potential reflection of national trends in these studies [134].

In summary, considering the established associations between overweight/obesity status and impairments in both static and dynamic balance [51,52], as well as alterations in gait behavior during unobstructed walking [53,54,68], the risk of falls during everyday activities, including obstacle crossing, is notably increased [72,135]. The findings from our comprehensive reviews suggest a significant area of interest in exploring the specific differences in obstacle crossing gait behavior between normal-weight and overweight individuals ($25 \leq \text{BMI} < 30 \text{ kg/m}^2$).

The findings from our second analysis highlight that the necessary data for comparing obstacle crossing performance between normal-weight and overweight individuals already exists within the Brazilian studies we reviewed. This enables the secondary analysis of previously published data, presenting several benefits for research advancement. Leveraging previously published data in new research offers distinct advantages. First, by re-analyzing existing datasets for new purposes, researchers can significantly reduce the time, cost, and logistical complexities associated with collecting new data [136], as well as reducing the environmental impact (e.g., carbon footprint by direct and indirect emission [137]) attributable to these protocols. Moreover, it opens avenues for cross-study comparisons that could reveal new insights regarding a specific topic [136,138]. In our case, reusing data allowed us to shed light on the influence of overweight in obstacle crossing performance. This focus could provide valuable insights into the ways in which BMI status influences gait performance during obstacle crossing tasks.

Our findings showed that BMI was poorly reported. In addition, BMI was never used as an eligibility criterion for participant inclusion nor was it investigated as a confounding factor. This review also highlighted that in previous Brazilian studies on adults, the study groups were commonly composed of a mix of individuals in different BMI categories, reflecting the diversity found in the general population. This suggests that specific data to investigate the effect of overweight alone had already been collected. Therefore, these existing datasets could be reanalyzed for this specific purpose.

8.1.2. Spatial-temporal and obstacle crossing parameters are reliable during within-session among young adults

Following the insights from our reviews, we delved into examining the intra-session reliability of various gait parameters during the approach phase (pre-obstacle crossing) and crossing phase, along with three specific obstacle clearance measurements for both the leading and trailing limbs. The evaluated gait parameters encompassed:

- Stride length, width, velocity, duration, and double support time (measured in appropriate units) for the approaching phase,

- Step length, width, velocity, duration, and double support time for the crossing phase.

Additionally, obstacle clearance assessments included the horizontal distance before and after the obstacle, alongside toe clearance (the vertical separation between the toe and obstacle at the while crossing it). Data for these parameters were captured utilizing a 10-infrared camera system (Vicon Motion System® at 200 Hz). A cohort of 43 healthy Brazilian male adults participated, walking barefoot over an 8.5-meter course and navigating a 15-cm tall obstacle positioned centrally, using their right leg as the leading limb across three trials. The individuals included had no factors that could interfere with gait, such as the use of assistive devices, diabetes, medication use, or the presence of lower limb musculoskeletal, neuromuscular, or cardiorespiratory diseases, as well as balance and vision disorders. The obstacle crossing parameters are presented in figure 1 from contribution 4: Impact of overweight on spatial-temporal gait parameters during obstacle crossing in young adults: a cross-sectional study (see page 196).

Relative reliability of gait and obstacle clearance parameters

During the approaching phase, every assessed gait parameter demonstrated substantial ($ICC > 0.60$ and ≤ 0.80) to almost perfect ($ICC > 0.80$ and ≤ 1.00) reliability, irrespective of the trial comparisons analyzed. For the crossing phase, metrics such as step length, duration, and velocity consistently showed substantial to almost perfect reliability across different trial comparisons. Notably, the reliability of step duration and double support time ranged from slight ($ICC > 0.00$ and ≤ 0.20) to moderate ($ICC > 0.40$ and ≤ 0.60) when the first trial was considered. However, these parameters attained substantial reliability when pooling the second and third trials. The relative reliability of obstacle clearance parameters varied from moderate

to almost perfect with the best results when pooling the second and third trials (except for trailing limb horizontal distance after the obstacle (best results found for T1-T3), showing consistency across different trial comparisons. Relative reliability is illustrated in figure 1 from contribution 3: Reliability of Obstacle-Crossing Parameters during Overground Walking in Young Adults (see page 155).

Absolute reliability of gait and obstacle clearance parameters

Table 2 from contribution 3: Reliability of Obstacle-Crossing Parameters during Overground Walking in Young Adults (see page 156) details the absolute reliability of both gait and obstacle clearance parameters, assessed through minimal detectable change (MDC) and the standard error of measurement (SEM). Except for stride width across all trial comparisons and double support time when analyzing the first and second trials together, all gait parameters during the approach phase exhibited low SEM% and MDC% values ($\text{SEM}\% \leq 10\%$, $\text{MDC}\% \leq 20\%$). In the crossing phase, the SEM% and MDC% for step width and double support time were notably higher, with the exception of the comparison between the second and third trials where the MDC for double support time fell within an acceptable range ($\text{MDC}\% \leq 40\%$). Conversely, all remaining gait parameters across both phases showed low to acceptable levels of SEM% and MDC%, regardless of the trial comparisons made. When considering obstacle clearance parameters, they generally demonstrated less favorable absolute reliability in comparison to the gait parameters. High SEM% values were observed across all comparisons for leading and trailing foot clearances. Specifically, the MDC% and SEM% for leading toe clearance were high across all comparisons, with first to second and first to third trial comparisons of trailing toe clearance also showing high values. The SEM% and MDC% for the horizontal distances before and after the obstacle for both leading and trailing feet were generally low or acceptable, regardless of the trial set considered. However, leading limb's horizontal distance after the obstacle demonstrated high SEM% and MDC%, except in the comparison between the first and second trials.

Number of trials to ensure reliable measurement

During the approaching phase, enhanced reliability metrics—higher ICC and lower SEM% and MDC%—were notably observed when combining data from the second and third

trials, across all gait parameters. This trend persisted during the crossing, with the exception of step duration's with greater ICC values when the first and third trials were pooled. In addition, the findings of this study suggest a higher consistency in gait behavior during the approach phase than during the crossing phase, which included both gait and obstacle clearance measurements. Importantly, pooling the second and third trials consistently yielded the most reliable results across nearly all parameters and phases. This pattern echoes findings from a prior study on flat ground walking (10-m walking test) in healthy participants, where gait speed, stride length, and double support time displayed excellent relative reliability ($ICC > 0.80$) and solid absolute reliability ($SEM\% < 10$, $MDC\% < 20$) [139]. Conversely, during the crossing phase, parameters like step width and double support time exhibited only slight to moderate relative reliability, and notably lower absolute reliability, particularly when including the first trial. The disparity in reliability between phases could be attributed to the unique demands of the crossing step, including heightened neuromuscular [86] and cognitive [82] challenges, alongside the complexities of maintaining medial-lateral dynamic balance.

Moreover, while obstacle clearance metrics overall showed lesser reliability compared to gait parameters, pooling the second and third trials improved outcomes, hinting at a possible learning or warming-up effect post-initial trial. Nonetheless, the reliability of certain obstacle clearance metrics remained suboptimal, even excluding the first trial's data. This indicates a potential need for additional trials to achieve consistent behavior in obstacle clearance, unlike for spatial-temporal gait parameters. Comparative studies, such as one involving stroke survivors crossing a 4-cm high obstacle [88], reveal differing strategies and reliability patterns, possibly due to task-specific difficulties and a more cautious approach by participants with stroke to ensure consistent obstacle clearance and minimize contact risks. The critical nature of obstacle clearance, particularly toe clearance, in preventing trips and falls is well-documented [97,140], emphasizing the importance of accurate and reliable measurement of these parameters in identifying fall risks during obstacle crossing tasks [141].

Reliability of gait and obstacle clearance parameters in normal-weight and overweight groups

It is worth noting that the initial reliability analysis of gait and obstacle clearance parameters did not consider participants' anthropometric characteristics, such as BMI, despite its known impact on obstacle-crossing performance. Therefore, we further conducted a separate

reliability analysis by categorizing participants based on their weight status: normal weight (n = 28) and overweight (n = 15).

Results first showed that, for each group, spatial-temporal gait parameters during both the approach and crossing phases and obstacle clearance parameters were reliable when pooling the values of the three trials (with the exception of step double support time during crossing phase for the normal weight group). Additionally, the results indicated that the mean of the second and third trials provided the highest relative and absolute reliabilities, except for obstacle clearance parameters in the overweight group where the best results were found when pooling the first and second or the first and third trials.

Figure 12 illustrates the relative reliability of gait and obstacle clearance parameters across all participants, as well as within the normal weight and overweight groups.

Relative reliability:
 slight (0.00 < ICC <= 0.20) fair (0.20 < ICC <= 0.40) moderate (0.40 < ICC <= 0.60)
 substantial (0.60 < ICC <= 0.80) almost perfect (ICC > 0.80)

	18.5 <= BMI < 30 kg/m ²				18.5 <= BMI < 25 kg/m ²				25 <= BMI < 30 kg/m ²				
	T1-T2	T1-T3	T2-T3	T1-T2-T3	T1-T2	T1-T3	T2-T3	T1-T2-T3	T1-T2	T1-T3	T2-T3	T1-T2-T3	
Approaching phase	Stride width (cm)	0.741	0.739	0.764	0.748	0.726	0.745	0.74	0.737	0.745	0.69	0.796	0.743
	Stride velocity (cm/s)	0.825	0.819	0.9	0.846	0.812	0.808	0.853	0.821	0.846	0.839	0.948	0.881
	Stride length (cm)	0.745	0.763	0.859	0.789	0.669	0.739	0.863	0.752	0.846	0.778	0.825	0.817
	Stride duration (s)	0.868	0.84	0.874	0.861	0.873	0.821	0.847	0.847	0.866	0.911	0.939	0.905
	Stride double support time (s)	0.764	0.774	0.814	0.784	0.781	0.829	0.794	0.8	0.721	0.642	0.848	0.742
Crossing phase	Step width (cm)	0.349	0.317	0.709	0.466	0.277	0.305	0.672	0.414	0.472	0.346	0.763	0.555
	Step velocity (cm/s)	0.719	0.771	0.816	0.767	0.612	0.725	0.718	0.681	0.858	0.83	0.93	0.874
	Step length (cm)	0.835	0.811	0.869	0.839	0.804	0.805	0.846	0.818	0.917	0.82	0.914	0.883
	Step duration (s)	0.6	0.778	0.763	0.711	0.398	0.656	0.651	0.558	0.868	0.921	0.879	0.89
	Step double support time (s)	0.188	0.443	0.648	0.416	0	0.374	0.624	0.31	0.707	0.575	0.734	0.663
Obstacle clearance	Vertical distance: toe clearance – trailing limb (cm)	0.673	0.576	0.728	0.657	0.626	0.473	0.699	0.596	0.852	0.876	0.799	0.84
	Vertical distance: toe clearance – leading limb (cm)	0.841	0.78	0.886	0.836	0.798	0.686	0.912	0.802	0.925	0.933	0.847	0.901
	Horizontal distance: obstacle foot – trailing limb (cm)	0.722	0.713	0.634	0.689	0.67	0.621	0.677	0.654	0.725	0.729	0.518	0.656
	Horizontal distance: obstacle foot – leading limb (cm)	0.712	0.605	0.696	0.669	0.629	0.516	0.6	0.579	0.842	0.74	0.837	0.803
	Horizontal distance: foot obstacle – trailing limb (cm)	0.744	0.699	0.804	0.746	0.634	0.659	0.787	0.693	0.921	0.785	0.844	0.852
	Horizontal distance: foot obstacle – leading limb (cm)	0.511	0.506	0.688	0.558	0.36	0.39	0.63	0.438	0.803	0.694	0.702	0.734

Figure 12. Mean ICC(2.1) for the means of trial 1–2, 1–3, 2–3 and 1–2–3 calculated for each obstacle crossing parameter in all participants, normal weight and overweight groups

Taken together, our findings demonstrate the reliability of a ten-infrared camera system for assessing spatial-temporal gait parameters in obstacle crossing tasks. However, it's noteworthy that the reliability of gait parameters during the crossing phase and obstacle clearance metrics fell short compared to those observed during the approach phase, particularly when including data from the first trial. This pattern implies a potential learning or warming-up effect among young male adult participants after their initial trial. Future investigations could further explore the reliability of these parameters through additional trials or incorporate several practice trials ahead of the experimental sessions. Such approaches would help identify the optimal number of trials necessary to achieve high relative and absolute reliabilities for these parameters in similar populations. Subsequent analyses utilized the same dataset but divided participants according to their BMI status, aiming to elucidate differences in obstacle crossing performance between young adults of normal weight and those overweight.

Our findings showed that most gait and obstacle clearance parameters during all phases are reliable using the mean of the three trials. However, both relative and absolute reliability were enhanced when pooling the second and third trials only. This suggests that a practice trial could be performed before the experimental trials in future studies to enhance the reliability of all obstacle crossing parameters. Finally, the lower reliability found in gait parameters during the crossing phase, as well as obstacle clearance parameters compared to the approaching phase, could be due to the more unusual nature of the crossing step compared to the steps during the approaching phase (i.e., level ground walking).

8.1.3. Overweight has a minimal influence on obstacle crossing during walking among young adults

Following the analysis of reliability regarding gait and obstacle clearance parameters, and according to the lack of knowledge identified during the two reviews, using the same dataset, the obstacle crossing performance of young adults normal-weight and overweight was compared. As above mentioned, to date and to the best of our knowledge, no study specifically investigated the influence of an overweight BMI during obstacle crossing, and no study investigated the influence of overweight through obstacle clearance parameters in adult participants. The characteristics of the participants of our study and in previous adult studies [63,68,117] are presented in table 1.

Table 1. Population characteristics of previous studies and in our study

Author	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male) (n)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ²
Silva et al., 2018	2: Non-OB OB	Non-OB: 27 OB: 40	Non-OB: F: 27 OB: F: 40	Non-OB: 58.2 (4.8) OB: 57.1 (4.7)	Non-OB: 1.558 (0.052) OB: 1.563 (0.045)	Non-OB: 58.4 (7.1) OB: 73.1 (7.3)	Non-OB: 24.0 (2.0) OB: 29.9 (2.5)
Gill. 2019	4: Normal BMI OW/OBI OBII OBIII	Normal BMI: 13 OW/OBI: 18 OBII: 16 OBIII: 20	Normal BMI: F: 13 OW/OBI: F: 18 OBII: F: 16 OBIII: F: 20	Normal BMI: 33.2 (7.04) OW/OBI: 36.16 (12.76) OBII: 41.17 (5.89) OBIII: 42.72 (11.43)	Normal BMI: NR OW/OBI: NR OBII: NR OBIII: NR	Normal BMI: NR OW/OBI: NR OBII: NR OBIII: NR	Normal BMI: 22.56 (1.61) OW/OBI: 29.36 (3.19) OBII: 37.78 (1.42) OBIII: 44.31 (4.24)
Desrochers et al., 2021	2: Non-OB OB	Non-OB: 20 OB: 14	Non-OB: F: 14, M: 6 OB: F: 12, M: 2	Non-OB: 45.55 (8.77) OB: 50.36 (10.97)	Non-OB: 1.7015 (0.08) OB: 1.6883 (0.0869)	Non-OB: 69.36 (12.17) OB: 120.58 (20.13)	Non-OB: 23.77 (2.53) OB: 40.95 (5.46)
Chardon et al. (submitted)	2: Normal BMI OW	Normal BMI: 28 OW: 15	Normal BMI: M: 28 OW: M: 15	Normal BMI: 28.3 (6.12) OW: 30.3 (5.39)	Normal BMI: 1.76 (0.0666) OW: 1.78 (0.061)	Normal BMI: 70.8 (6.78) OW: 86.5 (6.15)	Normal BMI: 22.8 (1.72) OW: 27.4 (1.41)

Note: BMI: Body mass index, OBI: Class I obesity: $30 \text{ kg/m}^2 \leq \text{BMI} < 35 \text{ kg/m}^2$; OBII: Class II obesity: $35 \text{ kg/m}^2 \leq \text{BMI} < 40 \text{ kg/m}^2$; OBIII: Class III obesity: $\text{BMI} > 40 \text{ kg/m}^2$, OW: Overweight: $25 \text{ kg/m}^2 \leq \text{BMI} < 30 \text{ kg/m}^2$. For Silva and colleagues OB levels were determined using the cut-off value of 27 kg/m^2 : Brochu et al., 2008. "Contribution of the Lean Body Mass to Insulin Resistance in Postmenopausal Women with Visceral Obesity: A Monet Study" [142], NR: not reported.

Our analysis revealed that overweight status influenced only two obstacle clearance parameters: the leading foot horizontal distance prior to the obstacle and the trailing foot horizontal distance after the obstacle. Spatial-temporal gait parameters during both the approaching and crossing phases, as well as toe clearance for both legs, showed no significant differences between the two study groups. Prior research has indicated that gait parameters during the crossing phase are adversely affected by obesity, with step crossing velocity notably decreased in obese individuals [63,68]. Gill. (2019) further found that this reduction in step velocity was even more pronounced among individuals with more severe obesity [63]. The study cohort in Gill. (2019) included a group of participants with BMI ranging from 25 to 35 kg/m^2 , thus covering both overweight and mildly obese individuals (overweight, Class I obesity), a $35 \leq \text{BMI} < 40$ group (Class II obesity), and a $40 \leq \text{BMI}$ group (Class III obesity)

[63]. It was observed that, relative to those with a normal BMI, individuals classified as overweight and Class I obese crossed obstacles 15.5% slower, yet moved faster than those in Class II ($35 \text{ kg/m}^2 \leq \text{BMI} < 40 \text{ kg/m}^2$, -13.5% vs overweight/Class I obesity group) and Class III ($40 \leq \text{BMI}$, -19.2% vs overweight/Class I obesity group) obesity categories, with no marked differences between the latter two groups. Our results could suggest that perhaps only individuals from Class I obesity (i.e., not overweight individuals) decreased their crossing step velocity in Gill. (2019) study [63]. This pattern indicates a direct influence of BMI levels in the reduction in crossing step velocity. Our findings imply that the observed decrease in step velocity within Gill. 2019's study may predominantly pertain to individuals classified under Class I obesity rather than those merely overweight.

A previous study indicated that obesity results in shorter leading leg step length and cadence, with a decrease in single limb support time and an increase in double limb support (as percent of the gait cycle) time and leading step width [68] during the avoidance phase. It was suggested these alterations in gait were due to compromised dynamic balance, leading obese individuals to widen their base of support for extended periods. To navigate the obstacle avoidance phase, reductions in both step length and velocity were observed. Notably, the avoidance phase saw a shift towards increased double limb support (as percent of the gait cycle time), implying that, despite a slower gait velocity, obese individuals completed the obstacle crossing quicker in terms of the gait cycle than their normal BMI counterparts. This suggests a deliberate strategy among obese individuals to minimize the time spent in dynamic balance while crossing the obstacle. The authors raised concerns that such a strategy could heighten the risk of tripping [68]. In contrast, our study found no significant differences in step length, step width, double-support time, or cadence between overweight and normal BMI groups, indicating that overweight individuals do not employ a notably different strategy from those of a normal BMI in terms of gait spatial-temporal parameters.

