

POST-GRADUATE PROGRAM IN MOVEMENT SCIENCES - INTERUNIT

MUSCULAR FATIGUE AND POSTURAL CONTROL IN YOUNG ADULTS

PhD: Tiago Penedo

Supervisor: Dr. Fabio Augusto Barbieri

Co-Supervisor: Dr. Nicolas Vuillerme



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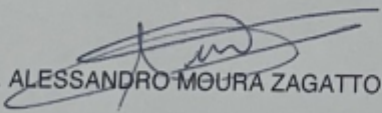
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ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DE TIAGO PENEDO, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DO MOVIMENTO, DA FACULDADE DE CIÊNCIAS - CÂMPUS DE BAURU.

Aos 16 dias do mês de janeiro do ano de 2025, às 14h, por meio de Videoconferência, realizou-se a defesa de TESE DE DOUTORADO de TIAGO PENEDO, intitulada **Muscular fatigue and postural control in young adults**. A Comissão Examinadora foi constituída pelos seguintes membros: Prof. Dr. LUIS MOCHIZUKI (Participação Virtual) do(a) Escola de Artes, Ciências e Humanidades / Universidade de São Paulo - SP, Dr. PAULO CEZAR ROCHA DOS SANTOS (Participação Virtual) do(a) Ciência Pioneira/ IDOR – Instituto D'OR de Pesquisa e Ensino, Prof. Dr. DANIEL BOARI COELHO (Participação Virtual) do(a) Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas, Laboratório de Biomecânica e Controle Motor / Universidade Federal do ABC, Prof. Dr. ALESSANDRO MOURA ZAGATTO (Participação Presencial) do(a) Departamento de Educação Física / UNESP - Faculdade de Ciências de Bauru - SP, Prof. Dr. VICTOR SPIANDOR BERETTA (Participação Virtual) do(a) Departamento de Educação Física / UNESP - Faculdade de Ciências e Tecnologia de Presidente Prudente - SP. 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. ALESSANDRO MOURA ZAGATTO

*À minha família, aos meus colegas
e a todos que contribuíram para o
cumprimento desta meta.*

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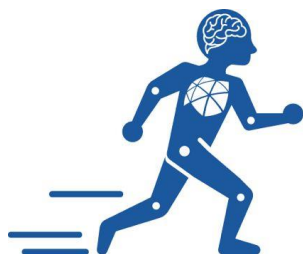
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MOVI-LAB

Laboratório de Pesquisa em Movimento Humano

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RESUMO

Esta tese explora os efeitos da fadiga induzida pelo exercício no controle postural de adultos jovens saudáveis, com foco nas adaptações comportamentais e corticais. O exercício fatigante, seja geral ou localizado, aumenta a oscilação corporal, destacando o papel crítico das estruturas subcorticais e corticais na manutenção da estabilidade. A ativação cortical compensatória atua como uma resposta adaptativa essencial, mas com um custo neuromuscular e cognitivo elevado. Efeitos residuais, como a dor muscular de início tardio (DOMS), podem causar prejuízos de longo prazo no controle postural. A tese aborda essas questões por meio de três estudos: i) **Revisão sistemática**: analisa os efeitos da fadiga no controle postural, as dinâmicas de recuperação e as lacunas metodológicas; ii) **Estudo comparativo**: examina como a fadiga geral (corrida em esteira) e localizada (exercício de tornozelo) afetam de forma diferenciada a atividade cortical e o controle postural; iii) **Investigação de efeitos de longo prazo**: avalia a recuperação do controle postural até 192 horas após a fatigabilidade localizada. A revisão sistemática revelou significativa variabilidade metodológica e a falta de estudos sobre as contribuições corticais para a regulação postural. Os achados experimentais mostraram que tanto a fadiga geral quanto a localizada prejudicam os sistemas musculoesquelético, sensorial e cortical. A fadiga geral resultou em maiores alterações corticais, com aumento da atividade delta e redução das atividades alfa, beta e teta, especialmente nas áreas pré-frontal, motora e occipital. A fadiga localizada também induziu mudanças corticais, embora em menor grau. Os efeitos de longo prazo indicaram déficits posturais persistentes por até 192 horas, ressaltando a necessidade de estratégias eficazes de recuperação. Ao integrar perspectivas biomecânicas e neurofisiológicas, esta tese

aprimora a compreensão do impacto da fadiga no controle postural. Os resultados ressaltam o papel crucial do envolvimento cortical e fornecem uma base para intervenções direcionadas em esportes, reabilitação e atividades diárias que exigem estabilidade do equilíbrio. Pesquisas futuras devem explorar as interações cortico-motoras para otimizar a recuperação e melhorar o desempenho motor e a segurança.

Palavras-chave: Controle motor; Postura; Fadiga; Eletroencefalografia; Dor tardia.

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ABSTRACT

This thesis explores the effects of exercise-induced fatigability on postural control in healthy young adults, focusing on behavioral and cortical adaptations. Fatiguing exercise, whether general or localized, increases body sway, emphasizing the critical role of subcortical and cortical structures in maintaining stability. Compensatory cortical activation serves as a key adaptive response but comes at a higher neuromuscular and cognitive cost. Residual effects, such as delayed-onset muscle soreness (DOMS), may cause long-term impairments in postural control. The thesis addresses these issues through three studies: i) **Systematic review**: To analyze the effects of exercise-induced fatigability on behavioral and cortical aspects of postural control, identifying recovery dynamics and methodological gaps; ii) **Comparative study**: To how general (treadmill running) and localized (ankle exercise) fatiguing protocols differentially affect cortical activity and postural control; iii) **Long-term effects investigation**: To assess postural control recovery up to 192 hours after localized fatigability. The systematic review revealed significant methodological variability and a lack of studies on cortical contributions to postural regulation. Experimental findings showed that both general and localized fatigue impair musculoskeletal, sensory, and cortical systems. General fatigue led to greater cortical changes, with increased delta and decreased alpha, beta, and theta activity, particularly in prefrontal, motor, and occipital areas. Localized fatigue also induced cortical changes, albeit to a lesser extent. Long-term effects indicated persistent postural deficits up to 192 hours, highlighting the need for effective recovery strategies. By integrating biomechanical and neurophysiological perspectives, this thesis enhances understanding of fatigability's impact on postural control. Findings underscore the crucial

role of cortical engagement and provide a basis for targeted interventions in sports, rehabilitation, and daily activities requiring balance stability. Future research should explore cortical-motor interactions to optimize recovery and improve motor performance and safety.

Keywords: Motor control; Posture; Fatigue; Electroencephalography; Delayed soreness.

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CHAPTER 1

GENERAL INTRODUCTION

1. General Introduction

In general, literature has advanced in understanding and clarifying the sensory and motor impairments causes by fatiguing exercise during daily motor actions, such as maintaining standing posture. Thus, studying exercise-induced fatigability helps explain the neural system's ability to adapt plastically (MILLET et al., 2011) through the sensory integration among the visual, somatosensory, and vestibular systems (JOHANSSON; MAGNUSSON; ÅKESSON, 1988), enabling compensation and/or correction of motor responses after neuromuscular disorders. The effects of fatiguing exercise on postural control, regardless of the type of exercise, are well documented in the literature: increased body sway (BARBIERI et al., 2019; PENEDO et al., 2021), primarily due to damage to the somatosensory system (LIN et al., 2009a), delayed motor responses (ENOKA; DUCHATEAU, 2008; PAILLARD, 2012), and failures in muscle activation from peripheral and central origins (BOYAS et al., 2013). However, limited scientific attention has been given to the effects of fatiguing exercise on cortical activation during postural control. The cortical regions involved in postural control remain poorly understood, especially under the influence of exercise-induced fatigability.

Fatiguing exercise can cause changes in neural activity at both spinal and supraspinal levels. Studies based on functional magnetic resonance imaging (fMRI) have indicated significant fatigue-related changes, particularly in cortex-related supraspinal pathways: the cerebral metabolism increase during fatiguing exercise, following by a decrease just after fatiguing exercise (HERATH et al., 2017; LIU et al., 2005). This is a compensatory response to the immediate adverse effects of exercise-induced fatigability on neuromotor aspects. However, the impacts of different types of fatiguing exercises on cortical activity during postural control, and whether these effects persist long-term, have not been thoroughly compared. Understanding the consequences of fatigability on

cortical activation during posture could clarify the neuromuscular mechanisms underlying postural compensation under limited neuromotor conditions, potentially aiding in the prevention of postural imbalances that can lead to falls and injuries in tasks that require effective standing posture control. This model could also provide insights into pathologies characterized by fatigability-related symptoms. Thus, the main scientific question of this thesis is:

How does the cortex of healthy young adults behave during a postural task after performing fatiguing exercise?

Therefore, the general aim of this thesis is to investigate the effects of fatiguing exercise on the cortical activation of healthy young adults during the control of standing posture. The general hypothesis of the thesis is that after performing the fatiguing exercise healthy young adults will change cortical activation during postural control (ENOKA; DUCHATEAU, 2017; POST et al., 2009) to compensate for the reduced excitation of spinal motor neurons (KLASS et al., 2008; MCNEIL et al., 2009).

1.1. Control of standing posture and cortical activity

Healthy humans can maintain an upright posture. For more than a century, the characteristics of human upright posture have been investigated (VARGHESE et al., 2015), revealing that people are never completely still, exhibiting small but continuous body sways even when instructed to remain motionless (FREITAS; DUARTE, 2012; HORAK; MACPHERSON, 1996; MEZZARANE; KOHN, 2007; STOFFREGEN et al., 2000). However, it took centuries for science to understand how balance control occurs during upright posture. The first evidence showed that postural control can be regulated

at subcortical levels, functioning as a reflexive and automatic behavior (VARGHESE et al., 2015). From a reflexive and automatic postural control perspective, previous studies showed the important role of subcortical structures such as the brainstem and spinal cord to control the upright posture (HORAK; MACPHERSON, 1996; TAKAKUSAKI, 2017; WOOLLACOTT; SHUMWAY-COOK, 2002)

Controlling posture requires continuous monitoring and correction of body sway. Postural control is defined as the ability to maintain a desired or required position during motor activity (WINTER, 1995), involving the constant regulation of body position in space to remain stable against gravity through two main behavioral objectives (PAPA; HASSAN; BUGNARIU, 2016; SHUMWAY-COOK; WOOLLACOTT, 2001): i) body balance: the ability to move in a controlled and organized manner while maintaining a desired position by managing external forces and internal torques acting on the body (HORAK; KUO, 2000) and; body orientation: the CNS integrates and interprets multisensory input from the visual, vestibular, and somatosensory systems, establishing a general representation of the body relative to the environment and among body segments, accurately regulating the efferent mechanisms that control posture (HORAK; KUO, 2000). Practically, postural control can be measured by the center of pressure (CoP), representing the average of all pressures applied to the surface in contact with the ground. The CoP can be conceptualized as the vector point of application of vertical ground reaction forces acting on the support base. In a quiet bipedal stance, the support base is defined in the anteroposterior direction by the tips of the feet and heels and in the medial-lateral direction by the outer edges of the feet (VAN WEGEN; VAN EMMERIK; RICCIO, 2002). During bipedal stance, the CoP oscillates in all directions to maintain balance between the two feet (IVANENKO; GURFINKEL, 2018). Effective postural control requires keeping the CoP within the stability limits formed by the support base

(WINTER, 1995). To maintain the CoP within the support base limits, ensuring stability during posture control, two joint strategies can be used: 1) ankle joint strategy involving ankle dorsiflexion and plantar flexion; and 2) hip joint strategy involving flexion and extension of the hip (CHOW et al., 2016; PENEDO et al., 2021; WINTER, 1995). Previous studies from our laboratory demonstrated that young adults prefer the ankle strategy, even after experiencing disturbances such as exercise-induced fatigability in the muscles responsible for controlling this region (PENEDO et al., 2021).

Controlling bipedal posture involves complex neuromotor and biomechanical challenges. Through several interconnected mobile segments, the body's support elements, such as the muscles of the postural control system, maintain stability (SLOBOUNOV et al., 2009). This stability counters external forces like gravity acting on the body (OZDEMIR; CONTRERAS-VIDAL; PALOSKI, 2017), which attempt to displace the elevated center of mass over a relatively small base of support (VARGHESE et al., 2015; WINTER, 1995). Therefore, the postural control system continuously performs adjustments, making movement voluntary. Voluntary movements originate from motor commands intentionally induced by cortical structures. So, from the point of view of voluntary postural control, although the role of subcortical structures in posture control has been proven, more recent studies have complemented this information, bringing evidence that cortical structures also play an important role to maintain balance during postural control (HÜLSDÜNKER et al., 2015; MIHARA et al., 2008; SLOBOUNOV et al., 2009; TAKAKUSAKI, 2017).

The standing posture is controlled by spinal and supraspinal pathways. However, the interaction between these levels involves two closed-circuit mechanisms: i) L1 loop, located in the spinal cord, triggered by limb mechanoreceptor input, generating corrective motor responses to compensate for postural disturbances; ii) L2 loop, comprising the

brainstem and motor cortex (BELOOZEROVA et al., 2003, 2005), triggered by limb mechanoreceptor signals while also receiving head orientation information from the visual and vestibular systems. Different descending pathways (reticulospinal, corticospinal, etc.) send phasic commands to the spinal cord, which, combined with spinal reflexes, contribute to postural corrections (DELIAGINA et al., 2006). Specific reflexes involved in spinal control of posture include stretch reflexes, reciprocal inhibition, non-reciprocal inhibition (autogenic inhibition), and flexion reflexes. In particular, the stretch reflex and non-reciprocal inhibition (Ib inhibition) play key roles in static posture control. However, spinal cord neural networks alone cannot fully control postural balance (ROSSIGNOL et al., 2008; ROSSIGNOL; DUBUC; GOSSARD, 2006). Complete postural control requires integrating descending supraspinal signals and peripheral sensory afferents at the spinal cord level (TAKAKUSAKI, 2017).

The supraspinal pathways also play a crucial role in regulating standing posture. These mechanisms seem to be in the cerebellum and brain stem (LYALKA et al., 2005), which are themselves influenced by inputs from the basal ganglia (TAKAKUSAKI, 2017). Tonic commands from sensory signals aid in detecting and correcting postural instability by acting on the cerebellum, brain stem (TAKAKUSAKI, 2017), and the cortex. The cerebellum regulates both automatic and cognitive processes of postural control through thalamocortical projections and brain stem connections. Information from the cortex via the cortico-cerebellar-spinal pathway and real-time sensory feedback through the spinocerebellar tract to the cerebellum are vital for these processes (TAKAKUSAKI, 2017). Regardless of whether the initiation is volitional or emotional, goal-oriented behaviors are always accompanied by automatic postural control processes, including balance adjustments and muscle tone regulation. This largely unconscious process is triggered by sequential neuron activations in the brain stem and spinal cord.

However, in unfamiliar circumstances or after disturbances such as exercise-induced fatigability, individuals require cognitive control of posture. This process depends on body awareness and the spatial location of objects in the surrounding environment (TAKAKUSAKI, 2017). Effective postural control, therefore, relies on understanding body orientation, movement in space, and the perception of spatial object locations (MAURER; MERGNER; PETERKA, 2006; MERGNER; BECKER, 2003). This integration of vestibular, somatosensory, and visual sensory signals occurs in both the cortex and cerebellum.

Cortical regulation is essential for maintaining human bipedal posture. Recent brain imaging studies using electroencephalography (EEG) have provided valuable insights into cortical neurophysiology related to postural instability (SLOBOUNOV et al., 2008). However, EEG studies remain inconclusive about the specific cortical regions activated during standing posture control. Some investigations have highlighted the role of frontal-central regions, such as the prefrontal cortex (MIHARA et al., 2008) which supports regulatory output for posture and visuospatial attention. The motor cortex (SLOBOUNOV et al., 2005) is responsible for initiating postural movements, while the anterior cingulate cortex (HÜLSDÜNKER et al., 2015) monitors motor actions and detects balance instability. Certain parietal cortical regions are also implicated in postural control. The upper parietal cortex integrates multimodal inputs from the vestibular, somatosensory, and visual systems (HÜLSDÜNKER et al., 2015), the primary sensory sources for maintaining posture. This region plays a central role in sensorimotor transformation and sensory information processing. Notably, activation signals in the frontal and parietal cortical areas are linked to increased theta-band activity, reflecting sensory information transfer from the parietal cortex to the anterior cingulate cortex for error detection and processing (HÜLSDÜNKER et al., 2015; SIPP et al., 2013). This

emphasizes the involvement of these cortical regions in sustaining postural control. The cortex's contribution to postural control is critical for acquiring new postural synergies and compensating for motor and postural disorders caused by disruptions to postural networks, such as those induced by exercise-induced fatigability. However, the literature still lacks clear identification of the most active cortical regions during standing posture control, especially under neuromotor disturbances like exercise-induced fatigability.

1.2. Effects of fatigability on cortical activity

First of all, it seems important to comment on the term “fatigability” instead of “fatigue” used in this thesis. The definition of fatigue is complex and, eventually, controversial and non-consensual. Historically, the concept of fatigue denotes reductions in both cognitive and physical function, ranging from feelings of tiredness and weakness that accompany some clinical conditions to exercise-induced impairment in motor performance (ENOKA; DUCHATEAU, 2017; KLUGER; KRUPP; ENOKA, 2013). Since the term “fatigue” has been commonly used without standardized definitions or direct measurements, currently a new unifying taxonomic proposal has been assigned to refer to the “fatigue” and “fatigability” terms. Therefore, since these terms seem to refer to different situations, it seems plausible to treat them in different ways. Therefore, it is proposed that fatigue be conceptualized as a disabling symptom in which both physical and cognitive functions can be limited by interactions between two attributes, respectively: (1) performance fatigability - a decline in one or more objective measures of performance within a discrete period of time and; (2) perceived fatigability - classifies changes in subjective sensations and perceptions, through self-reported scales (ENOKA; DUCHATEAU, 2017).

In this thesis, the concept of fatigability is attributed to exercise-induced objective changes related to performance. For example, it is possible to include resistance time or time to task failure (the duration that a task can be maintained) or the rate of change in variables such as rating perceived effort and strength production during maximum voluntary contraction (ENOKA; DUCHATEAU, 2017). So, the performance fatigability attribute depends on the contractile capabilities of the muscles involved for the proposed motor task. Additionally, it relies on the CNS's ability to generate an adequate activation signal based on descending commands and afferent feedback. Despite the different concepts about the origin of fatigability, most explanations still have a source and point of view based on physiology. The interrelationship between the areas of knowledge (i.e., physiology and motor control) can help to improve the explanations both the origin of the exercise-induced fatigability process and of what it causes to the movements.

Exercise-induced fatigability alters (impairs) the control of human movement and can be caused by the combination of peripheral and central origins (i.e., components). The peripheral component affects the muscles' contractile capabilities. This process may occur due to the failure of the excitation-contraction coupling within the muscle fibers, disturbances in the muscle's superficial membrane, and subsequent metabolic events that happen during the repetitive contraction-relaxation cycle that results in muscle activity (GREEN, 1997). During physical exercise, the motoneurons are excited in the spinal cord, and the axon of the motoneuron in the medulla transmits the action potential to the neuromuscular junction, generating muscle activation (TANAKA; WATANABE, 2012). The peripheral nerve, neuromuscular junction, and muscles are referred to as peripheral structures. Thus, a progressive decline in physical performance is caused by the repeated use of muscles, leading to the belief that much of the peripheral component of fatigability occurs in the muscles (TANAKA; WATANABE, 2012).

The central component comes from the spinal or supraspinal origin (GANDEVIA et al., 1996; GANDEVIA; ALLEN; MCKENZIE, 1995). It affects the nervous system's ability to provide an adequate activation signal to the muscles, derived from both downward commands and insufficient afferent feedback to perform the proposed task (ENOKA; DUCHATEAU, 2017). The central component occurs when there is a measurable reduction in muscle force attributable to a decline in motor neuronal output and voluntary activation, which can be measured by the twitch interpolation technique (MILLET et al., 2011). Thus, performance-related fatigability arises not only from peripheral processes in active skeletal muscles during exercise but also from supraspinal mechanisms within the brain (GANDEVIA, 2001), causing a reversible decline in the neuromuscular system's capacity to generate force. Supraspinal mechanisms contribute to central fatigability, which decreases M1 motor production, was seen during maximum voluntary isometric contractions (TANAKA; WATANABE, 2012), being responsible for 20 to 25% of force drop (TAYLOR; TODD; GANDEVIA, 2006).

Fatigability induces disturbances in the neuromuscular system, reducing muscle strength (BIZID et al., 2009a; HARKINS et al., 2005; PAILLARD, 2012). This problem hinders the quality of information input from the proprioceptive system (PENEDO et al., 2021), impairing sensory integration. Thus, by limiting the ability to quickly correct ineffective movements and increasing muscle co-contraction (FRANKLIN et al., 2007; HELBOSTAD et al., 2007; IZAWA et al., 2008; LORD et al., 1993; PARIJAT; LOCKHART, 2008; VAN DIEËN; KINGMA; VAN DER BUG, 2003) deficits in motor actions are generated due to central and peripheral limitations caused by fatiguing exercise. In this way, new motor units are recruited to compensate for these adverse effects, requiring a new organization of muscle activation and movement control to compensate for the deficits caused after fatiguing exercise (BISSON et al., 2011;

BOYAS; HAJJ; BILODEAU, 2013; LIN et al., 2009a; STRANG; BERG; HIERONYMUS, 2009; VUILLERME; BOISGONTIER, 2010; WOJCIK et al., 2011). However, there are still few studies that investigate the implications that fatiguing exercise has on the reorganization of movement, to prolong motor skills in tasks that do not require high strength production (AUNE; INGVALDSEN; ETTEMA, 2008). Understanding the consequences of fatiguing exercise on coordination and motor control adjustments can bring new knowledge of how the sensorimotor system responds to immediate requirements after a sensory disturbance caused by exercise-induced fatigability..

Previous evidence shows that supraspinal (i.e. central) mechanisms, related to an output of the motor cortex, can contribute intensely to fatigability after a prolonged period of low-intensity exercise (SMITH et al., 1999). Several investigations have reported a reduction in neural signals responsible for driving active agonist muscles in fatigued subjects during repeated contractions (BIGLAND-RITCHIE; WOODS, 1984; TAYLOR; TODD; GANDEVIA, 2006). This finding conclusively demonstrates the role of central factors in motor production. Since all peripheral phenomena are under central control, it is therefore conceivable that the cortex plays a role to the perception of fatigability.

Previous studies (HERATH et al., 2017) show that the central pre-motor cortex is a homogenous region responsible for phylogenetic and physiological motor planning in the human brain (ÖNGÜR; PRICE, 2000). Additionally, along with the anterior central pre-motor cortex, it has connections with the central and ventral caudate nucleus, the ventral striatum and the insula (YETERIAN; PANDYA, 1991), all of which play a role in the beginning of motor control. Another process that may contribute to supraspinal fatigability is the transcallosal inhibition of the contralateral motor cortex by the corresponding areas of the ipsilateral motor cortex (BÄUMER et al., 2002; LIANG et al.,

2008; MARUYAMA et al., 2006). During the performance of a maximum physical exercise, there is a decrease in the EEG beta power in the electrodes C3, Cz, C4, Fz, and Pz, corresponding to the muscle signals, such as voluntary force and electrical signals from the muscles (LIU et al., 2005). Also, a decrease in the intensity of activation was found in the contralateral M1 area (LIU et al., 2005), leading to a decreased response in contralateral M1. Thus, it is believed that a decrease in the excitatory stimulus to M1, together with a decrease in the responsiveness of motoneurons in M1 and an increase in the inhibitory stimulus to M1 is associated with the supraspinal component of fatigability (TAYLOR; GANDEVIA, 2008).

Therefore, the mechanisms that contribute to both the deceleration of the firing rates of motor units (MU) and the limitation of recruitment of MU are central to supraspinal fatigability (TANAKA; WATANABE, 2012). However, despite all this knowledge, the comparison between general and localized fatiguing exercises during the control of standing posture needs to be better explored. Therefore, this information may be important to clarify the complex pathways of the supraspinal systems that assist in the short- and long-term recovery from the effects of fatiguing exercise.

1.3. General and local fatiguing exercise and its implications for postural control

Fatigability affects the postural control of healthy young adults by combining two factors (ENOKA; DUCHATEAU, 2008; PAILLARD, 2012; THEDON et al., 2011): i) the peripheral factor alters proprioception (muscle, tendon, joint, and skin receptors) affecting the neuromuscular junction; ii) the central factor causes a modification of the body scheme due to the inadequate integration of sensory information at the central level. As a consequence, there are impairments in neuromuscular control and, consequently, in the motor response that deteriorate muscle contraction. So, fatigability contributes to the

redistribution of active muscles and to the reorganization of multiarticular coordination that controls posture (CÔTÉ et al., 2002; YIOU et al., 2009). Thus, fatigability can affect postural tone, impairing the generation of force against the ground to keep the body extended during specific postural actions to maintain standing posture (IVANENKO; GURFINKEL, 2018). The control of postural tone requires the control of specialized neural circuits. Therefore, to control the cellular processes underlying the generation of prolonged muscle force and stiffness, detailed information about the neural circuits involved in this process is required (IVANENKO; GURFINKEL, 2018), including the vestibular and mesodiencephalic nuclei, reticular formation, and cerebellum. Therefore, the control of standing balance depends on a complex interaction of physiological mechanisms, high-level processing of sensory information according to the postural body scheme and the expectations, objectives, cognitive factors, and the individual's previous experience (IVANENKO; GURFINKEL, 2018). In addition, these effects are independent of the type of fatiguing exercise and the body region fatigued.

Whatever the structures in which the fatiguing exercise is performed, two types of exercises are mainly used: general and localized fatiguing exercise. Therefore, some characteristics can differentiate these two types of exercises: i) the general exercise involves several muscle groups and multiple joints, while the localized exercise only one or a few muscle groups and a joint; ii) the localized exercise strongly stimulates the neuromuscular system, while the general exercise vigorously requests the energy metabolism; iii) most general muscle exercises demand total body displacement, while the localized exercises generate only segmental movements (PAILLARD, 2012). However, both general and localized fatiguing exercises affect the control of standing posture.

On the one hand, general exercise models such as walking, running, or cycling engage a large part of the body's musculature. These activities induce physiological changes and causing important biomechanical impacts on the neuromuscular and musculoskeletal system, influencing the effectiveness of postural regulatory mechanisms (GRIBBLE; HERTEL, 2004a; LEPERS et al., 1997; LUNDIN; FEUERBACH; GRABINER, 1993; NARDONE et al., 1997; PAILLARD, 2012). In addition, various sensory inputs are affected, including vestibular, proprioceptive, and visual systems (LEPERS et al., 1997). Consecutively, failures in sensorimotor integration to control the upright posture are caused by the central component of fatigability. Previous studies have found that postural control is affected by general exercises, such as running (DERAVE et al., 1998, 2002; LEPERS et al., 1997; NARDONE et al., 1997, 1998), cycling (GAUCHARD et al., 2002; HOFFMAN et al., 1992; VUILLERME; HINTZY, 2007), and triathlon (BURDET; ROUGIER, 2004; NAGY et al., 2004).

On the other hand, localized muscle exercises, performed by a simple joint movements such as plantar flexion and ankle dorsiflexion (PENEDO et al., 2021), induce localized fatigability. This occurs due to the inability to sustain repeated voluntary muscle contractions, maintain an isometric contraction overtime, or preserve muscle strength above a pre-established value (PAILLARD, 2012). Consequently, these factors impair the control of standing posture. In this sense, previous studies show that localized fatiguing exercise from different regions of the body, such as the ankle (BISSON et al., 2011; BIZID et al., 2009a; BOYAS; HAJJ; BILODEAU, 2013; CORBEIL et al., 2003; HARKINS et al., 2005; HLAVACKOVA; PRADON; VUILLERME, 2012; HLAVACKOVA; VUILLERME, 2012; PENEDO et al., 2021; ROERDINK; HLAVACKOVA; VUILLERME, 2011; VUILLERME; FORESTIER; NOUGIER, 2002; VUILLERME; NOUGIER; TEASDALE, 2002; WOJCIK et al., 2011), knee

(BIZID et al., 2009a; PAILLARD et al., 2010; WOJCIK et al., 2011), hip (BISSON et al., 2011; GRIBBLE; HERTEL, 2004b; PENEDO et al., 2021; VUILLERME; SPORBERT; PINSAULT, 2009), lumbar and neck (MADIGAN; DAVIDSON; NUSSBAUM, 2006; PINSAULT; VUILLERME, 2010a; VUILLERME et al., 2008; VUILLERME; ANZIANI; ROUGIER, 2007; VUILLERME; PINSAULT; VAILLANT, 2005; WOJCIK et al., 2011), deteriorated postural control. However, up to date, many questions about fatigability remain unanswered, mainly related to the duration of the effects of fatiguing exercise on the recovery of postural control.

1.4. Recovery of postural control after fatiguing exercise

Fatiguing exercise immediately disrupts the postural control system. During and shortly after performing a fatiguing task, there is a degradation of the somatosensory system (LIN et al., 2009b) or decreased proprioceptive joint acuity (DAVIDSON; MADIGAN; NUSSBAUM, 2004; PINSAULT; VUILLERME, 2010b; VUILLERME et al., 2007; VUILLERME; BOISGONTIER, 2008) due to the feeling of increased physical effort and greater difficulty for motor execution (TAYLOR; GANDEVIA, 2008), in addition to the delay in stabilizing muscle activation (DAVIDSON; MADIGAN; NUSSBAUM, 2004; LIN et al., 2009a). These factors can determine the worsening of physical performance (TANAKA; WATANABE, 2011) to control posture immediately after (acute effect) the end of the protocol for inducing fatigability. Thus, rapid recovery of the postural control system by the CNS must be performed by other sensory pathways. This corrective action prevents CoP from coming close and/or exceeding the limits of the base of stability and inducing a fall. However, the effects of exercise-induced fatigability on postural control mechanisms can remain even after some time of the execution of the

fatiguing exercise protocol, leaving residual effects in postural control (BRYANTON; BILODEAU, 2016).

Previous studies have assessed the time for recovery of postural control after fatiguing exercise. Despite expressive results, great divergences in the range of the findings are shown, revealing that general exercises (running and cycling) can remain for 13 to 15 minutes (FOX et al., 2008; NARDONE et al., 1997) and those localized exercises such as the ankle (LIN et al., 2009a; YAGGIE; MCGREGOR, 2002), lumbar extensors (LIN et al., 2009a; PLINE; MADIGAN; NUSSBAUM, 2006), knee and shoulder (LIN et al., 2009a), can remain from 5 to 20 minutes after performing the fatiguing exercise protocol. In addition to the immediate effects (5 to 20 minutes), fatiguing exercise can generate more lasting and delayed discomfort in the neuromuscular system. So far, to the best of our knowledge, only one study (PENEDO et al., 2021) investigated the late effects of fatiguing exercise on the postural control mechanism. In this study, it was found that the deleterious effects of fatigability on posture (i.e., increased body sway) remain for up to 48 hours after performing the fatiguing exercise. Although not measured in this study, the authors inferred that this phenomenon is related to the onset of delayed-onset muscle soreness. (DOMS).

