DESIGN E TECNOLOGIA ASSISTIVA

INTERDISCIPLINARIDADE NA PESQUISA E DESENVOLVIMENTO SOBRE MOBILIDADE EM CADEIRA DE RODAS

unesp

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DEDICATÓRIA

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À minha esposa Fernanda e meu filho Arthur, por todo amor, compreensão, alegria e união.

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INTRODUÇÃO

A Tecnologia Assistiva esteve presente desde as primeiras etapas de minha formação acadêmica,a partir do crescente interesse nos processos de reabilitação e inclusão social da pessoa com deficiência. Despertou-me especial interesse o grande potencial que o uso bem-sucedido de produtos como cadeira de rodas, próteses e órteses pode representar na vida de seus usuários. De forma mais intensa durante a especialização (Residência) e minha atuação como Professor e Supervisor de Estágio em Fisioterapia nas Condições Neurológicas, pude acompanhar as mudanças em todo o processo de reabilitação de pessoas - em sua maioria adultos jovens - que sofreram Traumatismo Raquimedular e apresentaram quadros de paraplegia e tetraplegia. O longo caminho de recuperação da independência representava uma transformação de vida e a descoberta de novos desafios mas, também, possibilidades de efetiva participação social. O sucesso deste processo resultava, em grande parte, do adequado uso das tecnologias assistivas e de reabilitação. Cadeiras de rodas, órteses, adaptações para atividades de vida diária e dispositivos auxiliares da marcha (tais como muletas, andadores) representavam instrumentos decisivos de etapas nas quais o paciente recuperava de forma progressiva o domínio de sua independência no dia-a-dia. A atuação em todas as etapas deste processo me possibilitou a experiência na indicação, seleção, configuração e adequação de produtos de Tecnologia Assistiva e de Reabilitação, assim como a confecção de adaptações em PVC para atividades de alimentação, escrita e digitação, e posicionadores provisórios feitos com atadura gessada.

Foi com a experiência no projeto de iniciação esportiva para pessoas com paraplegia e tetraplegia usuárias de cadeira de rodas que pude observar uma drástica mudança de visão e perspectiva na vida destas pessoas: de pacientes em ambiente ambulatorial e hospitalar a atletas participantes de competições. Os equipamentos assistivos para prática de esportes apresentavam características diferentes dos tradicionais para uso diário e específicas para o desempenho das modalidades. Foi um prazer e grande aprendizado poder atuar nestes dois contextos - reabilitação e esporte - e aprender sobre as especificidades das tecnologias assistivas.

O uso das cadeiras de rodas em um contexto esportivo de treinamento em forte intensidade traz à tona os problemas de sobrecarga biomecânica e interfaces inadequadas: queixas de dor e lesões nos ombros, cotovelos e punhos, assim como lesões de pele nas mãos em decorrência do atrito com as rodas ao impulsioná-las. Isto chamou a atenção para a necessidade e potencial de aprimoramento no design da cadeira de rodas e seus componentes/acessórios e, com esta motivação, desenvolvi nos cursos de mestrado e doutorado pelo Programa de Pós-graduação Interunidades Bioengenharia - EESC/FMRP/IQSC - Universidade de São Paulo, projetos de pesquisa e desenvolvimento em cadeira de rodas. O trabalho interdisciplinar entre saúde e engenharia, desenvolvido junto a meus orientadores Profa. Dra. Valéria Meirelles Carril Elui e Carlos Alberto Fortulan, no Laboratório de Tribologia e Compósitos - LTC-EESC (USP, São Carlos), foi muito importante em minha formação e me propiciou o desenvolvimento de competências e habilidades relacionadas ao Design de Produtos, tais como: Metodologias de Projeto, Desenho Técnico, Modelagem Tridimensional, Materiais em Engenharia, confecção de moldes, Impressão 3D e desenvolvimento de modelos e protótipos. Destes anos de pesquisa durante o mestrado e doutorado resultaram dois depósitos de patente (modelos de utilidade) relacionados à cadeira de rodas: um aro de propulsão com características ergonômicas; e uma cadeira de rodas manual com assistência motorizada com características inovadoras no sistema de transmissão e propulsão.

Muito além das respostas imediatas às questões de pesquisa exploradas durante o mestrado e doutorado, a pesquisa na área de mobilidade em cadeira de rodas me revelou ainda muitas perguntas a serem exploradas. Ao ingressar na Universidade Estadual Paulista "Júlio de Mesquita Filho" - UNESP como docente do Departamento de Design da Faculdade de Arquitetura, Artes e Comunicação - FAAC, estabeleci como principal objeto de pesquisa o design de cadeira de rodas e suas implicações para o usuário. Neste sentido, desenvolvi no Laboratório de Ergonomia e Interfaces - LEI-UNESP, projetos com financiamento da PROPeUNESP, FAPESP, e orientei alunos de iniciação científica, e mestrado em pesquisas relacionadas ao design de cadeira de rodas. Como resultado, diversos trabalhos na área foram publicados em revistas científicas e capítulos de livro, assim como apresentados em eventos científicos nacionais e internacionais. Agradeço aqui a parceria do Prof. Tit. Luis Carlos Paschoarelli, coordenador do LEI-UNESP, em grande parte destes trabalhos.

A ampliação da atuação em pesquisa para outros tópicos relacionados à área de Tecnologia Assistiva - tais como órteses, próteses e produtos para a independência nas atividades de vida diária - foi um processo natural que resultou do estudo e aprofundamento sobre o tema, colaborações com outros pesquisadores, e a procura por parte de alunos com manifesto interesse em desenvolver projetos e pesquisas na área. Desta forma, a partir de 2016 comecei a ampliar minha atuação em pesquisa na área de Design e Tecnologia Assistiva, abordando temas como impressão 3D aplicada a órteses e próteses personalizadas, desenvolvimento de brinquedos educativos inclusivos para crianças com deficiência visual, motora e cognitiva, projetos de produtos para idosos institucionalizados, entre outros. A descoberta do potencial de atuação do Design em áreas tão diversas relacionadas a produtos para pessoas com deficiência representou novos caminhos para minha atuação acadêmica e científica. Desta maneira, passei a, por meio de colaboração estabelecida com instituições de apoio e reabilitação à pessoa com deficiência, proporcionar aos alunos a experiência de desenvolvimento de projetos de design em um contexto de demandas reais dos usuários. Algumas atividades da disciplina Design Inclusivo e o desenvolvimento de projetos de conclusão passaram a ocorrer neste contexto, a partir do qual observei seu impacto positivo no engajamento dos alunos com os projetos e disciplina.

No âmbito da extensão universitária, coordenei (de 2015 a 2017) o projeto “O Design como instrumento para práticas inclusivas em escolas municipais”, por meio do qual a equipe desenvolvia estratégias em design e instrumentos lúdicos para abordar o tema da inclusão social da pessoa com deficiência com alunos do ensino fundamental em escolas de Bauru. Foi uma experiência muito gratificante e enriquecedora trabalhar de forma colaborativa com alunos do projeto e professores, diretores e coordenadores pedagógicos das escolas.

No ano de 2016, tive a oportunidade de trabalhar na proposição de um projeto internacional junto a pesquisadores da Oslo Metropolitan University (Oslo, Noruega), o qual foi submetido e aprovado em um edital de agência norueguesa para projetos de parceria entre instituições da Noruega e países do BRICS. O projeto, intitulado “*Collaborative Design and Prototyping of Assistive Technologies and Products for Independent Living*”, teve início em 2017 e por meio de financiamento deste projeto, alunos de mestrado e doutorado tiveram a oportunidade de realizar estágio para desenvolvimento de parte de suas pesquisas em Oslo.

Ainda no âmbito da internacionalização, tive aprovação no Edital PROPGUNESP 02/2019 - Redes de Pesquisa Internacionais, de uma proposta de criação de uma rede de pesquisa, da qual sou o pesquisador responsável, na área de Tecnologia Assistiva, Design e Reabilitação, junto a pesquisadores da UNESP, OsloMet e University of Queensland (Austrália).

Os diversos caminhos pelos quais desenvolvi minhas ações em ensino, pesquisa e extensão apresentam como denominador comum a área de Tecnologia Assistiva, e propiciaram condições para meu amadurecimento acadêmico, científico e profissional.

No texto a seguir, são apresentados os principais estudos desenvolvidos sobre a pesquisa e desenvolvimento de cadeira de rodas e suas as principais contribuições à área do Design e Tecnologia Assistiva. Destaca-se o caráter interdisciplinar presente na construção, desenvolvimento e discussão dos achados destes estudos: Design, Engenharias e Áreas da Saúde constroem as bases para a pesquisa dos aspectos práticos, estéticos e simbólicos da cadeira de rodas, bem como das propostas de inovação. Reflete, de algum modo, os caminhos pelos quais desenvolvi minha formação acadêmica e científica.

1. DEFICIÊNCIA E TECNOLOGIA ASSISTIVA

Em todo o mundo, estima-se que 15% da população apresente algum tipo de Deficiência (OMS, 2011). Em suas rotinas diárias, as pessoas com deficiência são frequentemente expostas a barreiras que podem limitar sua participação plena e efetiva na sociedade. A não-participação de uma pessoa com deficiência na sociedade deve ser compreendida a partir de uma perspectiva multifatorial. Embora muitas vezes as barreiras físicas são as mais comumente conhecidas ou visíveis, há aspectos sociais, emocionais e atitudinais que podem ser igualmente limitadoras da participação social.

A Classificação Internacional de Funcionalidade, Incapacidade e Saúde (CIF) define a deficiência como "problemas na função ou estrutura corporal, tais como um desvio ou perda significativos" e a incapacidade decorrente da deficiência como resultado da interação entre indivíduos com necessidades específicas e fatores pessoais e ambientais (DI NUBILA; BUCHALLA, 2008).

A Tecnologia Assistiva está diretamente relacionada à Deficiência. A Organização estima que mais de 1 bilhão de pessoas no mundo precisam de um ou mais produto assistivo (OMS, 2011). O conceito de Tecnologia Assistiva no Brasil refere-se a:

> [...] uma área do conhecimento, de característica interdisciplinar, que engloba produtos, recursos, metodologias, estratégias, práticas e serviços que objetivam promover a funcionalidade, relacionada à atividade e participação de pessoas com deficiência, incapacidades ou mobilidade reduzida, visando sua autonomia, independência, qualidade de vida e inclusão social (BRASIL, 2009, p.9).

Estando a pessoa com deficiência e as questões que determinam sua funcionalidade e independência em posição central no conceito de Tecnologia Assistiva, destaca-se o papel ímpar desempenhado pelo Design na abordagem de aprimoramento da interface entre usuário e produto assistivo.

A Tecnologia Assistiva é, portanto, um dos principais meios de melhorar a funcionalidade das pessoas com deficiência. Conforme destacado pela Organização

Mundial de Saúde (2011), os produtos assistivos geralmente representam o primeiro passo à inclusão e participação social, contribuindo para uma vida digna.