Nevertheless, differences between groups were observed in two specific obstacle clearance parameters. Overweight individuals positioned their leading limb at a greater distance before the obstacle and their trailing limb landed farther after crossing it. However, the vertical toe clearance was similar between the two BMI groups. Given that obstacle clearance parameters, especially vertical clearance, play a crucial role in determining the risk of tripping during an obstacle crossing task [108,109,143], it appears that young overweight adults have adopted a strategy that is both effective and safe for negotiating a 15-cm obstacle. Notably, there were no instances of obstacle contact reported for participants from either BMI group,

underscoring the safety of the horizontal obstacle distance strategy employed by overweight individuals compared to their normal BMI counterparts. This behavior might indicate a need for additional space by overweight individuals to preserve unchanged toe clearance. Regrettably, the absence of studies focusing on foot clearance during the avoidance phase for adults limits our ability to delineate the nuanced differences in strategy between overweight and obese individuals.

In summary, this investigation reveals that the impact of overweight on obstacle crossing is considerably less pronounced than that of obesity. There were no observable differences in gait spatial-temporal parameters across the approaching and crossing phases for overweight individuals. Furthermore, variations in obstacle clearance metrics did not appear to elevate tripping risk (i.e., vertical clearance) under the specific conditions of this study, which might be deemed optimal (e.g., crossing a 15-cm high obstacle at a self-selected pace in a controlled laboratory environment).

Our findings showed that overweight had only a slight impact on gait behavior while crossing a 15-cm high obstacle. Indeed, no changes in gait spatial-temporal parameters were observed between overweight individuals and normal weight individuals during both the approaching and crossing phases. Only two horizontal obstacle clearances were increased in overweight individuals compared to their normal weight peers. This suggests that a slight spatial strategy was adopted by overweight individuals, perhaps to keep vertical clearance unchanged compared to normal weight individuals. Therefore, in this specific context (i.e., the population studied and the obstacle crossing protocol performed), overweight individuals do not seem to have an increased risk of tripping on the obstacle. These findings led us to perform correlation analyses between anthropometric characteristics and the age of the subjects, aiming to shift from a dichotomous to a linear analysis of the potential impacts of these characteristics, particularly BMI.

8.1.4. Anthropometric parameters and age of individuals are correlated with spatial-temporal parameters of gait and obstacle clearances parameters while crossing an obstacle during walking

We examined the same gait and obstacle clearance parameters was continued, focusing on the same cohort of young Brazilian adults. Initially, Pearson correlation analysis was employed to explore potential links between anthropometric factors, age, and the performance in gait and obstacle clearance tasks. Advancing beyond preliminary correlations, multiple regression analysis was applied to delve into the linear relationships between anthropometric features, age, and specific gait parameters during obstacle crossing tasks.

The analyses of Pearson correlation and multiple regression produced similar results. In addition, a combination of age and anthropometric measurements provided a more comprehensive explanation for the variance in gait and obstacle clearance parameters than when these elements were evaluated as single factors. During the approaching phase, an increase in body height was positively correlated with longer stride length, stride duration, and double support time. This finding is consistent with prior research on flat-ground walking, as highlighted by Mikos and colleagues' [144]. By contrast, no significant associations were found between BMI and any of the gait parameters, a deviation from findings by Abbas and colleagues [145], who identified a negative correlation between BMI, stride length, and gait speed. The absence of associations between BMI and gait parameters in our study might be due to the smaller individuals' BMI range (normal weight and overweight only) included compared to Abbas and colleagues (2017) which included 3 distinct BMI group, with normal weight individuals, overweight individuals, and obese individuals [145].

Moreover, previous studies [68,146] reported that obese individuals exhibit an increased step width, further indicating variations in gait strategies across different BMI categories. The lack of correlation between BMI and spatial-temporal parameters observed in our study could be attributed to the smaller BMI ranges of our participants, compared to those in studies focusing on obese individuals [68,146] or combined overweight and obese populations [145].

Additionally, age was not a determinant for gait parameters within the approaching phase, diverging from literature evidencing age's impact on gait, where older adults are shown to walk slower and with shorter stride lengths [147,148]. This absence of correlation might also be due to the limited age range among our subjects. Our results align with the study by Barbieri and colleagues [149], which found no significant gait differences on the same spatial temporal

parameters between the 20-29 and 30-39 year old age groups during obstacle crossing in both the approaching and crossing phases, suggesting that proactive or conservative gait adaptations may not manifest until beyond the age of 40. Indeed, such conservative strategies were observed in more aged adults [150]. Older adults decreased their gait speed more during the approaching phase than in the crossing step, indicating a variation in adaptive strategies with aging [150].

During the crossing phase, a significant positive relationship was noted only between body height and step length, mirroring findings from the approaching phase. The lack of a correlation between BMI or body mass and various gait metrics, akin to observations in the approaching phase, may stem from the narrower BMI spectrum of our study's participants relative to those in previous research. Previous studies have documented that obese individuals exhibit decreased step velocity [63,68], along with a shorter step length and broader step width during the crossing phase [68] regardless of the height of the obstacle crossed (i.e., 4 cm, 8 cm, and 16 cm). Nonetheless, these findings are consistent with our earlier analysis that detected no significant variance in gait parameters between normal BMI and overweight participants during the crossing phase. Further, multiple regression analysis illuminated body height's positive influence on step length and duration, underscoring the lack of impact of body height on step velocity. Consequently, taller participants demonstrated increased step length without a corresponding change in step velocity, resulting in prolonged stride duration.

Regarding obstacle clearance parameters, our results showed that age, body height, body mass, and BMI all showed correlations with horizontal clearance metrics. Yet, none of these individual factors could account for the variability in toe clearance for either leg, aligning with the outcomes of our prior analysis. Body height and body mass correlated positively with the distance of the leading leg before the obstacle, whereas body mass and BMI correlated with the distance of the trailing leg after clearing the obstacle. This suggests that individuals who are heavier (within the normal-weight range), taller, or have a higher BMI may require additional horizontal space for safe obstacle negotiation, given that toe clearances did not correlate with body mass or height.

The multiple regression analysis further highlighted that a mix of age and body mass effectively explained the variance in horizontal clearance metrics. Intriguingly, oldest participants in our cohort shortened the horizontal distance before the obstacle and extended it afterwards. This indicates a strategy among adults up to approximately 40 years old to initiate the crossing phase closer to the obstacle and to land further away, a strategy that appears to mitigate tripping risks given its lack of association with toe clearances [80,90]. However, this

approach suggests a distinct foot trajectory, characterized by higher foot elevation early in the swing phase, possibly as a preemptive measure against balance impairments, preferring an earlier elevation over the obstacle for enhanced stability [151].

This analysis further elaborates on the findings from our initial comparison of normal-weight and overweight individuals, underscoring the lack of significant differences in gait spatial-temporal parameters between these two groups during both the approaching and crossing phases. Importantly, this in-depth investigation reveals that factors such as age, body height, and body mass influence gait dynamics and obstacle clearance across all phases of obstacle crossing. Nevertheless, akin to the outcomes from our comparative study, vertical clearance metrics for both legs did not correlate with anthropometric factors or age. Consequently, the extent to which these parameters might affect the risk of tripping is still uncertain, indicating an area ripe for future research to explore the complex interplay between body composition, age, and obstacle negotiation strategies.

Our findings indicated that both body height and body mass are correlated with spatial-temporal gait parameters and obstacle clearance metrics during obstacle crossing. Notably, body height was positively associated with stride length, stride duration, and double support time during the approaching phase. No significant associations were found between BMI and gait parameters, potentially due to the narrower BMI range of our participants. In the crossing phase, body height continued to show a positive relationship with step length. Additionally, age and body mass were significant predictors of horizontal clearance metrics, with heavier and taller individuals requiring more horizontal space for safe obstacle negotiation. These results suggest that a mix of age and anthropometric measurements provides a more comprehensive explanation for the variance in gait and obstacle clearance parameters, underscoring the importance of considering these factors in future studies. As in the comparative analysis, none of the anthropometric or age factors could explain the vertical clearance parameters, preventing any conclusions about the potential risk of tripping.

The main findings of the PhD thesis and suggestions for future studies are presented in Figure 13.

Literature Reviews:

Contribution 1:

Limited Research:

-Only a few studies have investigated the impact of obesity on obstacle crossing during walking.

Impact on Gait:

-Obesity does affect gait behavior while crossing an obstacle.

Clearance Parameters:

-Clearance parameters have not been investigated in an adult population.

Overweight Category:

-The overweight category was not specifically examined.

Contribution 2:

BMI Reporting:

-BMI was poorly reported in Brazilian adult studies on obstacle crossing.

Group Composition:

-In Brazilian studies, groups often included individuals from different weight categories.

Eligibility Criteria:

-BMI was not used as an eligibility criterion nor considered a confounding factor.

Existing Data:

-Data to specifically investigate the impact of overweight had already been collected.

Experimental studies

Contribution 3:

Reliability of obstacle crossing parameters:

-Gait and obstacle clearance parameters were reliable across three trials.

-Relative and absolute reliabilities improved when pooling the second and third trials for most parameters.

-Gait parameters during the crossing phase and clearance parameters were less reliable compared to those during the approaching phase.

Contribution 4:

Comparative analysis:

-Overweight minimally impacts gait behavior while crossing a 15-cm high obstacle, affecting only two horizontal clearance parameters.

-Overweight individuals do not seem to have an increased risk of tripping during this specific protocol.

Contribution 5:

Correlation analysis

-Age and anthropometric parameters were correlated with several obstacle crossing parameters.

-The variance in vertical clearance was not accounted for by age or anthropometric parameters.

Future studies:

Obstacle crossing protocols:

-Increase protocol challenges to mimic real-life scenarios with varying speed and obstacle height.

-Integrate cognitive and manual dual-tasks.

-Study the combined effects of overweight, obesity, and fatigue.

Population:

-Use BMI and other specific tools or techniques to better characterize the overweight and obese population.

-Investigate a larger sample, including older adults, female participants, and those with comorbidities commonly associated with overweight and obesity (such as knee and hip osteoarthritis).

Approaching phase to predict clearance parameters

-Investigate whether gait spatial-temporal outcomes during the approach phase can predict obstacle clearance parameters.

Figure 13. Summary of the findings of the PhD thesis and perspectives.

8.2 Clinical implications of the PhD thesis

This PhD thesis emphasizes the significance of obstacle crossing, a routine yet potentially hazardous daily activity. As an example, older adults are at a higher risk of falls due to tripping when crossing an obstacle [87]. Given the compounded risk factors associated with elevated BMI, such as functional limitations [70,71] and increased fall risk during daily activities [72], exploring the effects of overweight and obesity on obstacle crossing was deemed crucial. Utilizing the insights gained from our comprehensive reviews, our focus was directed towards analyzing overweight impacts on obstacle crossing behaviors among young Brazilian adults. An initial assessment of gait and obstacle clearance parameters was conducted using a 10 infra-red camera system across an 8.5-meter pathway featuring a 15-cm obstacle placed in the middle of the pathway. Findings indicated that the approaching phase exhibited the highest reliability, suggesting the necessity for future obstacle crossing studies to include a minimum of three trials to ensure robust reliability across parameters. Moreover, our analysis highlighted a distinctive strategy in horizontal foot placement among overweight individuals, contrasting with their normal-BMI counterparts. This variance, however, did not extend to vertical clearance, prompting further investigation into overweight's specific impacts. Interestingly, our findings suggest that the influence of overweight on gait behavior during obstacle crossing is notably less severe than that of obesity, proposing that modest reductions in BMI could significantly enhance functional mobility. This notion is supported by Gill's 2019 study, which observed a more pronounced decrease in crossing speed among individuals with higher obesity levels [63]. Therefore, the findings suggest that even any reductions in BMI can significantly enhance functional mobility, particularly in obstacle crossing activities. Hence, integrating weight loss programs that aim first to lower BMI from obese to overweight status may yield immediate and tangible improvements in mobility and safety for patients during daily living. This aligns with the principles of self-determination theory, highlighting the importance of setting clear and attainable goals to boost intrinsic motivation and adherence to weight management programs [152]. However, it is imperative that the primary objective of these programs remains the reduction of BMI to a normal-weight category, ensuring optimal long-term health benefits and substantial improvements in functional mobility. Additionally, a better understanding of the impact of overweight on different obstacle crossing task as well as a better categorization of overweight (see details in the following parts) could be clinically relevant to identify specific profiles at risk of falling during these specific tasks which could reduce the

amount of injuries during daily living and enhancing mobility among the different BMI populations.

8.3. Limitations and perspectives

8.3.1. Limitations

Several limitations can be identified in this PhD thesis. Firstly, the uniform obstacle crossing protocol, which involved a 15-cm high obstacle on an 8.5-meter pathway without dual-tasks, may not have been challenging enough to reveal differences between normal-BMI and overweight individuals. Secondly, relying solely on BMI to assess overweight can lead to misclassification, as it does not differentiate between lean and fat mass. Thirdly, focusing exclusively on Brazilian male adults aged 20 to 40 limits the generalizability of the findings, excluding potential sex differences and older adults. Lastly, this PhD thesis did not investigate muscular and kinetic factors, which are essential for a comprehensive understanding of gait and obstacle clearance dynamics, and obstacle contacts were poorly studied in previous research.

Obstacle crossing protocol

The first limit of this thesis was the uniformity in the obstacle crossing task employed. Participants walked across an 8.5-meter pathway in a laboratory setting, encountering a 15-cm high obstacle positioned at the midpoint, without engaging in any additional cognitive or physical dual-tasks. This setup likely represented an optimal condition for participants. Current clinical practices lack a standardized obstacle crossing test, in contrast to well-established flat-ground walking assessments such as the 10-meter walk test [153] or the 6-minute walk test (6MWT) [154]. The lack of standardized obstacle crossing protocols was also observed in our previous review investigating the effect of experimentally-induced fatigue on obstacle crossing performance [104].

Consequently, designing an obstacle crossing protocol that genuinely reflects the varied challenges encountered by different population segments is intricate. Our methodology involved a retrospective analysis of data from 3 Brazilian studies [99,100,149], originally not focused on examining BMI's influence on obstacle crossing performance. The selected obstacle height of 15 cm is indicative of common curb heights in Brazil [155], implying that the study population might regularly manage similar tasks in their daily routines. Hence, the task of

crossing a 15-cm high obstacle at a self-determined pace may not be sufficiently challenging to distinguish gait behavior variances between overweight and normal-weight individuals distinctly and might not represent the variety of obstacles encountered in daily living. Additionally, executing ecological (real-world) studies on obstacle crossing is rendered challenging by the necessity for advanced gait analysis equipment, such as motion capture systems and gait analysis carpets, to accurately measure kinematic, kinetic, muscular, and obstacle clearance parameters.

BMI

A second limitation noted in our analysis, is the reliance solely on BMI for assessing overweight. While BMI is notably straightforward to calculate, necessitating minimal equipment such as a weighing scale, and requires little expertise, its application is widespread in research for its association with body fat. However, it does not directly quantify body composition [156]. Due to its inability to differentiate between lean and fat mass, there is a potential for participants' weight status to be inaccurately classified. For instance, muscular athletes may present a high BMI reflective of significant lean body mass, whereas individuals with considerable body fat might fall within the “*normal-weight*” category if their lean mass is relatively low [157]. Therefore, BMI alone should not be regarded as a definitive diagnostic tool for identifying overweight. To enhance participant categorization accuracy, future investigations are encouraged to integrate BMI with additional methods for assessing body composition, thereby reducing the likelihood of misclassification. Suggested methods include bioimpedance, quantitative magnetic resonance [158], skinfold thickness [159], and the measurement of waist circumference and waist-to-hip ratio [160]. However, it is worth noting that these methods require rigorous training to have precise measurements or require costly specific tools. As an example, magnetic resonance which is the gold standard to assess both adipose tissue, skeletal muscle and their distribution [161,162] is costly and requires a long acquisition time for multi slice imaging [163]. As an alternative, a single abdominal slice has been often used in clinical settings [164,165], however this technique is not sensitive to assess body fat distribution (i.e., morphological differences) [166]. A recent study showed that using three single slices (T6-T7, L4-L5, and at mid-thigh) was accurate in assessing the body composition of overweight or obese people. The authors stated that this technique requires 20

minutes to be performed [167]. Combining this technique with BMI could be of interest for future studies to have a better categorization of individuals.

Population studied

Our work focused on one population, Brazilian male adults aged between 20 and 40 years old, encompassing two BMI-based weight categories: normal-BMI and overweight individuals. It is important to recall that this decision was informed by the findings from the two preliminary reviews of this thesis work. Specifically, our first review identified a gap in the literature, as no study had previously examined the gait behavior during obstacle crossing between normal-BMI and overweight individuals. Moreover, our second review, which concentrated on Brazilian studies of obstacle crossing, revealed that research groups typically included individuals from diverse weight categories, predominantly normal-BMI and overweight individuals. Although this approach enriched our understanding of the impact of a higher BMI on obstacle crossing, it constrained direct comparisons with existing studies. Earlier research on adult populations either exclusively involved women [63,117] or included both women and men without exploring potential sex differences [68]. Notably, previous studies have reported that males and females display differing gait behaviors on flat ground [168] and during inclined walking [169]. Therefore, the potential for sex-specific differences in obstacle crossing behavior warrants further investigation. Additionally, to our best knowledge, no studies have investigated an overweight or obese older adult demographic, a group notably at a higher risk for falls [72,170]. Consequently, the findings from our thesis cannot be extended to the entire spectrum of overweight and obese individuals, for both male and female individuals. It is also important to note that the participants were not in a state of experimentally-induced fatigue, a factor known to disrupt walking patterns during obstacle crossing [104], and lead to more frequent trips during crossing [171,172]. Since daily life activities can increase individuals' fatigue levels [173] (i.e., muscle fatigue is defined as the inability to maintain the required or expected force or power output [174,175]), and since overweight and obese individuals are more prone to fatigue [176,177], incorporating this element in studies with this particular population could be insightful for better describing the challenges overweight and obese individuals may encounter in real-life situations.

Gait and obstacle clearance parameters investigated during obstacle crossing protocols

In studies focusing on adult participants [63,68,117], the examination was largely confined to gait spatial-temporal parameters. Notably, no prior research that delved into obstacle clearance parameters in this population was found [63,68,117]. The only study that compared clearance parameters during an obstacle crossing task between normal weight and overweight/obese individuals involved only children aged between 4 and 13 years old [132]. Furthermore, adult studies have generally overlooked muscular and kinetic factors [63,68,117]. The inclusion of these additional parameters, namely ground forces reactions and muscular activity, could significantly enrich our understanding of the variations observed in spatial-temporal and obstacle clearance metrics. For instance, previous studies on children showed that obese children require more time to elevate their knees above obstacles [63,68,117] than normal weight children, a phenomenon attributed to the increased leg weight in this group [178]. Nonetheless, without direct measurements of muscle activation, these conclusions remain conjectural.