The DOMS-related symptoms start about 24 hours after the end of the exercise and reach their peak in 72 hours, dissipating slowly in five to seven days (EBBELING; CLARKSON, 1989; LEWIS; RUBY; BUSH-JOSEPH, 2012; THOMAS et al., 2017). Regardless of the individual's previous condition, after an episode of immediate or delayed muscle soreness, there is associated muscle weakness (FAULKNER; BROOKS; OPITECK, 1993; MACINTYRE et al., 2017; MACINTYRE; REID; MCKENZIE, 1995; PAULSEN et al., 2010; RAASTAD et al., 2015; RAASTAD; HALLÉN, 2000), related to cell damage and subsequent inflammatory response (INGALLS et al., 1998; LOUIS et

al., 2007; WARREN et al., 1999), resulting in force deficits that can take up to 2 weeks to be reestablished (LIEBER; FRIDEN, 2002). The delay in restoring force, previously mentioned, has been attributed mainly to the increased concentration of pro-inflammatory cytokines in the tissue (NIEMAN et al., 2015) and the blood (HARNISH; SABO, 2016). This enzymatic increase during and after exercise potentiates nerve endings and contributes to the perception of pain (ARMSTRONG, 1984; CHEUNG; HUME; MAXWELL, 2003). Thus, DOMS seems to be an interesting model for studying movement-evoked pain, helping to explain the adjustments that the postural control system makes in the face of the long-lasting effects of fatiguing exercise.

1.5. Objectives and design of the thesis

Based on what was presented, the specific objective of this thesis was to investigate cortical activity in healthy young adults during a standing postural task under the effect of fatigability, comparing the effects of general and localized exercise and the duration of the effects of fatiguing exercise. The specific thesis questions were: What did the literature reveal about the short- and long-lasting effects of fatiguing exercises during postural control? Did general and localized fatiguing exercises differently alter cortical activity during standing posture? Could fatiguing exercise leave residual (long-lasting) effects on postural control? To answer these questions, a sequence of three studies was proposed.

Study 1 consisted of a systematic review and meta-analysis, which reported the immediate, short- and long-term effects of fatigability on healthy young adults' postural control.

In Study 2, 20 participants performed postural assessments (force platform, electromyography, and electroencephalography) and maximum voluntary contraction

tests before and immediately after general (treadmill) and localized fatiguing exercise protocols (plantar flexion and ankle dorsiflexion) to compare whether the two different types of fatiguing exercises generated different responses in the cortical activity of healthy young adults during postural control.

In Study 3, postural control and maximum voluntary isometric contraction were carried out to investigate the short-term effects after 5 and 20 minutes, and the long-term effects after 48, 120, and 192 hours following the fatigability protocol. Twenty volunteers performed experimental conditions (fatiguing task or rest for 10 minutes).

CHAPTER 2

STUDY 1 – EXERCISE-INDUCED FATIGUE EFFECTS ON POSTURAL CONTROL OF YOUNG ADULTS: A SYSTEMATIC REVIEW AND META- ANALYSIS

2. Study 1 – Exercise-induced fatigue effects on postural control in young adults: a systematic review and meta-analysis

2.1. Introduction

Postural instability has been demonstrated to be a risk factor for falls. Ensuring adequate postural control is paramount for executing daily activities in a manner that ensures stability and safety. Postural control is a multifaceted process involving the integration of sensorimotor dynamic processes and various biomechanical mechanisms that collectively enable an individual to maintain an upright posture (HORAK, 2006). Numerous factors have the potential to exacerbate postural instability during specific tasks, thereby altering the interaction of the sensorimotor system. For example, the act of closing one's eyes while in an upright stance has been shown to augment body sway (BENJUYA; MELZER; KAPLANSKI, 2004), thereby compromising postural stability. A further salient factor contributing to postural instability in young adults is exercise-induced fatigue.

Fatigue is typically attributed to a decline in one or more objective measures of performance (e.g., a decrease in force production during a maximum voluntary contraction task) within a discrete period due to effort or clinical conditions (ENOKA; DUCHATEAU, 2017). Moreover, exercise-induced fatigue declines in performance are often accompanied by a subjective increase in exertion levels (ENOKA; DUCHATEAU, 2017). The impact of exercise-induced fatigue on neuromotor control limits the availability of internal resources, affecting the organization of adequate neural drives to the muscles (DOS SANTOS et al., 2020, 2024; MONJO; TERRIER; FORESTIER, 2015). Additionally, the presence of fatigue can induce disturbances within the neuromuscular system (ENOKA; DUCHATEAU, 2017), challenging, for example, the

execution of postural tasks. These impairments may result in a reduction in muscle strength (BIZID et al., 2009b; HARKINS et al., 2005; PAILLARD, 2012), and hinder the reception of information from the proprioceptive system (PENEDO et al., 2021). Brain activity may have a role in modulating the effects of exercise-induced fatigue on neuromotor control. Experimental evidence using functional magnetic resonance imaging has identified that fatigue is reflected by increasing activation in the anterior ventral pre-motor cortex, the insula and postcentral gyrus areas - critical nodes of the brain network (HERATH et al., 2017). In addition, the electroencephalography (EEG) power spectrum observed at the alpha 2 (C3), beta 1 (C3 and Fz) and beta 2 (C3, Cz, and C4) bands have been shown to decrease, suggesting alterations in the motor cortical signal during a fatiguing exercise (LIU et al., 2005).

While fatigue is often considered a natural consequence of exercise, it is reasonable to hypothesize that exercise-induced fatigue can result in impaired control of human movement, which can negatively impact the performance of daily living activities and sports actions, even among healthy young adults (CHARDON et al., 2022; ENOKA; DUCHATEAU, 2017). Specially, declines in daily movements and sports performance may be related to the effects of exercise-induced fatigue on postural control. The existence of a clear deterioration in reactive postural control caused by exercise-induced fatigue lends support to the examination of muscle endurance training as a fall risk intervention (PAPA; GARG; DIBBLE, 2015). Therefore, there is a growing interest in the scientific community in understanding and exploring the limits of postural control adaptation to fatigue.

In essence, fatigue has been demonstrated to augment body sway in young adults, leading to elevated postural instability. The existing literature has demonstrated that fatigue leads to an increase in the displacement and velocity of body sway (BARBIERI

et al., 2019; CLARKE et al., 2015; FAN et al., 2024; LYU et al., 2022; PENEDO et al., 2022), a reduction in the level of muscle activation (BERGER; REGUEME; FORESTIER, 2010; PENEDO et al., 2021), and an increase in muscle coactivation (BERGER; REGUEME; FORESTIER, 2010). Previous narrative reviews have addressed the effects of exercise-induced fatigue on postural control (PAILLARD, 2012). However, these reviews have not been systematically evaluated, and none of them have systematically identified the issues related to the short- (5 to 20 minutes following fatiguing exercise) and long-term (at least 24 hours) effects of fatiguing exercise on postural control, only reviewing the immediate effect. Experimental data indicates that persistent effects of exercise-induced fatigue on body sway are evident within short- (FOX et al., 2008; LIN et al., 2009a; PLINE; MADIGAN; NUSSBAUM, 2006; YAGGIE; MCGREGOR, 2002) and long-term (PENEDO et al., 2022). Consequently, if such exercise-induced fatigue effects persist, the instability in daily movements and sports performance may be exacerbated.

The discrepancy between the analyses of the variables performed, types of protocols used to induce fatigue and to assess upright posture, characteristics of the sample and the duration of the effects of exercise on posture (immediate, short- and long-term postural assessment) can still generate inconsistent results, rendering any potential assumption inconclusive. Consequently, a systematic investigation into how exercise-induced fatigue can adversely affect postural control, specifically in immediate, short- and long-term contexts, is timely and may facilitate a more profound comprehension of human adaptation to fatigue. The aim of this systematic review and meta-analysis was to evaluate and quantify the extent to which exercise-induced fatigue alters upright posture and the duration of these effects on postural control in young healthy adults. Conducting a systematic review and meta-analyses that address these issues would contribute to a

deeper understanding of aspects related to adaptations during postural control and provide information about the duration of the effects of fatiguing exercise on postural control. The findings could potentially elucidate the procedures that could be adopted to preserve postural control after exercise-induced fatigue.

2.2. Methods

This study adheres to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (PAGE et al., 2021) and the Cochrane Handbook (HIGGINS et al., 2019). The protocol was prospectively registered at The International Prospective Register of Systematic Reviews (PROSPERO – CRD 42021288276).

2.2.1. Search strategy

A comprehensive search was conducted for relevant studies from inception until September 2024 in the following electronic databases: PubMed/NCBI (United States National Library of Medicine), Web of Science (WoS) Core Collection (Clarivate™), and SCOPUS® (Elsevier B.V.). In instances where the full text was not available in the aforementioned databases, additional searches were conducted on Google Scholar (Google LLC). This approach enabled the identification of articles that were not accessible through the initial searches. The identification of additional articles was further facilitated by conducting manual searches of the reference lists of included articles. A combination of suitable descriptors was achieved through the utilization of Boolean operators (Table 1). These operators included the Boolean connectors "OR" between terms from the same column and "AND" between columns. The complete search strings

utilized for each database are provided in Table 2. The management of references was facilitated by specific software (Mendeley Ltd., New York, USA).

Table 1. PICO descriptors combined in the search strategy.

Population	Intervention	Comparison	Outcome
adults	fatig*	N/A	postur*
young adults	effort		body sway
	exhaustion		balance
	tired*		center of pressure
			cort*
			brain
			cerebral

* – wildcard term; N/A – not applicable.

Table 2. Full search strategy for each database with arguments presented as they were used.

PubMed
(((fatig*[Title/Abstract]) OR effort[Title/Abstract]) OR exhaustion[Title/Abstract]) OR tired*[Title/Abstract] AND ((postur*[tw]) OR balance[tw]) AND (((("body sway"[Title/Abstract]) OR "center of pressure"[Title/Abstract]) OR cort*[Title/Abstract]) OR brain[Title/Abstract]) OR cerebral[Title/Abstract]) AND ((adults[Title/Abstract]) OR "young adults"[Title/Abstract])
Web of Science
(TS=(((fatig*) OR effort) OR exhaustion) OR tired*) AND TS=((postur*) OR balance) AND TS=(((("body sway") OR "center of pressure") OR cort*) OR brain) OR cerebral) AND TS=((adults) OR "young adults")
SCOPUS
TITLE-ABS-KEY (fatig* OR effort OR exhaustion OR tired* AND postur* OR balance AND "body sway" OR "center of pressure" OR cort* OR brain OR cerebral AND adults OR "young adults")

Where: input terms used in literature search of 'fatiguing exercise' effects on both postural control and cortical activity of young healthy adults for all databases. *tw* text words. * - wildcard term. Searches on Web of Science database were using 'Title/Keywords/Abstract' fields.

2.2.2. Selection criteria

2.2.2.1. Inclusion criteria

The following requirements were met by the included studies: (1) original article, (2) with full-text and abstract available for screening, (3) published in an indexed scientific journal with an editorial policy for peer review, (4) no date of publication restriction, and (5) written in English. Excluded from consideration were books, theses, dissertations, monographs, conference abstracts, literature reviews, and meta-analyses. Additionally, the PICO (Population, Intervention, Comparison, Outcome) tool was used to guide the selection process (METHLEY et al., 2014). The population under study was defined as healthy young adults (18 – 45 years old) (P). The intervention referred exclusively to the effects of exercise-induced fatigue (I). The comparison referred to pre- and post-assessments (C), and the outcome must include at least one outcome measure regarding postural control (O) (e.g., body sway parameters, muscle activity). All studies must be obtained from controlled experimental setups and only bipedal stance postural tasks (e.g., side-by-side feet position, tandem position, Romberg position, feet together) were considered.

2.2.2.2. Exclusion criteria

The following criteria were used to identify studies that were excluded from the analysis: (1) inclusion of animal model, (2) focus on middle or older adults (above 40 years old), teenagers, or children, (3) inclusion of participants with a disease (e.g., Parkinson's, Alzheimer's, stroke, cerebral palsy, multiple sclerosis, etc.). The exclusion criteria also encompassed studies that lacked a thorough description of the fatiguing exercise and/or recovery or fatigue induced by means other than exercise, did not present any type of measure/variable indicating a decline in one or more objective measures of

performance (state of fatigue), included postural tasks performed on a unipedal support base or any other task than bilateral quiet standing position, any postural disturbance/reactive postural control, or in dual-task condition, and did not include pre and/or post-postural control analysis.

2.2.3. Methodological quality assessment

In the initial screening stage, two reviewers (TP/MC) independently evaluated the title, abstract, and keywords, according to the established inclusion and exclusion criteria. To enhance the reliability of the inter-rater process, a guide was developed with illustrative examples for each of the raters. In instances where there was a discrepancy between the two reviewers' analyses, a third reviewer (PCRS) was consulted to resolve the disagreement. The methodological quality of each study was evaluated using the Downs and Black checklist (DOWNS; BLACK, 1998). Initially, six items (6, 8, 14, 15, 19, 23, 24, and 26) were excluded from the original scale when applied to observational studies, as they were deemed non-applicable (SEVERIJNS et al., 2017). Consequently, the maximum attainable score for observational studies was adjusted to 18, in contrast to the 26 points allocated for randomized controlled trials. Then, the obtained scores were converted into percentage scores (100%). The methodological quality of the studies was classified as high ($\geq 75\%$), moderate (50-74%), and low ($< 50\%$) (VIEIRA et al., 2020). It is important to note that these scores were not utilized as an inclusion or exclusion criterion.

2.2.4. Data extraction and analysis

From the articles that met the inclusion criteria, three reviewers (TP/MC/PCRS) extracted the data regarding the following aspects: (1) the characteristics of the study

(name of the first author, study title, year of publication, name of the journal, study aim), (2) the characteristics of the sample (number of participants, age, gender, height, body mass, body mass index, physical activity level), (3) specifications of exercise to induce fatigue (protocol, time to fatigue, measure to determine the fatigue state), (4) specifications of postural control protocol (base of support, instructions, number of trials and its duration, visual condition, equipment used to collect data, outcomes analyzed), and (5) the main findings of exercise-induced fatigue on postural control task. Each reviewer's work was independently verified by the others, and discrepancies were resolved through discussion to ensure consistency. The extracted results were converted to the same unit of measurement (e.g., centimeters converted to millimeters). Not all articles included the required data in a directly extractable format, with some values being presented exclusively in graphs. In instances where attempts to obtain data from the authors proved unsuccessful, manual extraction of data from the figures was conducted using the WebPlotDigitizer software (available at: <https://apps.automeris.io/wpd/>). This approach ensured the accurate digitization of the information from the graphs, facilitating quantitative analysis.

2.2.5. Quantitative data synthesis and analysis

The meta-analysis compared the exercise-induced fatigue effects on postural control parameters at pre and post-periods. For the meta-analysis, different fatiguing exercise protocols were pooled as overall fatiguing effects, given that the protocol of fatigue is not an intervenient factor in the results (PAILLARD, 2012). Furthermore, the meta-analytic calculations were constrained to immediate effects of fatigue. Given the paucity and heterogeneity of studies assessing short- and long-term effects of exercise-induced fatigue on postural control, a systematic review was conducted but these studies

were not included in the meta-analysis. Subsequent to this, the screened studies were grouped by visual conditions (i.e., eyes open and closed), and the analysis was conducted for each outcome separately. The mean and standard deviation of center of pressure (CoP) outcomes were grouped for a subsequent analysis. To conduct the meta-analysis for a given outcome, a minimum of four studies were required to present their results. The meta-analytic procedures were conducted to verify the pre and immediate post-fatiguing exercise effects in the following CoP outcomes: displacement (total, anteroposterior (AP), and medial-lateral (ML) directions), mean velocity (total, AP, and ML directions), root mean square (RMS) (AP and ML directions), and area.

The meta-analysis was conducted using RStudio software (R Foundation for Statistical Computing, Vienna, Austria). Instances where articles made some form of comparison or utilized distinct samples, the data was grouped by the weighted mean and pooled standard deviation. Given the variation in CoP values across studies, the standardized mean difference (SMD) for random effects was calculated for the outcomes, along with the 95% confidence intervals (CI). The inverse variance method was employed to calculate the combined estimates of the effects. This method assigns the weight of each study. The effect size (Hedges' g) was employed to correct for SMD to small sample bias, and was interpreted as follows: small (≥ 0.2), medium (≥ 0.5), and large (≥ 0.8) (COHEN, 2013). To assess the heterogeneity among studies, the restricted maximum-likelihood estimator (REML) for τ^2 , the Q-Profile method for confidence interval of τ^2 and τ , and the I^2 were employed (BORENSTEIN et al., 2009). The I^2 values of 0-25%, 26-50%, 51-75% and 76-100% were considered low, moderate, substantial and high heterogeneity, respectively (HIGGINS et al., 2003). To verify the presence of publication bias, funnel plots were generated to examine the symmetry of effect sizes relative to their standard

errors. Additionally, the Egger test was employed to identify and adjust for potential asymmetries in the results. The level of significance was set at $p < 0.05$.

2.3. Results of study 1

2.3.1. Study selection

The initial search yielded 1,756 studies that met the inclusion criteria; however, this number was subsequently reduced to 1,463 after the removal of duplicates. Titles, abstracts, and keywords were subsequently screened, resulting in the exclusion of 1,319 studies. Thus, the full text of 144 studies was assessed, of which 111 were excluded for various reasons (see the flowchart – Figure 1). Thirty-three articles were included in this systematic review (APRIGIO et al., 2020; BARBIERI et al., 2019; BISSON et al., 2012; BOVE et al., 2007; CHENG et al., 2015; CLARKE et al., 2015; DAVIDSON; MADIGAN; NUSSBAUM, 2004; DEGACHE et al., 2014, 2019, 2020; DEMURA; UCHIYAMA, 2009; FAN et al., 2024; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; JANSSENS et al., 2010; KOYAMA; YAMAUCHI, 2017; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021, 2022; MARCHETTI; ORSELLI; DUARTE, 2013; MELLO; DE OLIVEIRA; NADAL, 2007, 2010; NARDONE et al., 1997, 1998; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022; PINSAULT; VUILLERME, 2008; PLINE; MADIGAN; NUSSBAUM, 2006; ROERDINK; HLAVACKOVA; VUILLERME, 2011; SANTOS et al., 2020; SCHIFFMAN et al., 2010). The included studies (see Table 1, Figure 2) were published from 1997 (NARDONE et al., 1997) to 2024 (FAN et al., 2024). The included studies (details in Table 3; Figure 2) were published from 1997 (NARDONE et al., 1997) to 2024 (FAN et al., 2024).

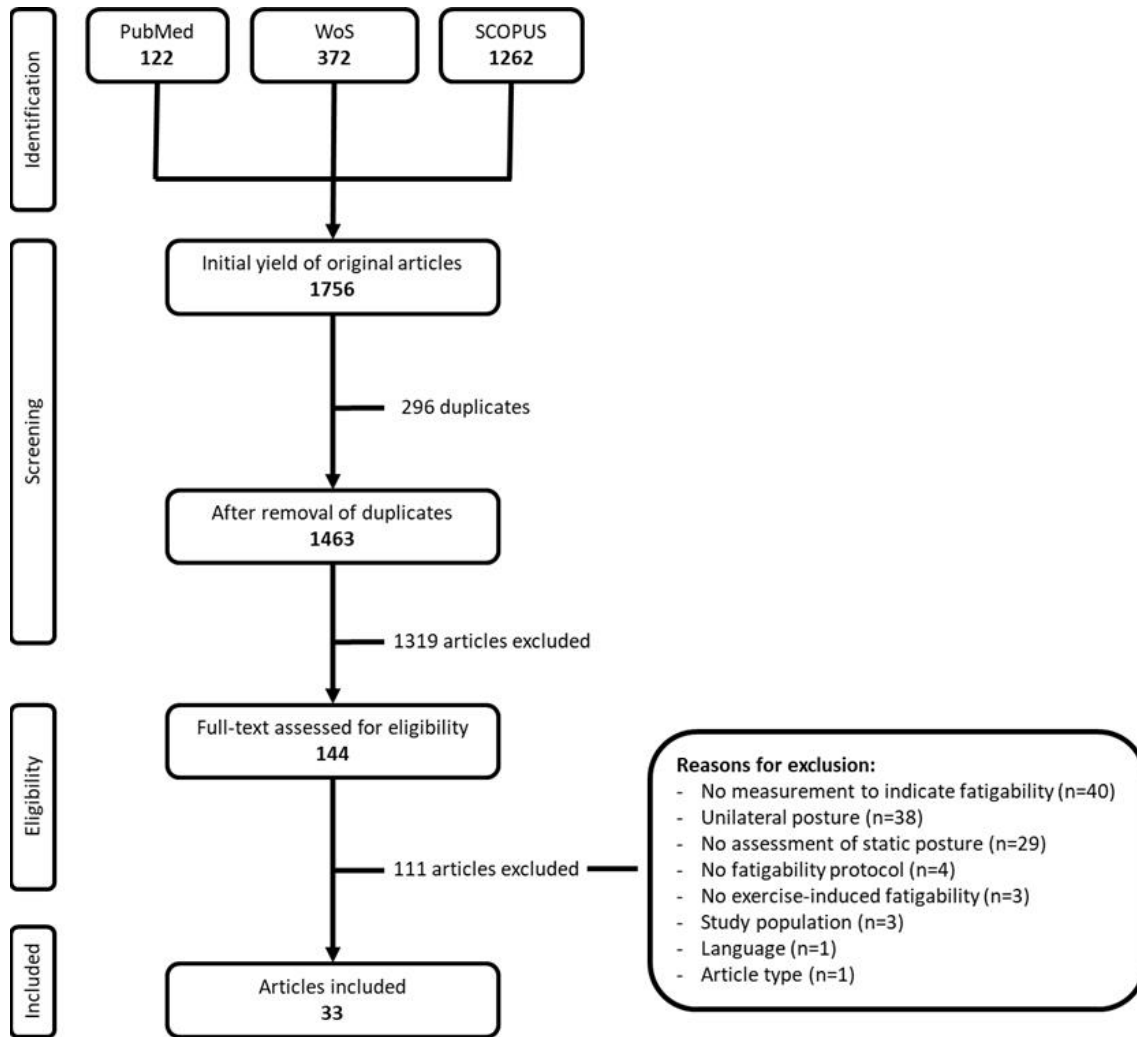


Figure 1. Flowchart of the study search and selection process.

Table 3. Studies included in the systematic review.

Article	Title	Name of the scientific journal	Main objective(s)
Barbieri et al., 2019	Effects of ankle muscle fatigue and visual behavior on postural sway in young adults	Frontiers in Physiology	to investigate the effects of visual information manipulation (eyes closed, eyes open with fixed target, and eyes open with saccadic eye movements) on postural sway during ankle (calf) muscle fatigue in young adults
Berger, Regueme & Forestier, 2010	Unilateral lower limb muscle fatigue induces bilateral effects on undisturbed stance and muscle EMG activities	Journal of Electromyography and Kinesiology	1) to examine, on the one hand, the uni-lateral ankle muscle fatigue effects on postural control parameters of each leg, separately; 2) to understand the impact of unilateral muscle fatigue onto postural sway as well as the estimated CoP resultant (CoPres) and his components (CG and CoP-CG trajectories)
Bisson et al., 2012	Effects of fatiguing isometric and isokinetic ankle exercises on postural control while standing on firm and compliant surfaces	Journal of NeuroEngineering and Rehabilitation	1) to compare the effects of isometric and concentric isokinetic fatiguing exercises on postural control during quiet stance, and 2) to assess whether the magnitude of these effects are dependent on the amount of proprioceptive information available
Bove et al., 2007	Postural control after a strenuous treadmill exercise	Neuroscience Letters	to investigate the mechanisms associated with the body instability observed after a strenuous treadmill exercise
Cheng et al., 2015	Changes of postural control and muscle activation pattern in response to external perturbations after neck flexor fatigue in young subjects with and without chronic neck pain	Gait & Posture	to assess the influence of neck pain and induced neck flexor muscle fatigue on standing balance when subjected to external perturbation
Clarke et al., 2015	Direct and indirect measurement of neuromuscular fatigue in Canadian football players	Applied Physiology, Nutrition, and Metabolism	to evaluate postural sway as a potential alternative or supplementary tool for monitoring NMF in collision based team sports by assessing the effect of simulated game induced fatigue on the balance of collegiate Canadian football players
Davidson, Madigan & Nussbaum, 2004	Effects of lumbar extensor fatigue and fatigue rate on postural sway	European Journal of Applied Physiology	to investigate the effect of lumbar extensor fatigue on balance; to investigate the effect of fatigue rate on: (1) the change of balance measures following lumbar extensor fatigue and (2) the rate of balance recovery from fatigue
Degache et al., 2019	Postural control follows a bi-phasic alteration pattern during mountain ultra-marathon	Frontiers in Physiology	to investigate how the postural control evolved throughout the Tor of Geants
Degache et al., 2014	Alterations in postural control during the world's most challenging mountain ultra-marathon	PLoS One	to investigate the aetiology of postural control and somatosensory integration measured using posturographic tests in the most extreme MUM in the world
Degache et al., 2020	The fatigue-induced alteration in postural control is larger in hypobaric than in normobaric hypoxia	Scientific Reports	to investigate the effect of muscular fatigue in three different conditions (HH, NH, NN) on postural control in healthy subjects

(continued)

Table 3. Continued.

Article	Title	Name of the scientific journal	Main objective(s)
Demura & Uchiyama, 2013	Influence of anaerobic and aerobic exercises on the center of pressure during an upright posture	Journal of Exercise Science & Fitness	to examine the effect of aerobic versus anaerobic cycling on upright postural control over time
Fox et al., 2008	Return of postural control to baseline after anaerobic and aerobic exercise protocols	Journal of Athletic Training	1) to evaluate the effects of fatigue on postural control after anaerobic and aerobic exercise protocols in healthy, college-aged varsity athletes; 2) to establish an immediate recovery time course from each exercise protocol over which the effects of fatigue lessened and postural control measures returned to baseline status
Gimmon et al., 2011	The effect of plantar flexor muscle fatigue on postural control	Journal of Electromyography and Kinesiology	to better understand postural control mechanisms during upright stance following plantar flexor fatigue
Hlavackova & Vuillerme, 2012	Do somatosensory conditions from the foot and ankle affect postural responses to plantar-flexor muscles fatigue during bipedal quiet stance?	Gait & Posture	to investigate the effects of somatosensory conditions from the foot and ankle on postural responses to plantar-flexor muscle fatigue during bipedal quiet stance
Janssens et al., 2010	The effect of inspiratory muscles fatigue on postural control in people with and without recurrent low back pain	Spine	1) to investigate the influence of acute IMF on postural stability and proprioceptive postural control strategies; 2) to investigate whether this influence is different in persons with LBP in comparison to healthy subjects
Koyama & Yamauchi, 2017	Altered postural sway following fatiguing foot muscle exercises	PLoS One	to investigate the immediate effects of fatiguing foot muscle exercises on foot muscle strength and postural control during standing
Lin, Nussbaum & Madigan, 2012	Efficacy of three interventions at mitigating the adverse effects of muscle fatigue on postural control	Ergonomics	to evaluate the efficacy of three interventions at reducing the adverse effects of muscle fatigue on postural control
Lyu et al., 2021	Effect of local and general fatiguing exercises on disturbed and static postural control	Journal of Electromyography and Kinesiology	to confirm the influence of local and general fatiguing exercise on static postural stability and explore the modulating factor of sensory distribution in postural control
Marchetti et al., 2013	The effects of uni- and bilateral fatigue on postural and power tasks	Journal of Applied Biomechanics	to investigate the effects of uni- and bilateral fatigue on both postural and power bipedal tasks
Mello, de Oliveira & Nadal, 2010	Effects of maximal oxygen uptake test and prolonged cycle ergometer exercise on the quiet standing control	Gait & Posture	to discriminate the effects of peripheral and central fatigue, after maximal oxygen uptake test and prolonged cycle ergometer exercises, respectively, on body sway control based on SDC parameters

(continued)

Table 3. Continued.

Article	Title	Name of the scientific journal	Main objective(s)
Mello, de Oliveira & Nadal, 2007	Anticipation mechanism in body sway control and effect of muscle fatigue	Journal of Electromyography and Kinesiology	to quantify the occurrence of an anticipatory mechanism in quiet standing control by measuring the lag between the myoelectric activity of the lateral gastrocnemius muscle and the stabilometric signal, as well as verifying the influence of a muscle fatigue on this process
Nardone et al., 1998	Time course of stabilometric changes after a strenuous treadmill exercise	Archives of Physical Medicine and Rehabilitation	to detect the effect of a strenuous exercise on equilibrium and to quantify its time course
Nardone et al., 1997	Fatigue effects on body balance	Electroencephalography and Clinical Neurophysiology	to compare common indicators of body sway (sway area (SA) and sway path (SP)) prior to and after two types of exercises (treadmill walking and cycle ergometer pedaling), each performed both below and above the threshold of fatigue
Noda & Demura, 2006	Comparison of quantitative analysis and fractal analysis of center of pressure based on muscle fatigue	Perceptual and Motor Skills	to examine each measure of center-of-pressure displacement during a static standing posture under the influence of lower leg muscle fatigue using quantitative analysis and fractal analysis
Penedo et al., 2021	Motor strategy during postural control is not muscle fatigue joint-dependent, but muscle fatigue increases postural asymmetry	PLoS One	to investigate the effects of ankle and hip muscle fatigue on motor adjustments and postural control symmetry during an upright standing task
Pinsault & Vuillerme, 2008	Differential postural effects of plantar-flexor muscle fatigue under normal, altered and improved vestibular and neck somatosensory conditions	Experimental Brain Research	to assess the effects of plantar-flexor muscles fatigue on postural control during quiet standing under normal, altered and improved vestibular and neck somatosensory conditions
Pline et al., 2006	Influence of fatigue time and level on increases in postural sway	Ergonomics	to determine the effects of fatigue time and fatigue level on postural sway following lumbar extensor fatigue
Roerdink et al., 2011	Effects of plantar-flexor muscle fatigue on the magnitude and regularity of center-of-pressure fluctuations	Experimental Brain Research	to observe the customary larger AP COP fluctuations with fatigued plantar flexors
Apriglio et al., 2020	Lower limb muscle fatigability is not associated with changes in movement strategies for balance control in the upright stance	Humam Movement Science	to investigate whether the acute fatigability of lower limb muscles affects the movement strategies for controlling postural stability during upright standing by analyzing the spatial patterns of COP position in 3D-SKG
Santos et al., 2020	Postural control and physiological responses to a simulated match in U-20 judo competitors	Sports Biomechanics	to evaluate the effects of judo combat on the athletes' postural control, assessing changes in CoP parameters before, during and after a simulated match

(continued)

Table 3. Continued.