O sucesso no uso de um produto assistivo pode representar a seu usuário a independência nas atividades diárias e efetiva participação social. É, portanto, fundamental que todo o processo de prescrição, seleção e treinamento de uso de Tecnologia Assistiva seja conduzido a partir de uma abordagem que considere os múltiplos fatores que podem levar ao sucesso ou insucesso no uso.

Diferentemente de diversos outros produtos amplamente utilizados pela população geral, os dispositivos assistivos apresentam características especiais na interação com o usuário. Primeiramente, há uma relação de necessidade de uso do produto, sem o qual determinadas atividades tornam-se dificultadas ou mesmo impossíveis de serem realizadas. Neste sentido, o produto deve estar adequado às condições e necessidades específicas do usuário para o desempenho de suas atividades nos ambientes em que estas são realizadas. De uma maneira geral, os determinantes do uso bem-sucedido da Tecnologia Assistiva (Figura 1), tomando como exemplo uma cadeira de rodas, podem ser organizados em três principais fatores: (i) do usuário; (ii) do produto; e (iii) do ambiente.

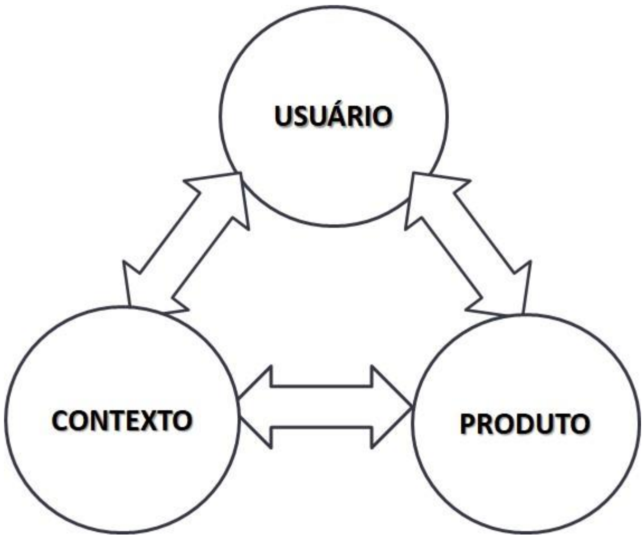


Figura 1. Uso bem-sucedido da Tecnologia Assistiva: principais fatores determinantes. Fonte: autor.

Os fatores do usuário compreendem suas: características físicas; independência funcional nas atividades diárias; capacidades e habilidades físicas, cognitivas e sensoriais; e necessidades, expectativas e preferências. No âmbito do produto, os fatores envolvem o desenho e os aspectos físicos como massa, dimensões, forma, cores; além da demanda de habilidades físicas, cognitivas e sensoriais exigidas para aprender e utilizar o produto. Por sua vez, os fatores do ambiente relacionam-se às condições gerais dos espaços nos quais o produto é utilizado, tais como: acessibilidade e condições do terreno e piso. Ressalta-se que o sucesso no uso do produto do equilíbrio entre estes três fatores e das condições da atividade: intensidade, duração e frequência.

A relação entre estes fatores gera interações, as quais podem ser investigadas a partir de pesquisas que, em última análise, podem fundamentar proposições para a otimização do desempenho geral do sistema. O estudo das interações entre usuário e produto contribuem para o entendimento da maneira com a qual as funções do produto atendem às demandas do usuário. De acordo com Lobach (2001), o design de um produto deve ser analisado considerando não somente suas funções práticas (de uso), mas também as funções estéticas e simbólicas. Esta constatação traz importantes implicações para a pesquisa em design e, mais especificamente, à pesquisa sobre produtos assistivos, pois aborda não somente o desempenho funcional dos produtos, mas igualmente suas representações e a maneira com a qual o usuário se identifica e relaciona com ele. A não-aceitação e o abandono de Tecnologia Assistiva estão relacionados, em alguma medida, a aspectos simbólicos e o estigma associado ao uso destes produtos. Portanto, o estudo do design de Tecnologia Assistiva a partir de uma visão mais ampla de suas funções e interações com o usuário pode contribuir com o desenvolvimento de produtos não apenas eficientes, mas também aceitáveis e desejáveis.

2. A CADEIRA DE RODAS E A MOBILIDADE

Dentre os diversos produtos de Tecnologia Assistiva, a cadeira de rodas é possivelmente um dos mais representativos. Observe-se a sinalização para estacionamentos e banheiros destinados à pessoa com deficiência: o símbolo mundialmente utilizado é de uma cadeira de rodas. Portanto, este é um produto que, além de sua função imediata de mobilidade, deve-se considerar que seu uso traz implicações sociais e emocionais igualmente importantes.

A cadeira de rodas é um produto que objetiva promover e melhorar a mobilidade de pessoas com incapacidade ou acometimento físico que impedem ou limitam a locomoção independente e segura por meio da marcha. Do ponto de vista biomecânico, o principal problema da cadeira de rodas é a sobrecarga à qual os músculos e articulações dos membros superiores são expostos durante a propulsão manual. Seu uso apresenta especificidades que a diferenciam dos demais produtos de mobilidade. O estudo de Sonenblum et al. (2012) demonstrou que os usuários ocupam a cadeira de rodas por um tempo diário médio de 11 horas, no entanto em pouco mais de 1 hora estão efetivamente se movimentando. Portanto, durante grande parte da interação, a cadeira de rodas é utilizada como um dispositivo postural, e não como um produto de mobilidade.

Ao aplicar forças de impulsão nas rodas de forma rítmica e repetitiva, o usuário impõe movimento e controla a trajetória e velocidade da cadeira. O estudo das técnicas de propulsão manual identificou padrões de movimento (Figura 2), os quais resultam de três principais fatores: a estratégia biomecânica do usuário; a posição do usuário em relação às rodas traseiras; e o contexto da atividade (condições de terreno, inclinação, velocidade, entre outros).

Figura 2. Técnicas de propulsão manual. Adaptado de: KOONTZ et al. (2009).

Do ponto de vista de trabalho muscular e desempenho do movimento, a técnica de propulsão manual mais efetiva é aquela em que o usuário impulsiona a roda por um arco maior de contato (ângulo de impulsão), e que o movimento de retorno (iniciado na liberação das mãos após a impulsão seguido de movimento para trás para iniciar um novo contato para nova impulsão) é feito com o menor trabalho muscular, ou seja, da forma mais passiva possível. Portanto, a combinação de amplo ângulo de impulsão com baixa demanda biomecânica no movimento de recuperação representa a melhor condição ergonômica para o usuário. A técnica de propulsão que melhor se encaixa nesta condição é o padrão semicircular. No entanto, em algumas situações a execução desta técnica não é possível, principalmente por conta de fatores do usuário, por exemplo condições de limitação de força e amplitude de movimento articular do ombro; e do design e configuração da cadeira, quando o eixo das rodas traseiras está posicionado muito para trás em relação ao usuário, o que melhora a estabilidade da cadeira porém acaba por limitar o alcance dos membros superiores às rodas, limitando o usuário a desempenhar uma técnica de propulsão ineficiente, com pequeno ângulo de impulsão, maior frequência de toque e trabalho muscular tanto na fase de impulsão quanto de recuperação. Portanto, considerar estes fatores no design de cadeira de rodas é fundamental para possibilitar ao usuário condições de uso mais eficientes do produto.

2.1 O Design da cadeira de rodas: aspectos que influenciam a mobilidade do usuário

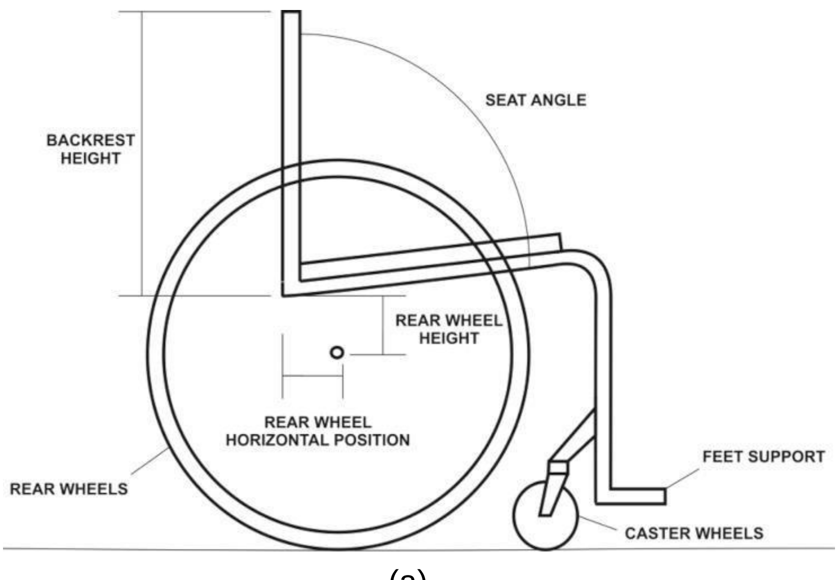
Existem diversos modelos de cadeira de rodas disponíveis comercialmente e com características diferentes no que diz respeito à estrutura, tamanho, massa, acessórios, posição dos componentes, ajustes, tipos e tamanhos de rodas e pneus, entre outros aspectos. No entanto, apesar das diversas possibilidades de design e configuração do equipamento, grande parte das decisões de escolha e indicação da cadeira de rodas para o usuário não leva em consideração as diversas possibilidades de personalização, normalmente limitando-se principalmente à massa e facilidade de desmontagem e transporte. Evidentemente estes são aspectos importantes para o usuário, familiares e cuidadores: um equipamento mais leve é sempre positivo; e, quanto maior sua facilidade de desmontar e montar o equipamento, mais fácil é o armazenamento e transporte no bagageiro do automóvel. Estas são situações que de fato devem ser consideradas na escolha de uma cadeira de rodas, uma vez que a facilidade de transporte é um aspecto fundamental para a independência do usuário em suas atividades.