Another overlooked aspect in previous research is the documentation of obstacle contact during the experiments. We argue that such data is crucial in obstacle crossing studies, especially given the potential for falls resulting from tripping over obstacles [87]. This is also particularly relevant for populations at a higher fall risk, such as obese individuals [72], suggesting that reports on obstacle crossing performance should systematically include success rates or the incidence of obstacle contacts. A systematic review focusing on older adults found that obstacle contact data were included in 10 out of 15 studies (approximately 67%) [97]. Similarly, in our review that investigated the impact of induced fatigue on obstacle crossing, only 2 out of 9 studies (22%) reported on obstacle contacts [104] (The full article can be found in Annex 2). It is worth noting that obstacle contacts were not reported in a recent systematic review on Parkinson Disease individuals [98].

8.3.2. Research perspectives

Given the results and limitations described in this PhD thesis, several research perspectives can be drawn for future studies.

Regarding the results and limitations presented in this PhD thesis, the following research perspectives are proposed to guide future studies. These include diversifying population groups

to include various ages and BMI categories, exploring the interaction between BMI and health conditions, examining the impact of daily living conditions like fatigue, and investigating the influence of environmental factors such as surface types, lighting, and temperature on obstacle crossing performance. Additionally, future research should enhance experimental protocols by integrating dual-tasking to better simulate real-life scenarios. Another promising direction is to develop predictive models that combine anthropometric factors with gait parameters during the approaching phase to forecast obstacle clearance parameters.

Population studied

Future studies investigating diverse age groups will be essential, as previous studies reported age-related variances in gait behavior during obstacle crossing, affecting both gait kinematics [149,179] and cognitive functions [179]. The interaction between aging, overweight, or obesity could significantly influence obstacle navigation due to the increased demand on muscular, cognitive, and sensory resources compared to unobstructed walking [82,83]. Given the deleterious effects of both aging and increased BMI on these resources, such as sarcopenia for older adults [180], reduced normalized muscle strength in obese individuals [181], reduced cognitive functions (see for ageing [182] and BMI [179,183], and impairments in proprioception (see for ageing [184], and BMI [185]), addressing this intersection is critical, especially as the prevalence of overweight, obesity, and older adults is expected to rise [186]. Our review of Brazilian obstacle crossing studies noted the inclusion of diverse BMI categories within both healthy and pathological groups, yet the interplay between BMI and health conditions remained unexplored. Given the associations between obesity and various pathologies that affect gait, such as multiple sclerosis [187], Alzheimer's Disease [188], and knee osteoarthritis [189], understanding the compounded impact on obstacle crossing is vital. Furthermore, obesity-related comorbidities like Type 2 diabetes or stroke [190], known to impair mobility and balance (see for diabetes [191,192], and stroke [27,193]), underscore the importance of examining these combined influences.

Aside from health status, daily living conditions such as fatigue can impact obstacle crossing. Fatigue, which diminishes muscle contractile force, cognitive resources allocation [194,195], and exacerbates imbalance risks [196]. Our previous review on the effect of experimentally-induced fatigue on obstacle crossing performance revealed task-dependent fatigue impacts [104]. Increased obstacle contacts post-fatigue [171,172] highlight the elevated

trip and fall risks during fatigue states, warranting further investigation into how fatigue and overweight/obesity collectively affect gait stability and control.

Experimental conditions

Future research should aim to diversify and enhance the complexity of obstacle crossing protocols to better understand the multifaceted nature of obstacle crossing, especially in relation to weight categories.

An immediate avenue for expansion involves the integration of dual-tasking into obstacle crossing protocols. Given the cognitive, sensory, and muscular demands highlighted during obstacle crossing, adding cognitive or physical tasks could simulate real-life scenarios more accurately, where individuals often multitask. This approach would allow researchers to explore how attentional resources and cognitive load affect the performance of individuals across different BMI categories, providing insights into potential risks associated with divided attention during obstacle negotiation. An example of dual task that could mimic real-life scenarios is the use of a mobile phone while walking. A previous study found that a concurrent phone texting during obstacle crossing impairs balance control in the frontal plane in healthy young adults [105].

Moreover, adopting more challenging obstacle crossing protocols can offer a deeper understanding of the capacities and limitations of participants with varying BMI. This includes altering the speed at which participants approach the obstacle, which could illuminate how body mass influences the ability to adjust gait dynamically in response to changing environmental demands [107]. Furthermore, prompting participants to alternate between fast-paced and slow-paced approaches to the obstacle may reveal how speed and urgency affect the risk of tripping or falling, especially in overweight and obese individuals. Additionally, varying the height of obstacles within the same protocol could shed light on the physical limitations and adaptability of individuals, particularly those who are overweight or obese. As an example, a recent study showed that obstacle crossing success rates declines as obstacle height increases in obese individuals [197]. Such modifications could reveal the extent to which BMI impacts the negotiation of obstacles that differ from everyday encounters, like higher curbs or unexpected barriers.

Regarding environmental conditions, surface types [198], lighting [199], and temperature [200], also influence walking behavior. For example, children adapt their crossing

strategies under different lighting conditions [74], suggesting the significant influence of environmental factors on gait behavior. While testing these variables in real-world conditions poses challenges due to the specialized equipment needed for comprehensive gait analysis, exploring horizontal and vertical obstacle clearances using simpler methods, such as a single camera system, might offer practical insights into overcoming these limitations.

Incorporating these elements—dual-tasking and dependent variables, more challenging obstacles or more realistic scenarios—into crossing protocols would not only align with the limitations and perspectives identified throughout this PhD thesis, but also address gaps in the literature regarding the interaction between overweight/obesity, aging, and the specific demands of obstacle crossing. Such an approach not only broadens the scope of obstacle crossing research, but also leverages technology to deepen our understanding of the complex interplay between body composition, physical environment, and movement strategies. Ultimately, this direction could lead to innovative, evidence-based solutions tailored to enhance the safety and mobility of individuals across the spectrum of BMI.

Another promising research perspective that emerges from this PhD thesis involves combining anthropometric factors with gait spatial-temporal parameters during the approaching phase to predict obstacle clearance parameters. Given the established reliability of spatial-temporal measurements and their correlation with body dimension, there is an interesting opportunity to develop predictive models that integrate these variables. Such models could offer nuanced insights into how individual differences in body height, body mass, and BMI interact with gait dynamics to influence obstacle crossing strategies. This approach not only bridges the gap identified between anthropometric characteristics and obstacle clearance outcomes but also paves the way for personalized assessments and interventions. By understanding the predictive relationship between these factors, researchers and clinicians could tailor obstacle crossing fall prevention strategies to accommodate the specific needs and risks associated with varying body compositions, enhancing mobility and safety. However, this would require a larger dataset than the one that was used, with potential other confounding factors such as sex, comorbidities (including medication), smoking and eating habits etc.

In addition, exploring beyond horizontal and vertical clearances to examine the whole foot's trajectory during obstacle crossing could be a relevant avenue for future research. Our findings indicate differences in horizontal clearances without corresponding changes in vertical clearances, suggesting a distinct foot trajectory, particularly in the initial phase of the lift-off. In older adults, a closer horizontal foot placement before the crossing phase resulted in a greater

vertical raise of the limb after toe-off and could compromised dynamic balance [201]. This would also allow for pinpointing critical foot crossings in relation to the obstacle (i.e., moments when the distance between the foot and the obstacle is smallest, increasing the risk of contact and, therefore, tripping) during its trajectory.

9. Conclusion

This PhD thesis aimed to evaluate the effect of overweight on obstacle crossing during walking. Despite the well-documented adverse effects of overweight and obesity on cardiovascular health, their impact on functional mobility, such as balance and gait disturbances, has been less explored, especially in the context of obstacle crossing.

First two systematic reviews were conducted, one focused on the available research investigating the influence of overweight and obesity on obstacle crossing during walking [202], the second aimed to characterize the BMI of Brazilian participants included in published studies.

Our initial systematic review highlighted a critical gap: no existing studies had compared the gait behavior of normal-BMI and overweight individuals during obstacle crossing. Furthermore, while overweight and obesity was found to alter kinematic and kinetic walking parameters in adults facing a vertical obstacle, the research specifically focusing on obstacle clearance parameters remained scarce. Notably, critical parameters for evaluating the risk of tripping, such as horizontal and vertical foot clearances, had not been thoroughly investigated in adults categorized as overweight or obese.

In addressing our main objective, a detailed analysis was conducted, which revealed that spatial-temporal and obstacle clearance parameters are reliable across trials, demonstrating the consistency of our measurement methods. Interestingly, our analysis indicated that overweight individuals showed increased horizontal clearances both before and after the obstacle when compared to their normal-BMI peers. This suggests a distinct strategy possibly aimed at navigating obstacles safely. However, no significant differences were found in kinematic parameters and vertical clearances between the two groups. Furthermore, our study identified correlations between age, body height, body mass, and various spatial-temporal and horizontal clearance parameters, yet these factors did not influence vertical clearances.

Based on these findings, several research perspectives emerge for future studies. The first relates the pressing need to investigate obstacle crossing under more diverse and challenging conditions that closely mimic everyday scenarios. This includes examining the effects of different obstacle heights and imposing varied walking speeds to uncover how these factors interact with weight status in obstacle negotiation. Additionally, the integration of dual-task protocols, such as manual and cognitive tasks, could offer valuable insights into the cognitive and physical demands of obstacle crossing and their interaction with overweight and

obesity. Expanding the participant pool to include a broader range of BMI categories, ages, and health statuses will also be crucial for generalizing findings and understanding the multifaceted impact of overweight and obesity on functional mobility.

This PhD thesis provides a foundational understanding of the minimal impact of overweight on obstacle crossing performance within specific experimental setups. However, it underscores the importance of further research into more dynamic and real-world applicable protocols to enhance our comprehension of mobility challenges and inform interventions aimed at improving safety and mobility for individuals across the BMI spectrum.

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11. Annexes

-Annex 1: Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N. The Effects of Overweight and Obesity on Obstacle Crossing During Walking: Protocol for a Systematic Review. *JMIR Res Protoc* 2022 May 20;11(5):e36234. doi: 10.2196/36234 [130].

-Annex 2: Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N. The effects of experimentally-induced fatigue on gait parameters during obstacle crossing: A systematic review. *Neurosci Biobehav Rev Pergamon*; 2022 Nov 1;142:104854. doi: 10.1016/J.NEUBIOREV.2022.104854 [104].

Protocol

The Effects of Overweight and Obesity on Obstacle Crossing During Walking: Protocol for a Systematic Review

Matthias Chardon^{1,2}, MSc; Fabio Augusto Barbieri², PhD; Tiago Penedo^{1,2}, MSc; Paulo Cezar Rocha Santos³, PhD; Nicolas Vuillerme^{1,4}, PhD

¹AGEIS, Université Grenoble Alpes, La Tronche, France

²Human Movement Research Laboratory, Department of Physical Education. School of Sciences, São Paulo State University, Bauru, Brazil

³Department of Computer Science and Applied Mathematics, Weizmann Institute of Science, Rehovot, Israel

⁴Institut Universitaire de France, Paris, France

Corresponding Author:

Nicolas Vuillerme, PhD

AGEIS

Université Grenoble Alpes

Faculty of Medicine

La Tronche, 38706

France

Phone: 33 476637104

Email: nicolas.vuillerme@univ-grenoble-alpes.fr

Abstract

Background: Overweight and obesity are significant global health concerns that involve deficits in gait and balance that affect daily activities. Although much is reported about the effect of overweight and obesity on gait during unobstructed walking, not much is known about how overweight and obesity could impact gait under more challenging conditions, such as environments with obstacles.

Objective: The aim of this study is to systematically review and synthesize the available data regarding the effects of overweight and obesity on obstacle crossing during walking.

Methods: This review will follow the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines. PubMed, Web of Science, Scopus, and SPORTDiscus will be systematically searched with no limitations on publication date. Only full-text English-language articles published in a peer-reviewed journal will be included. Included articles must have compared obstacle crossing during walking in individuals with overweight or obesity to individuals of normal body weight. A total of 2 independent reviewers will select the articles and extract the following 4 sets of data: (1) study characteristics, (2) sample description, (3) obstacle crossing task protocol, and (4) main results obtained. If a considerable number of homogeneous papers are included, a meta-analysis will be conducted. A preliminary search was conducted in November 2021.

Results: The results will include the article selection flowchart as well as tables and figures synthesizing the extracted data on the effects of overweight and obesity on obstacle crossing during walking. The preliminary search identified 73 original records, of which 5 articles met the inclusion criteria.

Conclusions: This review will present researchers and clinicians with an overview of published studies that have compared the performance of obstacle crossing for individuals with overweight and obesity to those of normal body weight. Gaining insight into the control strategies adopted by individuals with overweight and obesity is critical for safe and successful obstacle crossing in this population. We therefore believe that our findings could be useful for identifying people at risk of falls and developing and implementing fall prevention programs for individuals with overweight and obesity.

Trial Registration: PROSPERO CRD42021269949; <https://tinyurl.com/3yrwccu4>

International Registered Report Identifier (IRRID): DERR1-10.2196/36234

(*JMIR Res Protoc* 2022;11(5):e36234) doi: [10.2196/36234](https://doi.org/10.2196/36234)

KEYWORDS

obesity; obstacle crossing; gait; systematic review; overweight; weight; obstacle; walking; balance; fall; risk; prevention; mobility

Introduction

Overweight and obesity are defined as abnormal or excessive fat accumulation that presents a risk to health. According to the US Centers for Disease Control and Prevention, individuals with a BMI between 25 kg/m² and 29.9 kg/m² are considered overweight, and those with a BMI over 30 kg/m² are considered obese. Overweight and obesity have become a major public health issue, and the incidence of the condition is increasing at an alarming rate worldwide [1]. Recent data from the World Health Organization's Global Health Estimates report that the worldwide prevalence of obesity nearly tripled between 1975 and 2016 and that in 2016, 39% of the world's adult population was overweight and 13% was obese [2]. Overweight and obesity are associated with, among other things, impaired postural balance and gait limitations. Interestingly, biomechanical alterations imposed by the additional loading of the locomotor system have been analyzed and reported in recent reviews (eg, [3-5]). For instance, Molina - Garcia et al [4] recently reported strong evidence that suggests that gait patterns of children and adolescents with overweight and obesity are characterized by greater pelvis transversal plane motion, higher hip internal rotation and flexion, extension and abduction moments and power generation and absorption, greater knee abduction and adduction motion, and higher knee abduction and adduction moments and power generation and absorption compared with normal-weight counterparts. These biomechanical alterations observed in individuals with overweight and obesity during locomotor tasks further have been reported to significantly increase the risk of musculoskeletal disorders, especially in lumbar, hip, and knee regions (see [3,6] for reviews), the risk of injury while performing activities of daily living (ADL), functional limitations (eg, see [6-8] for recent reviews), and the risk of falls and multiple falls (eg, see [9] for a recent systematic review). We can first mention the systematic review and meta-analysis by Backholer et al [7] that demonstrated a graded increase in the risk of ADL limitations from normal weight (BMI 18.5 kg/m² to 24.9 kg/m²) to overweight (BMI 25 kg/m² to 29.9 kg/m²), obesity class I (BMI 30 kg/m² to 34.9 kg/m²), and obesity class II+ (BMI >35 kg/m²). Additionally, the systematic review and meta-analysis by Neri et al [9] showed that people with obesity over 60 years have a 16% increase in the risk of falls compared to older adults of normal weight.

At this point, however, although much is reported about the deleterious effect of overweight and obesity on gait during unobstructed walking (eg, see [10-16] for recent works published in 2021), not much is known about how overweight and obesity could impact gait under more challenging conditions, such as an environment with obstacles (eg, [12,17-20]). Interestingly, indeed, crossing an obstacle while walking is a challenging task, reflecting a higher risk of loss of balance, trips, and falls [21-26]. Actually, trips over an obstacle are one of the main causes (accounting for up to 53%) of falls during walking in healthy older adults [27]. It has been suggested that these observations could stem from the increased neuromuscular demand of obstacle crossing during walking in comparison to unobstructed walking [23,28,29]. Accordingly, considering the functional

limitations imposed by the additional loading of the locomotor system in individuals with overweight or obesity, it is of particular interest to evaluate whether and how overweight and obesity impair obstacle crossing during walking.

To the best of our knowledge, the available evidence on the effect of overweight and obesity on obstacle crossing during walking has not yet been systematically reviewed, and by identifying and synthesizing the current evidence on the topic, we can provide new insights on the potential influence of overweight and obesity on walking in an environment with obstacles. This work was therefore designed to address this issue. Our aim was to conduct a systematic review of published studies that have compared gait parameters related to the performance of the obstacle crossing task in individuals with overweight or obesity and those of normal body weight.

Methods

Guidelines and Registration

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) [30] statement and recommendations and Cochrane Handbook for Systematic Reviews guidelines [31] will be used for this systematic review to identify relevant studies. We will systematically review published studies that have described and compared obstacle crossing during walking in individuals with overweight or obesity and individuals of normal body weight. The protocol for this systematic review has recently been registered in PROSPERO (the International Prospective Register of Systematic Reviews; CRD42021269949).

Eligibility Criteria

Only full-text, peer-reviewed, scientific original articles published in English will be included in this review. Case reports, abstracts, editorials, letters to the editor, case studies, books, chapters, reviews, meta-analyses, and other grey literature materials (government reports, policy statements and conference proceedings, preprints, theses, and dissertations) will be not included. We will use the eligibility criteria below for study selection.

Population

Studies on individuals with overweight or obesity (defined as a BMI ≥ 25 kg/m²) may be included. Studies using animal models will be excluded.

Intervention

Studies using the following intervention were considered: obstacle crossing during walking.

Comparator

Studies where individuals with overweight or obesity (defined as BMI ≥ 25 kg/m²) and those of normal body weight (BMI 18 kg/m² to 24.9 kg/m²) were compared will be considered.

Outcomes

Studies including spatial-temporal, angular, kinetic, and muscle activation outcomes related to the performance of the obstacle crossing task will be considered.

Data Sources and Search Strategy

A total of 4 electronic databases, PubMed, Web of Science, Scopus, and SPORTDiscus, will be searched systematically from inception onwards to identify studies satisfying the search criteria. The search strategy includes a combination of the following keywords related to (1) the population (individuals with overweight or obesity) and (2) the intervention (obstacle crossing), using the Boolean operators “AND” and “OR” and, if applicable, Medical Subject Headings terms: “obes*” OR “overweight” OR “over - weight” OR “adipos*” OR “body mass index” OR “BMI”. The second category specifies the intervention task comprising a term related to obstacle crossing, such as the following: “obstacle crossing” or “obstacle negotiation” or “obstacle avoidance” or “obstructed walking”.

Study Selection

A total of 2 independent reviewers (MC and TP) will screen the titles, abstracts, and keywords of each article retrieved from the electronic database searches. Inclusion is based on the previously mentioned selection criteria. The same 2 independent reviewers (MC and TP) will screen the full-text articles for inclusion. A third reviewer (NV) will be consulted in cases of disagreement between the 2 reviewers.

Data Extraction

After completion of the screening process, the same 2 independent reviewers (MC and TP) will extract the following 4 categories of data from each included article: (1) study characteristics, (2) sample description, (3) obstacle crossing task protocol, and (4) main results. Means and standard deviations or medians associated with interquartile ranges or first and third quartiles will be extracted. In the case of missing or erroneous data, the study authors will be contacted for further information. Both independent reviewers will compare the data for consistency. Any disagreement between the 2 independent reviewers will be resolved by consensus or discussion with a third reviewer (NV).