Article	Title	Name of the scientific journal	Main objective(s)
Penedo et al., 2022	Ankle muscle fatigability impairs body sway for more than 24 h	Journal of Biomechanics	to investigate the effects of ankle-fatigability on body sway after 24/48 h of fatiguing exercise
Lyu et al., 2022	Effects of unilateral and bilateral lower extremity fatiguing exercises on postural control during quiet stance and self-initiated perturbation	Human Movement Science	to compare the effects of unilateral and bilateral lower extremity fatiguing exercises performed at the same relative workload on COP-based postural stability measures during quiet stance and EMG-based APAs/CPAs measures during self-initiated perturbation
Fan et al., 2024	Effects of unilateral and bilateral lower extremity fatigue on static stance and postural adjustments response to the externally initiated perturbation	Journal of Electromyography and Kinesiology	to elucidate the mechanisms underlying postural control in fatigued states and contribute to our understanding of the central nervous system's role in maintaining balance

AP – anteroposterior; **APA** – anticipatory postural adjustment; **CG** – center of gravity; **CoP** – center of pressure; **CPA** – compensatory postural adjustment; **EMG** – electromyography; **HH** – hypobaric hypoxia; **MUM** – mountain ultra-marathon; **NH** – normobaric hypoxia; **NMF** – neuromuscular fatigue; **NN** – normoxia; **SA** – sway area; **SKG** – statokinesigram; **SP** – sway path.

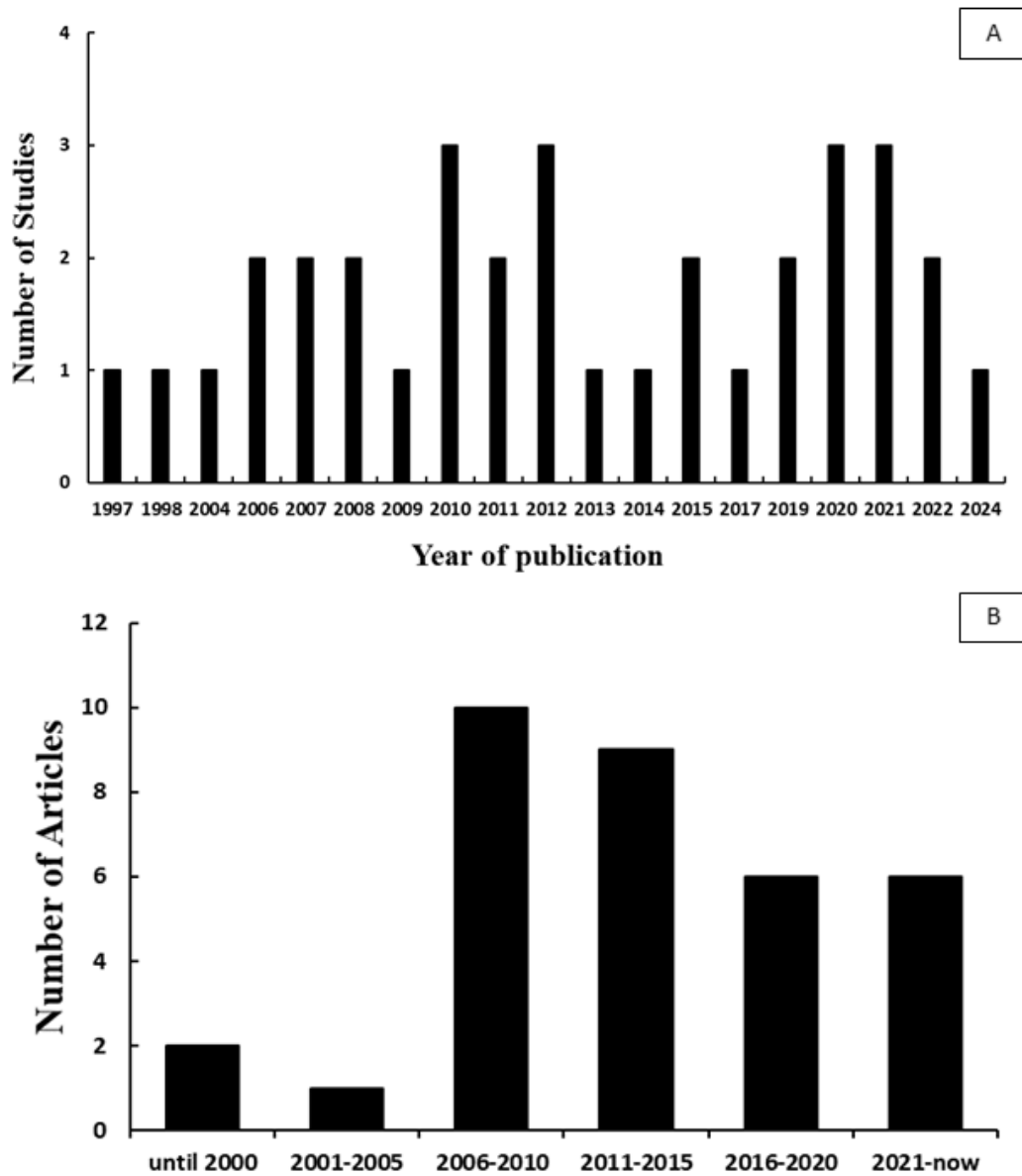


Figure 2. Article included distributed by year of publication (A – top panel) and a five-years histogram (B – bottom panel).

Table 4. Quality assessment of the included studies.

Studies	Field																											Total (%)
	Reporting							External validity		Internal validity - bias							Internal validity - confounding (selection bias)							Power				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		24	25	26	
Barbieri et al., 2019	1	1	1	1	2	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	70.97
Berger, Regueme & Forestier, 2010	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Bisson et al., 2012	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Bove et al., 2007	1	1	0	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	64.52
Cheng et al., 2015	1	1	0	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	0	1	1	1	1	0	1	0	0	61.29
Clarke et al., 2015	1	1	1	1	2	N/A	1	N/A	1	1	0	0	1	N/A	N/A	1	1	1	N/A	1	1	1	N/A	N/A	1	N/A	5	91.67
Davidson, Madigan & Nussbaum, 2004	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1	0	70.97
Degache et al., 2019	1	1	1	1	1	N/A	1	N/A	1	1	0	0	1	N/A	N/A	1	1	1	N/A	1	1	1	N/A	N/A	1	N/A	0	66.67
Degache et al., 2014	1	1	1	1	2	N/A	1	N/A	1	1	0	0	1	N/A	N/A	1	1	1	N/A	1	1	1	N/A	N/A	1	N/A	0	70.83
Degache et al., 2020	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	74.19
Demura & Uchiyama, 2009	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1	0	70.97
Fox et al., 2008	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	0	1	0	1	0	0	64.52
Gimmon et al., 2011	1	1	0	1	2	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	1	0	1	0	2	74.19
Hlavackova & Vuillerme, 2012	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Janssens et al., 2010	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Koyama & Yamauchi, 2017	1	1	1	1	2	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	5	93.55
Lin, Nussbaum & Madigan, 2012	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	0	1	1	1	0	1	0	0	64.52
Lyu et al., 2021	1	1	1	1	2	1	1	1	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1	0	67.74

Marchetti et al., 2013	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Mello, de Oliveira & Nadal, 2010	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Mello, de Oliveira & Nadal, 2007	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Nardone et al., 1998	1	1	0	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	61.29
Nardone et al., 1997	1	1	0	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	61.29
Noda & Demura, 2006	1	1	1	1	2	N/A	1	N/A	1	1	0	0	1	N/A	N/A	1	1	1	N/A	1	1	1	N/A	N/A	1	N/A	0	70.83
Penedo et al., 2021	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Pinsault & Vuillerme, 2008	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Pline et al., 2006	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Roerdink et al., 2011	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	67.74
Aprigio et al., 2020	1	1	1	1	2	N/A	1	N/A	1	1	0	0	1	N/A	N/A	1	1	1	N/A	1	1	1	N/A	N/A	1	N/A	0	70.83
Santos et al., 2020	1	1	1	1	2	N/A	1	N/A	1	1	0	0	1	N/A	N/A	1	1	1	N/A	1	1	1	N/A	N/A	1	N/A	0	70.83
Penedo et al., 2022	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	64.52
Lyu et al., 2022	1	1	1	1	2	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	64.52
Fan et al., 2024	1	1	1	1	2	1	1	1	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	0	0	61.29
Mean per item	1.00	1.00	0.85	1.00	1.91	1.00	1.00	1.00	0.94	1.00	0.06	0.09	1.00	0.00	0.00	1.00	1.00	1.00	0.96	0.97	1.00	0.94	1.00	0.04	1.00	0.19	0.36	

N/A – not applicable.

2.3.2. *Quality assessment*

Table 4 shows the quality assessment of the included studies. Only two studies (6%) achieved high ($\geq 75\%$) quality (CLARKE et al., 2015; KOYAMA; YAMAUCHI, 2017) and all other studies had moderate (50-74%) quality (APRIGIO et al., 2020; BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; BOVE et al., 2007; CHENG et al., 2015; DEGACHE et al., 2014, 2019, 2020; DEMURA; UCHIYAMA, 2009; FAN et al., 2024; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; JANSSENS et al., 2010; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021, 2022; MARCHETTI; ORSELLI; DUARTE, 2013; MELLO; DE OLIVEIRA; NADAL, 2007, 2010; MILLER et al., 2007; NARDONE et al., 1997, 1998; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022; PINSULT; VUILLERME, 2008; PLINE; MADIGAN; NUSSBAUM, 2006; ROERDINK; HLAVACKOVA; VUILLERME, 2011; SANTOS et al., 2020). Specifically, the quality assessment results revealed that the scores ranged from 61.29% (CHENG et al., 2015; FAN et al., 2024; NARDONE et al., 1997, 1998) to 93.55% (KOYAMA; YAMAUCHI, 2017). The main issues identified were inadequate reporting on the difference between participants who were asked and those who were recruited (Q11 and Q12), none of the studies achieved a score for participant and assessor blinding (Q14-15), allocation concealment (Q24), follow-up losses (Q26), and the study's power (Q27).

2.3.3. *Characteristics of participants*

The characteristics of the participants are delineated in Table 5. The total number of healthy young adults who participated in these studies was 534. The sample size ranged

from seven (LYU et al., 2021) to 41 participants (APRIGIO et al., 2020), with a mean sample size of 16 ± 7 participants.

In 13 studies (39%), both genders were included (114 females and 135 males), whereas in 18 studies (54%) only male subjects were included (285 participants). It is noteworthy that two studies (6%) (KOYAMA; YAMAUCHI, 2017; LYU et al., 2021) did not report the gender of the participants ($n = 25$ participants in total). The age of the participants ranged from 18 (SANTOS et al., 2020) to 45 years old (DEGACHE et al., 2019), with a mean age of 25 ± 6 years old. The mean body mass and height were documented in 30 studies (90%), ranging from 57.6 ± 9.6 (NODA; DEMURA, 2006) to 97.6 ± 14.7 kg (CLARKE et al., 2015), and from 1.62 ± 0.06 (NODA; DEMURA, 2006) to 1.87 ± 0.05 m (CLARKE et al., 2015), respectively. The body mass index (BMI) was documented in three articles (9%), while in 25 articles (75%), it was calculated manually ($\text{BMI} = \text{body mass} / [\text{body height}^2]$). The reported BMI ranged from 21.5 (FAN et al., 2024; LYU et al., 2021) to 27.9 (CLARKE et al., 2015) kg/m^2 . Notably, body characteristics (i.e., body mass, height, and BMI) were not reported only in five articles (15%) (BOVE et al., 2007; CHENG et al., 2015; GIMMON et al., 2011; NARDONE et al., 1997, 1998).

2.3.4. Fatiguing exercise protocols

Table 6 depicts the specifications of the fatiguing exercise protocols. In 13 studies, a general model of fatiguing exercise was used to induce fatigue, including: running on a track (FOX et al., 2008), on a treadmill (BOVE et al., 2007), or a marathon (DEGACHE et al., 2014, 2019); cycling on an ergometer (DEMURA; UCHIYAMA, 2009; MELLO; DE OLIVEIRA; NADAL, 2010; NARDONE et al., 1997); uphill walking (NARDONE et al., 1997, 1998); football (CLARKE et al., 2015); judo match (SANTOS et al., 2020);

and full-body workout (KOYAMA; YAMAUCHI, 2017). In 21 studies, fatigue was induced exclusively through localized exercise models, such as ankle plantar flexion and extension (APRIGIO et al., 2020; BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; DEGACHE et al., 2020; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; MELLO; DE OLIVEIRA; NADAL, 2007; NODA; DEMURA, 2006; PENEDO et al., 2022, 2021; PINSAULT; VUILLERME, 2008; ROERDINK; HLAVACKOVA; VUILLERME, 2011); lumbar flexion (DAVIDSON; MADIGAN; NUSSBAUM, 2004; LIN; NUSSBAUM; MADIGAN, 2012; PLINE; MADIGAN; NUSSBAUM, 2006); neck flexion (CHENG et al., 2015); hip flexion and extension (PENEDO et al., 2021); lower limbs (FAN et al., 2024; LYU et al., 2022; MARCHETTI; ORSELLI; DUARTE, 2013); and respiratory (JANSSENS et al., 2010). Only one article applied both models, general (rowing ergometer) and localized (knee extension) models to induce fatigue (LYU et al., 2021).

2.3.4.1. Endpoint

The exercise endpoint (determination of fatigue) was established by limiting the number of repetitions (FAN et al., 2024; LYU et al., 2021, 2022), task failure or voluntary exhaustion (APRIGIO et al., 2020; BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BOVE et al., 2007; DEMURA; UCHIYAMA, 2009; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; MARCHETTI; ORSELLI; DUARTE, 2013; MELLO; DE OLIVEIRA; NADAL, 2010, 2007; PENEDO et al., 2021; PINSAULT; VUILLERME, 2008; ROERDINK; HLAVACKOVA; VUILLERME, 2011), time limit (FOX et al., 2008; JANSSENS et al., 2010; KOYAMA; YAMAUCHI, 2017; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021; MELLO; DE OLIVEIRA; NADAL, 2010; NARDONE et al., 1997, 1998; SANTOS et al., 2020),

force drop (BISSON et al., 2012; CHENG et al., 2015; DAVIDSON; MADIGAN; NUSSBAUM, 2004; NODA; DEMURA, 2006; PLINE; MADIGAN; NUSSBAUM, 2006), or distance covered (CLARKE et al., 2015; DEGACHE et al., 2014, 2019). Only one article (DEGACHE et al., 2020) did not report the endpoint of the fatiguing exercise.

2.3.4.2. Fatigue-related measurement

To measure fatigue, most studies (n = 20, 60%) used more than one direct or self-reported tool to measure fatigue, and the other studies (n = 13, 40%) used only one tool. The most used tool (n = 20, 60%) was the Borg 6-20 or CR-10 (category-ratio) scale (APRIGIO et al., 2020; BARBIERI et al., 2019; CHENG et al., 2015; CLARKE et al., 2015; DEMURA; UCHIYAMA, 2009; FAN et al., 2024; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; PRADON; VUILLERME, 2012; JANSSENS et al., 2010; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021, 2022; NARDONE et al., 1997, 1998; PENEDO et al., 2021, 2022; PINSULT; VUILLERME, 2008; ROERDINK; HLAVACKOVA; VUILLERME, 2011; SANTOS et al., 2020); followed by maximum voluntary contraction (n = 14, 42%) (BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; CLARKE et al., 2015; DAVIDSON; MADIGAN; NUSSBAUM, 2004; FAN et al., 2024; KOYAMA; YAMAUCHI, 2017; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021, 2022; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022; PLINE; MADIGAN; NUSSBAUM, 2006); heart rate (n = 12, 36%) (BOVE et al., 2007; CLARKE et al., 2015; DEGACHE et al., 2020; DEMURA; UCHIYAMA, 2009; FOX et al., 2008; GIMMON et al., 2011; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021; MELLO; DE OLIVEIRA; NADAL, 2010; NARDONE et al., 1998, 1997; SANTOS et al., 2020); respiratory frequency (n =

Table 5. Participants' characteristics of the included studies. In parentheses the standard deviation values. In square brackets the minimum-maximum values.

Article	Participants (n)	Gender (F/M)	Age (years)	Body mass (kg)	Body height (m)	BMI (kg/m ²)
Barbieri et al., 2019	20	20 M	24 (3)	75.9 (12.9)	1.74 (0.06)	25.0 [c]
Berger, Regueme & Forestier, 2010	9	9 M	22 (2)	70.7 (6)	1.77 (0.07)	22.5 [c]
Bisson et al., 2012	10	10 M	29 (4)	73.6 (9.6)	1.78 (0.07)	23.2 [c]
Bove et al., 2007	20	5 F / 15 M	23.7 (3.6)	NR	NR	NR
Cheng et al., 2015	20	12 F / 8 M	22.1 (2.2)	NR	NR	NR
Clarke et al., 2015	15	15 M	21.8 (1.6)	97.6 (14.7)	1.87 (0.05)	27.9 [c]
Davidson, Madigan & Nussbaum, 2004	13	13 M	[20-22]	78.1 (11.6)	1.75 (0.07)	25.5 [c]
Degache et al., 2019	16	16 M	45.1 (9.6)	75.6 (8.6)	1.78 (0.09)	23.8 [c]
Degache et al., 2014	26 total RG: 18 CG: 8	26 M	RG: 44.0 (10.7) CG: 29.3 (8.1)	RG: 68.7 (5.6) CG: 70.9 (9.3)	RG: 1.73 (0.04) CG: 1.74 (0.05)	RG: 22.9 [c] CG: 23.4 [c]
Degache et al., 2020	12	12 M	24 (3)	78.3 (8.0)	1.78 (0.07)	24.7 [c]
Demura & Uchiyama, 2013	15	15 M	19.9 (1.0)	67.3 (5.2)	1.72 (0.05)	22.7 [c]
Fox et al., 2008	36	18 F / 18 M	19 (1.01)	69.7 (12.8)	1.72 (0.10)	23.5 [c]
Gimmon et al., 2011	10	7 F / 3 M	25.7 (2.2)	NR	NR	NR
Hlavackova & Vuillerme, 2012	22	4 F / 18 M	22.1 (1.9)	72.1 (4.5)	1.74 (0.03)	23.8 [c]
Janssens et al., 2010	12	7 F / 5 M	22.8 (0.6)	66.3 (3.4)	1.74 (0.02)	21.9 [c]
Koyama & Yamauchi, 2017	18	NR	21.11 (1.45)	63.8 (9.9)	1.69 (0.05)	22.3 [c]
Lin, Nussbaum & Madigan, 2012	16	8 F / 8 M	General - 20.8 [18-24] F - 21.3 (1.6) M - 20.3 (1.4)	General - 71.2 F - 62.8 (5.9) M - 79.5 (15.1)	General - 1.72 F - 1.64 (0.04) M - 1.80 (0.11)	General - 24.1 F - 23.3 [c] M - 24.5 [c]
Lyu et al., 2021	7	NR	22.3 (1.0)	66.7 (5.8)	1.76 (0.03)	21.5 [c]
Marchetti et al., 2013	10	10 M	25 (4)	73.0 (12.0)	1.76 (0.08)	23.5 [c]
Mello, de Oliveira & Nadal, 2010	16	16 M	20-32	72.3 (11.6)	1.73 (0.10)	24.1 [c]

(continued)

Table 5. Continued.

Article	Participants (n)	Gender (F/M)	Age (years)	Body mass (kg)	Body height (cm)	BMI (kg/m ²)
Mello, de Oliveira & Nadal, 2007	22	7 F / 15 M	23.2 (3.6)	70.6 (10.9)	1.69 (0.07)	24.7 [c]
Nardone et al., 1998	8	5 F / 3 M	30 (1.9) [22–37]	NR	NR	NR
Nardone et al., 1997	13	7 F / 6 M	30 (1.9) [18–39]	NR	NR	NR
Noda & Demura, 2006	12	6 F / 6 M	20.1 (0.75)	57.6 (5.8)	1.62 (0.06)	21.9 [c]
Penedo et al., 2021	20	20 M	23 (3) [20–33]	74.8 (12.9)	1.73 (0.06)	24.9 [c]
Pinsault & Vuillerme, 2008	30 (15 in each experiment)	30 M	General - 23.0 (2.9)	General - 72.2 (7.6)	General – 1.78 (0.05)	General - 22.6
			1) 23.3 (2.3) 2) 22.7 (3.4)	1) 71.0 (5.9) 2) 73.3 (9.2)	1) 1.79 (0.06) 2) 1.77 (0.05)	1) 21.9 [c] 2) 23.1 [c]
Pline et al., 2006	12	12 M	[20–22]	70.2 (6.6)	1.73 (0.06)	23.2 [c]
Roerdink et al., 2011	16	16 M	22.4 (1.9)	70.7 (7.6)	1.77 (0.06)	22.6 [c]
Aprigio et al., 2020	41	22 F / 19 M	23 (3)	72 (16)	1.68 (0.10)	25.4 (3.7)
Santos et al., 2020	17	6 F / 11 M	17.4 (1.6)	72.8 (11.6)	1.73 (0.08)	24.2 (2.7)
Penedo et al., 2022	16	16 M	23 (3) [20–33]	74.9 (13.7) [57.9–108.9]	1.74 (0.05) [1.63–1.81]	24.7 [c]
Lyu et al., 2022	15	15 M	23.7 (2.0)	66.0 (6.7)	1.74 (0.04)	21.8 (2.0)
Fan et al., 2024	14	14 M	23.5 (1.91)	65.3 (6.4)	1.74 (0.04)	21.5 [c]

BMI – body mass index; **CG** – control group; **F** – female; **M** – male; **NR** – not-reported; **RG** – running group. [c] - calculated by the authors.

Table 6. Characteristics of fatiguing exercise protocols in the included studies.

Article	Fatigue protocol	Time to fatigue	Fatigue-related measurement	Fatigue-related finding
Barbieri et al., 2019	Ankle fatigue - to repeatedly perform plantar flexion and dorsiflexion of the ankle at 30 beats/min until exhaustion	270 (188) s [94–955] s	Borg 6-20 scale MVC	↓ MVC (IM) Borg: 18 (2) [15–20] (IM)
Berger, Regueme & Forestier, 2010	Unilateral fatigue (Ankle + knee) – to repeatedly perform 5 sets of toe-lifts until exhaustion	10 (4) min	MVC	↓ MVC (IM)
Bisson et al., 2012	Bilateral ankle fatigue - (1) Isometric (IM) - maintaining 50% of pre-fatigue MVCIM until exhaustion (2) Isokinetic (IK) - performing continuous maximal concentric IK contractions of the plantarflexors	(1) 145.3 (34.6) s (2) 54.6 (12.1) s	MVC (1 and 2)	↓ MVC (IM)
Bove et al., 2007	Incremental running - from 6.5 km/h with steps of 1 km/h at each minute until failure	NR	HR VO2 RF RER	↑ HR (IM) ↑ VO2 (IM) ↑ RF (IM) ↑ RER (IM)
Cheng et al., 2015	Neck fatigue - To maintain an isometric neck flexion at 60% of the maximal isometric contraction until arbitrarily stopped by the examiner	NR	Borg CR-10 scale Slope EMG median frequency (SCM)	↓ EMG median frequency (IM)
Clarke et al., 2015	Football match - the session included 4 quarters of 12 to 18 high-intensity exercise stations (plays). Each station combined a 5-yard (4.6-m) shuttle sprint with an explosive upper body, agility, or whole-body movement designed to mimic those found within football	NR	Borg scale HR MVC (knee extensor muscles) PT VA High- and low-frequency fatigue TOV PP PF	↓ MVC (IM) ↓ TOV (IM) ↓ PP (IM)
Davidson, Madigan & Nussbaum, 2004	Lumbar fatigue - Multiple sets of back extensions performed at 30 beats/min-1 on a 45° Roman chair	10 or 90 min protocol (2 sessions)	MVC	↑ VAS fatigue (IM, ST)

(continued)

Table 6. Continued.

Article	Fatigue protocol	Time to fatigue	Fatigue-related measurement	Fatigue-related finding
Degache et al., 2019	Ultramarathon - Running/walking 338.6 km with a total of 30,914 m positive and negative elevation change	Average race time 73.14 (8.5) h	VAS	↑ VAS (IM, LT)
Degache et al., 2014	Ultramarathon - Running/walking 330 km with a total positive and negative elevation of 24,000 m	126 h 40 min (16 h 49 min)	VAS	↑ VAS fatigue (IM, LT)
Degache et al., 2020	Ankle fatigue - to do “as much as possible plantar flexion” in 8 sets of 30 s	420 s	HR SpO2 Pain threshold (mmHg) VAS RF	↑ HR ↑ Pain threshold ↑ VAS
Demura & Uchiyama, 2009	Cycling - (1) two trials (with a 1-minute rest) of maximal pedaling for 30 seconds at 120% (Kp) of the load (4, 7 or 10 Kp) with which the maximal anaerobic power (Watt) was obtained, or (2) pedaling at 60 rpm for 60 minutes with a 50% load of their maximal aerobic power (Watt)	(1) NR (2) 60 min	HR Systolic and diastolic blood pressures (bpm) Blood lactate concentration Borg 6–20 scale	(1) ↑ HR (IM, ST) ↑ Blood lactate (IM, ST) ↑ SBP (IM, ST) ↑ Borg (IM, ST) (2) ↑ HR (IM, ST) ↑ Blood lactate (IM, ST) ↑ SBP (IM) ↑ Borg (IM, ST)
Fox et al., 2008	(1) Aerobic - Yo-yo intermittent recovery test (level 1): Repeated 20-m shuttle runs from the starting line to the turning until exhaustion (2) Anaerobic: Maximum-effort sprints between the cones at level 23.1 (19 km/h)	(1) NR (2) 2 min	HR Borg 6-20 scale	↑ HR (ST) ↑ Pain threshold (ST) ↑ VAS (ST)
Gimmon et al., 2011	(1) to conduct as many concentric-eccentric ankle plantar flexor contractions as possible until exhaustion (2) performing push-ups until subjects insisted on stopping	NR	Borg Scale HR Lateral Gastrocnemius EMG Soleus EMG	(1) ↑ Borg (IM) ↑ HR (IM) (2) ↑ Borg (IM) ↑ HR (IM)
Hlavackova & Vuillerme, 2012	Ankle fatigue – repeatedly perform standing heel raise exercise at 40 beats/min until exhaustion	NR	Borg CR-10 scale	Borg: 8.1 (IM)

(continued)

Table 6. Continued.

Article	Fatigue protocol	Time to fatigue	Fatigue-related measurement	Fatigue-related finding
Janssens et al., 2010	Respiratory exercise fatigue - to inspire maximally and as rapidly as possible through a mouthpiece with the nose occluded. Resistance was added to the inspiratory valve so that the subjects had to generate a negative threshold pressure of 80% of their Pimax	399.1 (209.1) s	Borg CR-10 scale	Borg: 7.7 (IM)
Koyama & Yamauchi, 2017	Full-body fatigue – to perform (1) Ladder, (2) Mini-hurdle, (3) Balance ball, (4) Standing calf-raises strength, and (5) Towel-gathering strength exercise as quickly as possible	60 min	MVC toe flexor MVC plantar flexor	↓ TFS (IM) ↓ PFS (IM)
Lin, Nussbaum & Madigan, 2012	Lumbar fatigue - repetitive box handling (lifting + lowering) - during the fatiguing phase, the weight was maintained at 25% of BW for 60 min	(1) NR (2) 20 min	HR Borg CR-10 scale MVC Lumbar extension	↓ MVIC (IM) Borg - 4.2 (post 1) ↑ HR (post 1)
Lyu et al., 2021	(1) Knee fatigue – to perform 130 times of 5-second isometric knee extensions at the level of 40% of maximal voluntary torques (2) Rowing ergometer - to keep rowing for 20 min at a pace of 200 ± 5 m/min	60 min	(1) MVC of quadriceps, and Borg 6-20 scale (2) HR, and Borg 6-20 scale	(1) ↓ MVC (IM) ↑ Borg (IM) (2) ↑ HR (IM) ↑ Borg (IM)
Marchetti et al., 2013	Leg-press fatigue – to perform the lower-limb extension movement at (1) 40% of 1RM for unilateral fatigue or (2) 60% of 1RM for bilateral fatigue until concentric failure	NR	Jump height	(1) ↓ Jump height (post 1) (2) ↓ Jump height (post 1)
Mello, de Oliveira & Nadal, 2010	Cycling - (1) Maximal oxygen uptake test until exhaustion, and (2) Moderate and prolonged cycle ergometer exercise for 60 min	(1) NR (2) 60 min	SEMG RMS RF HR Blood lactate accumulation	(1) Lactatemia > 4 mmol/l (IM) ↑ SEMG RMS (IM) ↑ HR (IM) ↑ FR (IM) (2) Lactatemia < 4 mmol/l (IM) ↑ FR (IM)
Mello, de Oliveira & Nadal, 2007	Ankle fatigue - To perform a maximum isometric plantar flexion contraction until failure	3.63 (1.92) min	EMG median frequency	↓ Median frequency (IM)
Nardone et al., 1998	Full-body fatigue – Uphill walking on a treadmill at 120 watts for 25 in	25 min	RF HR Borg CR-10 scale	↑ RF (ST) ↑ HR (ST) Borg: 7 (ST)

(continued)

Table 6. Continued.

Article	Fatigue protocol	Time to fatigue	Fatigue-related measurement	Fatigue-related finding
Nardone et al., 1997	Full-body fatigue - (1) Incremental walk on a motor-driven treadmill for 25 min, and (2) pedalling on a cycle ergometer with a frictionally loaded fly-wheel for 25 min	(1) 25 min (2) 25 min	RF HR Borg CR-10 scale	(1) ↑ Borg (ST) ↑ HR (ST) ↑ FR (ST) (2) ↑ Borg (ST) ↑ HR (ST) ↑ FR (ST)
Noda & Demura, 2006	Ankle fatigue - Repeatedly perform ankle plantar flexion at 30 bpm until the force reduces by 50%	520.85 (171.65) s	Blood lactate concentration MVC	↓ MVC (IM) ↑ Blood lactate concentration (IM)
Penedo et al., 2021	Ankle (1) and hip (2) fatigue - (1) to repeatedly perform the tasks, keeping the movement frequency at 30 bpm until exhaustion	(1) 270 (188) s (2) 183 (107) s	Borg 6-20 scale MVC VA Db100 Db10 Db10/Db100 ratio	(1) ↓ MVC (IM) ↑ Borg (IM) ↓ VA (IM) ↓ Db100 (IM) ↓ Db 10 (IM) Db10/Db100 ratio: 1.10 (IM) (2) ↓ MVC (IM) ↑ Borg (IM) ↓ VA (IM) ↓ Db100 (IM) ↓ Db 10 (IM) Db10/Db100 ratio: 0.75 (IM)
Pinsault & Vuillerme, 2008	Ankle fatigue - to perform toe-lifts as many times as possible at 40 bpm until exhaustion	NR	Borg CR-10 scale	(1) Borg: 8.3 (IM) (2) Borg: 8.5 (IM)
Pline et al., 2006	Lumbar fatigue - multiple sets of back extensions performed on the 45° Roman chair at 30 bpm until the force drop to force target	(1) 14 min (2) 14 min (3) 14 min (4) 90 min	MVC	(1) Force target (86% of MVC): 81.9 (IM) (2) Force target (73% of MVC): 69.9 (IM) (3) Force target (60% of MVC): 59.9 (IM) (4) Force target (73% of MVC): 66.3 (IM)
Roerdink et al., 2011	Ankle fatigue - to repeatedly raise the heels by standing on the toes with straight knees as many times as possible at 40 bpm until exhaustion	NR	Borg CR-10 scale	Borg: 8.5 (IM)

(continued)

Table 6. Continued.