Entretanto, os diversos ajustes, configurações e desenhos de cadeira de rodas podem trazer implicações imediatas ao usuário no que diz respeito à estabilidade do equipamento e risco de quedas, assim como facilidade de impulsionar e realizar as diversas manobras e movimentos característicos da mobilidade diária. Especificamente entre dois aspectos de grande relevância - estabilidade da cadeira e facilidade de movimentação - há um tênue equilíbrio que, em muitas das vezes, não é conseguido, o que acaba por impactar comprometer a mobilidade em algumas situações. Por exemplo: a medida mais imediata para garantir a estabilidade da cadeira e, desta forma, reduzir o risco de quedas, é a escolha de modelos de cadeira cujo eixo das rodas traseiras fica em posição mais posterior; ou, quando este ajuste é disponível em determinados modelos, posicionar o eixo na posição mais posterior possível. De fato, ganha-se maior estabilidade por meio de um aumento da base de apoio no sentido posterior, diminuindo-se assim o risco de queda para trás (que pode ocorrer em rampas, subidas e por movimentos bruscos). Por outro lado, a roda traseira em posição mais posterior em relação ao usuário limita o alcance deste às rodas, ou seja, o arco de circunferência por meio do qual o usuário faz contato e impulsiona as rodas é reduzido (GORCE; LOUIS, 2012). Portanto, o usuário precisa aumentar a frequência de impulsão para compensar o menor ângulo de contato de ação nas rodas. Além disso, as rodas traseiras, quando posicionadas muito posteriores ao usuário, acabam por dificultar ou mesmo impedir a manobra de empinar a cadeira, que é um movimento fundamental para transpor diversos obstáculos encontrados durante a mobilidade diária.

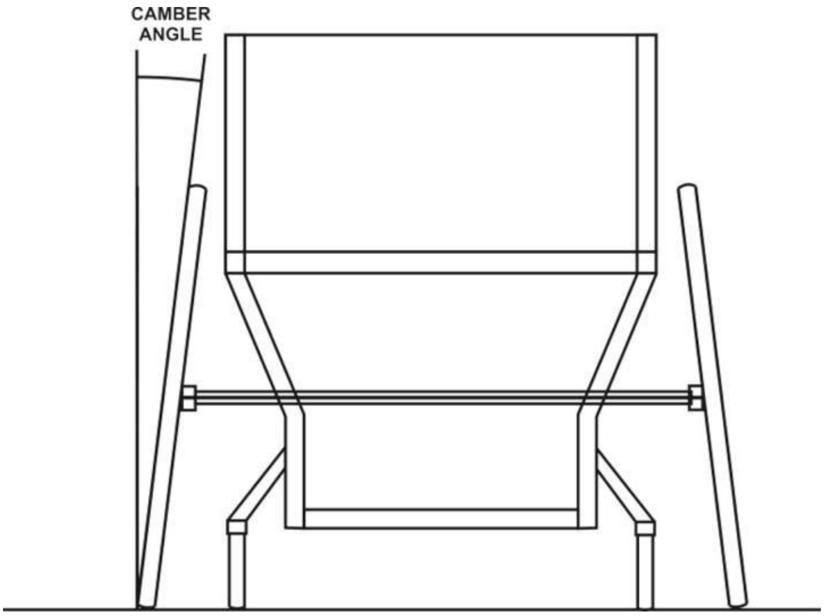
Diferentes designs e discretas alterações na configuração da cadeira de rodas podem trazer implicações tanto imediatas - estabilidade e facilidade de locomoção e realização de manobras - quanto tardias - demanda biomecânica - à interação do usuário com a cadeira. A necessidade de se compreender de que forma os mais diversos ajustes e configurações de componentes da cadeira influenciam a mobilidade do usuário justificou a realização de um estudo de revisão de literatura que analisou as evidências disponíveis em artigos científicos sobre aspectos específicos do design e configuração de cadeira de rodas (Figura 3). Neste estudo (MEDOLA et al., 2014a), foram analisados 55 artigos que ressaltam os problemas relacionados ao uso de cadeira de rodas manual, a necessidade de aprimorar as condições de mobilidade ao usuário e as evidências disponíveis acerca dos diversos aspectos de configuração da cadeira e seu impacto à mobilidade do usuário.

O estudo identificou doze aspectos do design e configuração da cadeira como principais fatores que influenciam a mobilidade do usuário:

- Altura do encosto;
- Ângulo entre o encosto e o assento;
- Posição horizontal das rodas traseiras em relação ao encosto/assento;
- Posição vertical das rodas traseiras em relação ao encosto/assento;
- Inclinação (cambagem) das rodas traseiras;
- Material da estrutura da cadeira;
- Design da estrutura da cadeira;
- Design e material das rodas traseiras;
- Tipo de pneu (maciço ou inflável);
- Tamanho e tipo de pneu das rodas dianteiras (*casters*);
- Posição do apoio dos pés; ● Design do aro propulsor.



(a)



(b)

Figura 3. Principais aspectos do design e configuração da cadeira de rodas que influenciam a mobilidade: vista lateral (a); vista frontal (b). Fonte: MEDOLA et al. (2014a).

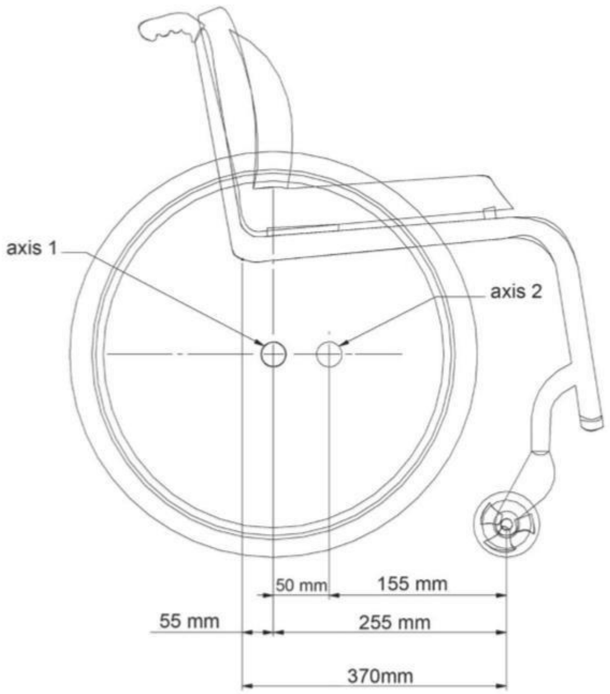
A posição relativa do usuário às rodas traseiras é possivelmente o principal aspecto que determina a facilidade na locomoção e as demandas biomecânicas da propulsão manual. Neste sentido, são aspectos determinantes a posição vertical/horizontal das rodas traseiras: Quanto mais alto e anterior estiver o usuário em relação às rodas, menor sua capacidade de alcance e ângulo de impulsão, limitando ao usuário uma propulsão manual caracterizada por pequeno ângulo de contato e maior frequência (BONINGER et al., 2000). Tem-se, portanto, uma situação de baixa eficiência da propulsão que, considerando o uso prolongado da cadeira, pode resultar em maior risco do desenvolvimento de lesões por sobrecarga biomecânica dos membros superiores. De forma complementar ao posicionamento das rodas traseiras, os demais aspectos do design e configuração da cadeira de rodas podem, quando adequados às características e necessidades específicas de cada usuário, favorecer a eficiência da propulsão manual, promovendo melhores condições para a mobilidade independente e segura por tempo prolongado. Este é o desfecho desejável, o qual resulta da aplicação de conhecimentos de maneira interdisciplinar em todas as etapas do projeto e processo de dispensação de cadeira de rodas.

O estudo traz de forma detalhada o impacto de diferentes ajustes e opções dos aspectos do design do equipamento na mobilidade do usuário. Contribui, portanto,

tanto a profissionais das áreas de projeto, ao fornecer diretrizes que podem ser aplicadas no design de cadeira de rodas que favoreça a eficiência na mobilidade do usuário, quanto a profissionais de saúde e reabilitação que atuam diretamente com a prescrição, adequação e treinamento de cadeira de rodas.

Ao demonstrar o impacto que decisões de design e configuração do equipamento podem representar ao usuário, este estudo destaca a importância do design em dialogar com as diferentes áreas do conhecimento, neste caso mais especificamente as áreas da Saúde, Reabilitação e Engenharias. Uma visão da interação do usuário e sua cadeira de rodas a partir de uma perspectiva interdisciplinar fornece condições ideais para a compreensão dos problemas decorrentes do uso prolongado de cadeira de rodas e, desta forma, a demanda por inovação no design deste dispositivo assistivo.

Com o objetivo de verificar as implicações da posição horizontal do eixo das rodas traseiras na demanda de trabalho muscular durante a propulsão manual de cadeira de rodas, foi realizado um estudo (BERTOLACCINI et al., 2018) cujos resultados demonstraram que, em uma cadeira de rodas com ajuste do posicionamento das rodas traseiras, 50 mm de deslocamento anterior das rodas traseiras reduziu a atividade dos músculos do membro superior durante a execução de tarefas de mobilidade em cadeira de rodas. Neste estudo, onze voluntários sem deficiência e sem experiência com uso de cadeira de rodas realizaram um protocolo de mobilidade em dois percursos: aceleração em trajetória retilínea, e percurso misto, conforme proposto em um estudo anterior (MEDOLA et al., 2014b). Os testes foram realizados com quatro configurações da mesma cadeira de rodas, variando em dois aspectos (Figura 4): posição do eixo das rodas traseiras (posterior ou anterior, com diferença de 50 mm entre as duas posições); e o uso ou não de acessórios (apoio dos braços e protetor lateral do assento).



(a)

(b)

Figura 4. Configurações de cadeira de rodas avaliadas: 50 mm de deslocamento anteroposterior do eixo das rodas traseiras (a); com e sem acessórios - apoio de braços e protetor de assento (b). Fonte: BERTOLACCINI et al. (2018).

Durante a realização dos testes, foi registrada, por meio de eletromiografia de superfície (sistema CAPTIV, TEA Ergo, França) atividade elétrica dos quatro principais músculos do membro superior dominante que atuam na propulsão manual de cadeira de rodas: bíceps braquial, tríceps braquial, deltoide anterior e peitoral maior.

Os resultados indicam que a posição anteriorizada em 50mm do eixo das rodas traseiras reduz a demanda de trabalho muscular, o que demonstra o impacto que discretas alterações em configurações da cadeira de rodas podem influenciar na mobilidade do usuário. Ainda, destaca uma correlação entre os aspectos mecânicos do equipamento e biomecânicos do uso. Por outro lado, não foi encontrado efeito do uso de acessórios (apoio de braços e protetor do assento) no nível de atividade muscular durante a propulsão manual de cadeira de rodas. Os achados reforçam, portanto, o papel central que o posicionamento do eixo das rodas traseiras desempenha - dentre diversos aspectos da configuração da cadeira - na demanda de trabalho muscular durante mobilidade do usuário e, portanto, deve ser abordado a partir de uma perspectiva ergonômica de redução de sobrecarga e aprimoramento da eficiência da atividade.

Do ponto de vista mecânico, a posição mais anterior das rodas traseiras deixa a cadeira mais compacta ao reduzir seu comprimento. Na prática, uma cadeira mais compacta torna-se mais ágil, com maior facilidade de realização de manobras de giro e curvas, além de deslocar-se com mais liberdade em espaços restritos. É, portanto, uma medida benéfica ao usuário posicionar o eixo das rodas traseiras o mais anterior possível, desde que não comprometa sua estabilidade e segurança. Inclusive esta é uma recomendação de um compêndio que diretrizes para a preservação da função dos membros superiores em usuários de cadeira de rodas (PARALYZED VETERANS OF AMERICA CONSORTIUM FOR SPINAL CORD MEDICINE, 2005).