Data Synthesis and Analysis

This systematic review is specifically designed to present an overview of the existing literature on the effect of overweight and obesity on obstacle crossing during walking. We will therefore systematically review published articles that have described and compared spatial-temporal, angular, kinetic, and muscle activation outcomes related to the performance of an obstacle crossing task for individuals with overweight or obesity and those of normal body weight. We will also report the magnitude of the potential differences (as percentages) between individuals with overweight or obesity and those of normal body weight. In the case of a considerable amount of nonheterogeneous studies that meet the eligibility criteria being included, we will verify the possibility of conducting a meta-analysis using specific packages in R (R Foundation for Statistical Computing). The risk of bias of the included studies will be assessed using the Cochrane Collaboration’s tool [32] and a specific tool created for a review with a similar scope [33]. Specifically, 2 independent reviewers (MC and TP) will examine the full texts regarding random sequence generation, allocation concealment, blinding of participants and personnel,

blinding of the outcome assessment, incomplete data, selective reporting, and other biases (ie, not covered by other criteria). Each criterion will be classified as low-risk (no bias or minimal effects on results), unclear risk (not specified or raises some doubt about the results), and high-risk (may alter the results) [32]. Considering the specific grid created by Galna et al [33], questions will be related to the internal validity, external validity, and reproducibility of the methods related to obstacle crossing. Each question on the quality assessment tool will be scored. A score of 1 will indicate that the study meets the assessment criterion, while a score of 0 will indicate that the assessment criterion is not met. A score of 0.5 will indicate a lack of information or a lack of clarity in the corresponding items. Any disagreement between the 2 reviewers will be resolved by consensus or discussion with a third reviewer (NV).

Ethical Considerations

As this review is limited to publicly available materials, it does not require ethical approval. Results will be shared with the scientific community and the general public.

Results

The search strategy described above was completed in November 2021 and led to 133 records; after removing duplicates, 73 records were identified. After screening titles and abstracts, 5 full texts were reviewed, and all of these articles were included in the review. Data extraction and synthesis are currently ongoing. In line with PRISMA guidelines [30], the number of citations reviewed at each stage of the systematic review will be summarized in a flow chart. The risk of bias of the included studies will be described [32]. Tables and figures summarizing the extracted data will be produced. The dissemination of study results to an international audience through publication in a peer-reviewed journal is expected at the end of 2022.

Discussion

We hypothesize that evidence will show how overweight and obesity negatively affect gait during obstacle crossing. Presumably, individuals with overweight and obesity, due to individual constraints imposed by the obesity on one’s gait, would have a higher risk of slips, trips, and falls during obstacle crossing. [27] Obstacle crossing represents an everyday life situation that has been shown to challenge balance and increase the risk of falls [21-26]. Obstacle crossing is therefore an important task to consider in individuals with overweight and obesity [34] and may be useful in identifying those at risk of falls, preventing falls, and reducing the risk of fall-related injuries. However, it is surprising that systematically analyzed data on the effects of overweight and obesity on obstacle crossing during walking are rather scarce. In fact, based on our initial screening process, only a limited number of published articles successfully met all of the eligibility criteria ($n=5$; [12,17-20]). A total of 2 articles focused on children [17,18], 2 on adults [12,20], and 1 on postmenopausal women [19]. The number of participants with overweight or obesity included in these 5 studies ranged from 12 [17,18] to 54 [20]. Of these studies, 4 [12,17,18,20] assessed the effects of 3 fixed obstacle

heights (low, medium, and high obstacles, measuring from 4 cm to 16 cm in height) on obstacle crossing; 1 study [19] used an obstacle height condition that was based on the length of the participants' lower limbs (30%). The lower-limb kinematics of participants with overweight or obesity and those with a normal BMI as they crossed over obstacles were reported in all studies [12,17-20]; 1 study further collected kinetic data that were time-synchronized with kinematic data [18]. A preliminary and very synthetic analysis tends to show that overweight and obesity impair gait patterns during obstacle crossing in children [17,18], adults [12,20], and postmenopausal women [19].

To the best of our knowledge, this will be the first systematic review to date identifying and synthesizing the available evidence on the effect of overweight and obesity on obstacle crossing during walking. The systematic review was registered in PROSPERO (CRD42021269949). This systematic review will follow the PRISMA statement and recommendations [30] and the Cochrane Handbook for Systematic Reviews guidelines [31] to develop high-quality research questions, capture relevant

studies, and critically appraise the relevant studies. A total of 2 independent reviewers will screen titles, abstracts, keywords, and full-text articles and rate the quality of these studies and the risk of bias. A synthesis will then be provided with the information presented in the main text, tables, and figures to summarize the characteristics and main findings of the included studies. On completion, the results of this systematic review will be presented at national and international conferences and submitted for publication in a peer-reviewed scientific journal.

We anticipate that the results of this systematic review will help researchers and health professionals increase the quality of care for people with overweight and obesity. We believe that gaining insight into the mechanisms and strategies adopted by individuals with overweight and obesity is critical for safe and successful obstacle crossing in this population. Along these lines, our findings could be useful for identifying individuals with overweight or obesity at risk of falls and developing and implementing tailored fall prevention programs for these individuals.

Acknowledgments

This work is part of the PhD thesis of the first author, MC (Université Grenoble Alpes, France and São Paulo State University, Bauru, Brazil). This work was supported by the French National Research Agency in the framework of the Investissements d'avenir program (grants ANR-10-AIRT-05 and ANR-15-IDEX-02), the Coordination for the Improvement of Higher Education Personnel Brazil (grant 001), and the Estate of Naomi K Shapiro (grant 721926). The sponsors had no involvement in the review and approval of the manuscript for publication. This work further forms part of a broader translational and interdisciplinary research program, GaitAlps (NV).

Data Availability

Data sharing is not applicable to this article as no data sets were generated or analyzed during the current study.

Authors' Contributions

MC, FAB, and NV devised the study scope and research questions and contributed to the study design. MC, FAB, PCRS, NV, and TP wrote and edited the manuscript. MC and TP will review the references and extract data. All authors approved the final manuscript.

Conflicts of Interest

None declared.

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Abbreviations

ADL: activities of daily living

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analyses

PROSPERO: International Prospective Register of Systematic Reviews

Edited by T Leung; submitted 06.01.22; peer-reviewed by C Villemazet, T Ndabu; comments to author 26.01.22; revised version received 01.02.22; accepted 28.02.22; published 20.05.22

Please cite as:

Chardon M, Barbieri FA, Penedo T, Santos PCR, Vuillerme N

The Effects of Overweight and Obesity on Obstacle Crossing During Walking: Protocol for a Systematic Review

JMIR Res Protoc 2022;11(5):e36234

URL: <https://www.researchprotocols.org/2022/5/e36234>

doi: [10.2196/36234](https://doi.org/10.2196/36234)

PMID:

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Review article

The effects of experimentally-induced fatigue on gait parameters during obstacle crossing: A systematic review

M. Chardon^{a,b,1}, F.A. Barbieri^{b,2}, T. Penedo^{a,b,3}, Paulo C.R. Santos^{c,4}, N. Vuillerme^{a,d,*,5}^a AGEIS, Université Grenoble Alpes, Grenoble, France^b Human Movement Research Laboratory (MOVI-LAB), Department of Physical Education, School of Sciences, São Paulo State University (UNESP), Bauru, Brazil^c Department of Computer Science and Applied Mathematics, Weizmann Institute of Science, Rehovot, Israel^d Institut Universitaire de France, Paris, France

ARTICLE INFO

Keywords:

Fatigue
Obstacle crossing
Gait
Biomechanics

ABSTRACT

Striking an obstacle while walking can be dangerous, reflecting the higher risks of losing one's balance, tripping and falling. Particular situations during which internal resources are limited, such as in a fatigued state, may impair performance when crossing obstacles, enhancing the risks of falls or accidents. Our goal was thus to review the effects of experimentally-induced fatigue (EIF) on gait parameters during obstacle crossing by healthy individuals. We systematically searched PubMed and Web of Science databases using 'fatigue', 'obstacle crossing' and their equivalent terms to extract data from studies investigating this domain. Nine studies were found. First, EIF-related effects on kinetics, EMG and obstacle contacts have been poorly studied. Second, consistent and inconsistent results were found in the kinematic outcomes after EIF. Consistent results included reductions in stride duration and increased step width. Inconsistent results included gait velocity (no-effect vs increased), leading and trailing-foot vertical clearance (reduced vs increased) and horizontal distance from foot to the obstacle before obstacle avoidance (no-effect vs increased). These findings should be interpreted cautiously, however, due to the heterogeneity of the obstacle crossing and EIF protocols.

1. Introduction

Striking an obstacle while walking can be dangerous, causing trips and falls (Pavol et al., 2001). Indeed, tripping over an obstacle is one of the main causes (up to 53%) of falls during walking (Pavol et al., 2001). The higher risk of falls is probably associated with the higher demands of obstructed walking than unobstructed walking (Patla and Rietdyk, 1993; Patla et al., 1991). This observation seems justified when considering the higher demands on muscle, cognitive and sensory resources during obstacle crossing versus unobstructed walking conditions. It is especially true in terms of neuromuscular (e.g., higher knee flexor activation) (MacLellan and McFadyen, 2013) and prefrontal cortex activity (Chen et al., 2017). The high demands of obstacle crossing are also accentuated by the need to efficiently integrate the

sensory information (e.g., optical flow and proprioception) (Billington et al., 2013) for adequately planning and adjusting those movements. Therefore, any activity that limits the availability of resources related to muscle, cognitive and sensory systems — like an experimentally-induced fatigue (EIF) protocol — might lead to gait changes during obstacle crossing. By systematically reviewing the literature, we gained an overview of how the internal perturbations induced by EIF could affect obstacle crossing tasks. To the best of our knowledge, this question has not been systematically examined before. It is probable that certain situations in which internal resources are limited or altered, due to fatigue, impair obstacle-crossing during walking performance tests in healthy individuals.

A state of fatigue could be conceptualised as the continuous interaction between a person's perceived fatigue and their performance

* Correspondence to: AGEIS, Université Grenoble Alpes, Faculty of Medicine, La Tronche 38706, France.

E-mail addresses: fabio.barbieri@unesp.br (F.A. Barbieri), nicolas.vuillerme@univ-grenoble-alpes.fr (N. Vuillerme).¹ ORCID: 0000-0002-9806-0639² ORCID: 0000-0002-3678-8456³ ORCID: 0000-0001-7541-4468⁴ ORCID: 0000-0001-7378-1897⁵ ORCID: 0000-0003-3773-393X

fatigue (Enoka and Duchateau, 2016), which is usually experimentally-induced by muscular physical activities. Muscle fatigue reflects reduced contractile force (Christie et al., 2011; Enoka and Duchateau, 2008) and a sub-optimal neural activation of the muscles (Gandevia et al., 1996). Muscle fatigue interferes with the capacity to continue working at a given exercise intensity following physical exercise (Booth and Thomason, 1991). Prolonged effort can also reduce a person's capacity to allocate cognitive resources to perform a task (Wang et al., 2015) and accentuate the risk of imbalance (Barbieri et al., 2013a). In this context, the combination of prolonged reduced strength, reduced cognitive resources and imbalance can interfere with gait while negotiating obstacles. Thus, the effects of muscle fatigue on obstacle crossing are somehow to be expected since this condition alters the capacity to generate muscle strength (Enoka and Duchateau, 2008) and interferes with muscle coordination by increasing the common drive to synergistic muscle pairs (Santos et al., 2020; Wang et al., 2015). Indeed, muscle fatigue induces changes during obstacle crossing, such as a shorter step duration (Barbieri et al., 2014, 2013b), and alters muscle activation (Enoka and Duchateau, 2008). While negotiating an obstacle, those fatigue-induced changes may lead to an increased likelihood of a foot striking the obstacle, leading to a trip or fall (Barbieri et al., 2014).

Considering that both obstacle crossing and fatigue affect gait stability and control, and that fatigued individuals may adapt their gait inadequately, increasing the risk of striking an obstacle during obstacle crossing, the questions this study sought to answer were whether and how individuals modified their gait when they needed to cross an obstacle after EIF. Performing a systematic review of the literature seemed timely since it would help to provide new insights in to the adaptive gait dynamics after EIF. Understanding the effects of EIF on gait parameters during obstacle crossing is also relevant for both fundamental and applied perspectives to determine underlying gait characteristics that differed between different states of fatigue, to identify individuals and situations at high risk of tripping and falls, to develop approaches to mitigate the deleterious effect of fatigue and to substantiate training focused on improving adaptive gait. Therefore, the present study systematically reviewed the effects of EIF on gait parameters during obstacle crossing tests on healthy individuals.

2. Methods

2.1. Protocol and registration

This systematic review's protocol has been registered with the International Prospective Register of Systematic Reviews (PROSPERO) (registration number: CRD 42020193135). The review follows the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page et al., 2021) (checklist available in [Supplementary Material](#)) and the Cochrane Handbook for Systematic Reviews guidelines (Higgins and Green, 2019).

2.2. Ethics and dissemination

As this review was limited to publicly available materials, it did not require ethical approval.

2.3. Data sources and search strategy

The search strategy and selection criteria were developed in line with the review questions and agreed upon by the team members. Two reviewers (MC and TP) independently performed a computerised systematic literature search, following the PRISMA statement (Page et al., 2021) and the Cochrane Handbook for Systematic Reviews guidelines (Higgins and Green, 2019), in PubMed and Web of Science from their dates of inception to January 2022. Note that these two electronic databases were recently used in a systematic review with a similar scope (Santos et al., 2019). The search strategy targeted articles containing

information relevant to EIF and gait during obstacle crossing and all subsets of these terms. An example search in PubMed is presented below. The full combination of Medical Subject Heading terms and keywords used for the search is available in the [Supplementary Material](#).

2.4. Eligibility and inclusion and exclusion criteria

A population, intervention, comparison, outcome and study designs tool (a PICOS tool) was used to select the eligibility, inclusion and exclusion criteria for the studies reviewed. Two independent reviewers (MC and TP) only included studies based on samples of healthy adults, excluding studies that selected participants with acute or overuse injuries or with neurological, musculoskeletal or systemic diseases (Population). They also considered studies that measured obstacle crossing tasks after an EIF protocol—muscular and exercise-induced, not resulting from a pathology or 'symptomatic fatigue' (Intervention). If a study examined obstacle crossing and other types of locomotion, only the data from obstacle crossing were considered. Also, we only included studies that compared obstacle crossing in fatigued and non-fatigued states (Comparison). We included studies that measured and reported kinematic, kinetic and electromyographic (EMG) parameters and obstacle contacts (errors), and the following outcomes were also extracted (Outcomes): gait spatial and temporal stride parameters (e.g., stride length and duration and obstacle clearances—horizontal and vertical feet-obstacle distances), kinetics (e.g., force outcomes such as momentum, work, power and ground reaction force) and muscle activation outcomes (e.g., amplitude, muscle onset, muscle activation duration, muscle synergy, mean frequency and power density). Randomised controlled trials, non-randomised controlled trials, and non-randomised, non-controlled trials (Study design) were included. Further study design inclusion criteria required original articles published in English in a peer-reviewed scientific journal. However, we excluded case reports, abstracts, editorials, letters to the editor, case studies, reviews, meta-analyses, theses, grey literature (annual, research, technical or project reports), working papers and government documents.

2.5. Study selection and eligibility

Two reviewers (MC and TP) independently selected the studies, screened the titles, abstracts and keywords identified via the search strategy and applied the eligibility criteria. After this initial selection, full-length texts were subjected to the same procedure. In cases of disagreement and if subsequent discussions between the two reviewers were inconclusive, a third reviewer was contacted (NV) to arbitrate the disagreement.

2.6. Quality assessment

Two reviewers (MC and TP) independently performed a qualitative analysis of the studies selected. Risk of bias was assessed using an analysis grid modified from the work from Galna and colleagues (Galna et al., 2009) to better match the outcomes of interest in the articles studied (Table 1). Additional questions regarding controlling for potential confounding factors, such as walking strength and speed, were included when comparing age groups. Questions of quality focused on the internal validity, external validity and reproducibility of the methods used. A scoring system was developed to quantify each study's quality and to assess the methodological strengths and weaknesses of the articles reviewed. Each question in our modified quality assessment tool (Galna et al., 2009) was scored: 1 indicated that the study met the assessment criterion, 0 indicated that it was not met, and 0.5 indicated a lack of information or clarity in that criterion.

Table 1

Results from the methodological quality appraisal. Y – Yes; L - lacking detail or clarity; N – No; AV – average. A score of one indicated high-quality research, and zero indicated lower quality.

Question	Scoring criteria	(Angelini et al., 2018)	(Hosp et al., 2018)	(Antonopoulos et al., 2014)	(Hatton et al., 2013)	(Barbieri et al., 2013b)	(Barbieri et al., 2014)	(Park et al., 2011)	(Hinkel-Lipsker et al., 2021)	(Santos et al., 2021a)	Average
1. Research aims or questions stated clearly.	Y: 1, L: 0.5, N: 0	1	1	1	1	1	1	1	1	1	1
2. Participants detailed.	Number	1	1	1	1	1	1	1	1	1	1
	Age	1	1	1	1	1	1	1	1	1	1
	Sex	0.5	1	1	1	1	1	1	1	0	0.83
	Height	1	1	1	1	1	1	1	1	1	1
	Subtotal	0.9	1	1	1	1	1	1	1	0.8	0.97
3. Recruitment and sampling methods described.	Y: 1, L: 0.5, N: 0	1	0.5	1	1	1	1	0.5	1	1	0.89
4. Inclusion and exclusion criteria detailed.	Y: 1, L: 0.5, N: 0	0.5	0.5	1	1	1	1	0.5	1	1	0.83
5. Controlled covariates.	Height	1	0.5	1	1	0	0	0	1	0	0.61
	Stride/step speed	0	0	0	1	1	1	0	0.5	1	0.5
	Age	0	1	1	1	1	1	1	1	1	0.89
	Sex	0	0	1	0	0	0	0	0	0	0.11
	Asymmetry	0.5	0.5	0	1	0	0	0	0	0	0.22
	Strength	0	0	1	1	1	1	0	0	1	0.55
	Subtotal	0.25	0.42	0.67	0.83	0.67	0.58	0.17	0.42	0.5	0.5
6. Key outcome variables clearly described.	Y: 1, L: 0.5, N: 0	1	1	1	1	1	1	1	1	1	1
7. Adequate methodology able to repeat study.	Participants	0.5	0	1	1	0	0	0	1	0.5	0.5
	Equipment	1	1	1	1	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1	1	0.5	1	0.94
	Processing	1	1	1	1	1	1	1	1	1	1
	Statistics	1	1	1	1	1	1	1	1	1	1
	Subtotal	0.9	0.8	1	1	0.9	0.8	0.9	0.9	1	1
8. Methodology able to answer a research question.	Participants	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	1	0.56
	Equipment	1	1	1	1	1	1	1	1	1	1
	Procedure	1	1	0.5	1	1	1	1	0.5	0.5	0.83
	Processing	1	1	0.5	1	1	1	1	1	1	0.94
	Statistics	1	1	1	1	1	1	1	1	1	1
	Subtotal	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.8	1	0.89
9. Reliability of the methodology stated.	Y: 1, L: 0.5, N: 0	0	0	0	0.5	0.5	0.5	0.5	0.5	1	0.39
10. Internal validity of the methodology stated.	Y: 1, N: 0	0	0	0	0	0	0	0	0	0	0
11. Research questions answered adequately in the discussion.	Y: 1, N: 0	1	1	1	1	1	1	1	1	0	0.89
12. Key findings supported by the results.	Y: 1, N: 0	1	1	1	1	1	1	1	1	1	1
13. Key findings interpreted logically, supported by references.	Y: 1, N: 0	1	1	1	1	1	1	1	1	1	1
14. Clinical implications stated.	Y: 1, L: 0.5, N: 0	0.5	0.5	0	0	0.5	0.5	0	0.5	1	0.39
Study Average.		0.74	0.74	0.81	0.89	0.81	0.81	0.68	0.81	0.77	0.78

2.7. Data extraction

In line with PRISMA guidelines, the number of citations reviewed at each stage of the review was summarised in a flow chart. Two reviewers (MC and TP) independently completed the data extraction process using a standardised data extraction form. The following five sets of data were extracted from each article retrieved:

Study characteristics: first author, title, year of publication, journal name, country, study design, mention of any adverse events occurring during the study, funding;

Sample description: sample size, age, sex, body weight, body height, body mass index, lower limb length, health status, fall status; limb preference;

Obstacle crossing protocol: task requirement, instrumentation, data acquisition methodology and gait parameters assessed;
 Fatigue protocol: task requirement, instrumentation, and data acquisition methodology, fatigue parameters assessed;
 Main results obtained from gait measurement: spatial-temporal parameters, joint angle and moment, ground force, muscle activity, and obstacle contacts.