Article	Fatigue protocol	Time to fatigue	Fatigue-related measurement	Fatigue-related finding
Aprigio et al., 2020	Ankle fatigue - To stand on the tip of the toes and to perform an isometric contraction of plantar flexion until voluntary exhaustion	278 (190) s	Borg CR-10 scale Slope EMG RMS Slope EMG median frequency	Borg: 6 (2) (IM) ↑ Slope RMS (IM) ↓ Slope median frequency (IM)
Santos et al., 2020	Judo match - to follow a tournament routine and maximally compete during the match for 7 min	420 s	HR Blood lactate Borg 6–20 scale	↑ HR (IM, ST) ↑ Blood lactate (IM, ST) Borg: 16.1 (IM)
Penedo et al., 2022	Ankle fatigue - To repeatedly perform the ankle plantar flexion and dorsiflexion on a step at 30 bpm until exhaustion	265 (158) s [94-655]	MVC Borg 6-20 scale	↓ MVC (IM) ↑ Borg (IM)
Lyu et al., 2022	Lower limb fatigue – To perform 5 sets of 20 reps at 50% of the unilateral (dominant) and bilateral MVC force of extension/flexion of the lower limb joints	NR	MVC Borg 6-20 scale	(1) ↓ MVC dominant (IM) ↓ MVC non-dominant (IM) ↓ MVC both legs (IM) ↑ Borg (IM) (2) ↓ MVC bilateral (IM) ↑ Borg (IM)
Fan et al., 2024	Cycling fatigue - (1) pedaling with both lower extremities simultaneously, or (2) pedaling with only the dominant lower extremity on the pedal	NR	MVC Borg 6-20 scale	(1) ↓ MVC bilateral (IM) ↑ Borg (IM) (2) ↓ MVC unilateral (IM) ↑ Borg (IM)

Db – double; **EMG** – electromyography; **HR** – heart rate; **IM** – immediate effect; **LT** – long-term effect; **MVC** – maximum voluntary contraction; **NR** – not reported; **PF** – peak vertical force; **PFS** – plantar flexor; **PP** – peak power; **PT** – peak twitch torque; **RER** – respiratory exchange ratio; **RF** – respiratory frequency; **RMS** – root mean square; **SBP** - Systolic blood pressure; **SpO2** – oxygen saturation; **ST** – shot-term effect; **TFS** – toe flexor; **TOV** – takeoff velocity; **VA** – voluntary activation; **VAS** – visual analogue scale; **VO2** – oxygen uptake.

5, 15% (BOVE et al., 2007; DEGACHE et al., 2020; MELLO; DE OLIVEIRA; NADAL, 2010; NARDONE et al., 1997, 1998) and EMG median frequency or RMS (n = 5, 15%) (APRIGIO et al., 2020; CHENG et al., 2015; GIMMON et al., 2011; MELLO; DE OLIVEIRA; NADAL, 2007, 2010); blood lactate (n = 4, 12%) (DEMURA; UCHIYAMA, 2009; MELLO; DE OLIVEIRA; NADAL, 2010; NODA; DEMURA, 2006; SANTOS et al., 2020); visual analogue scale (n = 3, 9%) (DEGACHE et al., 2014, 2019, 2020); twitch interpolation (n = 2, 6%) (CLARKE et al., 2015; PENEDO et al., 2021); jump height (n = 1, 3%) (MARCHETTI; ORSELLI; DUARTE, 2013); VO₂ (n = 1, 3%) (BOVE et al., 2007); or blood pressure (n = 1, 3%) (DEMURA; UCHIYAMA, 2009).

2.3.5. Postural control protocols

2.3.5.1. Stance condition during postural task

The specifications of the postural control protocols are exhibited in Table 7. Participants stood upright in a side-by-side stance in 16 studies (48%) (APRIGIO et al., 2020; BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BOVE et al., 2007; DEGACHE et al., 2014, 2019, 2020; HLAVACKOVA; VUILLERME, 2012; JANSSENS et al., 2010; KOYAMA; YAMAUCHI, 2017; MARCHETTI; ORSELLI; DUARTE, 2013; PENEDO et al., 2021, 2022; PINSAULT; VUILLERME, 2008; ROERDINK; HLAVACKOVA; VUILLERME, 2011; SANTOS et al., 2020), followed by feet together stance in 11 studies (33%) (BISSON et al., 2012; DAVIDSON; MADIGAN; NUSSBAUM, 2004; DEMURA; UCHIYAMA, 2009; FOX et al., 2008; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021; MELLO; DE OLIVEIRA; NADAL, 2007, 2010; NARDONE et al., 1997, 1998; PLINE; MADIGAN; NUSSBAUM, 2006), narrow stance in four studies (12%) (CHENG et al., 2015; FAN et

al., 2024; GIMMON et al., 2011; LYU et al., 2022) and Romberg stance in two studies (6%) (CLARKE et al., 2015; NODA; DEMURA, 2006). The main instructions given to participants were to stand barefoot with their arms extended at their sides and to remain “as still as possible”.

2.3.5.2. *Visual condition*

Ten studies (30%) requested that participants keep their eyes open during postural tasks (APRIGIO et al., 2020; DEGACHE et al., 2019, 2020; DEMURA; UCHIYAMA, 2009; FAN et al., 2024; LYU et al., 2021; MARCHETTI; ORSELLI; DUARTE, 2013; NODA; DEMURA, 2006; PENEDO et al., 2021; SANTOS et al., 2020), while 12 studies (36%) requested that participants keep their eyes closed during postural tasks (BERGER; REGUEME; FORESTIER, 2010; CLARKE et al., 2015; DAVIDSON; MADIGAN; NUSSBAUM, 2004; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; JANSSENS et al., 2010; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2022; PINSAULT; VUILLERME, 2009; PLINE; MADIGAN; NUSSBAUM, 2006; ROERDINK; HLAVACKOVA; VUILLERME, 2011). In addition, eight studies (24%) incorporated both visual conditions during postural tasks (BARBIERI et al., 2019; BOVE et al., 2007; DEGACHE et al., 2014; KOYAMA; YAMAUCHI, 2017; MELLO; DE OLIVEIRA; NADAL, 2010; NARDONE et al., 1997, 1998; PENEDO et al., 2022). Furthermore, saccadic eye movement (BARBIERI et al., 2019) and blindfolded conditions (BISSON et al., 2012) were employed during postural tasks. Two articles (6%) did not report visual conditions during the postural task (CHENG et al., 2015; MELLO; DE OLIVEIRA; NADAL, 2007).

2.3.5.3. Number, duration, and order of trials

Only one article (3%) did not report the number of trials performed in both pre- and post-fatiguing exercises (LYU et al., 2021). For the other studies, the number of trials ranged from two (APRIGIO et al., 2020; DEGACHE et al., 2020; JANSSENS et al., 2010; LYU et al., 2022; MELLO; DE OLIVEIRA; NADAL, 2007; ROERDINK; HLAVACKOVA; VUILLERME, 2011) to 40 trials (NARDONE et al., 1998). The duration of the trials ranged from 10 (SANTOS et al., 2020) to 120 seconds (APRIGIO et al., 2020; MELLO; DE OLIVEIRA; NADAL, 2007). Of the articles that reported having performed more than one trial (in sequence) pre or post fatigue, only eight (24%) reported the interval between attempts from 10 (KOYAMA; YAMAUCHI, 2017; MELLO; DE OLIVEIRA; NADAL, 2010) to 180 seconds (PLINE; MADIGAN; NUSSBAUM, 2006), and of those who performed more than one visual condition, only eight (24%) reported the order of the conditions that were randomized (BARBIERI et al., 2019; KOYAMA; YAMAUCHI, 2017), alternated (BOVE et al., 2007; NARDONE et al., 1997, 1998), intercalated (MELLO; DE OLIVEIRA; NADAL, 2010), counterbalanced (PENEDO et al., 2022), or in a fixed order (GIMMON et al., 2011).

2.3.5.4. Variables to assess postural control

The variables derived from the center of pressure (CoP) were the main parameters calculated to show the effects of fatiguing exercise on postural control (Table 7). Among them, the most used were the linear CoP variables, such as displacement, RMS, mean velocity, and area (ellipse). Furthermore, non-linear CoP variables were also included, such as mean and median frequency, detrend fluctuation analysis, and complexity index (entropy). In addition, muscle activation (EMG) parameters were shown as RMS and median frequency.

2.3.6. Time to assess the exercise-induced fatigue effects

The majority of articles (n = 29, 87%) evaluated the immediate effects of fatiguing exercise on postural control. Eleven studies (33%) have verified the short- and/or long-term effects of fatiguing exercise on postural control. Specifically, these studies assessed the effect of exercise-induced fatigue after 2 minutes (SANTOS et al., 2020), 10 minutes (NODA; DEMURA, 2006), 15 minutes (DEMURA; UCHIYAMA, 2009), 18 minutes (FOX et al., 2008), 25 min (NARDONE et al., 1997), 30 minutes (DAVIDSON; MADIGAN; NUSSBAUM, 2004; PLINE; MADIGAN; NUSSBAUM, 2006), 68 minutes (NARDONE et al., 1998), and 48 hours (CLARKE et al., 2015; PENEDO et al., 2022). It should be noted that one study (3%) did not report the time for assessment after fatiguing exercise (DEGACHE et al., 2020).

2.3.7. Fatigue-related effects on postural control parameters

The summary of the results is described in Table 8. Linear and non-linear CoP variables were analyzed in all studies (n = 33, 100%), while EMG was analyzed in three studies (9%) (APRIGIO et al., 2020; BERGER; REGUEME; FORESTIER, 2010; PENEDO et al., 2021). Our search attempted to find studies that analyzed cortical activity during postural task after exercise-induced fatigue, but no articles were included.

Table 7. Protocols of postural control assessments of the included studies.

Article	Task	Instructions	Total number of trials (pre and post fatigue)	Duration (s); interval between (s); and order of trials	Variables calculated	Time to post assessments (recovery)
Barbieri et al., 2019	SBS (feet shoulder- width apart)	to stand quietly in an upright position, barefoot, on a single force plate, with EC, EO (gaze fixation on a stationary target positioned in front of the participant), and saccadic eye movements (performing saccades directed to a target appearing on one side of a monitor, then disappearing and reappearing simultaneously on the opposite side of the monitor once per 2 s)	12 (6 pre and 6 post, 2 in each visual condition)	60; NR; randomized	AP and ML displacement AP and ML RMS 95% sway area of CoP AP and ML median frequency	post 1 - immediate
Berger, Regueme & Forestier, 2010	SBS (feet abducted at 30° and heels separated by 9 cm)	to remain upright and to minimize body movement as much as possible; EC	4 (2 pre and 2 post)	32; 32; N/A	Area AP and ML Variance Mean Velocity Mean SOL, GAM and TA activity TA/SOL and TA/GAM ratio	post 1 - immediate
Bisson et al., 2012	FTG	to stand as still as possible blindfolded (opaque ski goggles), to position their hands on their hips at the beginning of the trials and were allowed to use them to maintain their balance if necessary; blindfolded (opaque ski goggles)	6 (3 pre and 3 post)	30; NR; N/A	CoP area AP and ML CoP variability AP and ML mean CoP velocity	post 1 - immediate
Bove et al., 2007	SBS (spaced 10 cm on the platform)	to stand barefoot and quietly with the arms by the sides; EC and EO (looking at a target placed at eye level 1m in front)	24 (4 pre and 20 post, 12 in each visual condition)	51.2; 60; alternated	CoP displacement Sway path	post 1 - immediate
Cheng et al., 2015	NAR (two heels 3 cm apart and feet 30 degrees of abduction)	to stand upright with arms by the side and barefoot	6 (3 pre and 3 post)	60; NR; N/A	AP and ML displacement Sway area Mean velocity	post 1 - immediate
Clarke et al., 2015	ROM	to position the heel of the non-dominant foot in front of the toe of the dominant foot, leaving no space between the feet. The arms were stabilized by placing the hands on the hips with the elbows flexed at approximately 100°, to look straight ahead, stand as still as possible, and close the eyes after 5 s had elapsed (cued visually by the experimenter); EC	5 (2 pre and 3 post)	60; NR; N/A	AP and ML STD AP and ML displacement Area	post 1 - immediate post 2 - 24 h post 3 - 48 h

(continued)

Table 7. Protocols of postural control assessments of the included studies.

Article	Task	Instructions	Total number of trials (pre and post fatigue)	Duration (s); interval between (s); and order of trials	Variables calculated	Time to post assessments (recovery)
Davidson, Madigan & Nussbaum, 2004	FTG	to remain as still as possible, barefoot, with eyes closed, and arms resting at their side; EC	8 (1 pre and 7 post)	30, N/A; N/A	Mean and Peak velocity Modified ellipse area Sway area AP and ML Mean frequency AP and ML Median frequency Balance recovery rate	post 1 - immediate post 2 - 5 min post 3 - 10 min post 4 - 15 min post 5 - 20 min post 6 - 25 min post 7 - 30 min
Degache et al., 2019	SBS (feet formed a 30° angle)	to stand double leg with the arm at the sides; EO (to fix a target at a distance of 1m)	5 (1 pre and 4 post)	51.2; N/A; N/A	Surface of CoPs AP and ML Total displacement AP displacement of CoPy ML displacement of CoPx	post 1 - 50 km post 2 - 106 km post 3 - 151 km post 4 - 206 km
Degache et al., 2014	SBS (feet formed a 30° angle and inter-malleolar distance of 5 cm)	to stand with the arms at the sides and to look straight ahead while trying to maintain the postural stability to the best ability; EC and EO (to look at a fixed-level target at a distance of 90 cm)	6 (2 pre and 4 post)	51.2; NR; NR	AP, ML, and Total displacement	post 1 - MID (148.7 km) post 2 - POST (330 km)
Degache et al., 2020	SBS (feet formed a 30° angle and inter-malleolar distance of 5 cm)	to stand with the arms at the sides and look straight ahead while trying to maintain the postural stability to the best ability; EO (to look at a fixed-level target at a distance of 0.9 m)	2 (1 pre and 1 post)	51.2; N/A; N/A	CoP surface (90% confidence ellipse)	NR
Demura & Uchiyama, 2009	FTG	stood upright and barefoot with the arms by the sides; EO (to look at a 3-cm diameter red circle target placed at eye level about 3 m in front of them)	6 (2 pre and 4 post)	60; NR; N/A	AP and ML Mean position Sway area Path length per second AP and ML RMS AP and ML sway velocity AP and ML RMS of sway velocity AP and power spectrum	post 1 - immediate post 2 - 5 min post 3 - 10 min post 4 - 15 min
Fox et al., 2008	FTG	to stand quietly and motionless in the stance position, keeping the eyes closed and hands on the iliac crests; EC	5 (1 pre and 4 post)	20; N/A; N/A	COP average sway velocity Elliptical sway area (95% ellipse)	post 1 - 3 min post 2 - 8 min post 3 - 13 min post 4 - 18 min

(continued)

Table 7. Protocols of postural control assessments of the included studies.

Article	Task	Instructions	Total number of trials (pre and post fatigue)	Duration (s); interval between (s); and order of trials	Variables calculated	Time to post assessments (recovery)
Gimmon et al., 2011	NAR	to stand as still and stable as possible on a force platform, with the arms placed at the sides of the body; EC	30 (10 pre and 20 post)	30; NR; ordered (non-fatigue, plantar flexor, upper limb)	AP and ML sway range Mean velocity of CoP sway Sway area	post 1 - immediate
Hlavackova & Vuillerme, 2012	SBS (abducted at 30°, heels separated by 3 cm)	to sway as little as possible, barefoot with the arms hanging loosely by their sides; EC	6 (3 pre and 3 post)	32; NR; N/A	Surface area (90% confidence interval) Mean velocity (CoP displacements)	post 1 - immediate
Janssens et al., 2010	SBS	to stand barefoot on the force plate with the hands relaxed and at the sides, and to keep the gaze in a straight-ahead direction; EC	2 (1 pre and 1 post)	60; N/A; N/A	CoP RMS (AP displacement)	post 1 - immediate
Koyama & Yamauchi, 2017	SBS	to stand for as long as possible, to keep the standing leg still, with the arms by the sides; EC and EO (without information about visual task)	4 (2 pre and 2 post)	30; 10; randomized	Total length Mean velocity Sway area AP and ML range AP and ML mean velocity	post 1 - immediate
Lin, Nussbaum & Madigan, 2012	FTG	to ‘concentrate on standing as still as possible’ and to think about their level of ‘perceived stability’ (PS) during the period of the quiet standing, with the arms at the sides, and head pointed straight ahead; EC	6 (3 pre and 3 post)	75; 60; N/A	AP and ML mean velocity AP and ML fractal measure Sway area	post 1 - immediate
Lyu et al., 2021	FTG	to stand upright and relaxed, barefoot, shoulders placed in a neutral position, elbows in full extension, and hands rested by the sides; EO (eyes concentrating on a black cross marked 1.5 m away on the wall)	NR	30; NR; NR	AP and ML Sway velocity Total displacements Area Low-frequency band (0–0.3 Hz) Medium-frequency band (0.3–1 Hz) High-frequency band (1–3 Hz)	post 1 - immediate
Marchetti et al., 2013	SBS (feet hip-width apart)	to stand as still as possible, to select a comfortable standing position, and with the arms crossed on their chest; EO (to look straight at a point about 2 m ahead at head height)	6 (3 pre and 3 post)	30; NR; N/A	CoP mean speed CoP area	post 1 - immediate

(continued)

Table 7. Protocols of postural control assessments of the included studies.

Article	Task	Instructions	Total number of trials (pre and post fatigue)	Duration (s); interval between (s); and order of trials	Variables calculated	Time to post assessments (recovery)
Mello, de Oliveira & Nadal, 2010	FTG	to stay with barefoot and arms relaxed; EC and EO (looking at a target placed at 50 cm ahead at eye level)	20 (10 pre and 10 post)	50, 10; intercalated	Mean duration of the peaks Mean time interval between two consecutive peaks Mean distance between two consecutive peaks Mean velocity Elliptic sway area	post 1 - immediate
Mello, de Oliveira & Nadal, 2007	FTG	arms relaxed	2 (1 pre and 1 post)	120; N/A; N/A	COP displacement (area) AP and ML velocity	post 1 - immediate
Nardone et al., 1998	FTG	to stand as still as possible, barefoot and with their arms by their sides; EC and EO (to look at a target placed at eye level about 50 cm in front)	40 (10 pre and 30 post)	51; N/A; alternated	Sway Path and Area	post 1 - 8 min post 2 - 28 min post 3 - 68 min
Nardone et al., 1997	FTG	to stand as still as possible, barefoot and with their arms by their sides; EC and EO (to look at a target placed at eye level about 50 cm in front)	30 (10 pre and 20 post, 5 in each visual condition)	51; NR; alternated	Position of the instantaneous CoP Mean position of CFP Sway Path and Area AP and ML median frequency	post 1 - 5 min post 2 - 25 min
Noda & Demura, 2006	ROM	to stand barefoot with the arms relaxed comfortably at their side; EO (to fix a point in front)	5 (2 pre and 3 post)	60; NR; N/A	Path length Total, AP, and ML RMS Area AP and ML velocity RMS velocity	post 1 - immediate post 2 - 5 min post 3 - 10 min
Penedo et al., 2021	SBS (foot shoulder-width apart)	to remain as still as possible, barefoot and with arms extended and relaxed at the side of the trunk; EO (gaze directed at a target positioned one meter away at eye level)	4 (2 pre and 2 post)	60; NR; N/A	AP and ML displacement AP and ML mean velocity AP and ML RMS AP and ML median frequency of sway TA, GM, RF, and BF RMS TA, GM, RF, and BF median frequency Co-contraction index	post 1 - immediate

(continued)

Table 7. Protocols of postural control assessments of the included studies.

Article	Task	Instructions	Total number of trials (pre and post fatigue)	Duration (s); interval between (s); and order of trials	Variables calculated	Time to post assessments (recovery)
Pinsault & Vuillerme, 2008	SBS (feet abducted at 30°, heels separated by 3 cm)	to stand as still as possible, barefoot and with the arms hanging loosely by the sides; EC	12 (6 pre and 6 post)	32; NR; N/A	CoP surface area CoP AP and ML variance	post 1 - immediate
Pline et al., 2006	FTG	to stand as still and as quietly as possible with the arms at the sides; EC	14 (3 pre and 11 post)	30; 180; N/A	Mean and Peak velocity Sway area	post 1 - immediate post 2 - 3 min post 3 - 6 min post 4 - 9 min post 5 - 12 min post 6 - 15 min post 7 - 18 min post 8 - 21 min post 9 - 24 min post 10 - 27 min
Roerdink et al., 2011	SBS (feet abducted at 30°, heels separated by 3 cm)	to sway as little as possible and stood barefoot with the arms hanging loosely by the sides; EC	2 (1 pre and 1 post)	32; N/A; N/A	AP COP range and standard deviation (fluctuations) AP COP sample entropy (regularity)	post 1 - immediate
Aprigio et al., 2020	SBS (maintaining an angulation of 15° and spacing of 5 cm between the medial malleolus)	barefoot; EO (to stare to a 5 cm circle positioned 3 m ahead adjusted at eye-level)	2 (1 pre and 1 post)	120; N/A; N/A	CoP elliptical area CoP average velocity EMG RMS EMG RMS and median frequency slopes for Gastrocnemius	post 1 - immediate
Santos et al., 2020	SBS (stance width was set at 17 cm)	to stand as still as possible, barefooted, and hands were held akimbo; EO (to rest the gaze on a target (10 cm ² circle) that was elevated 1.7 m, and situated 2.5 m away from the platform)	4 (3 pre and 1 post)	10; 60; N/A	Length Area Velocity	post 1 - immediate post 2 - 2 min
Penedo et al., 2022	SBS (hip-width apart)	to stand upright and to remain as still as possible, barefoot and with the arms hanging loosely alongside; EC and EO (to gaze a target positioned one meter away at eye level)	12 (4 pre and 8 post)	60; 15; counterbalanced	AP and ML Mean velocity AP and ML RMS AP and ML median frequency AP and ML DFA AP and ML CI	post 1 - immediate post 2 - 24 - 48 h after (Later-F)

(continued)

Table 7. Protocols of postural control assessments of the included studies.

Article	Task	Instructions	Total number of trials (pre and post fatigue)	Duration (s); interval between (s); and order of trials	Variables calculated	Time to post assessments (recovery)
Lyu et al., 2022	NAR (heels and toes touching)	to stand upright as still as possible, barefoot and with the arms rested at sides; EC	2 (1 pre and 1 post)	30; N/A; N/A	AP and ML Sway velocity Total displacements Envelope area AP and ML low-frequency (0-0.3 Hz) AP and ML medium-frequency (0.3-1 Hz) AP and ML high-frequency (1-3 Hz)	post 1 - immediate
Fan et al., 2024	NAR (heels and toes touching)	to keep the body stable, barefoot and with the hands relaxed at sides; EO (eyes looking at the black dot on the white wall located at a horizontal distance of 1.5 m directly in front)	3 (1 pre and 1 post)	30; N/A; N/A	AP and ML Sway velocity Total displacements Envelope area	post 1 - immediate

AP – anteroposterior; **CI** – complexity index; **CoP** – center of pressure; **DFA** – detrend fluctuation analysis; **EC** – eyes closed; **EMG** – electromyography; **EO** – eyes open; **FTG** – feet together stance; **ML** – medial-lateral; **N/A** – not applicable; **NAR** – narrow stance; **NR** – not reported; **RMS** – root mean square; **ROM** – Romberg stance; **SBS** – side-by-side; **STD** – standard deviation.

Table 8. Main exercise-induced fatigue effects on young adults' postural control.

Article	CoP parameters	EMG parameters
Barbieri et al., 2019	↑ AP displacement (IM) ↑ ML displacement (IM) ↑ AP RMS (IM) ↑ ML RMS (IM) ↑ Area (IM)	N/A
Berger, Regueme & Forestier, 2010	↑ Area (IM) ↑ ML variance (IM) ↑ AP variance (IM) ↑ Mean velocity (IM)	↓ TA activity (IM) ↑ TA/SOL ratio (IM) ↑ TA/GAM ratio (IM)
Bisson et al., 2012	↑ AP variability (IM) ↑ AP mean velocity (IM)	N/A
Bove et al., 2007	↑ Sway path (IM)	N/A
Cheng et al., 2015	↑ AP displacement (IM)	N/A
Clarke et al., 2015	↑ AP STD (IM) ↑ ML STD (IM) ↑ AP displacement (IM) ↑ ML displacement (IM) ↑ Area (IM)	N/A
Davidson, Madigan & Nussbaum, 2004	↑ Mean velocity (IM) ↑ Modified ellipse area (IM) ↑ Sway Area (IM)	N/A
Degache et al., 2019	↑ Total displacement (IM, LT) ↑ AP displacement (IM, LT) ↑ ML displacement (IM, LT) ↑ Mean velocity (IM, LT)	N/A
Degache et al., 2014	↑ Total length (IM, LT) ↑ AP length (IM, LT) ↑ ML length (IM)	N/A
Degache et al., 2020	↑ Surface	N/A
Demura & Uchiyama, 2009	(1) ↑ Rectangle area (IM, ST) ↑ Path length per second (IM)	N/A
Fox et al., 2008	(2) ↑ Rectangle area (IM) ↑ Path length per second (IM) (1) ↑ Sway velocity (ST) ↑ Elliptical sway area (ST)	N/A
Gimmon et al., 2011	(2) ↑ Sway velocity (ST) ↑ Elliptical sway area (ST) (1) ↑ AP velocity (IM) ↑ ML velocity (IM) ↑ AP range (IM) ↑ Area (IM)	N/A
Hlavackova & Vuillerme, 2012	(2) No effects ↑ Surface area (IM) ↑ Mean velocity (IM)	N/A

(continued)

Table 8. Continued.

Article	CoP parameters	EMG parameters
Janssens et al., 2010	No effects	N/A
Koyama & Yamauchi, 2017	↓ AP velocity (IM)	N/A
Lin, Nussbaum & Madigan, 2012	↑ AP mean velocity (IM) ↑ AP DFA (IM) ↑ Sway area (IM)	N/A
Lyu et al., 2021	(1) ↑ AP sway velocity (IM) ↑ Total displacement (IM) (2) ↑ AP sway velocity (IM) ↑ Total displacement (IM)	N/A
Marchetti et al., 2013	(1) ↑ Mean speed (IM) (2) ↑ Mean speed (IM)	N/A
Mello, de Oliveira & Nadal, 2010	(1) ↓ Mean duration of the peaks (IM) ↑ Mean velocity (IM) (2) ↑ Mean velocity (IM) ↑ Elliptic sway area (IM)	N/A
Mello, de Oliveira & Nadal, 2007	↑ AP Mean velocity (IM) ↑ ML Mean velocity (IM) ↑ Area (IM)	N/A
Nardone et al., 1998	↑ Sway path (ST) ↑ Sway area (ST)	N/A
Nardone et al., 1997	(1) ↑ Sway path (ST) ↑ Sway area (ST) (2) No effects	N/A
Noda & Demura, 2006	↑ Mean path length (IM) ↑ AP mean velocity (IM > pre and ST) ↑ Mean standard deviation (IM > pre and ST)	N/A
Penedo et al., 2021	(1) ↑ AP displacement (IM) ↑ ML displacement (IM) ↑ AP mean velocity (IM) ↑ ML mean velocity (IM) ↑ AP RMS (IM) ↑ Area (IM) (2) ↑ AP median frequency (IM)	(1) ↓ RF %RMSmax (IM) (2) ↓ TA median frequency (IM) ↓ BF median frequency (IM)
Pinsault & Vuillerme, 2008	(1) ↑ Surface area (IM) ↑ AP variance (IM) ↑ ML variance (IM) (2) ↑ Surface area (IM) ↑ AP variance (IM)	N/A

(continued)

Table 8. Continued.

Article	CoP parameters	EMG parameters
Pline et al., 2006	↑ Mean velocity (IM, ST) ↑ Peak velocity (IM, ST)	N/A
Roerdink et al., 2011	↑ AP range (IM) ↑ AP standard deviation (IM) ↓ AP sample entropy (IM)	N/A
Aprigio et al., 2020	↑ Area (IM) ↑ Average velocity (IM)	No effects
Santos et al., 2020	↑ Length (IM) ↑ Area (IM) ↑ Velocity (IM)	N/A
Penedo et al., 2022	↑ AP RMS (IM, LT) ↑ ML RMS (IM, LT) ↑ AP mean velocity (IM) ↑ ML mean velocity (LT) ↑ ML median frequency (LT)	N/A
Lyu et al., 2022	↑ AP sway velocity (IM) ↑ ML sway velocity (IM) ↑ Total displacements (IM)	N/A
Fan et al., 2024	↑ AP sway velocity (IM) ↑ ML sway velocity (IM) ↑ Total displacements (IM) ↑ Envelope area (IM)	N/A

AP – anteroposterior; **BF** – biceps femoris; **EMG** – electromyography; **GAM** – gastrocnemius medialis; **IM** – immediate effect; **LT** – long-term effect; **ML** – medial-lateral; **N/A** – not applicable; **RMS** – root mean square; **SOL** – soleus; **ST** – short-term effect; **STD** – standard deviation; **TA** – tibialis anterior.

2.3.7.1. Immediate effects of fatiguing exercise

The included studies showed immediate effects of fatiguing exercises on CoP and EMG activity (APRIGIO et al., 2020; BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; BOVE et al., 2007; CHENG et al., 2015; CLARKE et al., 2015; DAVIDSON; MADIGAN; NUSSBAUM, 2004; DEGACHE et al., 2020, 2014, 2019; DEMURA; UCHIYAMA, 2009; FAN et al., 2024; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; LIN; NUSSBAUM; MADIGAN, 2012; LYU et al., 2021, 2022; MARCHETTI; ORSELLI; DUARTE, 2013; MELLO; DE OLIVEIRA; NADAL, 2007, 2010; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022; PINSAULT; VUILLERME, 2008; PLINE; MADIGAN; NUSSBAUM, 2006; ROERDINK; HLAVACKOVA; VUILLERME, 2011; SANTOS et al., 2020). In general, there was an increase in the linear parameters of the CoP and a decrease in muscle activity (EMG) immediately after performing the fatiguing exercise (Table 8).

It is worth mentioning that only 4 studies showed an immediate decrease in CoP AP velocity (KOYAMA; YAMAUCHI, 2017), CoP mean duration of peaks (MELLO; DE OLIVEIRA; NADAL, 2010), CoP AP sample entropy (ROERDINK; HLAVACKOVA; VUILLERME, 2011), or no effect on EMG (APRIGIO et al., 2020). Exclusively, one article reported that fatiguing exercise did not cause general effects on postural control (JANSSENS et al., 2010).