2.2 Uma visão mecânica sobre o movimento e design de cadeira de rodas

Mecanicamente, a força necessária para acelerar em trajetória retilínea uma cadeira de rodas depende da inércia linear, enquanto a força necessária para girar a cadeira depende da inércia rotacional (CASPALL et al., 2013). O posicionamento anteriorizado do eixo das rodas traseiras aproxima os elementos mais externos da cadeira ao centro desta, o que contribui para reduzir a inércia rotacional do sistema.

Portanto, decisões sobre o design, indicação e configuração da cadeira de rodas devem considerar o impacto destas aos aspectos mecânicos, os quais trazem implicações biomecânicas ao usuário, mais diretamente nas forças de propulsão necessárias para executar movimentos com a cadeira.

Considerando que as manobras de giro e curvas são movimentos muito frequentes na mobilidade diária do usuário, foi proposto um estudo (MEDOLA, SPRIGLE, 2014) com o objetivo de avaliar o impacto da massa e distribuição de massa na inércia rotacional de cadeira de rodas manual. A pesquisa foi realizada no *Rehabilitation Engineering Applied Research Lab* - (Rear-Lab), localizado no *Center for Assistive Technology and Environmental Access* (CATEA), Georgia Institute of Technology (Atlanta, Estados Unidos).

Para avaliação da Inercia Rotacional de cadeira de rodas, foi utilizada uma plataforma giratória denominada *Imachine,* disponível no REAR-Lab e cujo desenvolvimento foi descrito no estudo de Eicholtz et al. (2013). O sistema é composto por uma plataforma giratória presa com duas molas lineares em suas laterais, três sensores de força (células de carga) e um *encoder* ótico no centro da plataforma giratória, para detecção precisa de movimentos de rotação, conforme ilustrado na Figura 5.

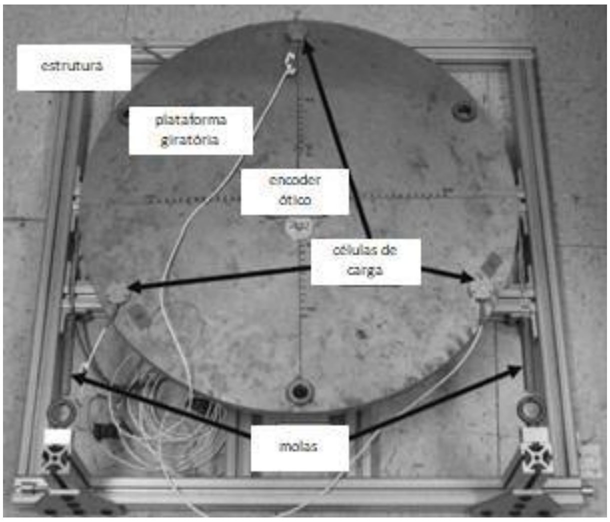
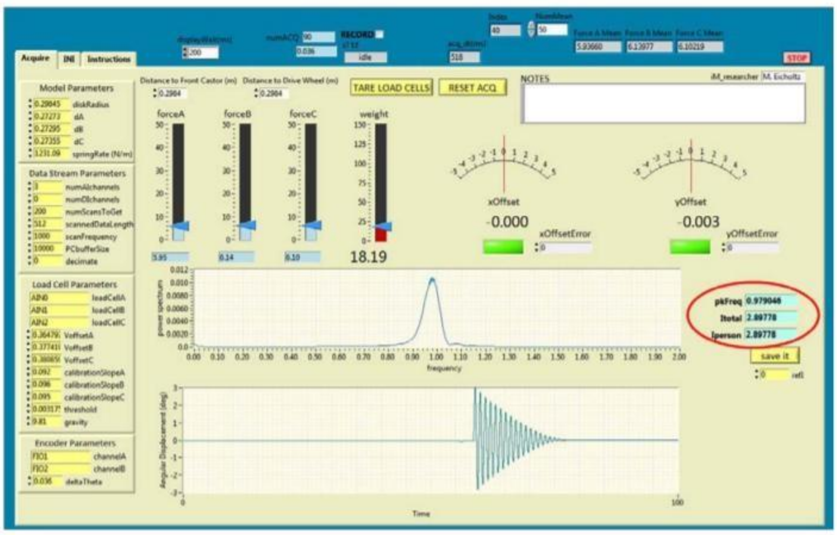


Figura 5. Plataforma iMachine para avaliação de inércia rotacional de cadeira de rodas. Adaptado de: EICHOLTZ et al. (2013).

O teste consistia em posicionar a cadeira de rodas no centro da plataforma e, por meio de um acionador mecânico, impor movimento de rotação à plataforma com frequência aproximada de 1,25 Hz em torno do eixo que cruza verticalmente o centro da plataforma (Figura 6). A inércia rotacional é então medida a partir dos registros de massa e período de oscilação da plataforma.

(a)



(b)

Figura 6. Avaliação da Inércia Rotacional: cadeira de rodas posicionada na plataforma iMachine (a); interface de registro e análise dos dados. Fonte: (a) MEDOLA; SPRIGLE, 2014; (b) MEDOLA, 2013.

O procedimento de medida foi repetido cinco vezes, e a média dos valores de inércia rotacional dos cinco registros foi então calculada.

Com o objetivo de compreender o impacto que alterações na massa e localização da massa podem acarretar na inércia rotacional da cadeira de rodas e, em consequência, na demanda biomecânica da mobilidade do usuário, foram avaliados os seguintes aspectos:

- Posição do eixo das rodas traseiras;
- Tipo de roda/pneu (Figura 7);
- Adição de peso e localização (no centro da cadeira ou nas rodas traseiras).

Figura 7. Dois modelos de rodas/pneus traseiros: roda multi-raios com pneu a ar (esquerda); rodas seis raios pneu maciço (direita). Fonte: MEDOLA (2013).

Os resultados, sumarizados nas Tabelas 1 e 2, comprovam que pequenas alterações no design da cadeira podem impactar de forma significativa os parâmetros mecânicos do equipamento, aqui destacado a inércia rotacional, a qual traz implicações ao usuário no que diz respeito à intensidade de força necessária para impor movimento de giro ou trajetória curva à cadeira.

Tabela 1. Médias da Inércia Rotacional com acréscimos de diferentes quantidades de massa em posição central (no assento) e externa (raios das rodas)

Configuração da Cadeira de Rodas	Massa Total (kg)	IR média (kg.m^2)	Porcentagem de aumento em relação à configuração original
Cadeira de rodas com configuração original	12,15	1,101	-
Cadeira de rodas + 0,25 kg no eixo de cada roda traseira	12,65	1,166	5,9 %
Cadeira de rodas + 0,4 kg no eixo de cada roda traseira	12,95	1,201	9 %
Cadeira de rodas + 1,2 kg no centro do assento	13,35	1,102	0,09 %
Cadeira de rodas + 5,5 kg no centro do assento	17,65	1,127	2,36 %

Tabela 2. Médias da Inércia Rotacional com diferentes configurações de pneu (a ar ou maciço), rodas traseiras (multi-raios e raios largos) e posição do eixo das rodas traseiras (anterior e posterior)

Posição do eixo das rodas traseiras	Conjunto Pneu / roda	Massa (kg)	IR Média (kg.m^2)	Porcentagem de aumento em relação à menor IR
Anterior	Pneus a ar / Rodas multi-raios	12,15	1,073	-
Posterior	Pneus a ar / Rodas multi-raios	12,15	1,101	2,6 %
Anterior	Pneus maciços / Rodas raio largo	13,30	1,169	8,94%
Posterior	Pneus maciços / Rodas raio largo	13,30	1,191	11%

O principal achado deste estudo foi o de que a distribuição de massa é um aspecto mais importante à Inércia Rotacional do que a massa total: conforme demonstrado na Tabela 1, o acréscimo de 0,4 kg em cada roda traseira implica em maior aumento (9%) da Inércia Rotacional do que 5,5 kg (2,36%) no centro do assento. Este é um achado que traz importantes implicações para o design, configuração e uso de acessórios em cadeira de rodas.

Um outro achado de contribuição para a prática de profissionais que atuam no design, prescrição e adequação de cadeira de rodas é a importância do uso de rodas e pneus leves, conforme demonstra os valores comparativos de IR nas duas configurações de roda/pneu avaliadas. Por fim, destaca-se que o posicionamento posterior em 44,5 mm do eixo das rodas traseiras implica em aumentos de 2,6% (na configuração com rodas multi-raios e pneus a ar) e 2,06% (rodas raios largos e pneus maciços) na IR do sistema. Embora sejam acréscimos relativamente discretos, deve-se considerá-los no contexto de um conjunto de alterações e tipos de rodas e acessórios. A soma de diversas alterações pode representar aumentos consideráveis à IR com impacto às demandas biomecânicas para a propulsão manual de cadeira de rodas. Neste estudo, o uso de pneus maciços e rodas de raio largo, com o eixo em posição posterior, representou um aumento total de 11% na Inércia Rotacional da cadeira de rodas.

Desta forma, este estudo contribuiu à área do design ao explorar as correlações entre o design e configuração da cadeira de rodas e as implicações mecânicas, aqui representadas pela inércia rotacional. Chama a atenção, portanto, para a necessidade de uma abordagem interdisciplinar ao processo de design, dispensação e adequação de cadeira de rodas.

Os problemas relacionados ao uso prolongado de cadeira de rodas manual referem-se tanto à elevada prevalência de lesões musculoesqueléticas potencialmente incapacitantes decorrentes da sobrecarga biomecânica da propulsão manual; quanto às limitações de mobilidade que o uso da cadeira de rodas impõe ao usuário em sua rotina diária.

3. INOVAÇÃO NO DESIGN DE CADEIRA DE RODAS: PESQUISA E DESENVOLVIMENTO

3.1 Uma Proposta Ergonômica para o Aro de Propulsão Manual

A propulsão manual de cadeira de rodas tem sido relacionada à alta prevalência de lesão nos membros superiores. A combinação de aplicação de forças e movimento repetitivo são fatores que contribuem para o risco biomecânico inerente a esta atividade e, como resultado, a ocorrência de problemas inflamatórios nos ombros e punhos (BONINGER et al., 2003; BONINGER et al., 2004) é frequente entre usuários de cadeira de rodas.