Any discrepancies between the two reviewers (MC and TP) were resolved by consensus. If disagreement persisted, a third reviewer (NV) was consulted to arbitrate a final decision. Hinkel-Lipsker and colleagues (Hinkel-Lipsker et al., 2021) were the only authors contacted. Because their results were presented in a graph, we asked them for the raw values of their parameters to calculate a percentage difference in their outcomes before and after fatigue. Because of the evident heterogeneity in the protocols used to induce fatigue, outcomes and consequently results, we were unable to perform a meta-analysis.

3. Results

3.1. Study selection

The study selection process is presented in Fig. 1. Our searches of PubMed and Web of Science resulted in 10 and 28 studies, respectively. After removing 9 duplicates, we screened 29 titles and abstracts and selected 10 studies. After reading the full texts, one study (Kunzler et al., 2018) did not meet all the inclusion criteria (no investigation of spatial-temporal or muscle activity or of kinetic parameters on an obstacle crossing task before and after an EIF protocol) and was excluded. Therefore, 9 studies fully met the criteria and were included.

3.2. Quality assessment

Table 1 summarises the quality assessment for each article retained (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Hosp et al., 2018;

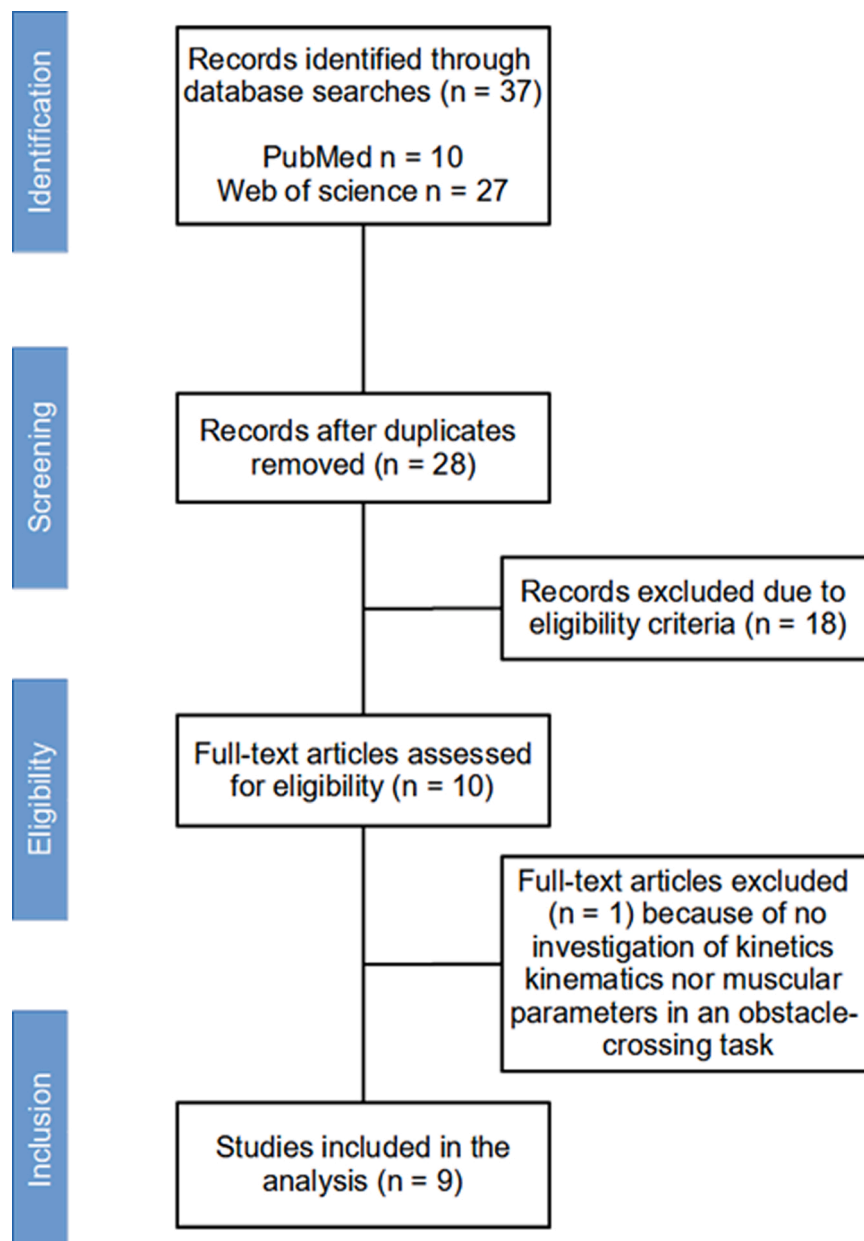


Fig. 1. Flowchart of articles included in the review. Numbers of original articles (i.e. not duplicates) are indicated at each stage of the search.

Park et al., 2011; Santos et al., 2021a). These articles adequately stated their objectives, provided an appropriate description of the participants, described the inclusion and exclusion criteria, detailed their main findings, used appropriate methodologies to answer their research questions and appropriately discussed their study results. The details provided were adequate to replicate their study, although participant recruitment (Hosp et al., 2018; Park et al., 2011) and sampling methods were not often described. All nine studies lacked detail and clarity on the clinical implications of their research.

Most studies controlled for height, age and sex, but generally not for limb asymmetries (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hinkel-Lipsker et al., 2021; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a) or body mass index (BMI) (Angelini et al., 2018; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a). Since none of the articles was of particularly poor scientific quality, data on outcomes were extracted from all of them (Table 1).

3.3. General information about the studies included in the systematic review

Table 2 shows basic information about the studies reviewed, including authors, year of publication, country, title, journal and funding sources (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a).

3.4. Methodological quality

3.4.1. Sample characteristics

The studies' demographic and anthropometric characteristics are described in Table 3.

A total of 296 participants were analysed across the 9 studies. Specific sample sizes in each study ranged from 12 (Antonopoulos et al., 2014; Hosp et al., 2018) to 120 (Barbieri et al., 2014). Most studies ($n = 6$, 66.7%) included only male participants (Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hosp et al., 2018; Park et al., 2011;

Santos et al., 2021a). Three studies (33.3%) (Angelini et al., 2018; Hatton et al., 2013; Hinkel-Lipsker et al., 2021) included both male and female participants, but only one (Hatton et al., 2013) (11.1%) indicated the number of females analysed ($n = 13$, 43.3%). The average ages of the participants in each study ranged from 22 ± 5 (Antonopoulos et al., 2014) to 78 ± 6 years (Hatton et al., 2013). Average body weights ranged from 71.6 ± 13.2 (Hinkel-Lipsker et al., 2021) to 90.7 ± 14.9 kg (Angelini et al., 2018), and average heights ranged from 1.65 ± 0.08 m to 1.82 ± 0.07 m (Angelini et al., 2018) (Table 3). Only one study (11.1%) reported BMI of the participants (Hatton et al., 2013). For the other studies, the review authors calculated BMIs from the average weight and height values presented, using the following formula: $(\text{Body mass (kg)} / [\text{Height}^2 \text{ (m)}])$ (Table 3).

3.5. Fatigue protocols and fatigue outcomes

The experimental protocols induced fatigue using different muscular and physical fatiguing tasks (Table 4). Four studies (44.4%) induced muscle fatigue using repeated sit-to-stand tasks (Barbieri et al., 2013b, 2014; Hatton et al., 2013; Santos et al., 2021a). Three of them (Barbieri et al., 2013b, 2014; Santos et al., 2021a) used a pre-determined cadence (30 cycles/min) and a maximum protocol time of 30 min. In the fourth study (Hatton et al., 2013), participants had to complete the task as quickly as possible until exhaustion. Four other studies (44.4%) induced fatigue through running/walking (Angelini et al., 2018; Antonopoulos et al., 2014; Hinkel-Lipsker et al., 2021; Hosp et al., 2018), with only one running protocol (11.1%) performed on level ground (Antonopoulos et al., 2014).

Running/walking protocols to induce fatigue included a continuous uphill walking velocity (4.5 km/h on a 2.5% incline) for 14 min (Angelini et al., 2018), a walk downhill (20% decline) for 30 min (Hosp et al., 2018), and a 25-minute walking protocol with speed and incline increments and a modified Bruce protocol on a treadmill (increments in speed and positive inclination every 3 min) until exhaustion (Antonopoulos et al., 2014). Other EIF included alternating 2-minute work-rest cycles of firefighting activities in an environmental chamber or a live-fire burn building for 14 min (Angelini et al., 2018) and 2-minute

Table 2
Studies included in chronological order of publication.

Author	Publication Year	Country	Title	Journal	Funding
(Park et al., 2011)	2011	USA	Assessing gait changes in firefighters due to fatigue and protective clothing	Safety Science	United States Department of Homeland Security's Fire Prevention and Safety Program
(Hatton et al., 2013)	2013	Australia	The effect of lower limb muscle fatigue on obstacle negotiation during walking in older adults	Gait & Posture	Endeavour Research Fellowship (Australia Awards) and Baroness Robson Travel Scholarship (Chartered Society of Physiotherapy), awarded to ALH
(Barbieri et al., 2013b)	2013	Brazil	Effect of muscle fatigue and physical activity level in motor control of the gait of young adults	Gait & Posture	FAPESP (São Paulo Research Foundation) and CAPES (Coordination for the Improvement of Higher Education Personnel)
(Barbieri et al., 2014)	2014	Brazil	Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing	Gait & Posture	CAPES (Coordination for the Improvement of Higher Education Personnel)
(Antonopoulos et al., 2014)	2014	Greece	The effect of fatigue on electromyographic characteristics during obstacle crossing of different heights in young adults	Journal of Sports Science and Medicine	Not mentioned
(Hosp et al., 2018)	2018	Austria	Does kinesiology tape counter exercise-related impairments of balance in the elderly?	Applied Ergonomics	Standortagentur Tirol, and region Vorarlberg
(Angelini et al., 2018)	2018	USA	Effects of simulated firefighting and asymmetric load carriage on firefighter obstacle crossing performance	Applied Ergonomics	United States Department of Homeland Security's Fire Prevention and Safety Grant
(Hinkel-Lipsker et al., 2021)	2021	USA	Gait adaptations to physical fatigue during the negotiation of variable and unexpected obstacles	Human Factors: The Journal of the Human Factors and Ergonomics Society	Partially supported by the Research, Scholarship, and Creative Activity Award at California State University, Northridge
(Santos et al., 2021a)	2021	Brazil	Being physically active minimizes the effects of leg muscle fatigue on obstacle negotiation in people with Parkinson's disease	Journal of Biomechanics	FAPESP (São Paulo Research Foundation) and CAPES (Coordination for the Improvement of Higher Education Personnel)

Table 2 shows basic information about the selected studies, including authors, year of publication, country, title, journal and funding sources.

Table 3

Basic demographic and anthropometric information of the participants included in each study.

Author	Number of groups (n)	Number of participants (n)	Sex (F: female; M: male) (n)	Age, mean (SD), years	Height, mean (SD), m	Body mass, mean (SD), kg	BMI, mean (SD), kg/m ²
(Angelini et al., 2018)	1	17	Not mentioned	28.6 (7.9)	1.82 (0.07)	90.7 (14.9)	27.4 ^[c]
(Hosp et al., 2018)	1	12	M: 12	68.3 (4.5)	1.78 (0.05)	80.3 (9.8)	25.2 ^[c]
(Antonopoulos et al., 2014)	1	12	M: 12	22.8 (5.4)	1.80 (0.06)	83.8 (13.4)	25.9 ^[c]
(Barbieri et al., 2014)	6 (G20, G30, G40, G50, G60, G70)	120: -G20: 20 -G30: 20 -G40: 20 -G50: 20 -G60: 20 -G70: 20	M: 20 M: 20 M: 20 M: 20 M: 20 M: 20	24.0 (2.8) 32.5 (2.7) 44.0 (2.9) 54.5 (3.2) 64.0 (2.6) 74.5 (4.5)	1.78 (0.04) 1.74 (0.06) 1.75 (0.06) 1.71 (0.07) 1.71 (0.06) 1.65 (0.06)	77.9 (14.7) 79.2 (14.2) 84.6 (15.5) 82.1 (13.4) 77.9 (12.6) 73.0 (12.2)	24.6 ^[c] 26.2 ^[c] 27.6 ^[c] 28.1 ^[c] 26.7 ^[c] 26.8 ^[c]
(Barbieri et al., 2013b)	2 (Active group, Inactive group).	20: - Active group: 10 - Inactive group: 10	M: 10 M: 10	24.7 (2.8) 24.7 (2.9)	1.78 (0.10) 1.78 (0.05)	73.2 (4.4) 82.7 (17.6)	22.9 ^[c] 26.1 ^[c]
(Hatton et al., 2013)	1	30	F: 13; M: 17	78.2 (6.1)	1.65 (0.08)	74.35 (15.5)	27.24 (4.7)
(Park et al., 2011)	2 Standard personal protective equipment (PPE), Enhanced PPE.	44: -Standard PPE: 21 -Enhanced PPE: 23	M: 21 M: 23	33.2 (5.5) 32.5 (9.5)	1.77 (0.07) 1.73 (0.06)	91.2 (12.4) 87.71 (18.1)	29.1 ^[c] 29.3 ^[c]
(Hinkel-Lipsker et al., 2021)	1	21	F: 8; M: 13	23.3 (3.4)	1.720 (0.115)	71.6 (13.2)	24.20 ^[c]
(Santos et al., 2021a) **	2 (Non-active group, Active group)	20 - Non-active group: 10 - Active group: 10	M: 20	Non-active = 71.4 (6.4) Active = 67.5 (6.5)	Non-active = 1.70 (0.7) Active = 1.65 (0.7)	Non-active = 78.7 (12.8) Active = 68.6 (9.4)	Non-active = 27.2 Active = 25.3

[c] indicates that the values were calculated by the paper's authors. e.g., BMI was calculated using the formula: (weight [kg]/(height² [m])) using the mean values reported in the articles. G20, G30, G40, G50, G60 and G70 are age groups ranging from 20 to 29, 30–39, 40–49, 50–59, 60–69 and over 70, respectively. The Standard PPE included bunker gear with a spun Nomex lining, a fully-encapsulating Kevlar hood, leather gloves with a Kevlar wrist gauntlet, rubber boots and a traditional style helmet; average weight: 11 kg. The Enhanced PPE included bunker gear with an Indura FR cotton lining, a Nomex hood, a low-profile helmet, leather gloves and lightweight leather boots. On average, a full set of Enhanced PPE weighed 9.5 kg.

alternating work–rest cycles of simulated firefighting activities for 18 min (Park et al., 2011).

One study (11.1%) (Angelini et al., 2018) EIF using three different tasks: i) treadmill walking; ii) firefighting activities in an environmental chamber; and iii) firefighting activities in a live-fire burn building. Another study (11.1%) (Hinkel-Lipsker et al., 2021) experimentally induced fatigue using four anaerobic firefighting activity exercises (2 min each with 30 s of rest between exercises) for 10 min, followed by 25 min of walking on a treadmill with speed increasing incrementally from 3 km/h to 5 km/h and positive incline increasing from 0% to 12%.

Two studies (22.2%) used similar fatigue protocols involving downhill walking for 30 min (Hosp et al., 2018) or simulated firefighting activities (Park et al., 2011), while Hosp and colleagues (Hosp et al., 2018) assessed fatigue's effects on obstacle crossing under different conditions: with or without kinesiology tape.

Seven studies reported on performance fatigue (77.8%) (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Santos et al., 2021a) (Table 4). Five studies (55.6%) used reductions in maximal voluntary isometric contraction to assess performance fatigue (calculating the maximal isometric force or joint torque) (Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Santos et al., 2021a), 3 studies (33.3%) used a Rating of Perceived Exertion (RPE) on a 6–20 Borg scale (Antonopoulos et al., 2014; Barbieri et al., 2014; Hinkel-Lipsker et al., 2021), and 3 studies (33.3%) used heart rate after the fatigue protocol (Angelini et al., 2018; Antonopoulos et al., 2014; Hinkel-Lipsker et al., 2021). For studies using maximum voluntary contraction, they reported reductions in isometric force ranging from 9.5% (Hatton et al., 2013) to 25.7% (Barbieri et al., 2014) in maximal isometric force and 29.4% in torque of the plantarflexion (Antonopoulos et al., 2014). (Angelini et al., 2018; Antonopoulos et al., 2014; Hinkel-Lipsker et al., 2021). In studies using heart rate, final heart rate (after fatigue) ranged from 178 (Angelini et al., 2018) to 190 bpm (Antonopoulos et al., 2014) were reported. In studies using a 6–20 Borg

scale (Antonopoulos et al., 2014; Barbieri et al., 2014; Hinkel-Lipsker et al., 2021) a final range (after EIF protocols) of 19–20 (Antonopoulos et al., 2014), an average value of 16.3 (Hinkel-Lipsker et al., 2021), or a maximal rate of perceived exertion at the end of the protocol (Barbieri et al., 2014) were reported. Two studies (22.2%) did not report fatigue's state after the completion of EIF (Hosp et al., 2018; Park et al., 2011).