2.3.7.2. Short-term effects of fatiguing exercise

The included studies showed that fatiguing exercise can promote short-term effects on CoP, ranging from five (DEMURA; UCHIYAMA, 2009; NARDONE et al., 1997) to 21 minutes (PLINE; MADIGAN; NUSSBAUM, 2006). These effects were

indicated by the increase in the CoP area ranging from five (DEMURA; UCHIYAMA, 2009; NARDONE et al., 1997) to eight minutes (NARDONE et al., 1998), and the CoP mean velocity ranging from eight (FOX et al., 2008) to 21 minutes (PLINE; MADIGAN; NUSSBAUM, 2006). Interestingly, one study (NODA; DEMURA, 2006) showed an immediate increase in the CoP mean velocity and standard deviation, but a short recovery period (i.e., five minutes) was sufficient to return to baseline values (Table 8).

2.3.7.3. Long-term effects of fatiguing exercise

Additionally to short-term effects, the included articles showed a long-term effects of fatiguing exercise on CoP, with a range from 24 (PENEDO et al., 2022) to 126 hours (DEGACHE et al., 2014). These effects were indicated by increases in the CoP AP and ML RMS, ML mean velocity, and ML median frequency that lasted for up to 48 hours (PENEDO et al., 2022), increases in the CoP total, AP and ML displacement, and the CoP mean velocity ranging from 30 to 45 hours (DEGACHE et al., 2019), and increases in the CoP total and AP length that lasted for 126 hours (DEGACHE et al., 2014) (Table 8).

2.3.8. Meta-analysis

2.3.8.1. Immediate effects of fatiguing exercise with eyes open

The CoP total displacement was assessed in six studies (18%) (BARBIERI et al., 2019; CHENG et al., 2015; DEGACHE et al., 2014, 2019; KOYAMA; YAMAUCHI, 2017; PENEDO et al., 2021), CoP AP displacement in five studies (15%) (BARBIERI et al., 2019; CHENG et al., 2015; DEGACHE et al., 2019; KOYAMA; YAMAUCHI, 2017; PENEDO et al., 2021), and CoP ML displacement in ten studies (30%) (BOVE et al., 2007; DEGACHE et al., 2014, 2019; FAN et al., 2024; KOYAMA; YAMAUCHI, 2017; LYU et al., 2021; NARDONE et al., 1997, 1998; NODA; DEMURA, 2006; SANTOS et

al., 2020). Post fatiguing vs. pre fatiguing exercise indicated significantly greater CoP total, AP, and ML displacement ($p < 0.05$ for all the outcomes), with a large effect size (> 0.8) for all variables. There was high heterogeneity in the studies for CoP total and ML displacement (values $> 76\%$), and moderate heterogeneity for AP displacement (36%) (Figure 3).

The CoP total mean velocity was assessed eight studies (DEMURA; UCHIYAMA, 2009; FAN et al., 2024; KOYAMA; YAMAUCHI, 2017; LYU et al., 2021; MELLO; DE OLIVEIRA; NADAL, 2007; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022), CoP AP mean velocity in seven studies (FAN et al., 2024; KOYAMA; YAMAUCHI, 2017; LYU et al., 2021; MELLO; DE OLIVEIRA; NADAL, 2007; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022), and CoP ML mean velocity in eight studies (APRIGIO et al., 2020; CHENG et al., 2015; DEGACHE et al., 2019; DEMURA; UCHIYAMA, 2009; KOYAMA; YAMAUCHI, 2017; MARCHETTI; ORSELLI; DUARTE, 2013; MELLO; DE OLIVEIRA; NADAL, 2010; SANTOS et al., 2020). Post fatiguing vs. pre fatiguing exercise indicated significantly greater CoP total and AP mean velocity ($p < 0.05$ for all the outcomes), with a large effect size (> 0.8) for all variables. There was high heterogeneity (values $> 76\%$) in the studies for CoP total, AP, and ML mean velocity (Figure 3).

The CoP AP and ML RMS were indicated in four each studies (BARBIERI et al., 2019; NODA; DEMURA, 2006; PENEDO et al., 2021, 2022). Post fatiguing vs. pre fatiguing exercise indicated significantly greater CoP AP and ML RMS ($p < 0.05$ for both), with a large effect size (> 0.8) for both. There was high heterogeneity (values $> 76\%$) for CoP ML RMS, and substantial heterogeneity (60%) for CoP AP RMS (Figure 3).

The CoP area were assessed in sixteen studies (48%) (APRIGIO et al., 2020; BARBIERI et al., 2019; CHENG et al., 2015; DEGACHE et al., 2020; DEMURA; UCHIYAMA, 2009; FAN et al., 2024; KOYAMA; YAMAUCHI, 2017; LYU et al., 2021; MARCHETTI; ORSELLI; DUARTE, 2013; MELLO; DE OLIVEIRA; NADAL, 2010, 2007; NARDONE et al., 1997, 1998; NODA; DEMURA, 2006; PENEDO et al., 2021; SANTOS et al., 2020). Post fatiguing vs. pre fatiguing exercise indicated significantly greater CoP area ($p < 0.05$), with a large effect size (> 0.8). The CoP area showed high heterogeneity (95%) (Figure 3).

2.3.8.2. *Immediate effects of fatiguing exercise with eyes closed*

The CoP total displacement was evaluated in six studies (BARBIERI et al., 2019; CLARKE et al., 2015; DEGACHE et al., 2014; GIMMON et al., 2011; KOYAMA; YAMAUCHI, 2017; ROERDINK; HLAVACKOVA; VUILLERME, 2011), CoP AP displacement in four studies (BARBIERI et al., 2019; CLARKE et al., 2015; GIMMON et al., 2011; KOYAMA; YAMAUCHI, 2017), and CoP ML displacement in six studies (BOVE et al., 2007; DEGACHE et al., 2014; KOYAMA; YAMAUCHI, 2017; LYU et al., 2022; NARDONE et al., 1997, 1998). Post fatiguing compared to pre fatiguing exercise indicated significantly greater CoP total displacement ($p < 0.05$), with high effect size (> 0.8). There was high heterogeneity (values $> 76\%$) between studies for all variables (Figure 4).

The CoP total mean velocity was assessed in six studies (BERGER; REGUEME; FORESTIER, 2010; DAVIDSON; MADIGAN; NUSSBAUM, 2004; FOX et al., 2008; HLAVACKOVA; VUILLERME, 2012; KOYAMA; YAMAUCHI, 2017; MELLO; DE OLIVEIRA; NADAL, 2010) studies, CoP AP and ML mean velocity were assessed in five each studies (BISSON et al., 2012; GIMMON et al., 2011; KOYAMA;

YAMAUCHI, 2017; LYU et al., 2022; PENEDO et al., 2022). Post fatiguing compared to pre fatiguing exercise indicated significantly greater CoP total, AP, and ML mean velocity (all $p < 0.05$), with high effect size for all variables (> 0.8). There was high heterogeneity (values $> 76\%$) between studies for all variables (Figure 4).

The CoP AP and ML RMS were measured respectively in eight (BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; CLARKE et al., 2015; JANSSENS et al., 2010; PENEDO et al., 2022; PINSAULT; VUILLERME, 2008; ROERDINK; HLAVACKOVA; VUILLERME, 2011) and six studies (BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; CLARKE et al., 2015; PENEDO et al., 2022; PINSAULT; VUILLERME, 2008). Post fatiguing compared to pre fatiguing exercise indicated significantly greater CoP AP and ML RMS (both $p < 0.05$), with high effect size for both (> 0.8). There was high heterogeneity (values $> 76\%$) between studies for both variables (Figure 4).

The CoP area were assessed in fourteen studies (BARBIERI et al., 2019; BERGER; REGUEME; FORESTIER, 2010; BISSON et al., 2012; CLARKE et al., 2015; DAVIDSON; MADIGAN; NUSSBAUM, 2004; FOX et al., 2008; GIMMON et al., 2011; HLAVACKOVA; VUILLERME, 2012; KOYAMA; YAMAUCHI, 2017; LYU et al., 2022; MELLO; DE OLIVEIRA; NADAL, 2010; NARDONE et al., 1997, 1998; PINSAULT; VUILLERME, 2008). Post fatiguing compared to pre fatiguing exercise indicated significantly greater CoP area ($p < 0.05$), with high effect size (> 0.8). There was high heterogeneity (values $> 76\%$) between studies (Figure 4).

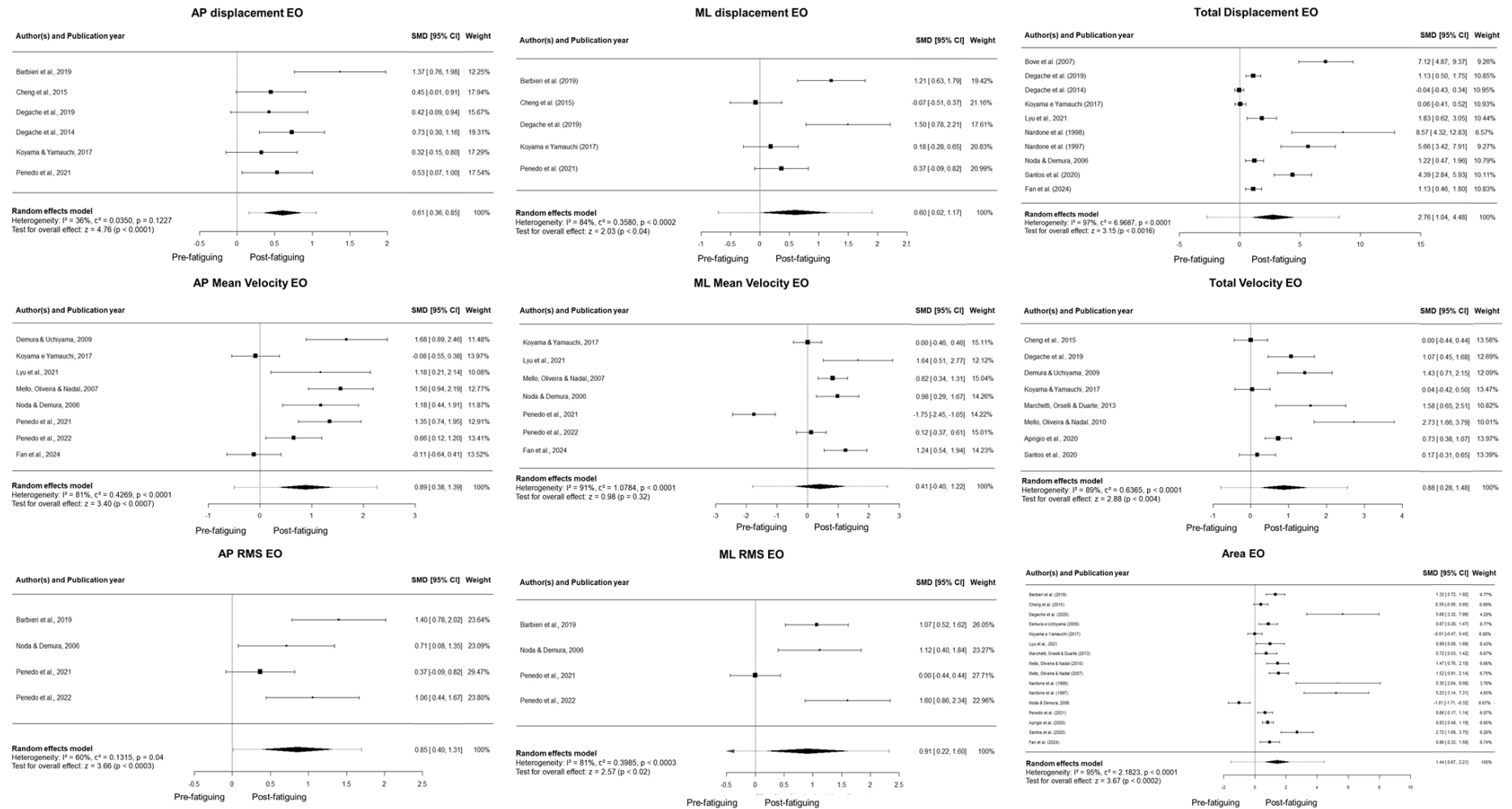


Figure 3. Forest plot of variables included in eyes open condition. **AP** – anteroposterior; **EO** – eyes-open; **ML** – medial-lateral; **RMS** – root mean square.

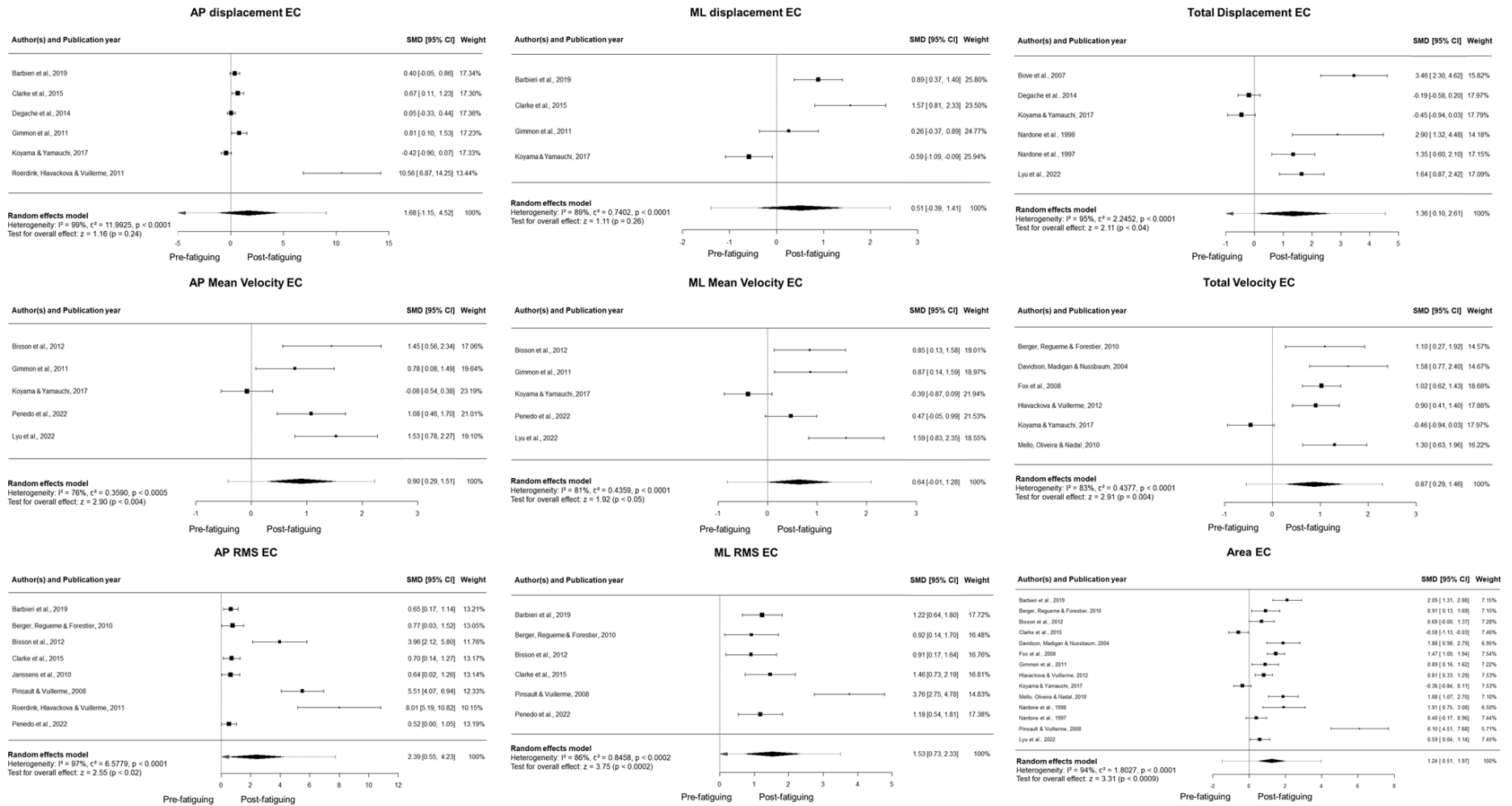


Figure 4. Forest plot of variables included in eyes closed condition. **AP** – anteroposterior; **EC** – eyes-closed; **ML** – medial-lateral; **RMS** – root mean square.

2.4. Discussion of study 1

The aim of this systematic review and meta-analysis was to evaluate and quantify the extent to which exercise-induced fatigue impacts upright postural control in healthy young adults, and to determine the duration of these effects. This study included a significant number of articles (33 in total), covering a relatively long-time span (from 1997 to 2024) and providing a comprehensive overview of the different methodologies used to investigate the immediate, short- and long-term effects of fatiguing exercise on postural control in healthy young adults. The systematic review revealed a variety of methodological approaches and gaps in studies on postural control and fatiguing exercises. Therefore, this systematic review and meta-analysis brings as its main novelty the robust and consistent impact of exercise-induced fatigue on the postural control (i.e., CoP parameters) of healthy young adults, confirming our hypothesis. Furthermore, it is possible to mention the distinction between the short- and long-term effects that fatiguing exercises have on standing posture. The following paragraphs will discuss the findings of this systematic review and meta-analysis.

2.4.1. Immediate effects of fatiguing exercise on posture

Fatiguing exercise causes robust and consistent immediate impacts on healthy young adults' postural control. The results of the meta-analysis revealed significant and high immediate effects of fatiguing exercise on postural control. These findings support the increase in body sway after exercise, compromising the postural stability of healthy young adults. The greater oscillation observed in CoP parameters immediately after fatiguing exercise is in line with the literature that associates fatigue with a reduction in the neuromuscular system's ability to maintain postural stability. Fatigue alters proprioception, muscle recruitment, and sensorimotor integration, negatively affecting

postural regulation (PAILLARD, 2012). This impact was evident (large effect sizes – values > 0.8) with increases in displacement (AP, ML, and total), mean velocity (AP, ML, and total), RMS (AP and ML), and area in both visual conditions (eyes open and closed) suggesting a substantial impact of fatigue on balance control.

The underlying mechanisms contributing to these immediate effects likely involve neuromuscular and proprioceptive impairments. Fatigue-induced reductions in muscle strength and coordination have been suggested to impair the ability to maintain postural stability (BOVE et al., 2007; ROERDINK; HLAVACKOVA; VUILLERME, 2011). Additionally, decreased somatosensory and vestibular inputs following exercise-induced fatigue may contribute to increased CoP excursions, as observed in the reviewed studies (PINSULT; VUILLERME, 2008). Notably, the observed increase in CoP displacement and velocity was consistent regardless of whether the eyes were open or closed, indicating that fatigue affects fundamental mechanisms of balance control, which are not entirely compensated by visual input (GIMMON et al., 2011; KOYAMA; YAMAUCHI, 2017).

The visual condition during the postural task plays a role after fatigue. In the eyes-closed condition, the impact of fatigue was visually more pronounced (higher effects sizes – see Figures 3 and 4), but with high heterogeneity observed for all parameters. This reflects the importance of vision as a crucial source of sensory information for maintaining balance. When vision is eliminated, the system relies more on proprioceptive and vestibular information, which can be compromised by fatiguing exercise (VUILLERME; NOUGIER; PRIEUR, 2001). Thus, the sensorimotor system is more susceptible to individual and methodological factors in the absence of visual information, especially after performing fatiguing exercise. The combination of greater magnitude and heterogeneity in the eyes-closed condition may reinforce the use of postural assessments without visual information as a sensitive way to detect impairments induced by fatiguing

exercise. In addition, it may explain the greater inter-studies variability (see funnel plots – Figures 5 and 6), especially in parameters such as displacement and area. Furthermore, the high heterogeneity identified in several parameters, particularly in the eyes-closed condition, can be attributed to methodological differences between studies, such as the type of fatiguing exercise and methods of assessing postural control. On the other hand, the meta-analysis showed moderate heterogeneity for AP displacement in the eyes-open condition. This result shows that this parameter is a particularly reliable, sensitive, and robust measure to assess the impact of fatiguing exercise on postural control in conditions in which vision is preserved.

2.4.2. Short- and long-term effects of fatiguing exercise on posture

The fatigue-related effects on young adults' postural control remain for a short-term after exercise. The systematic review revealed that the short-term effects were evident for up to 21 minutes post-exercise, with increases in CoP area and mean velocity (DEMURA; UCHIYAMA, 2009; FOX et al., 2008; PLINE; MADIGAN; NUSSBAUM, 2006). These results suggest that neuromuscular fatigue can persist beyond immediate recovery, potentially increasing fall risk in tasks requiring sustained balance control (NARDONE et al., 1997, 1998). Probably, the exercise-induced fatigue decreased the capacity of the neuromuscular response (e.g., decrease in muscle activation) in stabilizing posture, which may reflect enhanced velocity and area of the CoP, outcomes that are normally related to “poor” postural control.

Long-term effects, persisting up to 126 hours, were also observed, indicating prolonged neuromuscular alterations following fatiguing exercise (DEGACHE et al., 2014, 2019; PENEDO et al., 2022). These extended effects were characterized by increased CoP displacement and velocity, particularly in the ML direction, which may

reflect delayed muscle recovery or prolonged proprioceptive impairment (DEGACHE et al., 2014). Studies like those by Degache et al. (DEGACHE et al., 2014, 2019) have documented that fatigue induced by running exercise (i.e., ultramarathon) can affect postural control for up to 126 hours, suggesting that recovery mechanisms take an extended time to return to baseline after exhaustive efforts. This is particularly evident in exercises involving multiple muscle groups that result in widespread fatigue, impacting proprioceptive and neuromuscular systems essential for postural stability (DEGACHE et al., 2014, 2019). In contrast, localized models of exercise fatigue primarily affecting specific muscles indicates to have a shorter-lasting effect on CoP than general models of exercise, with recovery times for CoP ranging from 24 to 48 hours (PENEDO et al., 2022). These findings could support the idea that postural control recovery is linked to the exercise scope, with localized fatigue allowing for faster recovery, while generalized fatigue necessitates a longer recuperation period due to its broader impact on the neuromuscular system (PAILLARD, 2012; PENEDO et al., 2022).

Taking together, these findings hold practical implications for sports coaches, physical trainers and clinicians, especially for the planning of intensive physical activities. These professionals can use these insights, particularly in contexts where postural control is critical, such as in sports (mainly the ones that require a very stable quiet posture – e.g., target archery, shooting, etc.) and some functional and work-related occupations, to guide exercise and rehabilitation programs, emphasizing the importance of incorporating rest periods or targeted fatigue management strategies in activities that require postural stability. Adequate recovery periods are recommended after fatiguing exercises, depending on the type and duration, to prevent falls and injuries during sports and daily activities associated with prolonged postural instability (PAILLARD, 2012; ZECH et al., 2010).

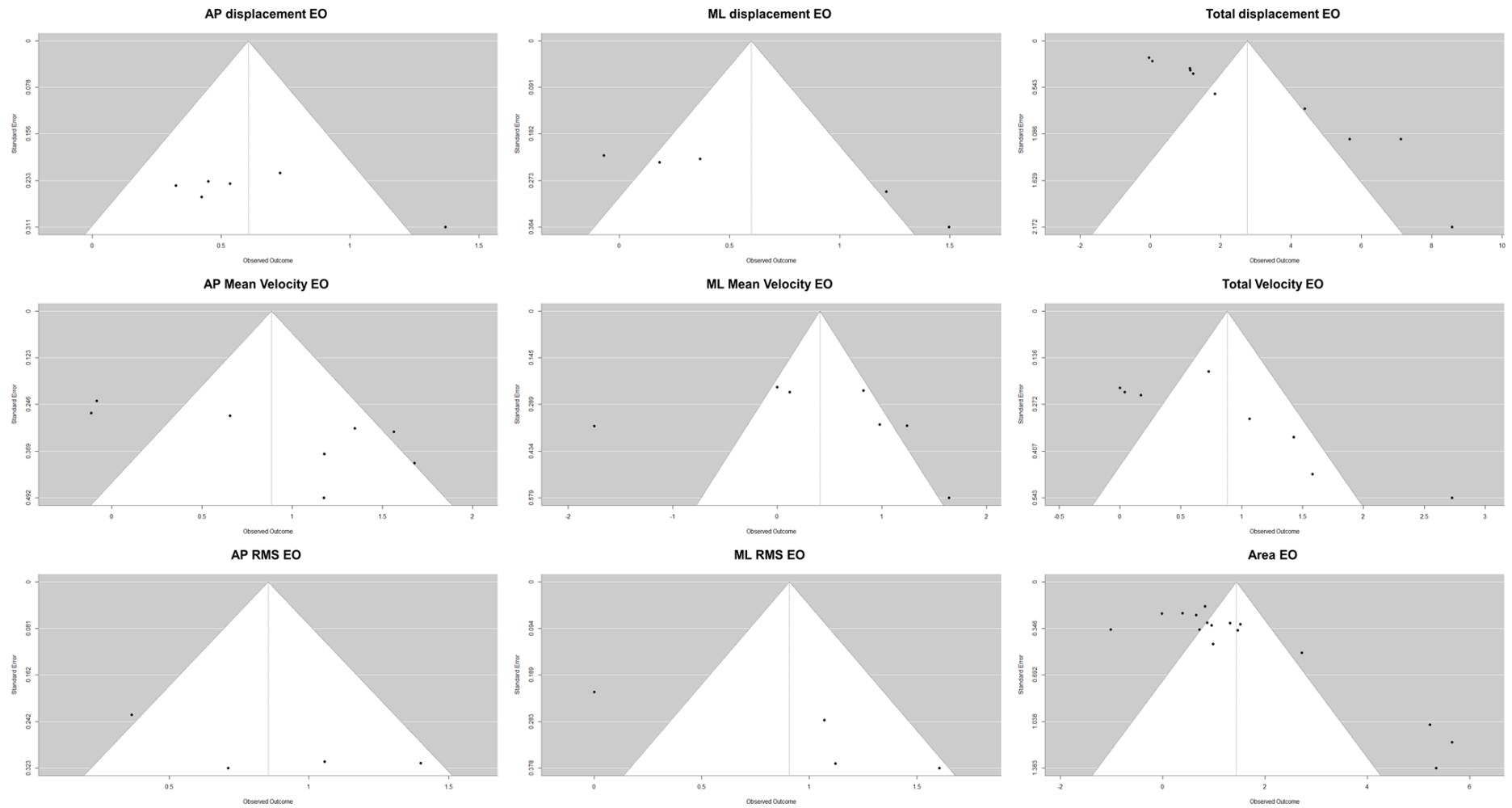


Figure 5. Funnel plot shows the data dispersion of variables included in eyes open condition.

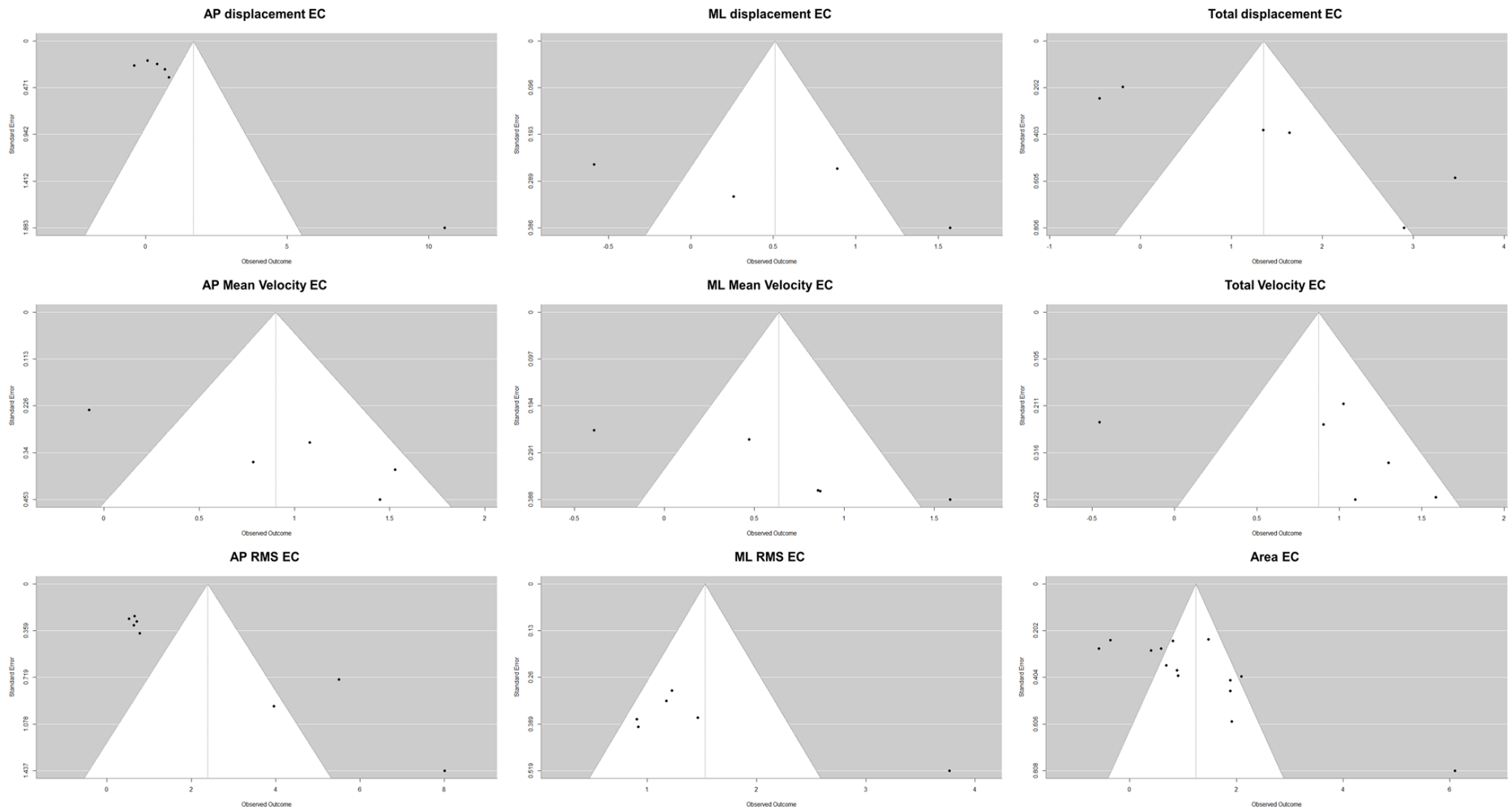


Figure 6. Funnel plot shows the data dispersion of variables included in closed open condition.