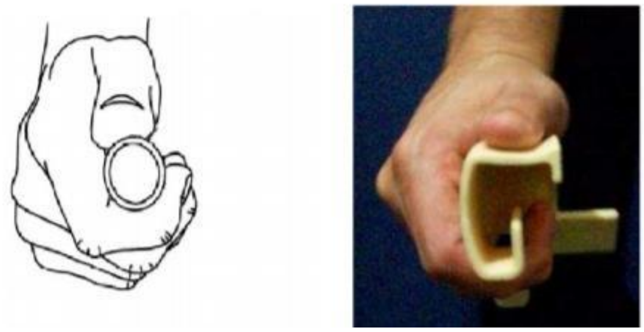
A interface da cadeira de rodas por meio da qual o usuário atua para promover o movimento é o aro de propulsão manual, um tubo cilíndrico metálico de 20 mm de diâmetro posicionado de 1 a 2 mm externamente às rodas. A atividade de propulsão implica na atividade repetitiva de segurar e impulsionar o aro já em movimento. Estudos têm apontado que, do ponto de vista ergonômico, o design do aro propulsor tradicional não oferece condições para uma impulsão eficiente, segura e confortável (KOONTZ et al., 2006; RICHTER et al., 2006). O design deste dispositivo pode ser um dos fatores de contribuem para a lesão nos membros superiores. O estudo de Perks et al. (1994) encontrou que parte dos usuários de cadeira de rodas não utilizam somente o aro propulsor para a impulsão, mas o seguram junto com o pneu da roda, provavelmente uma estratégia para conseguir uma preensão mais firme para impulsionar a roda. Há, portanto, uma demanda ergonômica para o aprimoramento no design do aro propulsor.

Com o objetivo de melhorar as condições ergonômicas da atividade de propulsão manual de cadeira de rodas, foi desenvolvida uma proposta de design para o aro propulsor com desenho adequado às características anatômicas e funcionais da mão no desempenho da atividade de propulsão manual de cadeira de rodas (MEDOLA et al., 2012; MEDOLA, 2010). Considerando que o aro convencional apresenta um design geométrico (cilíndrico) com tamanho insuficiente (20 mm de diâmetro) para apoio estável e confortável das mãos, a proposta de inovação desenvolvida neste estudo foi baseada em um design anatômico da interface manual. Foram, portanto, propostas as seguintes diretrizes de projeto:

- Oferecer maior área de contato para as mãos;
- Desenho adequado ao formato do encaixe das mãos para a atividade de impulsão manual;
- A solução desenvolvida não deve exigir do usuário a alteração de sua técnica de propulsão;
- A solução desenvolvida não pode aumentar as dimensões da cadeira.

A partir de estudos sobre antropometria das mãos e ergonomia de instrumentos manuais, o design proposto (Figura 8) buscou melhorar as condições ergonômicas da atividade. A maior área de contato, associada a um desenho anatômico, melhora a estabilidade das mãos ao aro e reduz a exigência de movimentos de pinça entre os dedos polegar e indicador para segurar o aro. A superfície superior do aro permite o apoio estável e superfície de contato suficiente para o apoio do polegar e eminência tenar, favorecendo o direcionamento da aplicação de força no sentido do deslocamento da cadeira. A superfície lateral é ampla e levemente convexa, para o apoio estável da palma das mãos durante a impulsão, assim como para a frenagem da cadeira.

(a)



(b)

Figura 8. Proposta ergonômica para o design do aro propulsor: vista em perspectiva do modelo virtual (a); encaixe com as mãos no aro tradicional à esquerda e protótipo à direita (b).
Fonte: MEDOLA (2010).

Foi desenvolvido um protótipo de aro propulsor para ser submetido à avaliação com usuários de cadeira de rodas. Para a confecção do protótipo, o processo compreendeu: modelagem tridimensional em software CAD (SolidEdge ST2); impressão tridimensional (impressora Zprinter 310, Z Corporation) em pó de peça representativa de ⅛ da circunferência do aro (devido à impossibilidade de impressão do aro completo devido ao da área de impressão da impressora); reprodução por molde de silicone de peças em resina de poliuretano (resina RP50, Oligom Tec); montagem do aro por colagem das peças; acabamento final.

Este processo possibilitou o desenvolvimento de um protótipo de um aro propulsor cujo design foi baseado em princípios de antropometria das mãos e ergonomia de instrumentos manuais. No entanto, para que o conceito seja validado e seus potenciais benefícios verificados, é fundamental a realização de testes, os quais podem comprovar as qualidades e/ou demonstrar ainda problemas e limitações que evidenciem a necessidade de aprimoramento no design do produto. No estudo em questão (MEDOLA et al., 2012), além da descrição das etapas de criação e desenvolvimento do aro propulsor, foi também descrito o teste realizado com usuários de cadeira de rodas. Este teste foi proposto baseado no estudo de Kilkens et al. (2004), e compreendeu a realização de um conjunto de tarefas de mobilidade em cadeira de rodas. Seis participantes, todos com paraplegia por lesão da medula espinhal e com experiência no uso de cadeira de rodas, realizaram o teste com os dois modelos de aro propulsor (convencional e o protótipo desenvolvido), em ordem aleatória e, posteriormente, responderam um questionário com perguntas sobre a percepção com relação a aspectos ergonômicos da realização da atividade com os dois modelos de aro.

A realização do teste comparativo do produto disponível e protótipo desenvolvido demonstrou que o este apresentou melhor avaliação por parte dos usuários, o que sugere que a concepção do design com base em aspectos antropométricos e ergonômicos de instrumentos manuais promoveu melhores condições de uso no contexto das tarefas realizadas no teste. Do ponto de vista da ergonomia e inovação de produtos em Tecnologia Assistiva, este resultado contribui para a validação do conceito desenvolvido e, desta forma, fornece subsídios para avaliação do impacto do uso mais a longo prazo e na rotina diária de usuários de cadeira de rodas, o que não foi investigado no âmbito deste estudo.

O estudo dos problemas relacionados à mobilidade em cadeira de rodas, assim como os achados positivos do estudo apresentado (MEDOLA et al., 2012), possibilitaram o aprimoramento no design do aro e sua aplicação em um projeto mais amplo de inovação no design de cadeira de rodas manual.

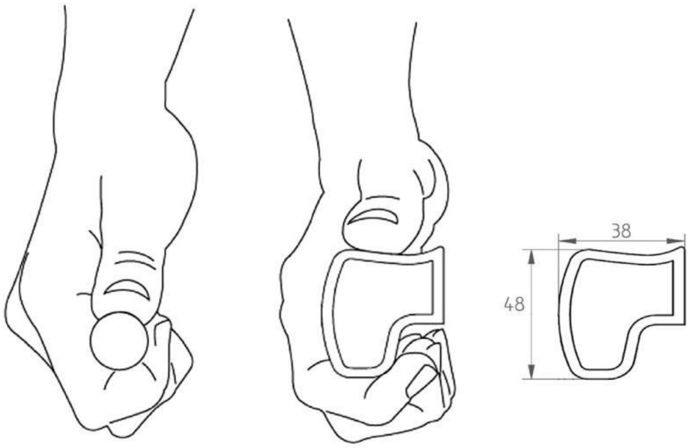
A otimização do design do aro propulsor favorece a ergonomia da interface manual por meio da qual o usuário impulsiona as rodas. Os potenciais benefícios são, desta forma, uma propulsão manual com menor desconforto e maior segurança e eficiência na mobilidade. A originalidade deste projeto foi reconhecida por meio da patente (modelo de utilidade) depositada junto ao Instituto Nacional de Propriedade Intelectual - INPI (Número BR102012027675A2, depósito em 29/10/2012).

3.1.1 Avaliação Ergonômica: contribuições para evidências em relação ao design do aro propulsor de cadeira de rodas

O estudo com usuários de cadeira de rodas indicou potenciais benefícios do uso de um aro propulsor com design anatômico e com maior superfície de contato para as mãos. Possivelmente, o encaixe mais firme e estável das mãos ao aro com menor desconforto seja devido à maior superfície de contato na região da palma das mãos, conseguido por meio de um design que considerou os aspectos antropométricos das mãos na condição da atividade de propulsão manual.

Com o objetivo de verificar o impacto desta proposta de design em um parâmetro ergonômico objetivo associado ao desconforto, foi proposto um estudo comparativo entre os dois aros – cilíndrico metálico convencional e aro ergonômico (Figura 9) – de avaliação da distribuição de forças de contato na superfície palmar das mãos (MEDOLA et al., 2014c). Do ponto de vista ergonômico, a ocorrência de maiores níveis de força de contato em uma mesma área representa maior pressão mecânica e, consequentemente, maior intensidade de desconforto e risco de lesão por pressão.

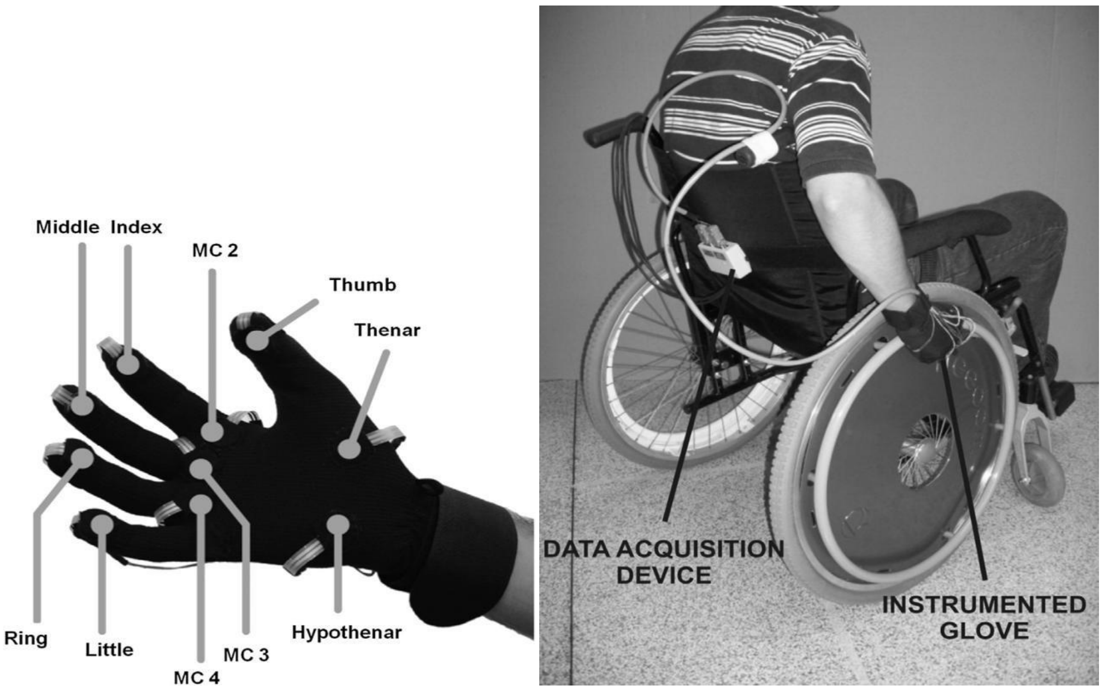
(a) (b)



(a) (b) (c)

Figura 9. Aros propulsores: convencional (a); e ergonômico (b, c). Fonte: MEDOLA et al. (2014c).