3.6. Obstacle crossing task

3.6.1. Walkway, obstacle shape and starting point

Pathway lengths ranged from 7.5 m (Angelini et al., 2018) to 12 m (Hatton et al., 2013), but most studies (n = 5, 55.6%) used an 8 m walkway (Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Park et al., 2011; Santos et al., 2021a). Two studies (22.2%) (Hinkel-Lipsker et al., 2021; Hosp et al., 2018) did not report walkway length (Table 5). Six studies (66.7%) clearly indicated to participants where the starting point was (Angelini et al., 2018; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a). These starting points were set individually to ensure that participants crossed the obstacle with a predetermined leg (n = 4 studies, 44.4%) (Barbieri et al., 2013b, 2014; Hatton et al., 2013; Santos et al., 2021a) or to maximise the chance that participants landed on a force plate (Angelini et al., 2018) (n = 1 study, 11.1%). One study set the same starting point for all participants, who were positioned 305 cm (10 ft) in front of the leading edge of the mat (n = 1, 11.1%) (Park et al., 2011). In addition, walking distances before arriving at the obstacle were different, varying from 2 m (Hosp et al., 2018) to 4 m (Antonopoulos et al., 2014; Barbieri et al., 2014, 2013b; Park et al., 2011) or changing at every trial (Hinkel-Lipsker et al., 2021). Five studies (55.6%) (Angelini et al., 2018; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Santos et al., 2021a) used rectangular-shaped obstacles, whereas three studies (33.3%) used plastic pipes (Antonopoulos et al., 2014; Hosp et al., 2018; Park et al., 2011) and one study (11.1%) (Hinkel-Lipsker

Table 4
Design and assessment of the experimentally-induced fatigue protocols.

Author	Number of fatigue protocols	Type of fatigue protocol			Time/Endpoint	Fatigue assessment	Fatigue outcomes
		Running/walking	Repetitive muscle contraction	Specific activities			
(Angelini et al., 2018)	3	Protocol 1) Treadmill walking (14 min at 4.5 km/h at 2.5% incline)		Protocol 2) Simulated firefighting in an environmental chamber (alternating 2 min work–rest cycles) Protocol 3) Simulated firefighting tasks in a live-fire burn building (alternating 2 min work–rest cycles)	14 min for each protocol	Heart rate	Heart rate: - Protocol 1: 178 bpm maximum during the fatigue protocol - Protocol: 190 bpm maximum during the fatigue protocol - Protocol 3: 188 bpm maximum during the fatigue protocol
(Hosp et al., 2018)	2	Protocol 1) Downhill at 'natural' walking speed on a treadmill inclined at 20% without kinesiology tape Protocol 2) Downhill at 'natural' walking speed on a treadmill inclined at 20% with kinesiology tape			30 min	Not mentioned	Not mentioned
(Antonopoulos et al., 2014)	1	Running on a treadmill with increasing speed according to the Modified Bruce protocol			Until exhaustion	Heart rate. Borg Scale (1–20); MVC Torque of the plantar flexion	Heart rate: 190 ± 10 bpm Borg Scale: '19 (n = 9) or 20 (n = 5) according to Borg's scale' Torque of the plantar flexion: Reduction of 29.4% on average
(Barbieri et al., 2014)	1		Repeated sit-to-stand task at a predetermined cadence (30 cycles/min), using a metronome		After reported exhaustion or 30 min maximum or when the movement frequency fell below and remained below 30 cycles/min after encouragement	Isometric MVC on a leg press device (test on both legs); Borg scale	Isometric force contraction: Reduction of 13.96% on average in all groups; All groups reported an almost maximum rate of perceived exertion at the end of the protocol
(Barbieri et al., 2013b)	1		Repeated sit-to-stand task at a predetermined cadence (30 cycles/min), using a metronome		After reported exhaustion or 30 min maximum or when the subject no longer performed at the desired movement frequency	Isometric MVC on a leg press device (test on both legs)	Isometric force contraction: Reduction of 12.3% and 11.9% for active and inactive individuals, respectively
(Hatton et al., 2013)	1		Repeated sit-to-stand movement, as fast as possible		Until exhaustion	Isometric quadriceps muscle strength (preferred leg)	Quadriceps isometric force: Reduction of 9.5% on average
(Park et al., 2011)	2			1. Drills consisted of four firefighting tasks alternating work–rest cycles (2 min intervals), wearing standard PPE 2. Drills consisted of four firefighting tasks alternating work–rest	18 min	Not mentioned	Not mentioned

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Table 4 (continued)

Author	Number of fatigue protocols	Type of fatigue protocol	Time/Endpoint	Fatigue assessment	Fatigue outcomes	
(Hinkel-Lipsker et al., 2021)	1	After completing anaerobic exercises, participants were asked to complete a 25 min graded treadmill walking activity, where the treadmill speed and grade increased over time (walking speed from 3 km/h to 5 km/h with an increment of 0.5 km/h every 5 min; incline from 0% to 12%, increased to 7% at the 4th minute, and then to 12% at the 6th minute)	cycles (2 min intervals); wearing standard PPE Exercises consisted of four anaerobic exercises used to mimic firefighters' activities: a self-paced 2 min stair ascent and descent, a 2 min bear crawl, and 2 min of kneeling and standing cable pull, down and across (9.1 kg for men, 4.5 kg for women; 30 s of rest between each anaerobic activity)	35 min maximum (including resting periods) or until exhaustion	Heart rate RPE from 6 (minimal effort) to 20 (maximal effort)	Heart rate: mean value after anaerobic exercise: 156 ± 15 bpm -mean value of RPE after anaerobic exercises: 14.1 ± 2.6 Only 38.1% of the individuals completed the entire walking protocol: -mean heart rate: 179 ± 17 -mean RPE: 16 ± 2
(Santos et al., 2021a)	1	Repeated sit-to-stand task at a predetermined cadence (30 cycles/min), using a metronome	After exhaustion or 30 min maximum or when the subject no longer performed at the desired movement frequency or when the participants reported being unable to continue	Isometric MVC on a leg press device (test on both legs)	Isometric force contraction: reduction of 13.7% and 11.25% for non-active and active individuals, respectively	

MVC: Maximum voluntary contraction; RPE: Rating of perceived exertion; PPE: Personal protective equipment.

et al., 2021) did not describe the obstacle's shape.

Seven studies (77.8%) used a single obstacle height condition (Angelini et al., 2018; Barbieri et al., 2013b, 2014; Hinkel-Lipsker et al., 2021; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a). This height varied from 15 cm (Barbieri et al., 2013b, 2014; Santos et al., 2021a) to 30 cm (Angelini et al., 2018; Hinkel-Lipsker et al., 2021; Park et al., 2011), or was individually determined at 60% of the participant's leg length (Hosp et al., 2018). Two studies (22.2%) investigated the effects of walking by varying the height of the obstacle to 10% or 20% of the individual's leg length on a 12 m walkway comprising seven different obstacles (Hatton et al., 2013), or on an 8 m walkway with one single obstacle (Antonopoulos et al., 2014). One study (11.1%) used seven obstacles (smallest, 53 cm width, 0.5 cm height, 6 cm length; highest, 110 cm width, 18 cm height, 6 cm length) placed at irregular intervals (from 0.8 m to 2.15 m apart) along a 12 m walkway; the position of the 'target obstacle' (obstacle 6) was not clearly stated (Hatton et al., 2013). Finally, in one study (11.1%) (Hinkel-Lipsker et al., 2021), the obstacle appeared unexpectedly along the walking path. In this study, participants had to walk along a predetermined path in a darkened room with an invisible obstacle placed at a random location somewhere along the way. Once the participants were within 50 cm of the obstacle, a motion-triggered light illuminated it.

3.7. Effects of fatigue protocols on gait outcomes during obstacle crossing

Table 6 shows the gait parameters measured during obstacle crossing and the associated data acquisition methods.

All included studies examined kinematic parameters (n = 9, 100%) (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a), three examined kinetic parameters (33.3%) (Barbieri et al., 2013b; Hatton et al., 2013; Hosp et al., 2018); one examined muscular parameters (11.1%) (Antonopoulos et al., 2014) and two reported contacts with the obstacle (crossing error) (22.2%) (Angelini et al., 2018; Park et al., 2011) (Table 6).

Three studies (33.3%) investigated both kinematic and kinetic parameters (Antonopoulos et al., 2014; Barbieri et al., 2013b; Hosp et al., 2018), two (22.2%) investigated both kinematic parameters and obstacle contacts (Angelini et al., 2018; Park et al., 2011) and one (11.1%) investigated both kinematic and muscular parameters (Antonopoulos et al., 2014).

3.7.1. Assessment of kinematic, kinetic and muscular parameters, and contacts with the obstacle

The most frequently applied tools for assessing kinematic parameters were camera motion capture/analysis (n = 4 studies, 44.4%) (Angelini et al., 2018; Antonopoulos et al., 2014; Hinkel-Lipsker et al., 2021; Hosp et al., 2018) or optoelectronic/scanning systems (n = 3 studies, 33.3%) (Barbieri et al., 2013b, 2014; Santos et al., 2021a). One study (11.1%) used an instrumented gait-mat (Park et al., 2011). Kinetics parameters were assessed through ground reaction force using force plates (n = 3 studies, 33.3%) (Barbieri et al., 2013b; Hatton et al., 2013; Hosp et al., 2018). Muscular parameters were assessed using EMG signals (n = 1 studies, 11.1%) (Antonopoulos et al., 2014). Contacts with the obstacle were recorded by one (Angelini et al., 2018) or two investigators (Park et al., 2011) (n = 2 studies, 22.2%).

The most investigated kinematic parameters were foot vertical, and horizontal clearance (n = 8 studies, 88.9%) (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Park et al., 2011; Santos et al., 2021a). In most of the studies, the leading foot's horizontal clearance corresponded to its distance from the obstacle after the crossing step during its stance phase and the swing of the trailing foot; and the trailing foot's horizontal clearance corresponded to its distance from the obstacle during its stance phase and the crossing swing of the leading foot. Nevertheless, one study (11.1%) investigated horizontal clearance in both phases for both feet: before and after crossing the obstacle (Barbieri et al., 2013b). Another study (11.1%) investigated only the horizontal clearance of both feet before crossing the obstacle (Hinkel-Lipsker et al., 2021). One study (11.1%) investigated only trailing leg horizontal

Table 5
Description of the obstacle crossing tasks.

Author	Task	Obstacle	Expected/ Unexpected	Starting point	Number of sessions	Number of conditions	Number of Trials per condition	Walking Speed	Experimental condition	Practice
(Angelini et al., 2018)	Participants walked down an elevated walkway (8.3 cm high x 7.5 m long x 1.2 m wide)	Rectangular frame obstacle (30 cm high x 14 cm long x 124 cm wide) constructed from lightweight 1.5 cm diameter PVC pipe; obstacle was not rigidly attached	Expected	Determined individually to maximise the likelihood of clean force plate strikes when stepping over the obstacle	3: 1 session for each fatigue protocol.	8: Rested: 2 1. without load carriage 2. with load carriage After the first fatigue protocol 2: 1. without load carriage 2. with load carriage After the second fatigue protocol: 2 1. without load carriage 2. with load carriage After the third fatigue protocol 2: 1. without load carriage 2. with load carriage	2	Self-selected 'fireground pace'	Single task: unloaded Dual-task: Manual -Carrying a 'high rise pack (hose, 11.3 kg consisting of 15.2 m of 6.4 cm hose folded back and forth in 1.8 m lengths)	Participants completed a baseline session before the first testing session; they made several practice runs
(Hosp et al., 2018)	Participants walked along a 2-m walkway, stepped over an obstacle with the preferred leg and continued walking along the walkway	Adjustable upright stands and a padded plastic crossbar (1.5 m long and 2.5 cm Ø) placed at 60% of the individual's leg length	Expected	Not mentioned	2: 1. without kinesiology tape 2. with kinesiology tape	4: Rested: 2 1. without kinesiology tape 2. with kinesiology tape After fatigue: 2 1. without kinesiology tape 2. with kinesiology tape	3	Comfortable self-selected	Single task	Participants completed two practice trials
(Antonopoulos et al., 2014)	Participants walked on an 8-m walkway with an obstacle placed midway	A lightweight plastic tube (1 cm Ø) placed on height-adjustable metal plates at 10% and 20% of the individual's leg length	Expected	Not mentioned	1	4: Rested: 2 1. Obstacle height of 10% of leg length 2. Obstacle height of 20% of leg length After fatigue: 2 1. Obstacle height of 10%	5 at baseline for each obstacle height 2 after fatigue protocol for each obstacle height 2 other, 5 min after the immediate post-test trials	Preferred	Single task	Not mentioned

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Table 5 (continued)

Author	Task	Obstacle	Expected/ Unexpected	Starting point	Number of sessions	Number of conditions	Number of Trials per condition	Walking Speed	Experimental condition	Practice
(Barbieri et al., 2014)	Participants walked on an 8-m wooden walkway with an obstacle placed midway	Rectangular, 15 cm high, 80 cm wide, 2 cm thick obstacle	Expected	Set so that individuals crossed the obstacle with the right leg, with at least two strides before the crossing	1	of leg length 2. Obstacle height of 20% of leg length 2: 1. Rested 2. After fatigue	3	Self-selected	Single task	Not mentioned
(Barbieri et al., 2013b)	Participants walked on an 8-m wooden walkway with an obstacle placed midway	Rectangular, 15 cm high, 80 cm wide, 2 cm thick obstacle	Expected	Set so that individuals crossed the obstacle with the right leg, with at least two strides before the crossing	1	2: 1. Rested 2. After fatigue	3	Self-selected	Single task	Not mentioned
(Hatton et al., 2013)	12-m obstacle course with 7 obstacles while completing a secondary visual task	Sixth obstacle along the walkway was height-adjustable; this 'target' obstacle was set to two different height conditions: 10% and 20% of participant's leg length	Expected	Start trial with the same foot to have the same crossing leg in all the trials	1	4: Rested: 2 1. Obstacle height 10% of leg length 2. Obstacle height 20% of leg length After fatigue: 2 1. Obstacle height 10% of leg length 2. Obstacle height 20% of leg length	6	Preferred speed	Visual secondary task: "read aloud a sequence of 10 monosyllabic letters"	One practice trial
(Park et al., 2011)	Individuals walked on an 8-m instrumented gait mat (GaitRite) with an obstacle placed midway	10 cm wide, 113 cm long, 30 cm high obstacle made of lightweight plastic piping placed in middle of pathway	Expected	Started 305 cm (10 ft) in front of the leading edge of the mat		6 Baseline (without wearing personal protective equipment): 2 1. Normal pace 2. Fast pace Pre-activity: 2 1. Normal pace 2. Fast pace Post-activity: 2 1. Normal pace 2. Fast pace	2.	Preferred and fast pace	Single task	Not mentioned
(Hinkel-Lipsker et al., 2021)	Participants were tasked with walking along a predetermined course in a darkened room with an	-30 cm high obstacle; other dimensions were not mentioned	Unexpected: Once participants were within	Not mentioned: The initial obstacle distance from the start	1	2: 1. Rested 2 After fatigue	5: During the rested and fatigued states, a trial where the	Not mentioned	Single task	Participants were allotted 10 familiarisation trials.

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Table 5 (continued)

Author	Task	Obstacle	Expected/ Unexpected	Starting point	Number of sessions	Number of conditions	Number of Trials per condition	Walking Speed	Experimental condition	Practice
(Santos et al., 2021a)	unseen obstacle placed in a random location somewhere along the path; participants began with their back to the walkway and were asked to turn around and walk through the course Participants walked the middle of an 8 m wooden walkway	Rectangular, 15 cm high, 80 cm wide, 2 cm thick obstacle	Expected	changed in each trial	1	2: 1. Rested 2. After fatigue	obstacle was completely removed from the course was executed (trials were excluded from data analysis)	Self-selected	Single task	Not mentioned
				Set so that individuals crossed the obstacle with the right leg, with at least two strides before the crossing						

Table 6

Description of the parameters measured during obstacle crossing and data acquisition method.

Authors	Parameters measured	Acquisition system
(Angelini et al., 2018)	-Kinematics: horizontal and vertical foot clearances Obstacle contact: minor (contacted the obstacle but did not knock it over) and major (obstacle fell over) errors	Eight-camera motion capture system (Oqus 100, Qualisys AB, Sweden; sampling rate: 200 Hz) and 12 reflective markers An investigator recorded error when participants contacted the obstacle
(Hosp et al., 2018)	Kinematics: whole-body motion and dynamic balance COM-COP (centre of mass-centre of pressure) Kinetics: ground force reaction	Eight-camera motion analysis system (Vicon, Oxford Metrics, UK; sampling rate: 125 Hz) and 30 reflective markers Simulation software (OpenSim3.3, NCSRR, USA) Two force plates (AMTI, Watertown, MA; sampling rate: 1250 Hz)
(Antonopoulos et al., 2014)	Kinematics: vertical and horizontal distance of the feet Muscular: the EMG of the trailing limb for the activity of the medial gastrocnemius, soleus, and tibialis anterior muscles	Six cameras (type M3) of a VICON 612 motion analysis system (Oxford Metrics, Ltd., Oxford, Oxfordshire, UK, sampling rate: 120 Hz) and 8 infrared-reflective markers BTS TELEMG remote system (BTS Bioengineering, Milano, Italy, sampling rate: 1000 Hz) Bipolar disc surface electrodes (Ag/AgCl, 1 cm diameter)
(Barbieri et al., 2014)	Kinematics: stride length, duration, speed, single and double support duration, step width, and vertical and horizontal clearances	Three-dimensional optoelectronic system (OPTOTRAK Certus; sampling rate: 100 Hz) and four infrared markers
(Barbieri et al., 2013b)	Kinematics: stride length, duration, speed, single and double support duration, step width, foot-obstacle distance before and after obstacle crossing, and toe-clearance for the leading and trailing limbs Kinetics: ground force reaction, maximum braking vertical force, maximum propulsive vertical force, maximum braking anterior-posterior force, maximum propulsive anterior-posterior force	Three-dimensional optoelectronic system (OPTOTRAK Certus; sampling rate: 100 Hz) and four infrared markers Two force plates (AccuGait, Advanced Mechanical Technologies; sampling rate: 200 Hz)
(Hatton et al., 2013)	Kinematics: trail limb approach distance, trail limb toe clearance, lead limb heel clearance, lead limb landing distance, obstacle crossing stride length, obstacle crossing velocity Kinetics: ground force reaction, vertical loading rate of lead limb	Two CODA scanner units (Model cx1, Codamotion, Charnwood Dynamics Ltd., Rothley, UK; sampling rate: 200 Hz) A single force plate after the target obstacle (Model 9286AA, Kistler, Alton, UK; sampling rate: 1000 Hz)
(Park et al., 2011)	Kinematics: average gait speed, average step length, average step width, single leg stance time horizontal clearances Obstacle contact: obstacle fell (the obstacle fell over), and obstacle touch (contacted the obstacle, but it did not fall)	8-m instrumented gait mat (GAITrite Platinum, CIR Systems Inc., Havertown; sampling rate: Not provided) Two investigators were assigned to record occurrences of movement errors
(Hinkel-Lipsker et al., 2021)	Kinematics: vertical toe and heel clearance on each foot, horizontal foot placement	Eight-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA)

(continued on next page)

Table 6 (continued)

Authors	Parameters measured	Acquisition system
	before obstacle on each foot, step length, step width and gait velocity during approach phase	CA; sampling rate: 60 Hz) and 22 retro-reflective markers Visual 3D (C-Motion, Germantown, MD). MATLAB R2020a (Mathworks, Natick, MA)
(Santos et al., 2021a)	Kinematics: stride length, width duration, speed for approach and crossing phases and foot-obstacle distance and clearance for the leading and trailing limbs before the obstacle	Three-dimensional optoelectronic system (OPTOTRAK Certus; sampling rate: 100 Hz) and four infrared markers

clearance before the obstacle, and leading leg horizontal clearance after the obstacle (Hatton et al., 2013). The second most investigated parameter was stride/step length ($n = 6$ studies, 66.7%) (Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Park et al., 2011; Santos et al., 2021a). This was done during the crossing step (by two studies (Barbieri et al., 2014; Hatton et al., 2013)), as the average length over the entire obstacle-crossing course (Park et al., 2011), or as the stride before obstacle crossing (Hinkel-Lipsker et al., 2021). One study separated step length into three phases: the approach phase to the obstacle, the crossing step (N) and the step after crossing (N + 1) (Barbieri et al., 2013b). Step/stride duration and step/gait speed were investigated by four studies (44.4%). Finally, four studies (44.4%) (Barbieri et al., 2013b, 2014; Park et al., 2011; Santos et al., 2021a) investigated single support duration, two (22.2%) (Barbieri et al., 2014, 2013b) investigated double support duration, and four (44.4%) (Barbieri et al., 2013b, 2014; Park et al., 2011; Santos et al., 2021a) looked at step width during the crossing step (Barbieri et al., 2014) or on average over all the steps (Park et al., 2011) or separated into the three phases of approach to the obstacle, crossing step (N) and the step after crossing (N + 1) (Barbieri et al., 2013b). One study assessed the centre of mass-centre of pressure distance (COM-COP distance) (Hosp et al., 2018), and one other study (11.1%) assessed the braking latency time of vertical force (11.1%) (Barbieri et al., 2013b). Four studies (44.4%) (Barbieri et al., 2013b; Hinkel-Lipsker et al., 2021; Park et al., 2011; Santos et al., 2021a) also investigated kinematics parameters during the approach phase to the obstacle, with all four using step length, step width and step/gait speed. Three studies (33.3%) investigated stride duration during the approach phase (Barbieri et al., 2013b; Park et al., 2011; Santos et al., 2021a), two (22.2%) investigated single support duration (Barbieri et al., 2014; Park et al., 2011), and one (11.1%) examined double support duration in the approach phase (Barbieri et al., 2013b).