2.5. Study strengths, limitations and future directions

Regarding fatiguing exercise protocols, a variety was observed between the use of general models of exercises ($n = 12$), such as running and cycling; localized models of exercises ($n = 20$), for example ankle plantar flexion and extension; or combining both ($n = 1$) - rowing ergometer and knee extension. The inclusion of a wide variety of fatiguing exercise models provides a more detailed analysis of how different fatiguing exercises affect postural control. This may be a novelty in relation to previous narrative reviews that may not have focused on such a wide diversity of exercises. However, for the meta-analysis, the lack of similarity between the fatiguing exercise and postural task protocols was not considered, as the intention was to evaluate the general effects of fatiguing exercise in a wide range of contexts. Since exercise-induced fatigue alters postural control regardless of the type of fatiguing exercise performed (PAILLARD, 2012), this approach allows us to identify global trends and understand the general impact of fatiguing exercise on postural control, regardless of the methodological specificities of each study. This decision is justified by the fact that the heterogeneity of the protocols reflects the diversity of real conditions found in clinical, sports, or functional contexts. A meta-analysis that encompasses different methodologies provides a more comprehensive view of the effects, increasing the external relevance of the results (BORENSTEIN et al., 2009). Furthermore, by including studies with different types of exercises and tasks, it is possible to capture the breadth of the effects of fatigue on different motor and sensory systems, aligning with an ecosystemic perspective.

The methods for determining fatigue have varied, including tools that combine objective measures (biomarkers, force loss, and EMG) and subjective scales (Borg and VAS) to provide a broad view of exercise-induced fatigue and recovery processes after exercise. This negatively reflect a lack of consensus regarding the best way to determine

fatigue, which may impact comparisons between study results. On the other hand, the integration and comparison of these different methods may positively offer innovative insights into the measurement of fatigue and its implications for postural control. As a strong point, only studies that presented a variable that proved the state of fatigue were included. At this point, the main reason for exclusion of articles ($n = 40$) during the eligibility phase was the lack of measurement to indicate fatigue (for more details see Figure 1). In these excluded studies the participants' fatigue levels were not confirmed, not guaranteeing that they were fatigued. A previous systematic review included two articles in which the authors did not prove (only reported) the fatigue state, arguing that this may have played a role in explaining the divergence in subjects' locomotor adaptations after exercise (CHARDON et al., 2022). Assessing fatigue levels, whether using objective or subjective tools, is crucial to better understand the features during postural control tasks, preventing profound consequences such as the risk of falls due to postural instability caused by increased body sway after fatiguing exercise. Finally, this review only included exercise-induced fatigue studies, excluding, for example, mental fatigue. Performing a postural task while fatigued certainly increases internal complexity compared to the non-fatigued state, increasing the need for the use of cognitive resources (BEURSKENS et al., 2016; SARAIVA et al., 2022). Thus, it appears that the state of mental-induced fatigue may well affect healthy young adults' postural control, since mental fatigue affects the ability to accurately allocate cognitive resources (VAN CUTSEM et al., 2017), and may be an important topic for future systematic reviews.

Differences in postural control protocols was evident in the included studies. Most of them used a bipedal side-by-side stance, while others used more challenging postures, such as feet together or Romberg stance. Visual condition also varied, with many studies requiring participants to perform the postural task with their eyes closed (CLARKE et al.,

2015) or with a saccadic eye movements (BARBIERI et al., 2019). These variations in stances and visual conditions reflect differences in postural control demands, which may influence the synthesis of results, especially in conditions of exercise-induced fatigue. The analysis of different postural control protocols (foot position, visual condition, etc.) can provide new insights into how posture is influenced by different bases of support (greater or lesser stability) and bring new discoveries about the importance of sensory systems in maintaining balance after performing fatiguing exercise. Furthermore, several studies were excluded (Figure 1) because their protocols included non-quiet stance (n = 29) or unipedal support (n = 38). However, despite the considerable number of articles included (n = 33) and the robustness of the results on the effects of fatiguing exercise on postural control in young adults, the lack of homogeneity in the protocols compromises and limits the interpretation of the results of the meta-analysis. Thus, future studies need to adopt more homogeneous approaches to improve meta-analytic comparisons and increase the validity of the findings.

Surprisingly, none of the included articles reported cortical features during the postural control protocol. Of all the screened articles, only one investigated how physical and mental fatigue influence healthy young adults' balance and brain activity during a postural task (GEBEL et al., 2022). Although some findings from this study underscore the complex role of cortical activity in postural control, especially under fatigue state, it was excluded because it assessed a challenging postural task (Figure 1). This points to an emergent niche for future research, which is to understand the underlying cortical mechanism related to the adaptability of postural control to exercise-induced fatigue.

2.6. Final Considerations of Study 1

To conclude, this systematic review and meta-analysis highlighted that exercise-induced fatigue impairs the healthy young adults' postural control in different visual

conditions. The immediate consequences were more pronounced, but also can remain for a short- and long-term. This finding highlights the need for appropriate recovery strategies to minimize the functional impact of fatiguing exercise in high-risk settings such as sports, rehabilitation, and locomotor activities, where the fatigued state is evident, and reduced stability may lead to falls or injuries. The effects of fatiguing exercise on cortical activity during postural control need to be further explored.

CHAPTER 3

STUDY 2 – EFFECTS OF GENERAL AND LOCAL FATIGUING EXERCISE ON THE CORTICAL ACTIVATION OF HEALTHY YOUNG ADULTS DURING THE CONTROL OF STATIC STANDING POSTURE

3. Study 2 – Effects of general and local fatiguing exercise on the cortical activation of healthy young adults during the control of static standing posture

3.1. Introduction

Exercise-induced fatigability disturbs the neuromotor system. The disruption caused by fatiguing exercise impairs motor control and the biomechanics of human movements, such as controlling the upright posture (PENEDO et al., 2022). These losses have been attributed to two evident components: the peripheral component, which affects the contractile capabilities of the muscles; and the central component, which affects the adequate supply of activation signals to muscles by the nervous system (ENOKA; DUCHATEAU, 2017), by both spinal and supraspinal mechanisms (GANDEVIA, 2001). These harms are independent of the type of fatiguing exercise performed.

Fatiguing exercise is identified by two modalities: general and localized. General fatiguing exercise requires total body displacement, involves several joints and muscle groups, and requires high participation of energy mechanisms (PAILLARD, 2012). Localized fatiguing exercise usually requires only segmental movements, involving only one joint and one muscle or few muscle groups, and strongly stimulates the neuromuscular system (PAILLARD, 2012). Recent studies have used separately both general (e.g., running, cycling) (LUNDIN; FEUERBACH; GRABINER, 1993; NARDONE et al., 1997; PAILLARD, 2012) and localized exercises (e.g., ankle dorsiflexion and plantarflexion) (BOYAS; HAJJ; BILODEAU, 2013; PENEDO et al., 2021) to measure deficits in postural control after exercise-induced fatigability. However, to date, the literature does not compare the implications of both types of fatiguing exercise, general and localized, on body sway and the functions and cortical areas activated during postural control. Comparing general and localized fatigue protocols is

essential to understand how different types of exercise affect the neuromechanics of postural control.

Regulation of cortex activity is essential for postural control. The prefrontal cortex (MIHARA et al., 2008) and the primary motor cortex (SLOBOUNOV et al., 2005), responsible for maintaining the regulatory output for posture and initiation of postural movements, have been related to the detection of instability and maintenance of postural balance. In addition, the parietal cortex receives information from the vestibular, visual, and somatosensory systems (HÜLSDÜNKER et al., 2015), which seems a key region for processing sensory information regulating standing posture. Fatigability interferes with the supraspinal (central) mechanisms, impairing the output of the primary motor cortex, with decreased electrical signals from the muscles and voluntary strength, indicated by the reduction in the beta power frequencies specifically in the electrodes C3, Cz, C4, Fz and Pz (LIU et al., 2005). Therefore, cortical activity seems to have a great influence during postural control to mitigate the effects caused by general and local fatiguing exercise.

The aim of this study was to compare the effects of general and localized fatiguing exercises on healthy young adults' standing posture. The hypotheses of the study are: i) both exercise protocols (i.e., general and localized) will impair the control of posture; ii) for harming a key region for the postural control of young adults (i.e. ankle) (WINTER, 1995), localized fatiguing exercise will affect more postural control of healthy young adults compared to general exercise. To answer the questions, the participants performed a postural control protocol before and after the execution of two different fatiguing exercise protocols (general and localized), and it was measured participants' body sway by force platform and cortical activity by electroencephalography technique (EEG).

3.2. Methods

3.2.1. Participants

The sample size calculation indicated 12 individuals (power = 95%, $\alpha = 0.05$) and was performed using the G*Power[®] 3.1.9.2 software (Universität Düsseldorf, Germany) based on experimental studies by Barbieri and collaborators (BARBIERI et al., 2019), considering the variable AP displacement of the CoP. However, considering a sample loss, 20 healthy young adults aged between 20 and 35 years were invited to participate in this study, selected from the following inclusion criteria: do not use drugs that interfere with postural control, do not having musculoskeletal and/or neuromuscular, cardiorespiratory diseases and disturbances of balance and vision that interfere with experimental procedures. Before the experimental procedures, participants were informed about all the procedures and objectives of the study, allowing their participation by signing the informed consent form. The experimental studies of this thesis were approved by the Ethics Committee of the School of Sciences at São Paulo State University (CAAE: 33587520.0.0000.5398).

3.2.2. Experimental Design

Participants attended two visits to the laboratory to perform experimental procedures: one visit for general fatiguing exercise, and one visit for localized fatiguing exercise (Figure 6). The order of the fatiguing exercise to be performed was balanced among the participants to minimize potential order effects. The same evaluation schedule was maintained for the two visits to avoid environmental (e.g., temperature) and individual (e.g., daily routine) interferences. To allow full recovery of the experimental protocol (for example, late-onset muscle soreness) each exercise protocol (general or localized) was performed on a specific week, with an interval of 7 to 10 days between the

last evaluation of the first week and the first evaluation of the second week. Participants were instructed to not perform any physical activity in the 48 hours prior to each visit, not to drink stimulant beverages (i.e., caffeine), and to avoid fatty foods before the assessments (i.e., pizza, hamburger). Before each fatiguing exercise, participants warmed up for five minutes, with walking and stretching exercises. On the first visit, participants answered an anamnesis and the IPAQ (MATSUDO et al., 2001) to verify the level of physical activity, and familiarize themselves with the equipment for assessing maximum voluntary isometric contraction (MVIC), determined by the participants' verbal comfort report. In both two visits, participants performed the tasks in the following order: 1) postural assessment protocol; 2) MVIC protocol; 3) fatiguing exercise protocol according to the type of fatiguing exercise; 4) items 1 and 2 were repeated immediately after the fatiguing exercise.

3.2.3. Postural control protocol

Postural control was assessed using a 50cm x 50cm force platform (AccuGait, Advanced Mechanical Technologies Inc. - AMTI, Boston, MA), and sampled at 200Hz. Participants were evaluated barefoot in bipedal support hip-width apart and instructed to position their feet parallel to the force platform and remain as still as possible in an upright position, keeping their arms extended and relaxed on the side of the trunk, and to gaze at a target positioned one meter apart and at eye level. To ensure constant foot positioning on all trials and evaluation days, the outline of each participant's feet was drawn on a sheet of paper. An attempt of 120s was made before and immediately after the fatiguing exercise, to ensure greater consistency and sensitivity of the data (VAN DER KOOIJ; CAMPBELL; CARPENTER, 2011).

For postural control data, the three components of force and moments of force in the vertical, anteroposterior, and medial-lateral directions were collected using the Netforce software (AccuGait, AMTI, Boston, MA). The average signal of interest was calculated and removed from the analysis. Subsequently, the data was filtered through a 4th order low-pass digital Butterworth filter, with a 5 Hz cutoff frequency. The center of pressure (CoP) was calculated (MARCHETTI; CORSO, 2009). The following CoP variables were analyzed in the anterior posterior (AP) and medial-lateral (ML) directions for each attempt: displacement (length of the CoP path in the support base); mean velocity (total displacement divided by the total duration of the attempt); root mean square (RMS - CoP variability over CoP displacement). Besides, a spectral analysis of the signal was performed (DUARTE; FREITAS, 2010). The frequencies of the CoP signal were estimated by calculating the power spectral density using the Welch periodogram separately for each direction (AP and ML). The median frequency for each direction was calculated (AP e ML) (DUARTE; FREITAS, 2010). CoP data was grouped into mean and standard deviation according to the experimental conditions and participants.

Also, during the postural task, muscular electrical activity (EMG) was measured using 8-channel surface electromyography (Noraxon MyoMuscle, Noraxon Inc., Scottsdale, Arizona, USA), with 2000 samples/s. For the acquisition of EMG, the skin was trichotomized, lightly scraped with fine sandpaper for abrasion of dead cells and sanitized with 70% alcohol in the places where surface electrodes were fixed. The electrodes were positioned bilaterally on the tibialis anterioris (TA), gastrocnemius medialis (GM), vastus lateralis (VL), and biceps femoris (BF) following the recommendations of the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) (STEGEMAN; HERMENS, 2007). The EMG signals were filtered (Butterworth bandpass filter 6 - 500Hz and Butterworth low-pass 4th order filter, with a

cutoff frequency of 10Hz), rectified, and amplified (1000 times gain). The following EMG variables were calculated for the postural control protocol: RMS and median frequency. These variables express the level of muscle activation and the firing rate of the motor units, respectively.

The recording of the cortex activity was performed in the same interval as the measurement of postural control (i.e., 120 seconds). For this, a cap with 64 active electrodes (eegoTM sports, ANT Neuro, Enschede, Netherlands) was used, connected to an amplifier that recorded and sent the signal in real-time via Wi-Fi to the control computer, sampled at 1024 Hz. The positioning of the cap followed the standards of the international electrode positioning system (standard positioning 10/10) (CHATRIAN; LETTICH; NELSON, 1985). The data was collected according to the procedures suggested by the manufacturers of the portable EEG system. Also, an electrode was used to detect eye movements. Participants were subjected to some previous attempts to familiarize themselves with the equipment. The data on the electrical activity of the cortex was recorded by the EEGoTM software (ANT Neuro, Enschede, Netherlands). Subsequently, the collected data was exported to the MATLAB environment (MathWorks Natick, MA, USA) and processing by the open-source software EEGLAB (sccn.ucsd.edu/eeglab; (DELORME et al., 2011; DELORME; MAKEIG, 2004)). The raw signal was filtered with a 0.1-100 Hz Butterworth bandpass filter (LI et al., 2020). Artifacts (i.e., any differences in electrical potential of extracerebral origin registered as a signal) of ocular (blinking), instrumental (electrical network), and muscular (biting) origin were removed by automatic procedures (period with absolute difference > 150mV (PLUTA et al., 2018), by visual inspection and independent component analysis (ICA) (DELORME; SEJNOWSKI; MAKEIG, 2007), through specific interfaces available in the ASAlabTM software (version 4.9.1; ANT Neuro, Enschede, Netherlands). The

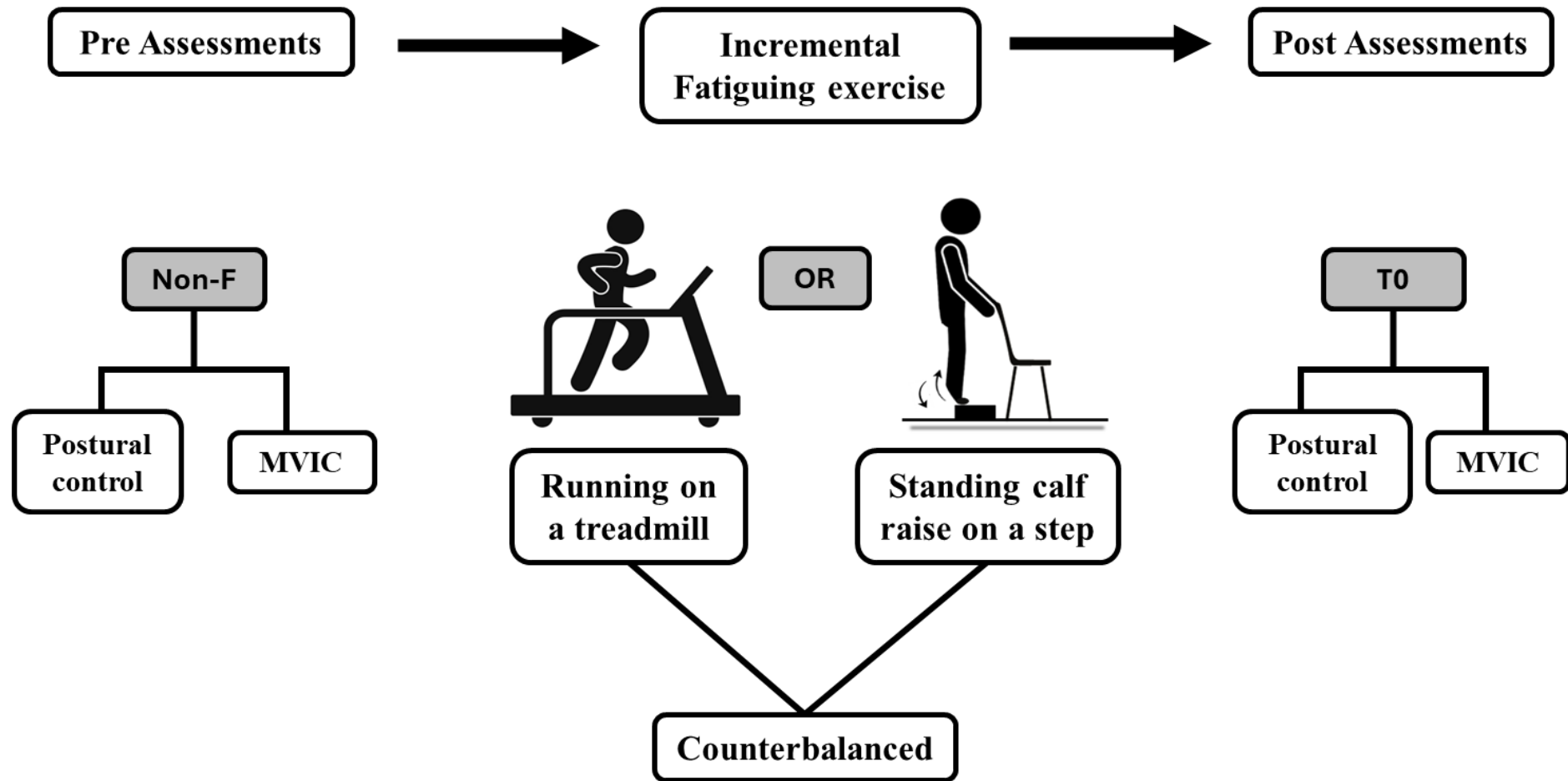


Figure 6. Exemplification of the experimental design of study 2. **Non-F** – after fatiguing exercise; **MVIC** - maximum voluntary isometric contraction; **T0** – immediately after fatiguing exercise.

electrode data was grouped according to the following regions of interest: the prefrontal cortex (F3, Fz, and F4), the motor cortex (C3, Cz, C4), the parietal cortex (P3, Pz, P4), and the occipital (O1, Oz and O2) (PRESACCO; FORRESTER; CONTRERAS-VIDAL, 2012). Besides, the following frequency bands were considered for the analysis and calculation of the power spectral density (PSD): delta (δ): 0.5–4 Hz; theta (θ): 4–8 Hz; alpha (α): 8–13 Hz; beta (β): 13–30 Hz; gamma (γ): 31–100 Hz (CHUANG; HUANG; HUNG, 2013). Absolute PSD values were transformed into relative values, in which the power of each band was divided by the sum of the powers of all bands (values expressed as a percentage from 0 to 100%).

3.2.4. MVIC protocol

MVICs were performed through the bilateral ankle plantar flexion exercise on an adapted Leg Press. The participant was positioned seated on the equipment, with the knee extended to 180° (180° = total extension) and the hip flexed to 90°, and the foot in a neutral position. Only the upper half of the feet contacted the Leg Press platform during MVIC. The participant's trunk was fixed by velcro straps to the back of the equipment to avoid any mobility during the protocol. In both visits, the participants were familiarized with the equipment (adapted Leg Press). The angulation of the joints involved in the activities to maintain the correct positioning during MVICs was measured using a mechanical goniometer. Participants were instructed to perform the MVIC by applying the greatest force as quickly as possible and maintaining the maximum force for five seconds. Each participant performed two attempts before and two attempts after fatiguing exercise, with an interval of 120s between them.

The force produced bilaterally at MVIC was measured using a load cell (MK Controle e Instrumentação Ltda., Model CSA / ZL-500, São Paulo, SP, Brazil) with a

precision of 0.98 N, coupled to the Leg Press. The signal acquisition from the force transducer was performed through an analog signal amplifier captured by an acquisition board (National Instruments®) and acquired by the LabVIEW 2015 software (National Instruments Inc., Austin, TX). The force data in the MVICs was filtered by a 4th order low-pass digital Butterworth filter with a cut-off frequency of 6Hz. The force (in N) was determined as the average of the maximum values recorded in each attempt, before and after fatiguing exercise. The decrease in force production after fatiguing exercise allows proving the state of fatigability (ENOKA; DUCHATEAU, 2017).

3.2.5. Fatiguing exercise protocols

The participant performed the following incremental tasks according to the fatiguing exercise: i) general - treadmill running protocol; ii) localized - ankle plantar flexion and dorsiflexion task (stand calf raise exercise) under a step (BARBIERI et al., 2019). Before the start of both protocols (i.e., general and localized), participants warmed up for 5 minutes at 6 km/h on the treadmill. For the general exercise, an electric treadmill (ATL, Inbrasport, Porto Alegre, Brazil) was used. After the warm-up, general exercise was initiated at a speed of 6.5 km/h and was increased by 1.6 km/h every minute (for example, 6.5 to 8.1, 8.1 to 9.7, 9.7 to 11.3 km/h). The general exercise was interrupted due to voluntary exhaustion of the participant. For the localized exercise, initially, a period of adaptation to the movement and frequency of the task was provided. Then, participants were instructed to repeatedly perform the incremental stand calf raise exercise with the greatest range of motion (ROM) possible until exhaustion. The movement frequency (controlled by a metronome) for both incremental protocols started at 25 beats/min and was increased by 5 beats every minute (for example, 25 to 30, 30 to 35, 35 to 40 beats/min). During the localized exercise protocol, the participants were

allowed to touch their hands to a support surface to maintain balance. The localized exercise was interrupted by i) inability to perform the repetitions due to concentric failure and marked decrease in ROM (visually inspected); ii) voluntary exhaustion; iii) technical exhaustion - not maintaining the frequency of movements for five consecutive strokes of the metronome. In both protocols, participants were verbally encouraged to make maximum efforts and every 1 minute of exercise reported the perceived effort using the numerical scale from 6 to 20 with 20 being exhaustion (BORG, 1982). The time limit (Tlim) for each protocol was measured.

3.2.6. Statistical analysis

The significance level was maintained at 0.05 for all analysis and the SPSS 22.0 software (SPSS, Inc.) was used for statistical treatment. Shapiro Wilk's, Mauchly's, and Levene's tests checked data normality, sphericity, and equality of variances. The Tlim was analyzed by paired t-test (general x localized). Two-way ANOVAs with repeated measures were performed to analyze the parameters of interest for CVIM (force - in N), Borg, and postural control (CoP, EMG, and EEG) with factors for fatiguing exercise (general and localized) and moment (Non-F and T0). Tukey's Post hoc tests, with adjusted significance levels, were used when an interaction between factors was indicated in the analysis. The partial eta-square (η^2) was reported to measure the effect size and was interpreted as small (effect size > 0.01), moderate (effect size > 0.06) or large (effect size > 0.14) (COHEN, 1988).

3.3. Results of Study 2

All 20 participants (27 ± 4 years old [20 – 35]; 1.76 ± 0.08 m [1.63 – 1.96]; 82.96 ± 16.12 kg [47.60 – 120.65]; 26.68 ± 3.99 kg/m² [17.92 – 35.25] completed both general

and localized fatiguing exercise protocols. Ten participants were classified as "very active" and the other 10 participants as "active" by IPAQ (Table 9).

3.3.1. *Fatigability state indicator*

Participants performed the general fatiguing exercise for 434 ± 56 s [297 – 525 s] and reported 6 ± 0.4 pts [6 – 7 pts] and 20 ± 1 pts [17 – 20 pts] of effort perception in the Non-F and the T0 conditions, respectively. They performed the localized fatiguing exercise for 300 ± 93 s [128 – 483 s] and reported 6 ± 0.7 pts [6 – 9 pts] and 20 ± 1 pts [17 – 20 pts] of effort perception in the Non-F and the T0 conditions, respectively. The paired t-test revealed that participants performed the general fatiguing exercise for a significant longer duration compared to the localized ($t_{(19)} = 7,962$, $p < 0.001$).

Force (N) decreased after fatiguing exercise (Figure 7). ANOVA showed a large main effect of moment for MVIC ($F_{(1,38)} = 104,538$; $p < 0.001$; $n^2 = 0.73$). Post hoc indicated lower force at T0 compared to Non-F ($p < 0.001$).

Both fatiguing exercises (i.e., general and localized) reduced MVIC. ANOVA showed a large interaction between the moment x exercise factors for MVIC of general ($F_{(1,38)} = 42,913$; $p < 0.001$; $n^2 = 0.53$) and localized ($F_{(1,38)} = 62,546$; $p < 0.001$; $n^2 = 0.62$) fatiguing exercise. Post hoc showed that force decreased after both general and localized fatiguing exercises ($p < 0.001$ for both).

There was no main effect of exercise ($p > 0.05$).

Table 9. Anthropometric characteristics and physical activity level of participants.

Code	Body mass (kg)	Body Height (m)	Body mass index (kg/m ²)	Age (years)	IPAQ														Physical activity level
					Low activity				Moderate activity				Vigorous activity				Total / METs		
					Days per week	Time per day	Total	METs	Days per week	Time per day	Total	METs	Days per week	Time per day	Total	METs			
#1	106.30	1.84	31.40	35	6	30	180	594	5	35	175	700	3	50	150	1200	2494	active	
#2	99.10	1.88	28.04	27	3	120	360	1188	4	60	240	960	2	75	150	1200	3348	very active	
#3	47.60	1.63	17.92	20	0	0	0	0	0	0	0	0	4	90	360	2880	2880	very active	
#4	79.25	1.74	26.18	33	7	10	70	231	5	40	200	800	4	50	200	1600	2631	very active	
#5	76.75	1.74	25.35	23	7	20	140	462	3	15	45	180	7	60	420	3360	4002	very active	
#6	120.65	1.85	35.25	30	7	30	210	693	7	30	210	840	6	30	180	1440	2973	active	
#7	77.45	1.64	28.80	29	4	30	120	396	0	0	0	0	4	70	280	2240	2636	very active	
#8	76.30	1.70	26.40	27	7	15	105	346.5	5	60	300	1200	5	60	300	2400	3946.5	very active	
#9	94.00	1.77	30.00	26	6	270	1620	5346	3	90	270	1080	2	40	80	640	7066	very active	
#10	81.70	1.70	28.27	26	2	20	40	132	5	40	200	800	5	50	250	2000	2932	very active	
#11	83.75	1.83	25.01	26	3	30	90	297	2	30	60	240	6	120	720	5760	6297	very active	
#12	87.6	1.68	31.04	31	2	50	100	330	2	30	60	240	3	45	135	1080	1650	active	
#13	70.70	1.72	23.90	22	5	40	200	660	5	30	150	600	1	15	15	120	1380	active	
#14	72.60	1.74	23.98	30	5	30	150	495	5	20	100	400	1	30	30	240	1135	active	
#15	74.60	1.74	24.64	20	0	0	0	0	3	80	240	960	2	90	180	1440	2400	active	
#16	92.50	1.96	24.08	29	3	20	60	198	3	30	90	360	2	20	40	320	878	active	
#17	80.45	1.75	26.27	25	7	30	210	693	4	20	80	320	3	60	180	1440	2453	active	
#18	82.60	1.73	27.60	23	1	60	60	198	0	0	0	0	4	60	240	1920	2118	very active	
#19	58.85	1.73	19.66	20	5	40	200	660	3	30	90	360	0	0	0	0	1020	active	
#20	96.40	1.80	29.75	30	6	40	240	792	4	30	120	480	2	10	20	160	1432	active	

IPAQ – international physical activity questionnaire; **MET** – metabolic equivalent of task.

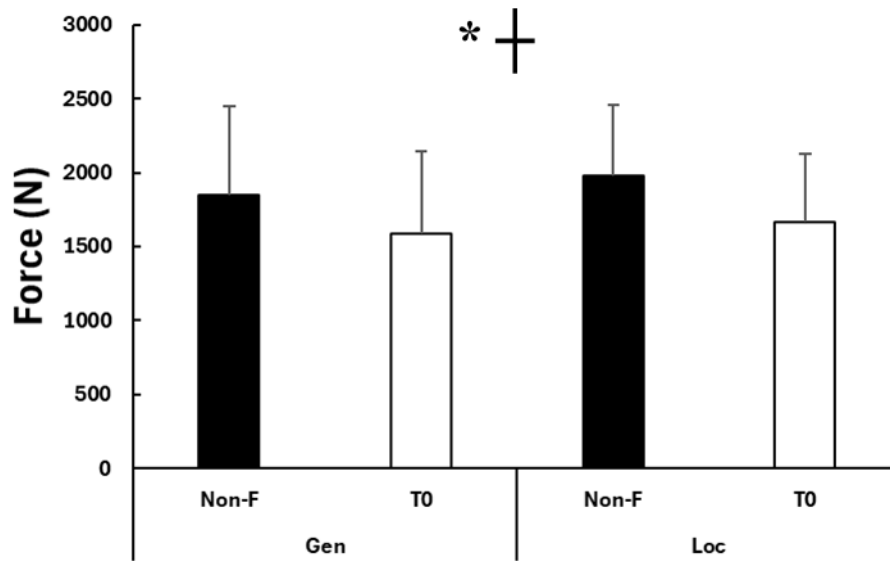


Figure 7. Force (N) produced during maximum voluntary isometric contractions before (Non-F) and immediately after (T0) general (Gen) and localized (Loc) fatiguing exercises. * – main effect of moment; † – interaction between moment x exercise factors.

3.3.2. Postural control

3.3.2.1. Cortical activity

Fatigability state alters the cortical activity during standing posture (Figure 8). ANOVA showed moderate and large main effects of moment for prefrontal (delta - $F_{(1,38)} = 12,633$; $p < 0.001$; $n^2 = 0.24$; theta - $F_{(1,38)} = 38,107$; $p < 0.001$; $n^2 = 0.50$; alpha - $F_{(1,38)} = 12,238$; $p < 0.001$; $n^2 = 0.24$; beta - $F_{(1,38)} = 15,081$; $p < 0.001$; $n^2 = 0.28$), motor (delta - $F_{(1,38)} = 13,536$; $p < 0.001$; $n^2 = 0.26$; theta - $F_{(1,38)} = 28,861$; $p < 0.001$; $n^2 = 0.43$; alpha - $F_{(1,38)} = 15,637$; $p < 0.001$; $n^2 = 0.29$; beta - $F_{(1,38)} = 20,646$; $p < 0.001$; $n^2 = 0.23$; gamma - $F_{(1,38)} = 6,171$; $p < 0.01$; $n^2 = 0.14$), parietal (delta - $F_{(1,38)} = 5,115$; $p < 0.03$; $n^2 = 0.11$; theta - $F_{(1,38)} = 25,666$; $p < 0.001$; $n^2 = 0.40$; alpha - $F_{(1,38)} = 10,292$; $p < 0.003$; $n^2 = 0.21$; beta - $F_{(1,38)} = 5,393$; $p < 0.02$; $n^2 = 0.12$), and occipital (delta - $F_{(1,38)} = 12,965$; $p < 0.001$; $n^2 = 0.25$; theta - $F_{(1,38)} = 27,501$; $p < 0.001$; $n^2 = 0.42$; alpha - $F_{(1,38)} = 12,667$; $p < 0.001$; $n^2 = 0.25$; beta - $F_{(1,38)} = 13,886$; $p < 0.001$; $n^2 = 0.26$) areas. The post hoc indicated a decrease in theta (prefrontal, motor, parietal, and occipital areas – $p < 0.001$ for all), alpha (prefrontal, motor, and occipital – $p < 0.001$; parietal – $p < 0.003$), beta (prefrontal, motor,

and occipital – $p < 0.001$; parietal – $p < 0.02$), and gamma (motor – $p < 0.01$), in addition to an increase in delta (prefrontal, motor, and occipital – $p < 0.001$; parietal – $p < 0.03$) bands at T0 compared to Non-F.