Para avaliar as forças de contato na superfície palmar, foi utilizada uma luva instrumentada com dez sensores de força, cujo desenvolvimento foi descrito no estudo de Silva e Paschoarelli (2009). A localização dos dez sensores de força foi definida considerando os pontos de maior preocupação ergonômica na superfície manual (FIGURA 10), agrupados em duas principais áreas: falanges distais (pontas dos dedos) e região metacarpal (palma das mãos).



(a) (b)

Figura 10. Luva instrumentada com sensores de força (a); localização de dispositivo de aquisição de dados e cabos em situação de coleta de dados (b). Fonte: MEDOLA et al. (2014c).

Participaram da pesquisa 20 voluntários, sem deficiência e sem experiência com o uso de cadeira de rodas. Os participantes realizaram um protocolo de propulsão manual em linha reta repetido por três vezes, partindo com a cadeira parada, acelerando e freando a cadeira, num total de cinco toques. Este estudo foi realizado no Laboratório de Ergonomia e Interfaces - LEI-UNESP.

Os resultados demonstram que o design do aro propulsor influencia a ergonomia da propulsão manual de cadeira de rodas, ao influenciar a intensidade e distribuição das forças de contato na superfície palmar. Os resultados apontam para um favorecimento ergonômico com o uso do protótipo aro propulsor desenvolvido. Foi observado uma redução nas forças de contato sobre a superfície palmar nas duas regiões - falanges distais e metacarpal - durante a impulsão inicial, aceleração em deslocamento retilíneo e frenagem da cadeira de rodas (Figura 11).

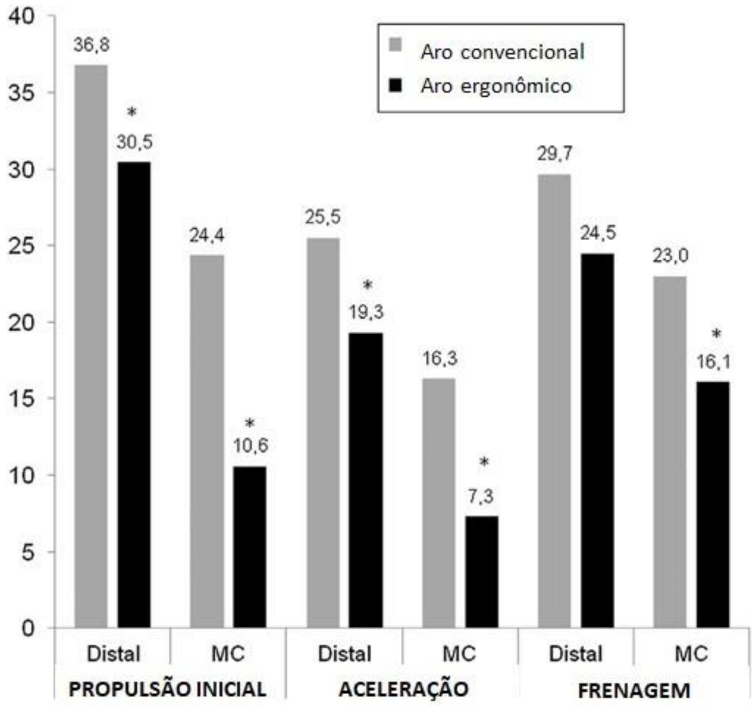


Figura 11. Média de forças de contato nas regiões distal (falanges distais dos dedos) e MCmetacarpal (palma das mãos) durante início, aceleração e frenagem da cadeira de rodas. Adaptado de: MEDOLA et al. (2014c).

Além disso, pode-se observar um pico nas forças de contato sobre a superfície das mãos durante o início do movimento com o uso do aro propulsor convencional

(Figura 12), o que demonstra a necessidade de maior intensidade de força para segurar e impulsionar o aro na impulsão inicial, a qual é explicada pelos desafios inerciais em impor movimento a uma cadeira parada.

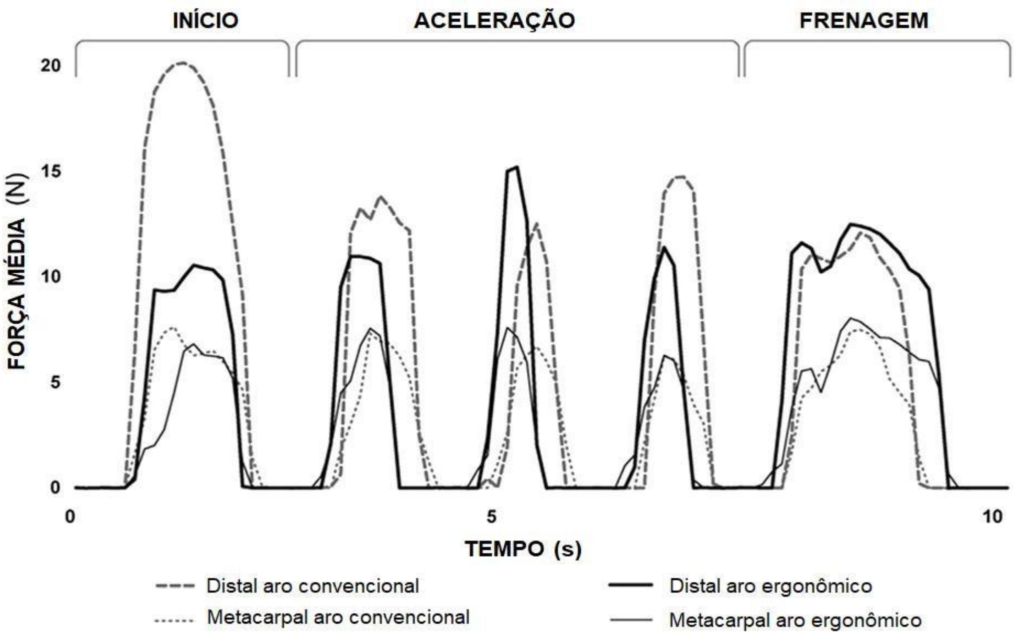


Figura 12. Cinco impulsões consecutivas nos aros propulsores partindo com a cadeira parada. Adaptado de: MEDOLA et al. (2014c).

Mais recentemente, foi desenvolvido um estudo (SILVA et al., 2019) comparativo dos mesmos aros propulsores (convencional e ergonômico), buscando avaliar a distribuição de pressão nas mãos utilizando um sistema (Grip Versatek, Tekscan) de sensoriamento mais completo, que monitora as forças de contato em toda a face palmar, e um protocolo de mobilidade composto por trajetória mista: retilínea e curva. Os materiais e procedimentos do estudo são apresentados na Figura 13.

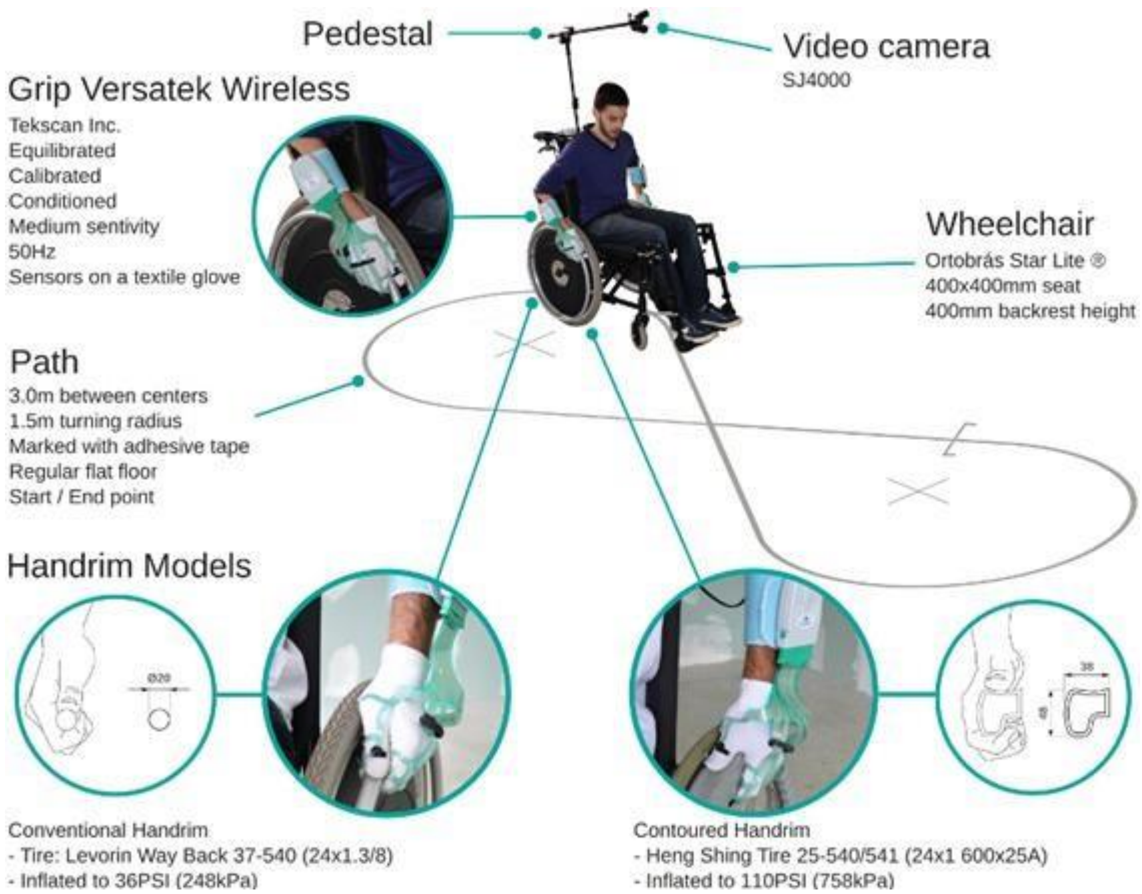


Figura 13. Esquema representativo dos materiais, métodos e procedimentos para o teste dos aros propulsores com o sistema Grip Versatek. Fonte: SILVA et al. (2019).

Corroborando os achados do estudo anterior (MEDOLA et al., 2014c), os resultados deste estudo demonstram que o protótipo do aro propulsor ergonômico esteve relacionado a menores índices de pressão na maior parte das regiões analisadas, com exceção da região da falange medial dos dedos (Figuras 14 e 15), o que pode ser explicado pelo contorno inferior da face externa do aro ergonômico, a qual oferece um anteparo para suporte da região da falange medial dos dedos. Ainda, os resultados indicam que a propulsão manual com aros propulsores tradicionais (tubo cilíndrico metálico de 20 mm de diâmetro) tende a concentrar altos níveis de pressão nas falanges distais e eminência hipotenar, enquanto o aro com design ergonômico promove melhor distribuição da pressão na superfície palmar, ainda que também os maiores níveis de pressão na região hipotenar. As falanges distais dos dedos são áreas de muita sensibilidade e, portanto, reduzir os níveis de pressão sobre esta região é um aspecto ergonômico positivo.