The kinetic parameters studied were: the vertical loading rate of the leading limb (Hatton et al., 2013); or the maximum braking vertical force (area under the curve from the heel strike to middle stance), maximum propulsive vertical force (area under the curve from middle stance to the toe-off), maximum braking anterior-posterior force and maximum propulsive anterior-posterior force (Barbieri et al., 2013b); or ground forces reaction to assess COM-COP distance (Hosp et al., 2018).

The EMG parameters were recorded for the activities of three muscles (tibialis anterior, soleus and medial gastrocnemius) in the trailing lower limb during the stance and swing phases (crossing step) in one study (11.1%) (Antonopoulos et al., 2014).

Two studies assessed contacts with the obstacle (crossing error) (22.2%) (Angelini et al., 2018; Park et al., 2011). One study (11.1%) classified obstacle contacts as 'minor' (obstacle did not fall), and 'major' (obstacle fell) errors (Angelini et al., 2018), whereas the other study (11.1%) classified obstacles contacts as 'obstacle touch' (contacted the obstacle, but it did not fall) and 'obstacle fell' (the obstacle fell over) (Park et al., 2011).

3.7.2. Effects of experimentally-induced fatigue on kinematic parameters

EIF increased the COM-COP distance in participants with no kinesiology tape compared to those wearing kinesiology tape (Hosp et al., 2018). Consistent changes were also found for step width, stride duration and stride/step length. After fatigue, step width increased during the approach phase (Barbieri et al., 2013b; Santos et al., 2021a;) and during the obstacle-crossing phase (Barbieri et al., 2014, 2013b), whereas step/stride length did not significantly change with fatigue (Barbieri et al., 2013b, 2014; Hatton et al., 2013; Park et al., 2011; Santos et al., 2021a). Inconsistent changes due to EIF were found in trailing and leading-foot vertical clearance and horizontal clearance (Angelini et al., 2018; Hinkel-Lipsker et al., 2021; Santos et al., 2021a): two studies observed significant reductions in those parameters after EIF (Angelini et al., 2018; Hinkel-Lipsker et al., 2021) (also, only in the 10%-of-leg-length obstacle condition (Antonopoulos et al., 2014)), but a third study (Santos et al., 2021a) found significant increases in both parameters. Regarding the effects of EIF on step/stride duration, three studies reported a decrease in duration during obstacle crossing (Barbieri et al., 2014, 2013b), combined with reductions in single (Park et al., 2011) and double support duration (Barbieri et al., 2013b). Different studies reported contradictory effects of muscle fatigue on gait (step) velocity and leading-foot vertical clearance. Whereas three studies indicated increases in gait velocity after EIF during the approach (Barbieri et al., 2013b; Hinkel-Lipsker et al., 2021) and crossing phases (Barbieri et al., 2014), another showed no significant difference for this parameter (Antonopoulos et al., 2014). Regarding leading-foot vertical clearance, one study (11.1%) indicated a significant reduction in vertical toe clearance (Hinkel-Lipsker et al., 2021), and two studies (22.2%) found a significant increase of vertical heel clearance after the EIF protocol (Barbieri et al., 2014; Hinkel-Lipsker et al., 2021). Concerning trailing-foot vertical clearance after EIF, two studies (22.2%) found a significant reduction in this parameter (Angelini et al., 2018; Hinkel-Lipsker et al., 2021), three others (33.3%) found no significant difference (Antonopoulos et al., 2014; Barbieri et al., 2014, 2013b), and a last study (11.1%) found a significant increase in clearance (Santos et al., 2021a).

One study (11.1%) reported age interaction with EIF (Barbieri et al., 2014), indicating that the G40 and G50 age groups (individuals aged from 40 to 59) increased their leading-limb heel clearances, while the other age groups showed no significant difference for this parameter between rested and fatigued conditions. The same study (Barbieri et al., 2014) indicated the G70 age group (individuals aged 70 or over) showed significantly increased trailing-foot clearance, but there were no effects among the other groups. Two studies (22.2%) compared active and inactive individuals (Barbieri et al., 2013b; Santos et al., 2021a), with one revealing that inactive individuals had a greater step width than active individuals after EIF (Santos et al., 2021a). Fatiguing-protocol type (firefighting activities vs treadmill walking) also affected gait after EIF (pre vs post) (Angelini et al., 2018). Whereas firefighting activities protocols (in an environmental chamber or a live-fire burn building) induced a decrease in leading-foot horizontal clearance, treadmill protocols induced increased foot vertical clearance and contact errors (Angelini et al., 2018). Angelini and colleagues (Angelini et al., 2018) also observed links between time (pre- vs post-activity) and asymmetric load carriage (loaded or unloaded). After both fatiguing protocols, trailing and leading-foot vertical clearances significantly decreased in the loaded situation, while leading-foot vertical clearance significantly increased in the unloaded situation.

3.7.3. Effects of experimentally-induced fatigue on kinetic parameters

EIF increased the vertical loading rate of the leading limb after the obstacle (for the leading-limb crossing step) when the obstacle measured 10% of the individual's leg length (Hatton et al., 2013), and it decreased the vertical maximum braking force during the approach phase (Barbieri et al., 2013b).

3.7.4. Effects of experimentally-induced fatigue on muscle activity

EIF led to an immediate increase in the muscle activation amplitude of the medial gastrocnemius of the trailing leg during the swing phase that was directly related to the obstacle height (10% vs 20% of individual's leg length) (Antonopoulos et al., 2014). These immediate effects were not observed 5 min after the end of the EIF protocol (Antonopoulos et al., 2014).

3.7.5. Effects of experimentally-induced fatigue on obstacle contacts

EIF increased the number of contacts with the obstacle with 56% of minor contact errors and 86% of major contact errors (Angelini et al., 2018) occurring after EIF. Angelini and colleagues further reported that most obstacle contacts were committed with the trailing foot and that fewer obstacle contacts occurred following the treadmill protocol compared to the environmental chamber and burn building simulated firefighting task protocols (9 for treadmill vs. 12 for each simulated firefighting task protocol). Park and colleagues (Park et al., 2011) reported that the number of participants who made errors increased from

the baseline to the post-activity (baseline: 20%, pre-activity: 43%, post-activity: 61%), and the number of obstacle contacts increased. (baseline: 13.3%; pre-activity: 28.9%; post-activity: 57.8%).

4. Discussion

This systematic review aimed to synthesise research on the effects of EIF on the gait parameters of healthy individuals during obstacle crossing. The review consistently showed that EIF caused changes in kinetic, kinematic and muscular parameters during obstacle crossing tasks. Specifically, our findings showed that participants reduced their stride duration (including single and double-support time) and vertical maximum braking force, and they increased their step width, COM-COP distance (balance dynamic) and the leading limb's vertical loading rate. The medial gastrocnemius' muscle activity amplitude increased after EIF, but the tibialis anterior showed no change. What is more, obstacle contacts increased after EIF, and most of the contacts occurred with the trailing leg. Contradictory effects (increasing, decreasing or no effects)

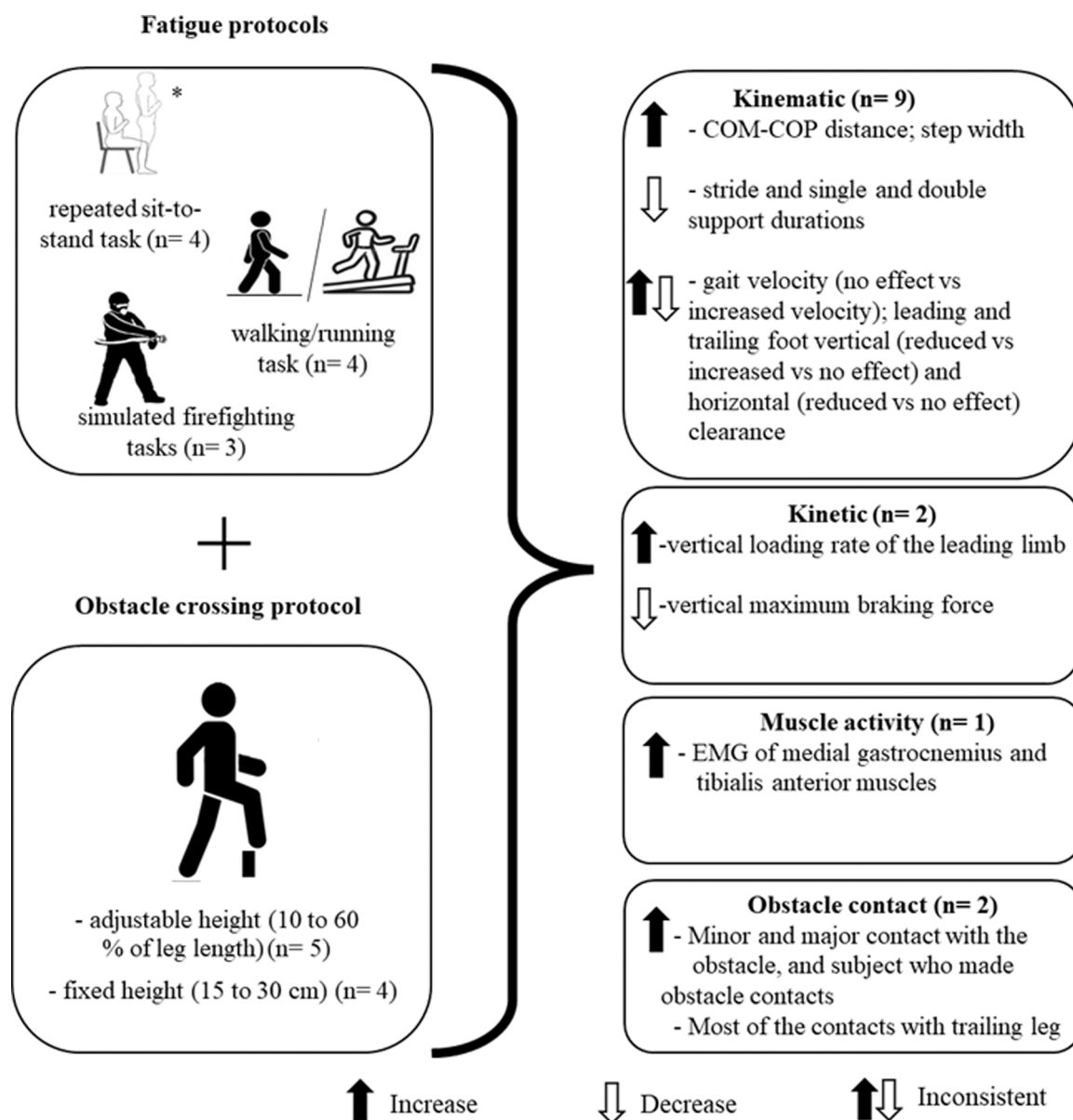


Fig. 2. Flowchart summarising the effects of experimentally-induced fatigue on obstacle crossing parameters. Numbers in brackets indicate the number of articles that used those fatigue protocols or obstacle crossing protocols and measured kinetic, kinematic and muscle activity parameters.

*Adapted from Santos et al., 2021a.

of EIF were revealed in gait velocity and leading and trailing-foot vertical and horizontal obstacle clearance, and these parameters should be analysed carefully in the future. Fig. 2 and Table 7 summarise the review's main findings, including the contradictory findings in the included studies.

4.1. Wide variability among experimentally-induced fatigue protocols

Experimental protocols and measurements used to induce and assess fatigue varied widely among the studies included in this systematic review. While some studies focused on localised multi-joint (Angelini et al., 2018; Hinkel-Lipsker et al., 2021; Park et al., 2011) and single-joint fatigue (Barbieri et al., 2014, 2013b; Hatton et al., 2013), others focused on endurance (aerobic/anaerobic) activities (Angelini et al., 2018; Antonopoulos et al., 2014; Hinkel-Lipsker et al., 2021; Hosp et al., 2018) to induce fatigue ('whole-body fatigue'). When levels of force were measured, reductions ranged from 9.5% to 29.4% after EIF (Antonopoulos et al., 2014; Barbieri et al., 2013b; Hatton et al., 2013). When heart rate was measured (Angelini et al., 2018; Antonopoulos et al., 2014; Hinkel-Lipsker et al., 2021), mean end-of-fatiguing-protocol values varied from 178 (Angelini et al., 2018) to 190 bpm, which could be interpreted as high-intensity activities (Karvonen and Vuorimaa, 1988). In addition, at the end of both protocol types (repeated contractions and aerobic), RPEs (varying from 16 to 20, or 'hard to very, very hard') confirmed the high intensity required to sustain the fatiguing protocol (Borg and Löllgen, 2001; Karvonen and Vuorimaa, 1988). Although our findings indicated that the protocols succeeded in experimentally inducing fatigue, the wide variability in the methods used may be one possible explanation for the variation in the consistency of the changes seen in obstacle crossing outcomes. This observation might, at least partly, support the idea that the specificity of the EIF protocols determined the consistency or divergence in fatigue-related changes in gait during obstacle crossing.

4.2. Effects of experimentally-induced fatigue on obstacle crossing parameters

Among the consistent results after EIF on obstacle crossing, we found reductions in stride duration (Barbieri et al., 2014), including the single (Park et al., 2011) and double-support phases (Angelini et al., 2018; Barbieri et al., 2013b; Hinkel-Lipsker et al., 2021), and no significant effect of fatigue on stride/step length (Barbieri et al., 2013b, 2014; Hatton et al., 2013; Park et al., 2011; Santos et al., 2021a). Increases in gait speed observed in two studies (Barbieri et al., 2014, 2013b) could be explained by a higher gait cadence (outcome not reported in any included studies), as significant decreases in stride duration (Barbieri et al., 2014), and double-support phase (Barbieri et al., 2013b) have been reported with no significant effect on stride/step length. From the perspective of task specificity, shorter durations were certainly to be expected after endurance-fatiguing protocols (running/walking), as they demand considerable effort in terms of the muscles and energy (Ament and Verkerke, 2009) and the maintenance of the cadenced/cyclical aspects of these tasks (Le Bris et al., 2006). Therefore, it seems plausible that such protocols might limit spatial-temporal aspects of obstacle crossing. From the perspective of repetitive muscle contractions, a decrease in step duration might be due to the direct relationship with the alteration/increase in gait velocity, as observed by Barbieri et al. (2014, 2013b). From the gait stability perspective, shorter step duration facilitates control of the body's COM in the mediolateral and fore-aft direction (Hof et al., 2007). When combined with increased step width, which provides a greater margin of safety in controlling mediolateral movements of the body's COM (Hof et al., 2007), this is a preferred strategy for dealing with threats to balance (Hak et al., 2012), such as obstacle crossing, even if it coincides with an increased gait speed.

Reductions in trailing-foot vertical clearance appeared to be the most

Table 7

Percentage changes in gait outcomes after experimentally-induced fatigue (EIF) protocols.