The ANOVA showed moderate and large main effects of exercise for motor (delta - $F_{(1,38)} = 9,797$; $p < 0.003$; $n^2 = 0.20$; alpha - $F_{(1,38)} = 3,926$; $p < 0.05$; $n^2 = 0.09$), occipital (delta - $F_{(1,38)} = 6,497$; $p < 0.01$; $n^2 = 0.25$; beta - $F_{(1,38)} = 5,701$; $p < 0.02$; $n^2 = 0.13$). The post hoc showed a higher delta band (motor and occipital, $p < 0.003$ and $p < 0.01$, respectively), and smaller alpha (motor area – $p < 0.05$) and beta (occipital area – $p < 0.02$) bands for the general fatiguing exercise compared to the localized fatiguing exercise.

In addition, the ANOVA showed large interactions between moment x exercise for prefrontal (delta - $F_{(1,38)} = 23,027$; $p < 0.001$; $n^2 = 0.37$; theta - $F_{(1,38)} = 7,420$; $p < 0.01$; $n^2 = 0.16$; alpha - $F_{(1,38)} = 12,018$; $p < 0.001$; $n^2 = 0.24$; beta - $F_{(1,38)} = 18,383$; $p < 0.001$; $n^2 = 0.32$; gamma - $F_{(1,38)} = 8,141$; $p < 0.007$; $n^2 = 0.17$), motor (delta - $F_{(1,38)} = 29,690$; $p < 0.001$; $n^2 = 0.43$; theta - $F_{(1,38)} = 11,021$; $p < 0.002$; $n^2 = 0.22$; alpha - $F_{(1,38)} = 26,477$; $p < 0.001$; $n^2 = 0.41$; beta - $F_{(1,38)} = 37,067$; $p < 0.001$; $n^2 = 0.49$; gamma - $F_{(1,38)} = 7,838$; $p < 0.008$; $n^2 = 0.17$), parietal (delta - $F_{(1,38)} = 15,330$; $p < 0.001$; $n^2 = 0.28$; alpha - $F_{(1,38)} = 10,788$; $p < 0.002$; $n^2 = 0.22$; beta - $F_{(1,38)} = 8,580$; $p < 0.006$; $n^2 = 0.18$), and occipital (delta - $F_{(1,38)} = 38,577$; $p < 0.001$; $n^2 = 0.50$; theta - $F_{(1,38)} = 10,781$; $p < 0.002$; $n^2 = 0.22$; alpha - $F_{(1,38)} = 27,771$; $p < 0.001$; $n^2 = 0.42$; beta - $F_{(1,38)} = 31,934$; $p < 0.001$; $n^2 = 0.45$; gamma - $F_{(1,38)} = 6,020$; $p < 0.01$; $n^2 = 0.13$) areas. The post hoc indicated that immediately after (T0) general fatiguing exercise there was an increase in delta band (prefrontal, motor, parietal, and occipital – $p < 0.001$ for all), and a decrease in theta (prefrontal, motor, and occipital – $p < 0.001$ for all), alpha (prefrontal, motor, parietal, and occipital – $p < 0.001$ for all), beta (prefrontal, motor, parietal, and occipital – $p < 0.001$ for all),

and gamma (prefrontal – $p < 0.02$; motor – $p < 0.001$; and occipital – $p < 0.009$) bands compared to Non-F. In addition, the post hoc indicated that immediately after (T0) localized fatiguing exercise there was a decrease in theta band (prefrontal area – $p < 0.02$) compared to Non-F.

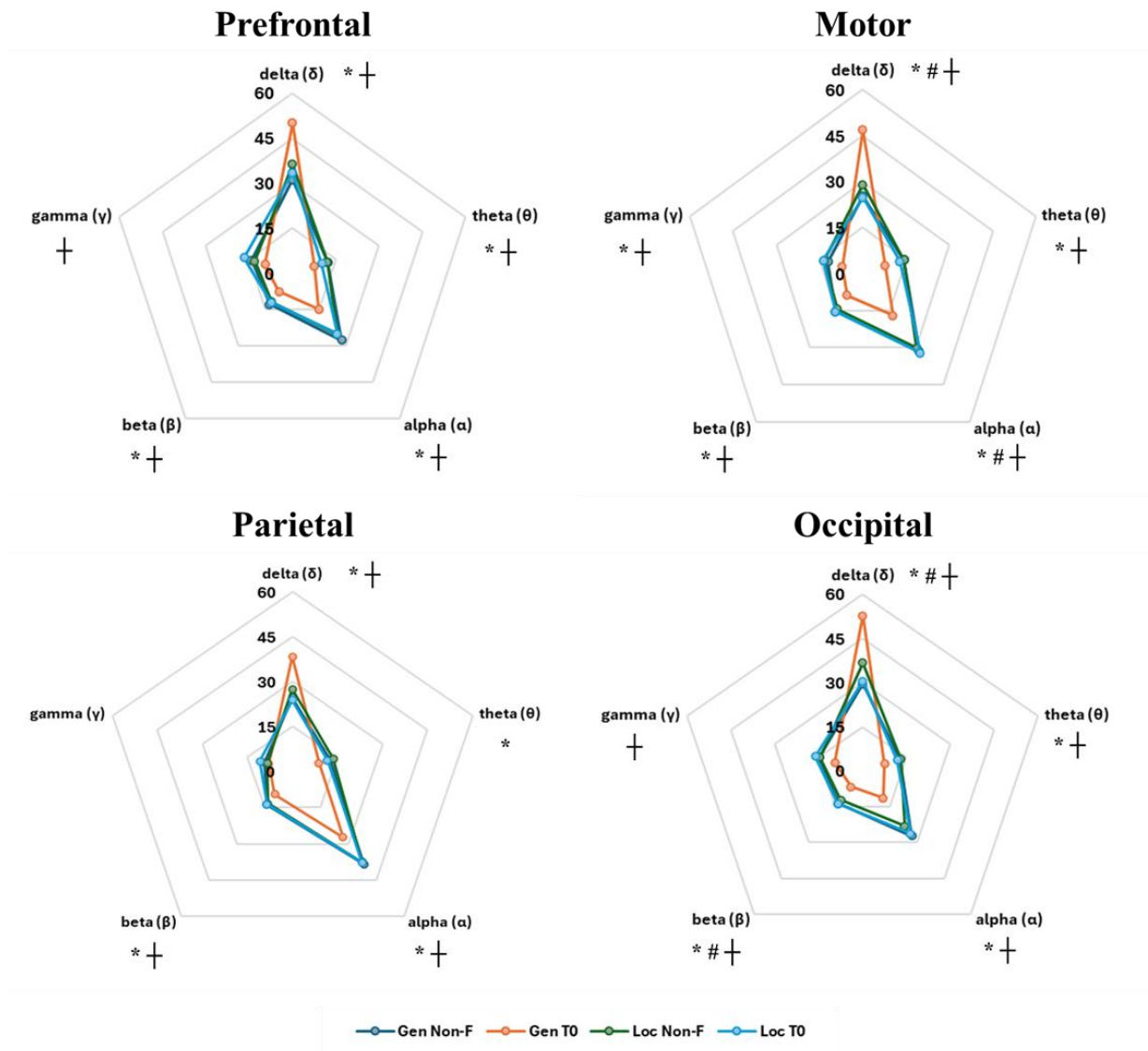


Figure 8. Cortical activity (EEG) bands (delta, theta, alpha, beta, and gamma) analyzed before (Non-F) and immediately after (T0) general (Gen) and localized (Loc) fatiguing exercises in the Prefrontal, Motor, Parietal, and Occipital areas. **Navy lines** – Gen Non-F; **Orange lines** – Gen T0; **Green lines** – Loc Non-F; **Blue lines** – Loc T0; * – main effect of moment; # – main effect of exercise; † – interaction between moment x exercise factors.

3.3.2.2. EMG parameters

Muscle electrical activity (EMG) during postural task is altered after fatiguing exercise (Table 10). The ANOVA indicated a large main effect of moment for VL ($F_{(1,38)} = 10.954$; $p < 0.002$; $n^2 = 0.22$) and BF RMS ($F_{(1,38)} = 18.401$; $p < 0.001$; $n^2 = 0.32$), GM median frequency ($F_{(1,38)} = 16.118$; $p < 0.001$; $n^2 = 0.29$), and VL-BF CI ($F_{(1,38)} = 19.819$; $p < 0.001$; $n^2 = 0.34$), and a moderate effect for VL median frequency ($F_{(1,38)} = 6.147$; $p < 0.01$; $n^2 = 0.13$). The post hoc indicated an increase in VL and BF RMS ($p < 0.002$ and $p < 0.001$, respectively), in addition to a decrease in GM and VL median frequency ($p < 0.001$ and $p < 0.01$, respectively) and VL-BF CI ($p < 0.001$) after the fatiguing exercise.

The ANOVA indicated a moderate main effect of exercise for TA RMS ($F_{(1,38)} = 6.201$; $p < 0.01$; $n^2 = 0.14$). The post hoc showed a higher TA RMS ($p < 0.01$) for the general fatiguing exercise compared to the localized fatiguing exercise.

In addition, there was a moderate and large interaction between the moment x exercise factors for GM ($F_{(1,38)} = 4.419$; $p < 0.04$; $n^2 = 0.10$), VL ($F_{(1,38)} = 12.541$; $p < 0.001$; $n^2 = 0.24$), and BF ($F_{(1,38)} = 12.955$; $p < 0.001$; $n^2 = 0.25$) median frequency. The post hoc indicated a decrease in GM, VL, and BF ($p < 0.001$, $p < 0.001$, and $p < 0.002$, respectively) median frequency at T0 compared to before (Non-F) general fatiguing exercise.

3.3.2.3. Center of pressure (CoP)

Fatiguing exercise immediately increases postural sway in healthy young adults (Figure 9). The ANOVA revealed a moderate and large main effect of moment for ML displacement ($F_{(1,38)} = 4.425$; $p < 0.04$; $n^2 = 0.10$), AP ($F_{(1,38)} = 11.016$; $p < 0.002$; $n^2 = 0.22$) and ML ($F_{(1,38)} = 9.277$; $p < 0.004$; $n^2 = 0.19$) mean velocity, ML RMS ($F_{(1,38)} = 5.299$; $p < 0.02$; $n^2 = 0.12$), and ML median frequency ($F_{(1,38)} = 4.136$; $p < 0.04$; $n^2 =$

0.09). The post hoc indicated an increase in ML displacement ($p < 0.04$), AP and ML mean velocity ($p < 0.002$ and $p < 0.004$, respectively), and ML RMS ($p < 0.02$), in addition to a decrease in ML median frequency ($p < 0.04$) at T0 compared to Non-F.

The ANOVA showed large and moderate interaction between the factors moment x exercise for the ML displacement ($F_{(1,38)} = 17.348$; $p < 0.001$; $n^2 = 0.31$), AP and ML mean velocity ($F_{(1,38)} = 48.360$; $p < 0.001$; $n^2 = 0.56$ and $F_{(1,38)} = 39.021$; $p < 0.001$; $n^2 = 0.50$, respectively), ML RMS ($F_{(1,38)} = 18.378$; $p < 0.001$; $n^2 = 0.32$), AP and ML median frequency ($F_{(1,38)} = 7.360$; $p < 0.01$; $n^2 = 0.16$ and $F_{(1,38)} = 4.136$; $p < 0.05$; $n^2 = 0.09$, respectively). The post hoc indicated that immediately after general fatiguing exercise there was an increase in ML displacement ($p < 0.001$), mean AP and ML velocity ($p < 0.001$ and $p < 0.001$, respectively), ML RMS ($p < 0.001$), and ML median frequency ($p < 0.007$) compared to Non-F. In addition, the post hoc indicated that immediately after localized fatiguing exercise there was a decrease in AP median frequency ($p < 0.02$) compared to the Non-F.

There was no main effect of exercise ($p > 0.05$).

Table 10. Muscular activity parameters (EMG) analyzed before (Non-F) and immediately after (T0) general (Gen) and localized (Loc) fatiguing exercises.

		Gen		Loc	
		Non-F	T0	Non-F	T0
RMS	TA #	5.62 ± 4.32	7.61 ± 6.65	3.82 ± 1.06	4.45 ± 2.38
	GM	13.92 ± 8.10	12.40 ± 8.02	12.37 ± 4.60	12.14 ± 9.04
	VL *	5.70 ± 5.67	8.91 ± 8.32	3.83 ± 3.12	7.75 ± 7.27
	BF *†	6.13 ± 4.08	10.09 ± 8.05	5.20 ± 3.31	7.71 ± 5.56
Median Frequency (Hz)	TA	77.54 ± 21.74	70.28 ± 17.04	66.97 ± 15.91	70.89 ± 13.27
	GM *†	92.11 ± 14.40	80.37 ± 15.75	86.06 ± 14.71	82.39 ± 17.25
	VL *†	71.11 ± 16.47	58.95 ± 13.27	63.60 ± 4.65	65.74 ± 11.36
	BF †	72.37 ± 10.71	63.95 ± 14.80	67.46 ± 11.47	71.86 ± 10.21
TA-GM CI (%)		36.46 ± 11.42	37.03 ± 10.19	36.32 ± 10.04	33.57 ± 11.56
VL-BF CI (%) *		40.28 ± 9.18	34.20 ± 11.08	42.51 ± 9.92	31.89 ± 12.96

BF – biceps femoris; CI – cocontraction index; GM – gastrocnemius medialis; RMS – root mean square; TA – tibialis anterioris; VL – vastus lateralis; * – main effect of moment; # – main effect of exercise; † – interaction between moment x exercise factors.

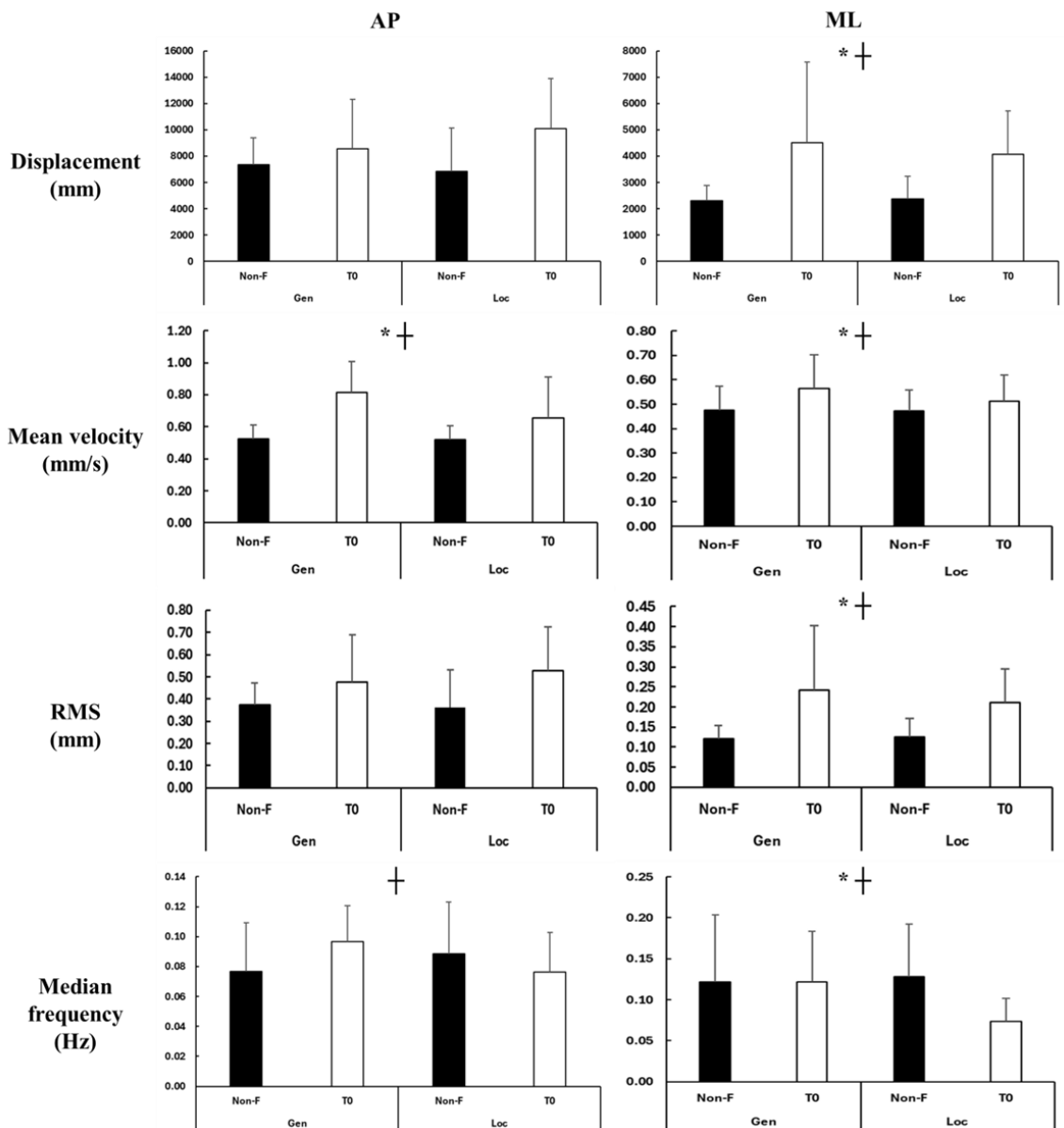


Figure 9. Mean and standard deviation of center of pressure parameters outcomes analyzed before (Non-F) and immediately after (T0) general (Gen) and localized (Loc) fatiguing exercises. **AP** – anteriorposterior; **ML** – medial-lateral; **RMS** – root mean square; * – main effect of moment; † – interaction between moment x exercise factors.

3.4. Discussion of study 2

The results of this study indicate that exercise-induced fatigability reduced maximal voluntary isometric contraction (MVIC), and altered the postural control, revealing significant changes in cortical activity (EEG), muscle activation (EMG), and center of pressure (CoP) parameters. These findings align with previous research highlighting the interaction between fatigability and central motor control during challenging postural tasks (ENOKA; DUCHATEAU, 2008; GANDEVIA, 2001). However, the main result of this study revealed significant changes in cortical activity during standing posture after both general and localized fatiguing exercise in healthy young adults. The main changes observed included increased activity in the delta bands and decreased activity in the theta, alpha, beta, and gamma bands in different cortical regions. These changes were most pronounced immediately after general fatiguing exercise, indicating that general fatiguing exercise has a more pronounced impact on cortical activity than localized fatigue.

Both fatiguing exercises (general and localized) reduced force, with no main effect of exercise type, indicating that both fatiguing exercises can similarly affect force production. The significant reduction in MVIC after fatiguing exercises corroborates previous studies reporting decreased force production capacity due to fatigability state (PENEDO et al., 2021, 2022).

Changes in EMG parameters, such as increased RMS of the VL and BF, suggest compensatory recruitment to sustain posture after fatiguing exercise (PAILLARD, 2012). The reduction in median frequency of the GM and VL after fatiguing exercise indicates potential slowing of nerve conduction and increased activation of low-frequency motor units (FARINA; MERLETTI; ENOKA, 2024). In addition, increased CoP parameters after exercise demonstrate impaired postural control, consistent with literature linking

fatigability to greater postural sway (GRIBBLE; HERTEL, 2004a; VUILLERME; PINSAULT; VAILLANT, 2005). The significant interaction between moment and exercise suggests that general fatiguing exercise has a more pronounced impact on postural control, possibly due to greater involvement of the sensory-motor and vestibular systems, in addition to cortical activity.

The cortical activity plays a role during standing posture after fatiguing exercise. Our results showed that fatiguing exercise caused alterations in all bands and cortical areas analyzed during postural tasks. These changes suggest greater cortical involvement to supply for the decrease in motor automaticity while performing postural task due to fatigability state (TAUBE; GRUBER; GOLLHOFER, 2008). After general fatiguing exercise, there was a significant increase in the delta band in prefrontal, motor, parietal and occipital cortical areas. This increase is associated with compensatory cortical monitoring mechanisms that seek to preserve postural control in the face of fatigability, as suggested by previous studies (SLOBOUNOV et al., 2005). Simultaneously, the decrease in the theta, alpha and beta bands reflect a reduction in the capacity for sensorimotor integration and in the efficiency of the neural networks involved in postural regulation (GROOMS; APPELBAUM; ONATE, 2015). The observed decrease in the gamma band, particularly after generalized exercise, may be related to the overload of motor and sensory control processes, resulting in a reduced capacity to adapt to postural perturbations (SANTORIELLO et al., 2024; SLOBOUNOV et al., 2005). In contrast, after localized fatiguing exercise, the changes were less extensive, being mainly limited to a decrease in the theta band in the prefrontal region, suggesting that the impact of localized fatiguing exercise is more restricted to specific cortical systems (PETRUO; MÜCKSCHEL; BESTE, 2018).

Generalized fatiguing exercise was more detrimental to postural control than localized exercise, with broader effects on all cortical regions investigated. This can be explained by the greater metabolic and neuromuscular demand associated with generalized exercise, which affects not only sensorimotor systems, but also cognitive and emotional processes mediated by the prefrontal cortex (PETRUO; MÜCKSCHEL; BESTE, 2018). Furthermore, our data revealed significant interactions between moment and exercise type for all cortical regions assessed. The significant interaction between moment and exercise type indicates that different cortical activation patterns may be required to maintain posture depending on fatigability intensity and location. These interactions highlight that the immediate effects of fatigability are exercise-dependent, with general fatiguing exercises inducing a more comprehensive and intense cortical response (WEAVIL; AMANN, 2018).

The changes in cortical activity identified in this study have important implications for understanding postural control mechanisms after fatiguing exercise. Increases in delta activity, for example, may reflect a greater reliance on subcortically compensatory strategies to maintain postural stability (JACOBS; HORAK, 2007). However, these strategies may not be sustainable in the long term, especially in situations of chronic or repetitive fatigability. From a practical perspective, these findings highlight the need for targeted interventions to mitigate the effects of fatiguing exercise on postural control. Rehabilitation and sports training programs should consider including techniques that promote efficient recovery, especially from general fatiguing exercise, such as active recovery strategies and training that improves neuromuscular and cortical efficiency (PAILLARD, 2012).

Although this study provided important insights into the impact of fatiguing exercise on cortical activity during postural control, some limitations should be

acknowledged. The sample consisted exclusively of healthy young adults, limiting the generalizability of the findings to older populations or those with neurological conditions. Furthermore, the absence of recovery measures prevents conclusions about the time required for the return to normal cortical activity after different types of fatiguing exercise. Additionally, EEG presents methodological limitations regarding variability and normalizations. The high inter- and intraindividual variability in cortical activity recordings makes it difficult to interpret results consistently. The challenge of normalizing EEG metrics across individuals and conditions is another limitation, particularly given significant baseline variability. Lastly, cortical adaptation to fatigue may introduce temporary changes or compensatory mechanisms, requiring robust strategies to ensure data reliability. Future research should explore the temporal dynamics of cortical activity recovery and its impact on postural control in different populations after fatiguing exercise. Furthermore, studies that integrate neurophysiological and biomechanical measures may deepen the understanding of adaptive mechanisms over time. In addition, future studies should adopt rigorous normalization approaches and control individual variability, to enhance data interpretation and reliability.

3.5. Final Considerations of Study 2

These results reinforce the idea that fatigability affects not only the musculoskeletal and sensory systems, but also cortical activity involved in postural control. This study contributes to the understanding of the effects of general and localized fatiguing exercises on postural control, highlighting the relevance of cortical activity as a critical component in perceive instability under fatigability conditions. The observed changed activation may reflect an attempt to maintain stability, albeit at greater neuromuscular and cognitive costs. Furthermore, the findings indicate that general

fatiguing exercise led to greater impairments in postural control compared to localized fatigue. This suggests that whole-body fatigue imposes a higher demand on the postural regulation system, likely due to its widespread effects on multiple sensory and motor components. These differences emphasize the need for targeted recovery strategies depending on the type of fatigue induced. The observed changes in postural control point to the need for specific interventions to mitigate the negative effects of fatiguing exercise, thus promoting safety and performance in sports and rehabilitation contexts. Future investigations should explore the relationship between cortical activity changes and specific motor behaviors to better understand adaptive mechanisms to fatigability.

CHAPTER 4

STUDY 3 – SHORT- AND LONG-TERM EFFECTS OF FATIGUING EXERCISE ON HEALTHY YOUNG ADULTS' POSTURAL CONTROL

4. Study 3 – Short- and long-term effects of fatiguing exercise on healthy young adults' postural control

4.1. Introduction

Fatiguing exercise causes immediate damage to the control of standing posture. To combat these immediate losses (BARBIERI et al., 2019; PENEDO et al., 2021), the postural control system must adapt quickly because of the neuromotor disturbance caused by fatiguing exercise. Previous studies have shown that postural control remains altered from 5 to 20 minutes after fatiguing exercise (FOX et al., 2008; LIN et al., 2009a; PLINE; MADIGAN; NUSSBAUM, 2006; YAGGIE; MCGREGOR, 2002). However, this result should be interpreted with caution, as it reflects a short recovery period, since the deleterious processes that the fatiguing exercise causes remain for a longer time.

Deficits due to exercise-induced fatigability can leave residual effects on the body (BRYANTON; BILODEAU, 2016), remaining for a longer time (more than 48 hours of recovery). Several shortening-stretching cycles occur during high-intensity fatiguing exercises, making them highly harmful to the body and resulting in high levels of inflammation (BRANCACCIO et al., 2008; VÁCZI et al., 2018). The body sends metabolic and immunological responses to reestablish homeostasis, causing symptoms such as contractile dysfunction and delayed-onset muscle soreness (DOMS) (LEWIS; RUBY; BUSH-JOSEPH, 2012). Symptoms of DOMS peak between 48 and 72 hours and dissipate slowly from five to seven days (120 to 196 hours) after performing the fatiguing exercise (EBBELING; CLARKSON, 1989; LEWIS; RUBY; BUSH-JOSEPH, 2012; THOMAS et al., 2017). To our knowledge, only one study evaluated the prolonged effect (up to 48 hours) of localized fatiguing exercise on postural control in young adults, reporting that body sway remains increased, even after this time (PENEDO et al., 2022).

To know the long-lasting effects of fatiguing exercise on the postural control of young adults, can help to understand the adjustments and integration of postural neural and motor networks in the long-term, due to neuromuscular disorders caused by fatiguing exercise. Therefore, this study aims to investigate the long-lasting effects of fatiguing exercise on body sway during the postural control on healthy young adults. In general, the hypotheses of the study are: i) fatigability will cause late impairments to postural control (increased body sway from 48 to 120 hours after exercise); ii) postural control tends to return to baseline levels as the exercise protocol is performed (recovery from 120 to 196 hours after).

4.2. Methods

4.2.1. Participants

The number of participants was determined using the “G power” software based on the article by Barbieri and collaborators (PENEDO et al., 2022), according to the variable CoP AP displacement. The sample calculation indicated 16 individuals. This number of participants represents an index of probability of finding a significant difference at 0.95 and a value of α : 0.05. Estimating a sample loss of at least 20%, 20 healthy young adults participated in this study. The same exclusion and inclusion criteria for study 2 were used.

4.2.2. Experimental design

Participants attended eight visits to the laboratory to carry out experimental procedures (Figure 10). Thus, four visits were carried out for each protocol (ankle fatiguing exercise – LF and control situation - CC), to check the immediate (T0), the short-term effect of 5 (T5m), and 20 minutes (T20m), and the long-lasting effects of 48

(T48h), 120 (T120h), and 192 (T192h) hours after the protocols. The choice of this interval of days is justified by the onset of DOMS symptoms (24 to 48 hours after exercise), peak symptoms (72 to 120 hours after exercise), and symptom dissipation (from 120 to 192 hours after exercise) (EBBELING; CLARKSON, 1989; LEWIS; RUBY; BUSH-JOSEPH, 2012; THOMAS et al., 2017). The experimental procedures were performed at the same time of day. The experimental procedures and instructions were similar to the previous study, except for the control condition, in which participants remained at rest (sitting on a chair) for 10 minutes, instead of performing the fatiguing exercises. The control condition allows comparing experimental situations with an organized pattern to verify inferences deduced from an experiment (OAKLEY, 1998). The order of conditions was counterbalanced between participants. During all visits, participants performed the tasks in the same order as in the previous study.

4.2.3. Postural control protocol

The postural control protocol adopted was like that carried out in study 2, following the same experimental design, the same instructions, and data analysis. CoP parameters were investigated through the same procedures and equipment used in the previous study. Data analysis was also performed like the previous study.

4.2.4. MVIC protocol

The MVICs were performed through the adapted Leg Press exercise, like study 2. The same procedures, equipment, and instructions for participants, and the same data analysis were performed.

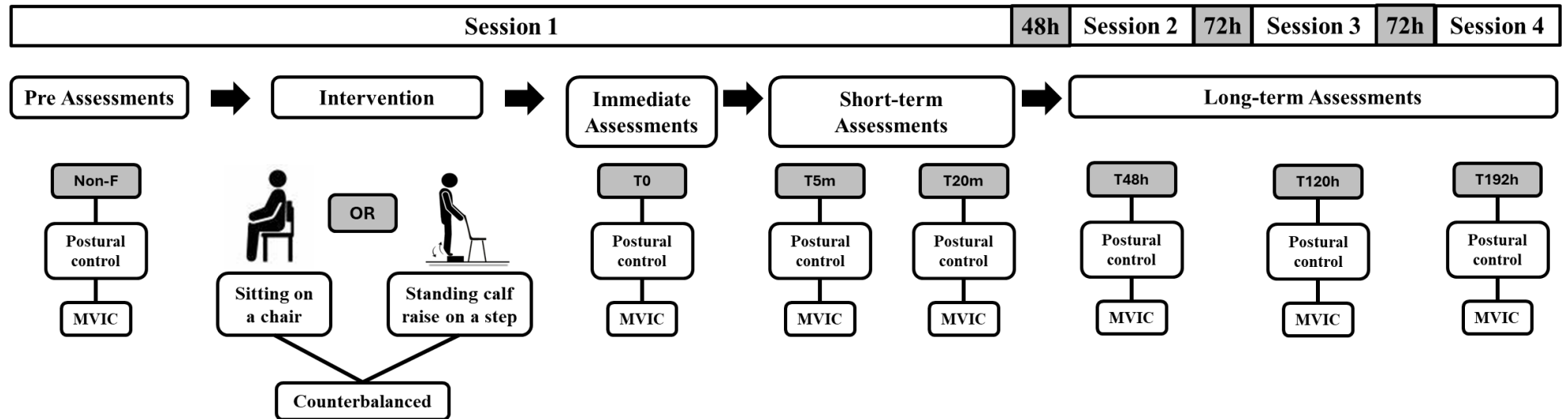


Figure 10. Exemplification of the experimental design of study 3. **Non-F** – after fatiguing exercise; **MVIC** - maximum voluntary isometric contraction; **T0** – immediately after fatiguing exercise; **T5m** – five minutes after fatiguing exercise; **T20m** – twenty minutes after fatiguing exercise; **48h** – forty-eight hours after fatiguing exercise; **T120** – one hundred and twenty hours after fatiguing exercise; **T192h** – one hundred and ninety-two hours after fatiguing exercise.

factors were used to analyze the parameters of interest for VAS, MVIC, and CoP. Tukey's Post hoc tests, with adjusted significance levels, were used when an interaction between factors was indicated in the analysis. The partial eta-square (η^2) was reported to measure the effect size and was interpreted as small (effect size > 0.01), moderate (effect size > 0.06) or large (effect size > 0.14) (COHEN, 1988).