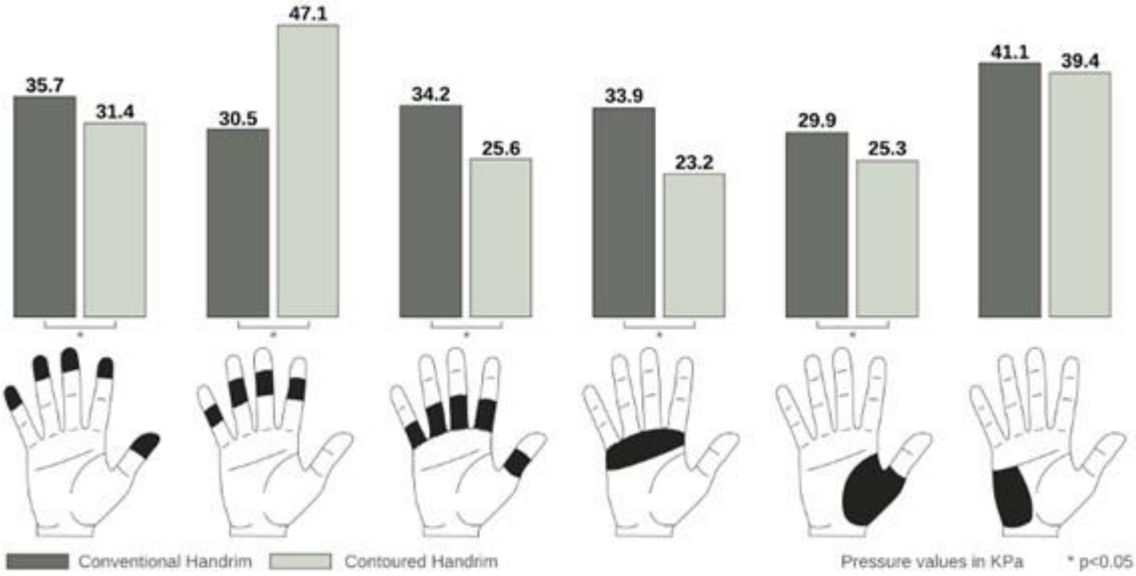


Figura 14. Média dos níveis de pressão em cada região da mão direita durante curva para esquerda. Fonte: SILVA et al. (2019).

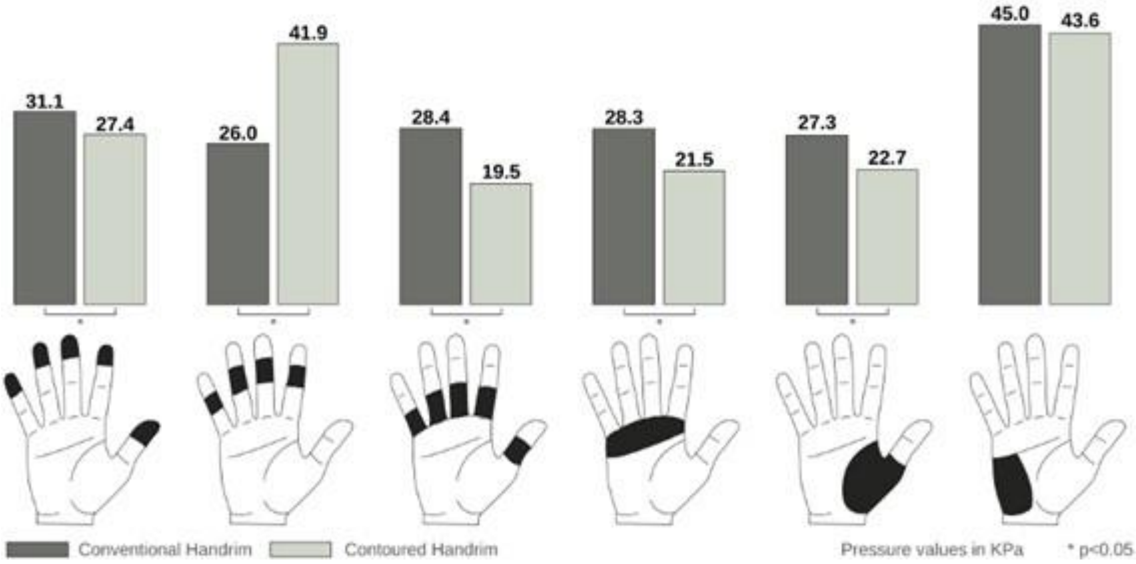


Figura 15. Média de pressão em cada região da mão direita em trajetória retilínea. Fonte: SILVA et al. (2019).

A distribuição de pressão na superfície das mãos é um parâmetro ergonômico relevante no uso de cadeira de rodas manuais, uma vez as ações do usuário para movimentar-se com a cadeira são concentradas na interface entre aros propulsores e as mãos. Estes estudos reforçam o potencial do design em influenciar os aspectos ergonômicos desta interação.

Considerando que os usuários utilizam a cadeira de rodas na maior parte de suas rotinas diárias, ressalta-se, por fim, que melhorar as condições ergonômicas da cadeira de rodas deve ser uma meta a ser buscada no design desses dispositivos, considerando o potencial impacto positivo que este aprimoramento pode trazer ao usuário na interação com o produto.

3.2 Análise do Movimento livre em Cadeira de Rodas: contribuições para a inovação no Design de Cadeira de Rodas

Além das questões biomecânicas diretamente relacionadas à eficiência da propulsão manual, há também desafios na rotina diária como a locomoção em rampas, aclives e por longas distâncias ainda são elevados e acabam por limitar a mobilidade geral do usuário. Buscando abordar esta lacuna, foi desenvolvido um projeto de cadeira de rodas manual com assistência motorizada (Figura 16), cujo conceito de design foi descrito em Medola et al. (2014d). Enquanto no trabalho anterior (MEDOLA et al., 2012) foi desenvolvido um novo design para um componente da cadeira de rodas, o desafio no trabalho de Medola et al. (2014d) foi repensar o design de uma cadeira manual a partir da implementação de um sistema de motorização assistida. Alguns princípios nortearam o projeto: não aumentar o tamanho da cadeira, o que poderia trazer problemas de acessibilidade; manutenção da propulsão manual como meio de o usuário impor movimento à cadeira; e manter as mesmas condições de dirigibilidade de uma cadeira de rodas manual convencional.

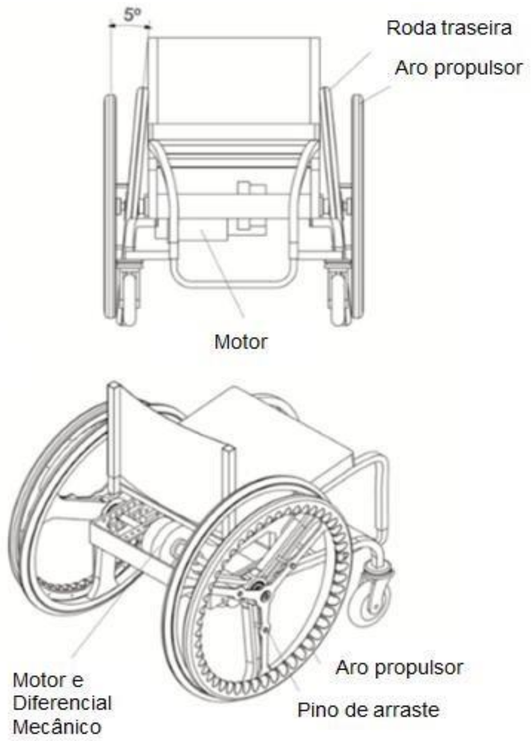


Figura 16. Projeto conceitual de uma cadeira de rodas manual com assistência motorizada por um servo-motor posicionado entre os eixos das rodas traseiras. Adaptado de: MEDOLA et al. (2014d).

Para implementar este projeto de inovação na área de mobilidade em cadeira de rodas, foi necessário inicialmente estudar como o ocorre o movimento da cadeira de rodas, a partir de uma perspectiva mecânica, nas mais diversas condições de movimento livre. Para isto, foi realizado um estudo no Rehabilitation Engineering Applied Research Laboratory (RearLab), do Center for Assistive Technology and Environmental Access (CATEA), Georgia Institute of Technology, Atlanta, Estados Unidos. Neste estudo (Medola et al., 2014b), buscou-se avaliar o comportamento da energia cinética da cadeira de rodas em diferentes movimentos. De forma simplificada, pode-se compreender a Energia Cinética do movimento em cadeira de rodas manual como o resultado da força de impulsão aplicada pelo usuário, a qual interage com os aspectos mecânico (inerciais) do equipamento e as forças de resistência (principalmente o atrito). A saída desta função que representa o movimento da cadeira e tem como entrada a ação do usuário pode ser descrita pela Energia Cinética e, portanto, sua análise traz contribuições importantes para a compreensão sobre o efeito do design do equipamento na eficiência do movimento. Considerando os problemas decorrentes da sobrecarga biomecânica do uso prolongado de cadeira de rodas manual, torna-se fundamental à saúde e segurança do usuário compreender os fatores do design que contribuem para maior eficiência de movimento e menor sobrecarga.

De um ponto de vista mecânico, a cadeira de rodas pode ser considerada um conjunto de 7 corpos rígidos unidos (Figura 17): estrutura, duas rodas traseiras, duas rodas dianteiras (*casters*) e dois garfos (suporte para as rodas dianteiras). Portanto, a análise da energia cinética de toda a cadeira de rodas deve considerar o movimento da cadeira inteira, das rodas traseiras, dos garfos e dos *casters*, cada um destes em eixos definidos de movimento.

Figura 17. Cadeira de rodas: composição de sete corpos rígidos: estrutura com encosto/assento (a); duas rodas traseiras (b); duas rodas dianteiras (c); dois garfos (d). Fonte: MEDOLA; SPRIGLE (2014).

A principal contribuição deste estudo está no desenvolvimento de um método para analisar a energia cinética de cadeira de rodas manual em movimento livre no solo, o que permite compreender implicações do design e configuração do equipamento no desempenho do movimento. Para isto, foi desenvolvida uma equação para determinação da energia cinética, a qual considera como dado de entrada a velocidade de rotação das rodas traseiras e, a partir da qual obtém-se o raio de curvatura, a velocidade do centro de massa do sistema e a taxa de giro da cadeira, conforme modelo mecânico proposto (Figura 18).