Author	Effect of fatigue
(Angelini et al., 2018)	Main effect: - ↓: 6.5% lead-foot horizontal clearance - ↓: 6.7% trailing-foot vertical clearance - ↑: minor and major obstacle contacts (56% and 86% respectively post-activity) Interactions: 2 times (pre vs post-activity) x 3 fatigue protocols (protocol 1 vs protocol 2 vs protocol 3) 1) environmental chamber and live-fire burn building: - ↓: 9.7% lead-foot horizontal clearance - no effect on the lead-foot vertical clearance 2) treadmill walking: - ↑: 11.7% lead-foot vertical clearance - no effect on the lead-foot horizontal clearance - ↑: errors (contact with the obstacle) Interactions: 2 times (pre vs post-activity) x 2 load carriage conditions (unloaded vs loaded) - ↓: 11.5% trailing-foot vertical clearance (loaded) - No effect on trailing foot (unloaded) - ↑: 5.3% lead-foot vertical clearance (loaded) - ↓: 12.2% lead-foot vertical clearance (unloaded)
(Hosp et al., 2018)	Main effect: - ↑: COM-COP distance Interactions: 2 times (pre vs post-exercise) x 2 taping conditions (no tape vs kinesiology tape) - NT: ↑: 10.5% COM-COP - KT: ↑: 0.5% COM-COP
(Antonopoulos et al., 2014)	Main effect: - No effects for gait speed and leading limb from the obstacle during stance after obstacle clearance - ↓: 11.5% of the distance of the trailing foot before crossing for the 10% obstacle height (compared to rested and 5 min after the fatigue induced protocol) - ↑: 27.9% Trailing leg medial gastrocnemius activity during swing phase (10% leg length obstacle height); 30.7% (20% leg length obstacle height) directly after the fatigue-induced protocol, but no significant effect found 5 min after the fatigue induced protocol
(Barbieri et al., 2014)	Main effect: - ↑: 13.9% step width - ↑: 5.9% leading heel-clearance - ↑: 4.7% step speed - ↓: 2.7% shorter stride duration Interactions: 6 groups (G20 vs G30 vs G40 vs G50 vs G60 vs G70) x 2 fatigue conditions (Before and after EIF) - G40 and G50 groups: ↑: 12.2% (G40); 13.3% (G50) leading limb heel-clearance without effects for individuals from G20, G30, G60 and G70 groups - G70 ↑: 3.3% trailing-limb heel clearance compared to individuals from G20, G30, G40, G50 and G60 groups
(Barbieri et al., 2013b)	Main effect: - ↑: increased step width (approach phase: 2.8% and crossing steps: 17.1%) - ↑: step speed (approach: 2.7% phase and crossing steps: 5.5%) - ↓: 2.6% single support (approach phase) - ↑: 3.7% stride duration (approach phase) - ↓: 18.3% double support time (crossing steps) - ↓: 2.6% vertical maximum braking force (approach phase)
(Hatton et al., 2013)	Main effect: - ↑: 6.1% leading-limb vertical loading rate after stepping over the 10% target obstacle
(Park et al., 2011)	Main effect: - ↓: 2.5% single-leg support time (crossing step) - ↑: number of subjects made movement error (baseline: 20%; pre-activity: 40%; post-activity: 61%) - ↑: Obstacle contacts (baseline: 13.3%; pre-activity: 28.9%; post-activity: 57.8%)
(Hinkel-Lipsker et al., 2021)	Main effect: - ↓: 13% leading toe clearance - ↓: 5.8% trailing heel clearance - ↓: horizontal foot placement before the obstacle (both feet): 9.9% leading foot; 9.8% trailing foot

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Table 7 (continued)

Author	Effect of fatigue
(Santos et al., 2021a) * *	-↓: 21.8% leading heel clearance
	-↓: 7.3% gait velocity (approach phase)
	-Height and VO2max are significant predictors for leading-foot horizontal placement
	-VO2max is a significant predictor of trailing-foot horizontal placement
	Interaction 2 groups (CG vs PwPD) x 2 fatigue conditions (Before and After EIF) (only CG data considered)
	- ↑: 20.1% trailing-foot horizontal clearance
	- ↑: 14.2% increased trailing-foot vertical clearance
	Interaction 2 groups (CG vs PwPD) x 2 subgroups (active and inactive) x 2 fatigue conditions (Before and after EIF) (only CG data considered)
	- ↑: 22.6% step width (approach phase) in inactive control group
	- no other significant effects specifically involving the CG (without Parkinson's disease)

COM-COP (centre of mass–centre of pressure); KT: Kinesiology tape condition; NT: no tape condition. G20, G30, G40, G50, G60 and G70 are age groups ranging from 20 to 29, 30–39, 40–49, 50–59, 60–69 and over 70 respectively, ↑: increase after EIF, ↓: decrease after EIF. * * Data were extracted based on the reported analysis for post-hoc differences involving group*fatigue or group*subgroup*fatigue interactions in which we could differentiate between the control group (CG) of the people with Parkinson's disease group (PwPD).

common observed change during obstacle crossing after fatiguing protocol (Angelini et al., 2018; Hinkel-Lipsker et al., 2021). From one perspective, this behaviour might be a direct consequence of fatiguing tasks on force and energy production, but from another, reductions in vertical clearance might be an unsuccessful attempt to avoid destabilising the COM during the obstacle crossing under fatiguing conditions. Regarding the first, fatiguing protocols (regardless of protocol type) potentially reduce force and energy, affecting obstacle crossing by making the trailing limb cross closer to the obstacle when participants are fatigued. In terms of the second perspective, reductions in trailing-limb vertical clearance observation might be an attempt by the motor system to compensate fatigue and avoid destabilisation of the COM. This observation may be supported by studies showing that increasing the vertical clearance of the crossing limb (e.g., trailing limb) leads to destabilisation of the mediolateral COM that needs to be mainly controlled/maintained under the narrow bases of support of the stance limb (e.g., leading limb) (Bruijn and van Dieën, 2018; Yamagata et al., 2021). Although maintaining the vertical clearance closer to the obstacle after EIF seems reasonable as it would avoid mediolateral destabilisation, the risk of trips (obstacle contacts) increases. This is supported by the results reported by Angelini et al. (2018) and Park et al. (2011) that indicated an increase in obstacle contacts and the number of participants who contacted the obstacle after EIF protocols. In addition, Angelini et al. (2018) showed that most of the obstacle contacts occurred with the trailing leg (regardless of the fatigue condition) and increased with fatigue (86% pre-fatigue; 97% post-fatigue; 93% overall).

Additional evidence indeed supports that crossing an obstacle with one's feet close to it is particularly dangerous, increasing the risk of a trip (Chou and Draganich, 1998), especially the trailing foot crossing the obstacle without visual exproprioceptive input (Patla et al., 1996; Vuillerme et al., 2001). It seems that the effects of EIF on obstacle crossing outcomes are exacerbated by the absence of sensory information. This corroborates the idea that availability of visual cues allows individuals to compensate for the destabilising effect of fatigue (Miura et al., 2004; Vuillerme et al., 2005, 2002a; Vuillerme and Boisgontier, 2008). Indeed, it is recognised that visual information plays an important role in maintaining dynamic stability and control when crossing obstacles (Patla et al., 1991). Vision plays a further important role in compensating for muscle fatigue in the control of upright standing, as repeatedly reported in previous studies (Barbieri et al., 2019; Penedo et al., 2021; Vuillerme et al., 2006, 2001). This idea also supports the

pronounced effects of fatigue on obstacle crossing in the absence of kinesiology tape (Hosp et al., 2018), which is known to improve proprioceptive information (Park and Lee, 2016).

The specificity of the protocols also helps to explain the divergent results reported in the literature. Some studies provided evidence indicating increases in leading-limb vertical clearance (Barbieri et al., 2014) and gait velocity (Barbieri et al., 2014, 2013b) after the fatiguing protocol, whereas others indicated decreases (Angelini et al., 2018) or no effects (Antonopoulos et al., 2014) and no effects on gait velocity (Antonopoulos et al., 2014; Park et al., 2011). Also, one study found significant increases in trailing-limb vertical and horizontal clearance (Santos et al., 2021a), whereas two other studies found reductions for those parameters after EIF (Angelini et al., 2018; Hinkel-Lipsker et al., 2021). Concerning leading-foot horizontal clearance, one study found that it decreased (Angelini et al., 2018), while another reported no significant differences after EIF compared to the 'rested' state (Antonopoulos et al., 2014). Diverging results might reflect the protocols used to induce fatigue (Table 4) and assess gait during obstacle crossing (Table 5). For instance, since the sit-to-stand task puts substantial demands on knee extensors (50–90% of relative maximal capacity), but also requires substantial efforts from the dorsiflexors to maintain postural control (Bieryla et al., 2009; Santos et al., 2021a), it is conceivable that repetitive sit-to-stand would impair deceleration of the COM and the clearance distance during the late swing phase, and hip flexion and vertical clearance during obstacle crossing (Angelini et al., 2018; Hinkel-Lipsker et al., 2021; Hosp et al., 2018). Similarly, when plantar flexor muscle functions are impaired by muscle fatigue (Antonopoulos et al., 2014), push-off power may be affected. Such alterations, induced by localised muscle fatigue, would thus explain the decrease in vertical clearance (impairing hip flexion, push-off and dorsiflexion). It is curious, however, that the alteration caused by muscle fatigue resulted in increased speed. Although counterintuitive, an increase in speed might be associated with a necessary compensatory increase in the anteroposterior margin of stability (i.e., by increasing the step/stride length (Santos et al., 2021b). Unexpectedly, increased gait speed might be accompanied by an increase in braking force rather than a decrease (Peterson et al., 2011), as observed by Barbieri and colleagues (Barbieri et al., 2013b). An increase in gait speed may potentially be accompanied by an increase in heel-strike velocity, reinforcing the evidence indicating a relationship between gait speed and braking forces (Keller et al., 1996; Peterson et al., 2011). As repetitive sit-to-stand is supposed to induce fatigue in knee extensors, and knee extensors act in decelerating COM (Hatton et al., 2013), a decrease in braking force after fatigue is somehow unexpected. Another unexpected divergent result is the absence of significant changes in gait speed after ankle muscles were fatigued (Antonopoulos et al., 2014). Perhaps, the substantial increase in muscle activation amplitude (27–30%) compensated for the potentially deleterious effects of EIF on kinematic outcomes.

From the different perspective of 'whole-body fatigue', extenuating aerobic/anaerobic exercises degrade dynamic postural control (Paillard, 2012). During this type of task, metabolic activation increases cardiac and breathing rhythms and leads to hyperventilation and tachycardia. Such behaviours accentuate the amplitude of body sways (Paillard, 2012; Springer and Pincivero, 2009). This explains the increased COM-COP distance observed by Hosp and colleagues (Hosp et al., 2018). Additionally, if a positive relationship between COM-COP distance and COP velocity exists, the increase in COM-COP distance might require a reactive longer step or higher frequency to maintain the dynamic stability, resulting in an increased gait velocity. Although this would be a necessary reactive strategy on one side, increasing the gait velocity reduces the time available to perform adjustments when needed, especially when obstacle crossing, and can increase the risk of accidents. And this seems correct, as indicated by the increased number of obstacles struck during crossing after EIF (Angelini et al., 2018; Park et al., 2011).

Common hypotheses for explaining these results involve the

compensatory mechanisms that try to cope with the effects of fatigue. Indeed, during less demanding tasks, such as unobstructed walking or a standing postural task, participants somehow seek to compensate for these effects by changing behavioural aspects of the task (e.g., increasing their gait speed) (Barbieri et al., 2013a), reorganising joint coordination (Paillard, 2012; Pinsault and Vuillerme, 2010), or increasing or balancing contributions from sensory information (e.g., increasing dependency on visual information) (Barbieri et al., 2013a; Vuillerme et al., 2006, 2002a, 2002b). It is, therefore, possible that: (1) it is more difficult to compensate for EIF because there is no visual exproprioceptive input (Patla et al., 1996) for the trailing foot while this limb is crossing the obstacle; (2) an increase in gait speed could be a compensatory strategy to improve gait stability in a fatigued state (Barbieri et al., 2014, 2013b); (3) the effects of EIF affect obstacle crossing, increasing the risk of tripping on that obstacle, and that risk may be even higher in obstacle vs level walking (Nagano et al., 2014) due to the high demands of that task. Combining these three points, it is important to consider that even though some outcomes indicate that a compensatory strategy/mechanism is at work to minimise fatigue's effects, they do not seem to be as efficient during obstacle crossing as during unobstructed walking tasks since trailing foot clearance significantly decreased (Angelini et al., 2018; Hinkel-Lipsker et al., 2021) and the number of times the obstacle was struck increased (Angelini et al., 2018; Park et al., 2011).

5. Studies limitations and future directions

The present study had some limitations. The number of articles included in this systematic review was low ($n = 9$), and despite their high quality, some aspects were not reported. Participant recruitment and sampling methods were not often mentioned, including no mentions of limb asymmetries or body fat. Also, the clinical implications of the nine studies' research lacked detail and clarity (Angelini et al., 2018; Antonopoulos et al., 2014; Barbieri et al., 2013b, 2014; Hatton et al., 2013; Hinkel-Lipsker et al., 2021; Hosp et al., 2018; Park et al., 2011; Santos et al., 2021a).

Of 296 participants, only about 8% were women, and none of the studies including women ($n = 3$ studies, 33.3%) compared the sexes. Future studies should investigate potential differences as women and men have been reported to exhibit different gait behaviours in level walking (Smith et al., 2002). We also noted that no comparisons of participants' anthropometric characteristics (e.g., height, weight, BMI) were performed despite the fact that being overweight and obesity are known to significantly affect flat walking (Browning and Kram, 2007). We could hypothesise that a more demanding task, like crossing an obstacle under the effects of EIF, would cause different locomotor adaptations among those individuals than among individuals of normal weight. Furthermore, the fatiguing protocols worked in various ways. Some studies applied localised muscle fatigue (e.g., sit-to-stand task) (Barbieri et al., 2013b, 2014; Hatton et al., 2013; Santos et al., 2021a), whereas others used combined activities (Angelini et al., 2018; Hinkel-Lipsker et al., 2021; Park et al., 2011) or aerobic locomotor/walking tasks (Angelini et al., 2018; Antonopoulos et al., 2014; Hosp et al., 2018). Moreover, no two sets of authors use the same obstacle crossing protocol; thus, there was a lack of standardisation between studies and sometimes a lack of information (e.g., test starting point for individuals). Obstacle crossing tasks were very different from one another: fixed heights varied from 15 cm to 30 cm; varying heights according to the length of each subject's legs, from 10% to 60%; double tasks or not; number of repetitions; number of sessions, etc.). It seems obvious that obstacle height is one of the variables that most affect the muscular, kinetic and kinematic outcomes of an individual's walk during the crossing (Patla and Rietdyk, 1993) and, therefore, that their great variability may have played a role in the differences observed in the results.

The effects of practice or familiarisation with the obstacle crossing protocol were never discussed, despite four studies (44.4%) clearly

indicating that participants had practice runs. During walking on flat ground, practice or familiarisation with the protocol enhanced between-day test–retest reliability (Hamacher et al., 2017). Obstacle crossing is a more demanding task (Patla and Rietdyk, 1993; Patla et al., 1991), however, so investigating the effects of practising it would seem relevant when trying to appreciate the effects of fatigue during obstacle crossing.

Future studies could aim to improve the consistency of EIF protocols. Because the effects of fatigue might be task-specific, more consistent use of protocols would enhance the mechanical and functional relevance of studies. Relevant studies should focus on comparing the effects of different types of EIF protocols on gait, e.g., whole-body fatigue vs localised muscle fatigue of the lower limbs. This type of study would be a useful means of enhancing the discussions on whether fatigue-induced changes in muscle or physical performances are task-dependent and whether they might induce changes in obstacle crossing. They would also help to refine interpretations of fatigue's effects on obstacle crossing tasks. In addition, assessing mental fatigue and integrating dual cognitive tasks (only performed by one of our studies, 11.1%) during obstacle crossing would be relevant to investigating whether fatigue interferes with the capacity to allocate cognitive resources in motor tasks with higher cognitive involvement (Billington et al., 2013). This could include observations indicating mental fatigue's interference in gait when walking is combined with a secondary cognitive task (van Cutsem et al., 2017). Further potential experiments should also consider individual characteristics since sex or anthropometric features might interfere with EIF's effects on muscle and physical function and on obstacle crossing tasks.

We could consider our findings for kinematic outcomes consistent because nine studies assessed these parameters; however, only three studies assessed kinetics and only one assessed EMG parameters—a rather limited number. Accordingly, the results presented for these parameters were more inconsistent and dependent on the study design (type of fatigue protocol, obstacle crossing protocols, population recruited, etc.). Including these assessments in future studies would be appropriate to increase understanding of the mechanisms related to EIF's effects during obstacle crossing tasks.

In addition, although few studies reported participants' obstacle contacts (errors) during the performance of the obstacle crossing task (Angelini et al., 2018; Park et al., 2011) ($n = 2$, 22.2%), all of them (Angelini et al., 2018; Park et al., 2011) showed increased obstacle contacts after EIF and that most contacts occurred with trailing leg. Considering tripping on or collision with an obstacle as responsible for more than a half of falls during walking (Pavol et al., 2001), these results underscore the importance of carefully examining this outcome that could identify risk for falls during obstacle crossing. In line with this suggestion, we can mention the recent systematic review from Galna and colleagues on obstacle crossing in older adults (Galna et al., 2009), in which obstacle contacts have been reported in 10 out of the 15 included studies (66.7%) showing that older adults made more obstacle contacts compared to young adults. Interestingly, these authors further concluded that “*Given the infrequent nature of obstacle contact events that occur when conducting obstacle crossing studies, it is recommended that future obstacle crossing studies report the frequency and nature of any obstacle contacts that occur.*” (Galna et al., 2009, p 273).

Finally, two of the review's nine studies did not confirm their participants' post-protocol fatigue levels (Hosp et al., 2018; Park et al., 2011) (or even whether they were fatigued). In addition to the absence of a fatigue assessment, the use of different measurement tools, both objective and subjective, may also have had a role in explaining the divergence in subjects' locomotor adaptations after EIF: a study's objective data (e.g., quadriceps isometric strength) cannot be compared using other means of assessing fatigue levels, especially subjective ones. As a result, evaluating fatigue levels using objective means (e.g., the level of force developed by a muscle) and subjective means (e.g., Borg scale rating of perceived exhaustion) is one of the essential elements to comprehending subjects' locomotor adaptations better during this

complex walking task—fatigue is not a binary state going from complete rest to total exhaustion. A better understanding of fatigue's effects during obstacle clearance across different populations would be clinically relevant because it would identify the profiles most at risk of slips, trips and falls during this type of task, which can lead to serious or even fatal consequences. Lastly, certain forms of fatigue were not evaluated by our studies, notably mental fatigue. Obstacle crossing is a more complex task than walking flat, especially in its need for an individual to use relevant environmental information (Billington et al., 2013) and more cognitive resources (Chen et al., 2017). Since mental fatigue affects the capacity to accurately allocate cognitive resources (van Cutsem et al., 2017), it would seem that a state of mental fatigue could well affect obstacle crossing, and this could be a topic for examination in the future.

6. Conclusion

The present systematic review of nine studies revealed that EIF affected the kinematic, kinetic and muscular aspects of walking tasks involving obstacle crossing. However, a great variety of consistent and inconsistent outcomes were observed, with differences explained by the heterogeneity of the obstacle crossing protocols, the protocols for inducing fatigue and the populations chosen for study. We also noted that few studies to date have investigated obstacle contacts, and kinetic and muscular parameters, and none has assessed the effects of mental fatigue on this type of task, which could be appropriate research elements for future studies. Finally, these findings should be interpreted with caution as no overarching or generalisable conclusions could be drawn regarding the effects of EIF on obstacle crossing tasks.

Authors contributions

This work is part of MC's PhD thesis (Univ. Grenoble Alpes, France & São Paulo State University (Unesp), Bauru, Brazil), co-supervised by NV and FAB. MC, NV and FAB contributed to conceiving and designing this study. MC and TP extracted the data. All the authors interpreted the data. MC wrote the manuscript's first draft. All authors contributed to manuscript revision and read and approved the manuscript's final submitted version. All the authors have approved the version submitted and have agreed to be both personally accountable for the first author's contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which they were not personally involved, were appropriately investigated, resolved and documented in the literature.

Conflict of interest

The authors declare that they have no proprietary, financial, professional or other competing or conflicting interests regarding this study and the publication of this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgements

This study was part of MC's PhD thesis (Univ. Grenoble Alpes, France & São Paulo State University (Unesp), Bauru, Brazil) co-supervised by NV and FAB. It was supported by the French National Research Agency within the framework of the Investissements d'avenir programme (ANR-10-AIRT-05 and ANR-15-IDEX-02) and by Brazil's Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Finance Code 001. This work is part of a broader translational, interdisciplinary research project, GaitAlps (NV).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2022.104854.

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