4.3. Results of study 3

The same participants from the previous study (Table 9) performed all sessions in this study. Participants reported 6 ± 0.7 pts [6 – 9 pts] and 20 ± 1 pts [17 – 20 pts] of effort perception for localized fatiguing exercise in the Non-F and the T0 conditions, respectively, and 6 ± 0.3 pts [6 – 7 pts] and 6 ± 0.3 pts [6 – 7 pts] of effort perception for resting in the Non-F and the T0 conditions, respectively.

The evidence of DOMS and its recovery is reported in figure 12. ANOVA indicated a large main effect of moment for VAS ($F_{(6,33)} = 36,911$; $p < 0.001$; $\eta^2 = 0.87$). The post hoc showed that participants reported greater muscle soreness at T0 compared to Non-F, T5m, T20m, T120h, and T192h ($p < 0.001$ for all comparisons), at T5m compared to Non-F, T20m, T120h, and T192h ($p < 0.001$ for all comparisons), at T48h compared to Non-F, T20m, T120h, and T192h ($p < 0.001$ for all comparisons), and at T20m and T120h compared to T192h ($p < 0.007$ and $p < 0.02$, respectively). There was a large main effect of condition ($F_{(1,38)} = 141,441$; $p < 0.001$; $\eta^2 = 0.78$), in which the post hoc showed that LC was worse for muscle soreness compared to CC ($p < 0.001$). In addition, ANOVA showed a large interaction between factors moment x condition for VAS ($F_{(6,33)} = 72,844$; $p < 0.001$; $\eta^2 = 0.93$). Post hoc showed that muscle soreness increased after LC at T0 compared to Non-F, T5m, T20m, T48h, T120h, and T192h ($p < 0.001$ for all comparisons except for T48h – $p < 0.04$), at T5m compared to Non-F, T20m,

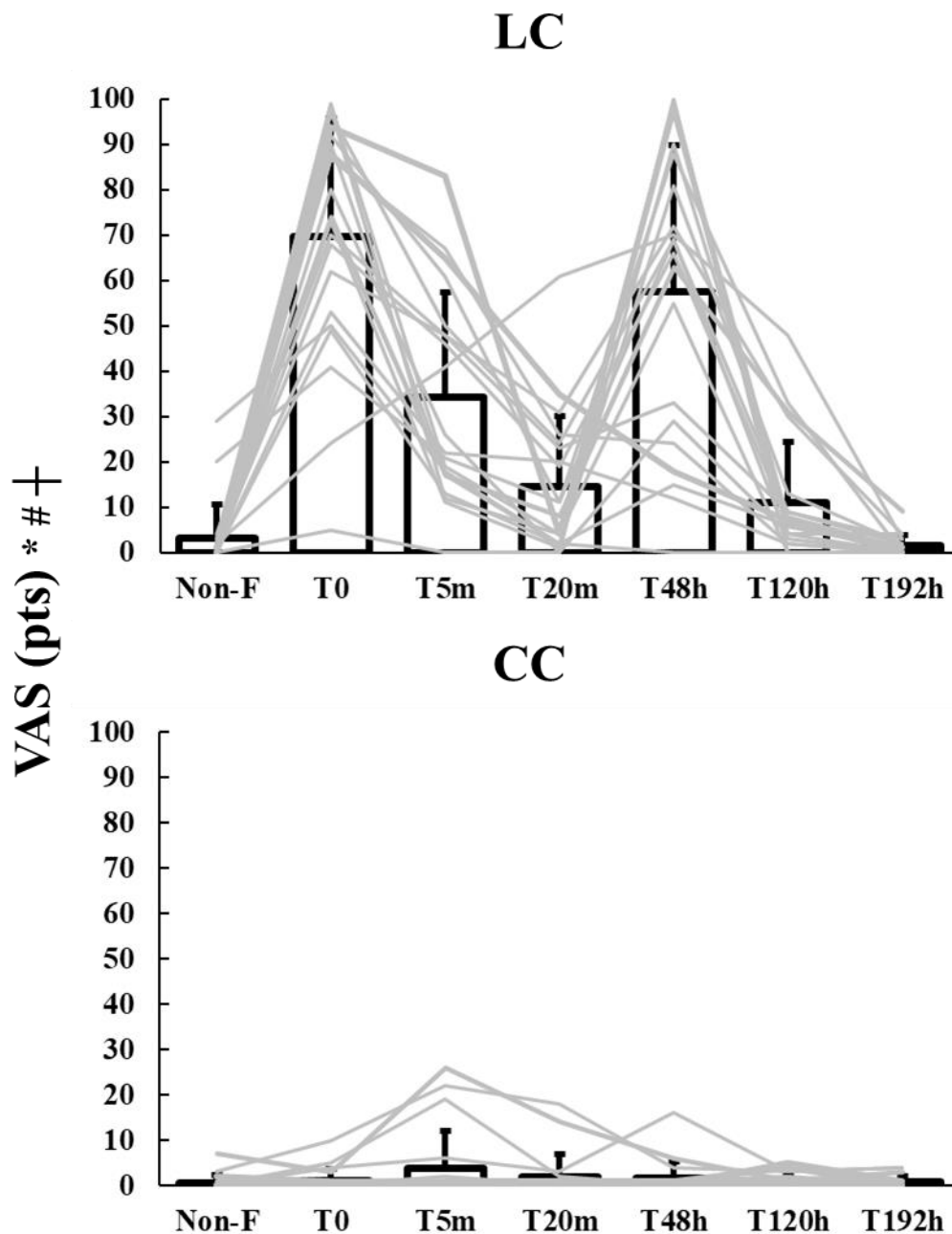


Figure 12. Visual analogue scale (VAS) to indicate the delayed onset muscle soreness in localized fatiguing exercises (LC) and sitting on a chair (control condition – CC) conditions before (Non-F), immediately after (T0), five minutes (T5m), twenty minutes (T20m), forty-eight hours (T48h), one hundred and twenty hours (T120h), and one hundred and ninety-two hours (T192h) after the interventions. Bars indicate the mean and standard deviation, and the gray lines indicate the individual participant values. * – main effect of moment; # – main effect of condition; † – interaction between moment x condition factors.

T120h, and T192h ($p < 0.001$ for all comparisons), at T20m compared to Non-F and T192h ($p < 0.001$ for both), at T48h compared to Non-F, T5m, T20m, T120h, and T192h ($p < 0.001$ for all comparisons), and at T120h compared to Non-F and T192h ($p < 0.002$ and $p < 0.001$, respectively).

4.3.1. Maximum voluntary isometric contraction (MVIC)

ANOVA evidenced a large main effect of moment for MVIC ($F_{(1,38)} = 14,273$; $p < 0.001$; $n^2 = 0.72$). Post hoc indicated lower force at T0 and T5m compared to Non-F ($p < 0.001$ and $p < 0.05$, respectively).

Localized fatiguing exercise reduced MVIC. ANOVA showed a large interaction between the moment x condition factors for MVIC of localized ($F_{(1,38)} = 11,611$; $p < 0.001$; $n^2 = 0.68$) fatiguing exercise. Post hoc showed that force decreased after localized fatiguing exercises at T0, T5m, T20m and T48h compared to Non-F ($p < 0.001$, $p < 0.001$, $p < 0.003$, and $p < 0.05$, respectively), and at T120h and T192h compared to T0 ($p < 0.007$ and $p < 0.002$, respectively) and T5m ($p < 0.01$ and $p < 0.004$, respectively), and at T120h compared to T20m ($p < 0.04$).

There was no main effect of condition ($p > 0.05$).

4.3.2. Center of Pressure (CoP)

Fatiguing exercise increases postural sway in healthy young adults in the short- and long-term (Figure 14). The ANOVA revealed a moderate and large main effect of moment for AP ($F_{(6,228)} = 4,714$; $p < 0.006$; $n^2 = 0.11$) and ML ($F_{(6,228)} = 7,582$; $p < 0.001$; $n^2 = 0.16$) displacement, AP ($F_{(6,228)} = 5,617$; $p < 0.01$; $n^2 = 0.12$) and ML ($F_{(6,228)} = 5,633$; $p < 0.004$; $n^2 = 0.12$) mean velocity, AP ($F_{(6,228)} = 5,345$; $p < 0.002$; $n^2 = 0.12$) and ML ($F_{(6,228)} = 7,795$; $p < 0.001$; $n^2 = 0.17$) RMS. The post hoc indicated an increase in

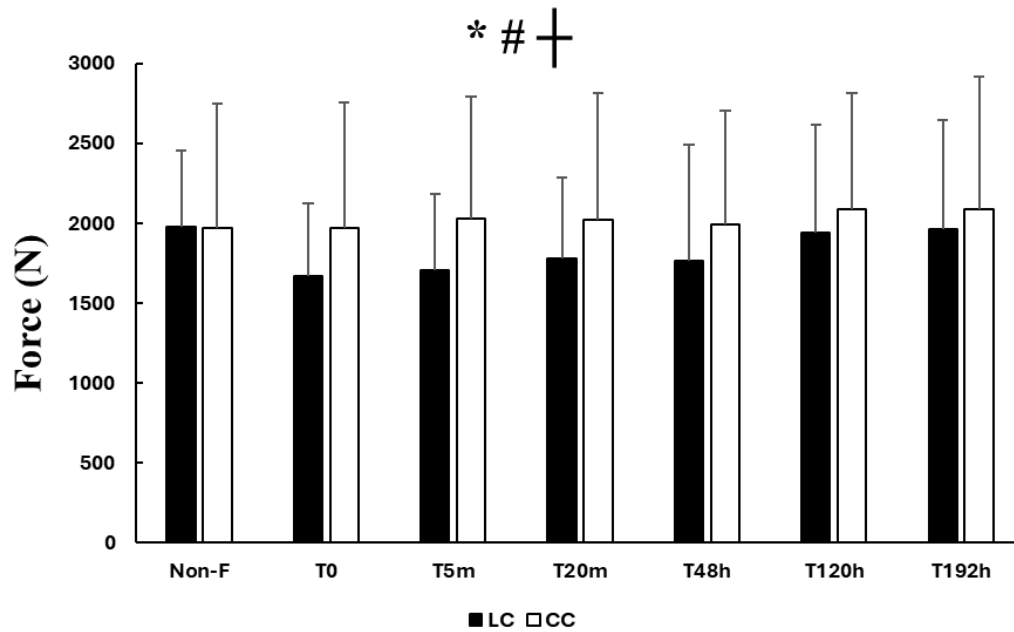


Figure 13. Force (N) produced during maximum voluntary isometric contractions in localized fatiguing exercises (LC – black bars) and sitting on a chair (control condition – CC – white bars) conditions before (Non-F), immediately after (T0), five minutes (T5m), twenty minutes (T20m), forty-eight hours (T48h), one hundred and twenty hours (T120h), and one hundred and ninety-two hours (T192h) after the interventions. * – main effect of moment; # – main effect of condition; † – interaction between moment x condition factors.

AP displacement at T0 compared to Non-F, T20m, T48h, T120h, and T192h ($p < 0.05$, $p < 0.03$, $p < 0.004$, $p < 0.002$, and $p < 0.005$, respectively), ML displacement at T0 compared to Non-F, T20m, T48h, T120h, and T192h ($p < 0.001$, $p < 0.01$, $p < 0.02$, $p < 0.001$, and $p < 0.001$, respectively), AP mean velocity at T5m compared to T20m ($p < 0.003$), ML mean velocity at T0 and T5m compared to T20m ($p < 0.02$ and $p < 0.02$, respectively), AP RMS at T0 compared to Non-F, T20m, T48h, T120h, and T192h ($p < 0.03$, $p < 0.02$, $p < 0.002$, $p < 0.001$, and $p < 0.002$, respectively), and ML RMS at T0 compared to Non-F, T20m, T48h, T120h, and T192h ($p < 0.001$, $p < 0.02$, $p < 0.02$, $p < 0.001$, and $p < 0.001$, respectively).

The ANOVA showed moderate interaction between the factors moment x condition for the ML displacement ($F_{(6,228)} = 3,507$; $p < 0.008$; $\eta^2 = 0.08$), AP and ML mean velocity ($F_{(6,228)} = 6,185$; $p < 0.01$; $\eta^2 = 0.14$ and $F_{(6,228)} = 4,683$; $p < 0.009$; $\eta^2 =$

0.11, respectively), and ML RMS ($F_{(1,38)} = 3,617$; $p < 0.007$; $\eta^2 = 0.08$). The post hoc indicated that after localized fatiguing exercise there was an increase in ML displacement at T0 compared to Non-F, T5m, T20m, T48h, T120h, and T192h ($p < 0.001$, $p < 0.01$, $p < 0.001$, $p < 0.001$, $p < 0.001$, and $p < 0.001$, respectively), at T5m compared to Non-F, T48h, T120h, and T192h ($p < 0.001$, $p < 0.01$, $p < 0.03$, and $p < 0.01$, respectively), and at T20m compared to Non-F ($p < 0.04$), AP mean velocity at T0 compared to Non-F, T5m, T20m, T48h, T120h, and T192h ($p < 0.001$, $p < 0.003$, $p < 0.001$, $p < 0.001$, $p < 0.001$, and $p < 0.001$, respectively) and at T5m compared to Non-F, T20m, T48h, T120h, and T192h ($p < 0.003$, $p < 0.001$, $p < 0.02$, $p < 0.01$, and $p < 0.009$, respectively), ML mean velocity at T0 compared to Non-F, T5m, T20m, T48h, T120h, and T192h ($p < 0.001$, $p < 0.003$, $p < 0.001$, $p < 0.002$, $p < 0.001$, and $p < 0.001$, respectively), at T5m compared to T20m ($p < 0.001$), and at T20m compared to T48h ($p < 0.04$), and ML RMS at T0 compared to Non-F, T5m, T20m, T48h, T120h, and T192h ($p < 0.001$, $p < 0.02$, $p < 0.001$, $p < 0.001$, $p < 0.001$, and $p < 0.001$, respectively) and at T5m compared to T48h, T120h, and T192h ($p < 0.01$, $p < 0.03$, and $p < 0.01$, respectively).

There was no main effect of exercise ($p > 0.05$).

4.4. Discussion of study 3

The present study investigated the short- and long-term effects of localized ankle fatiguing exercise on postural control in healthy young adults. The results revealed significant increases in DOMS, reductions in MVIC, and impairments in postural control metrics immediately following fatiguing exercises, with varying recovery patterns observed between conditions. These results underscore the complex interplay between fatigability and neuromuscular control, reflecting impaired neuromuscular performance and postural stability after fatiguing exercise.

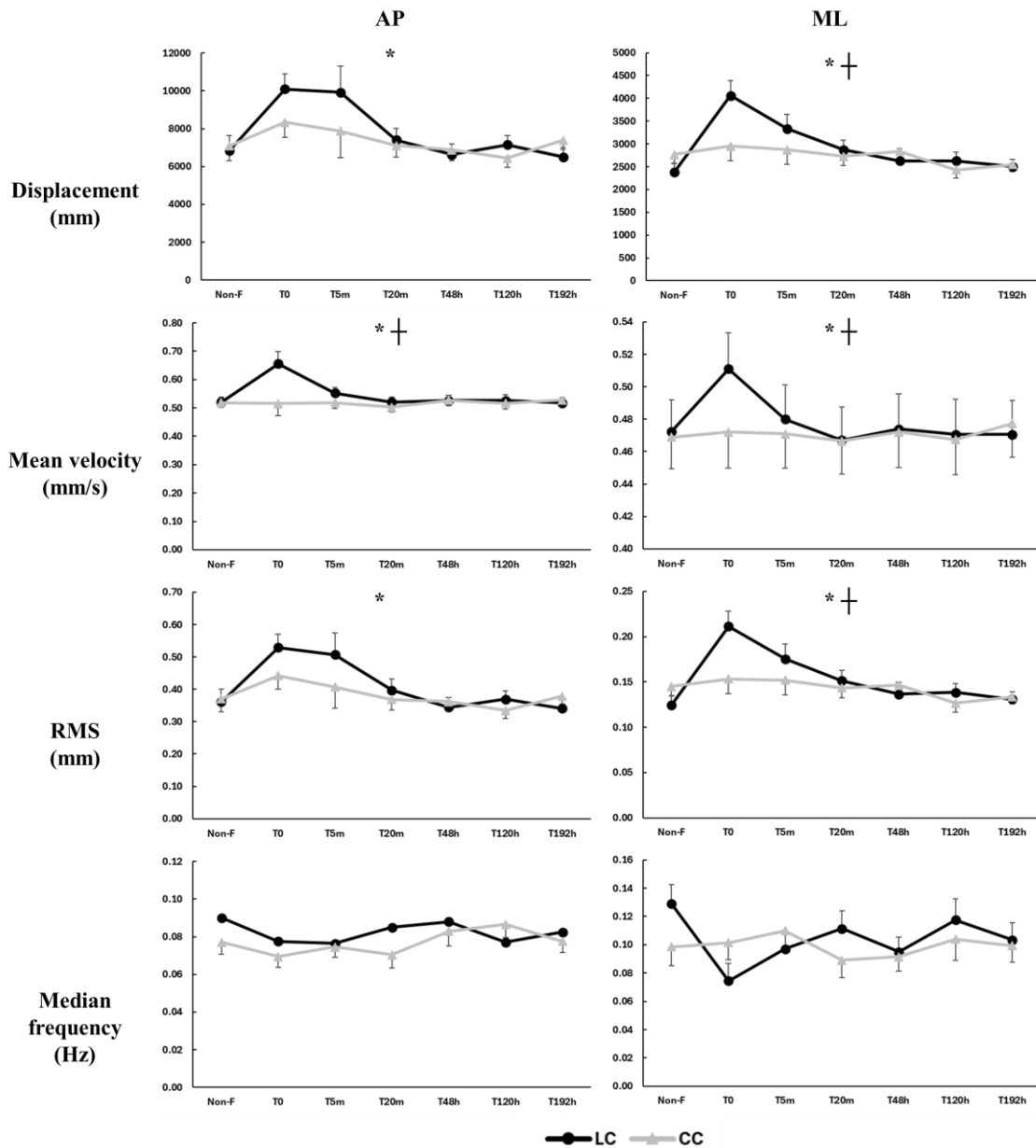


Figure 14. Mean and standard error of center of pressure parameters outcomes analyzed in localized fatiguing exercises (LC – black lines) and sitting on a chair (control condition – CC – grey lines) conditions before (Non-F), immediately after (T0), five minutes (T5m), twenty minutes (T20m), forty-eight hours (T48h), one hundred and twenty hours (T120h), and one hundred and ninety-two hours (T192h) after the interventions. * – main effect of moment; † – interaction between moment x condition factors.

The analysis of DOMS (Figure 12) indicated significant increases in muscle soreness immediately after the fatiguing exercise (T0), particularly in the localized condition (LC), followed by a short-term recovery (T20m). In addition, there was a new peak of muscle soreness at T48h (i.e., DOMS), a possible dissipation of muscle soreness at T120h, and a complete recovery at T192h. This recovery pattern is consistent with established timelines for DOMS resolution, highlighting the importance of temporal monitoring in rehabilitation strategies (EBBELING; CLARKSON, 1989; LEWIS; RUBY; BUSH-JOSEPH, 2012; THOMAS et al., 2017).

The reductions in MVIC immediately following the fatiguing exercises (T0 and T5m) suggest a significant decline in neuromuscular performance due to short-term effects of fatigability. This aligns with prior research suggesting that localized fatiguing exercise leads to reduced force output due to central and peripheral mechanisms (ENOKA; DUCHATEAU, 2017). The localized fatiguing exercise had a pronounced effect on MVIC, particularly in the early phases of recovery, corroborating findings that localized fatiguing exercise affects muscle force production (GANDEVIA, 2001). Although MVIC began to recover after T48h, the delayed recovery in the localized condition highlights the persistent impact of localized fatiguing exercise on muscle contractility and strength. The observed recovery trend indicates that muscle strength gradually returns, though it remains below baseline for several days, consistent with studies on delayed muscle recovery following intense eccentric exercise (CAIRNS et al., 2005).

Fatiguing exercise significantly affected postural stability, as indicated by increased center of pressure (CoP) displacement, mean velocity, and RMS in both AP and ML directions. These findings are consistent with previous research showing that fatigability impairs postural control by altering proprioceptive input and motor output

strategies (PAILLARD, 2012). Immediately after exercise (T0), participants exhibited increased AP and ML CoP displacement, mean velocity, and RMS values. These changes likely reflect compensatory adjustments due to decreased ankle muscle strength, as the body attempts to maintain balance with compromised sensorimotor function (GRIBBLE; HERTEL, 2004a). Additionally, reduced proprioceptive sensitivity from fatigued ankle muscles may explain the increase in postural sway. The persistence of postural instability at T5m and T20m suggests that neuromuscular recovery is not immediate. These results support the concept of residual fatigability effects on young adults' postural control, which can impair motor coordination for extended periods (PENEDO et al., 2022). The observed recovery of postural control parameters followed distinct temporal patterns, with ML displacement and RMS metrics showing prolonged impairments compared to AP metrics. Notably, localized fatiguing exercise caused greater and more sustained increases in ML postural sway, emphasizing the role of muscle-specific fatigability in destabilizing lateral stability (GRIBBLE; HERTEL, 2004a). Interestingly, ML displacement remained affected longer than AP displacement, possibly due to the greater reliance on ankle strategies in the ML plane for maintaining upright posture (WINTER, 1995), even after ankle fatiguing exercise (PENEDO et al., 2021). These results suggest that different dimensions of postural control recover at different rates, with ML stability requiring more prolonged recovery time.

Significant interaction effects between moment and condition factors further highlight that localized fatiguing exercise induce complex adaptive responses in postural control for a long-term. This indicates that fatigability may disrupt not only muscular but also central nervous system processes involved in balance regulation (FORESTIER; TEASDALE; NOUGIER, 2002). Localized exercises resulted in greater and more persistent impairments in muscle soreness, force, and postural control, supporting the

notion that targeted fatigability has a greater influence on localized neuromuscular function and stability. This is particularly relevant for activities requiring precise motor control or lateral stability, such as sports or balance-demanding tasks. It is important to note that a previous study published by our group (PENEDO et al., 2022) showed that fatiguing ankle exercise left residual effects on linear parameters, but without altering CoP adaptability and complexity. This long-term change was attributed to the DOMS effects on postural control. However, no objective DOMS data was shown in this previous study, as participants indicated DOMS verbally. The data shown in this current study follow the same way: long-term CoP change. However, the exercise-related DOMS of the participants was measured objectively through the VAS. Although we did not establish any relationship between these variables, it is possible to note that the peaks of immediate (T0) and late increase (T48h) in addition to the recovery (T120h and T192h) of the CoP and VAS parameters coincide. On the other hand, the persistence of increased CoP for up to 48h that was shown in this thesis does not appear to have been of the same magnitude as in our previous study (PENEDO et al., 2022). We can attribute this to the physical activity level of the participants in this current study, who were active or very active (according to the IPAQ), unlike the previous study that did not report the participants' physical activity levels. The perception of DOMS can vary according to the intensity and type of fatiguing exercise performed, as well as among individuals with different levels of physical fitness (SMITH et al., 2019), generating consequences of the same magnitude on postural control. Consistent engagement in physical activity (e.g., being active or very active) can enhance pain tolerance and mitigate DOMS following exercise (SMITH et al., 2019). This can generate increased long-term responses to CoP, but with a smaller magnitude compared to individuals with lower levels of physical activity. Therefore, exercise adaptation (i.e., physical activity level) may play a

significant role in modulating the perception of DOMS after fatiguing exercise, as well as the postural response.

These findings have important implications for sports and rehabilitation settings. The delayed recovery observed in muscle soreness, force, and postural control following localized fatigability highlights the need for targeted interventions, such as neuromuscular training or proprioceptive exercises, to mitigate the fatigability effects and expedite recovery. In addition, prolonged postural instability following fatiguing exercise highlights the need for adequate recovery protocols to prevent injuries caused by impaired balance. So, incorporating balance training after fatiguing tasks may enhance motor control recovery.

While this study provides robust evidence of the effects of fatiguing exercise on muscle and postural recovery, some limitations should be noted. The reliance on laboratory-based assessments may not fully capture the complexity of postural control during dynamic, real-world activities. Furthermore, although we have previous evidence of fatigability generated by centrally-mediated factors (PENEDO et al., 2021), this study did not analyze the possible neural mechanisms responsible for mediating the short- and long-term effects of fatiguing exercise on postural control in healthy young adults. Future research should explore the underlying neural mechanisms (i.e., the role of cortical activity) contributing to prolonged postural instability using neuroimaging techniques, as well as the underlying mechanisms of differential recovery patterns and investigate the role of interventions such as hypoxia in accelerating DOMS recovery and postural control.

4.5. Final Considerations of study 3

In conclusion, this study highlights the significant impact of short- and long-term fatiguing exercise on muscle soreness, force, and postural control in healthy young adults. The distinct recovery patterns observed underscore the need for tailored approaches to training, recovery and rehabilitation. The findings of this study underscore the importance of considering both immediate, short- and long-term effects of fatiguing exercise on balance performance in contexts such as athletic training and rehabilitation programs.

CHAPTER 5

FINAL REMARKS OF THE THESIS

5. Final remarks of the thesis

The contributions of this thesis to the literature (highlights) and the perspective for future research are shown in the Figure 15. The present thesis explored the multifaceted impact of exercise-induced fatigability on postural control in healthy young adults, emphasizing both behavioral and cortical adaptations. In addition, this doctoral thesis underscores the pivotal role of cortical activity in maintaining postural control in healthy young adults following exercise-induced fatigability. The findings reveal that fatigability impairs not only musculoskeletal and sensory systems but also impacts cortical mechanisms critical for stability. Changed cortical activation appears to be a key response aimed at preserving postural equilibrium, though at an increased neuromuscular and cognitive cost.

The systematic review and meta-analysis conducted highlighted the methodological variability across studies assessing fatiguing exercise and postural control emerged as a critical factor limiting the generalizability of findings. Standardizing assessment protocols, including fatigability induction procedures and postural control measurements, is essential for advancing knowledge in this field. Surprisingly, no studies that showed cortical contributions to postural regulation were included in the systematic review and meta-analysis. This reinforces the importance of considering cortical engagement when designing interventions in sports, rehabilitation, and other locomotor activities, where reduced stability due to fatigability may elevate the risk of falls or injuries. Additionally, exploring cortical mechanisms associated with postural adjustments presents a promising avenue for future research, with potential implications for developing targeted interventions to enhance balance and reduce injury risks.

The persistent impact of localized ankle fatigability on strength and postural stability further emphasizes the necessity of short- and long-term recovery strategies. This finding highlighting the complex interplay between neuromuscular and sensory systems involved in balance regulation, in addition to underscoring the necessity of implementing effective recovery

strategies to mitigate the risks associated with reduced stability in sports, rehabilitation, and daily locomotor activities. Future research should explore the dynamic interplay between cortical activity and specific motor behaviors to deepen our understanding of adaptive neural mechanisms underlying fatigability management. Standardization of methodological approaches is essential to advance this field and establish more definitive conclusions about cortical roles in postural control.

Overall, this thesis contributes to a deeper understanding of how fatigability affects the human postural control system by integrating biomechanical and neurophysiological perspectives. Future investigations should continue examining the links between cortical activity and specific motor behaviors to better elucidate adaptive strategies and optimize training and rehabilitation protocols. Through this comprehensive approach, meaningful advancements can be made in mitigating the adverse effects of fatiguing exercise and enhancing overall motor performance and safety.

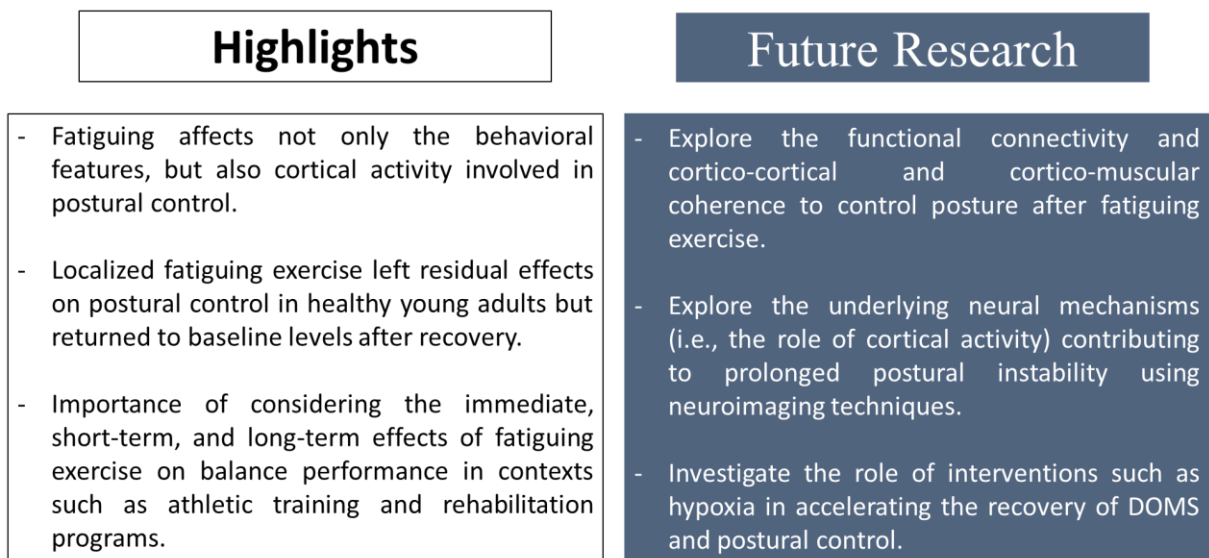


Figure 15. Contributions of the PhD thesis to the literature (highlights) and the perspective for future research.

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