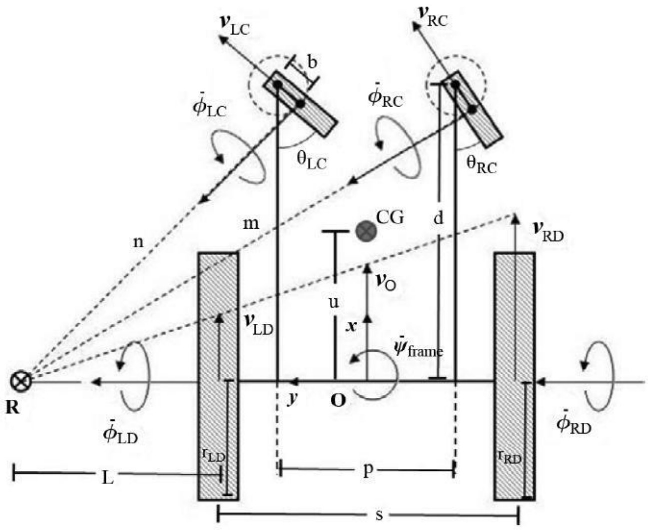


Figura 18. Modelo para determinação do raio de curvatura, velocidade do centro de massa e velocidade de giro a partir da medição de velocidade das duas rodas traseiras.

Fonte: MEDOLA et al. (2014b).

A equação da Energia Cinética da cadeira de rodas (eq. 1) em movimento livre compreende, portanto, a análise dos aspectos inerciais e movimento de todo o sistema e cada um dos componentes: rodas traseiras, rodas dianteiras e garfos.

$$\begin{aligned} KE = {} & \frac{1}{2} m_{sys} v_G^2 + \frac{1}{2} I_{ZZ,sys}^G \dot{\Psi}_{frame}^2 + \frac{1}{2} I_{YY,LD} \dot{\phi}_{LD}^2 \\ & + \frac{1}{2} I_{YY,RD} \dot{\phi}_{RD}^2 + \frac{1}{2} I_{YY,LC} \dot{\phi}_{LC}^2 + \frac{1}{2} I_{YY,RC} \dot{\phi}_{RC}^2 \\ & + \frac{1}{2} I_{ZZ,LFLC} \dot{\Psi}_{LC}^2 + \frac{1}{2} I_{ZZ,RFRC} \dot{\Psi}_{RC}^2 . \end{aligned}$$

Eq. 1

Em que:

KE = Energia Cinética m_{sys} = massa total do sistema V_G = velocidade do centro de massa

I^G_{zz}= Momento de inércia da cadeira de rodas sobre seu centro de massa

I_{yyLD}, I_{yyRD}= Momento de inércia das rodas traseiras esquerda e direita sobre seus próprios eixos

I_{yyLC}, I_{yyRC}= Momento de inércia das rodas dianteiras esquerda e direita sobre seus próprios eixos

$I_{zzLF,LC}$, $I_{zzRF,RC}$= Momento de inércia dos garfos das rodas dianteiras esquerda e direita sobre seus próprios eixos

A maior contribuição desta equação foi possibilitar a análise do comportamento do movimento da cadeira de rodas em diferentes trajetórias e, desta forma, compreender quais os componentes mecânicos mais envolvidos para cada situação de movimento. Para isto, foi realizada uma análise da decomposição da energia cinética em componente translacional, rotacional e de giro (Figura 19).

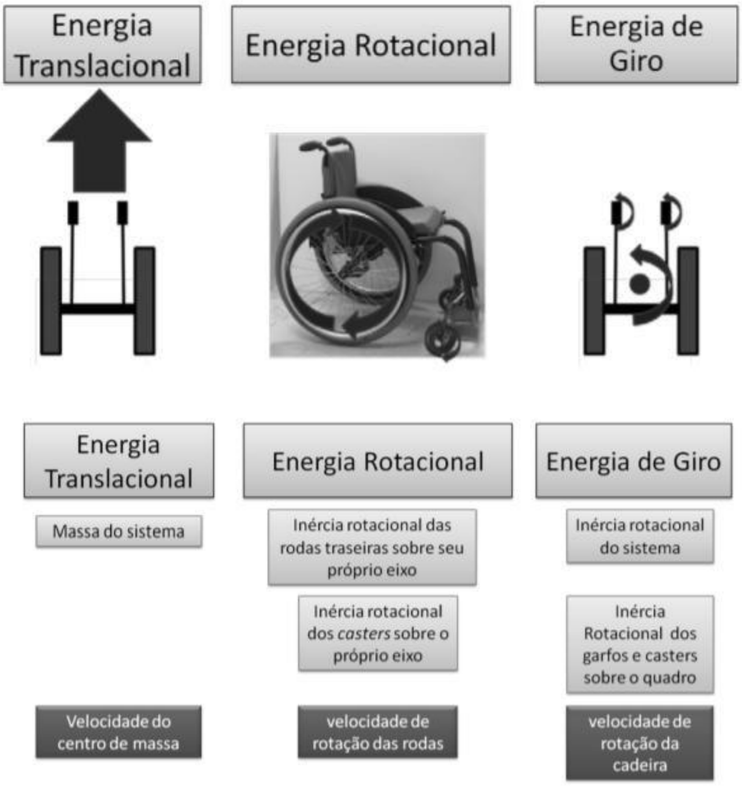


Figura 19. Decomposição da energia cinética da cadeira de rodas e seus determinantes mecânicos.

Fonte: MEDOLA (2013).

Considerando o componente de rotação como a rotação das rodas sobre o próprio eixo, a análise mais interessante sob a perspectiva do design do dispositivo é o comportamento dos componentes translacional e de giro, ou seja, deslocamentos lineares e curvos - respectivamente - da cadeira. Na figura 20 pode-se observar o comportamento dos componentes da energia cinética em movimento retilíneo: com a cadeira de rodas parada, houve aceleração por meio de seis impulsões. O componente translacional é o responsável por quase a totalidade da energia cinética da cadeira de rodas em movimento retilíneo. Retomando a eq.1, tem-se que a massa total do sistema é o principal componente inercial da energia cinética e, portanto, a massa total da cadeira é o fator que mais influencia nos deslocamentos retilíneos.

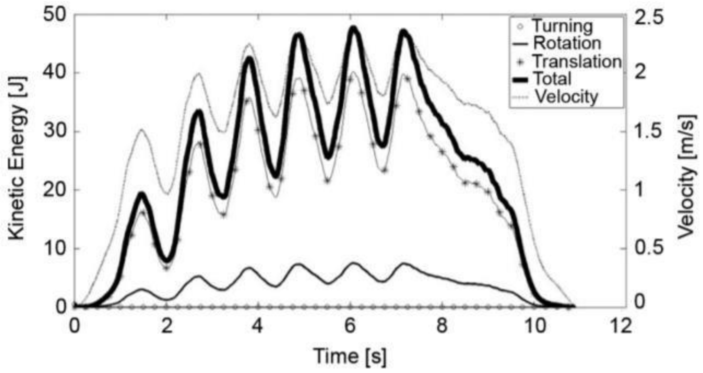


Figura 20. Comportamento dos componentes da energia cinética em movimento retilíneo.
Fonte: MEDOLA et al. (2014b).

Por outro lado, em um movimento de giro sobre o próprio eixo (Figura 21), o principal componente da energia cinética total é o de giro (*turning*) no eixo vertical (ZZ) e, de acordo com a eq. 1, tem-se que os principais componentes inerciais são a inércia rotacional de todo sistema e o conjunto garfo/roda dianteira girando sobre o eixo Z. Como a massa de todo sistema girando sobre o eixo Z exerce maior influência do que a massa do dos garfos e rodas dianteiras, conclui-se que a distribuição de massa é o fator que mais diretamente influencia este tipo de movimento de giro. Portanto, sob a perspectiva do design da cadeira de rodas, duas diretrizes podem ser propostas para melhorar a eficiência do movimento: reduzir o máximo possível as dimensões da cadeira; e concentrar os elementos de maior massa mais próximos do centro da cadeira. Destaca-se, desta forma, a importância de se utilizar rodas traseiras leves, uma vez que são componentes posicionados mais externamente e, portanto, distantes do centro da cadeira, uma vez que pequenos aumentos no peso das rodas podem resultar em aumento significativo na inércia rotacional do sistema. Esta, como dito anteriormente, representa a resistência imposta ao usuário para realizar movimento de giro da cadeira. Uma vez que estes movimentos são muito frequentes na rotina diária do usuário, reduzir a demanda de esforço biomecânico ao usuário é uma condição positiva para a ergonomia do uso do dispositivo na medida em que representa maior eficiência do movimento.

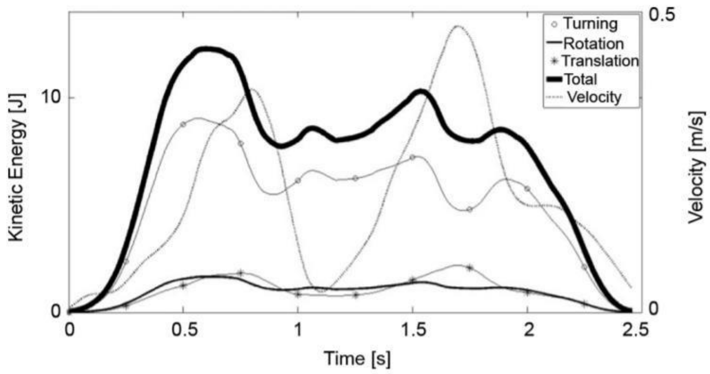


Figura 21. Comportamento dos componentes da energia cinética em movimento de giro sobre o próprio eixo. Fonte: MEDOLA et al. (2014b).

A grande maioria dos deslocamentos em cadeira de rodas realizados na mobilidade diária é caracterizada por numerosos episódios de movimento de curto deslocamento (SONEMBLUM et al., 2012), e compostos por acelerações, frenagens, movimentos curvos, retilíneos e mistos, é importante que o design do dispositivo considere não somente a menor massa possível, mas igualmente a distribuição de massa com dimensões mais reduzidas e componentes mais externos (rodas traseiras, rodas dianteiras e garfos) com menor massa, de forma a melhorar a eficiência do movimento ao reduzir as demandas biomecânicas para realização das diferentes ações que compõem a mobilidade do usuário.

A condição mista entre a trajetória retilínea e o giro sobre o próprio eixo representa, na prática, o movimento por uma trajetória curva. Neste caso, há uma troca de energia entre os componentes translacional e o de giro de acordo com a trajetória executada.

Este estudo (MEDOLA et al., 2014b) que abordou a análise da decomposição da energia cinética da cadeira de rodas em movimento livre contribuiu para a compreensão das implicações que decisões sobre o design e configuração do equipamento podem trazer para a eficiência da mobilidade do usuário. Chamou a atenção, também, para a importância de se estudar a mobilidade em cadeira de rodas em condições similares às da mobilidade diária do usuário, ou seja, movimento livre em solo, composto por diferentes trajetórias (retilínea, curva, mista e de giro) e acelerações. Uma proposta de circuito com estas características foi proposta também neste estudo (Figura 22).

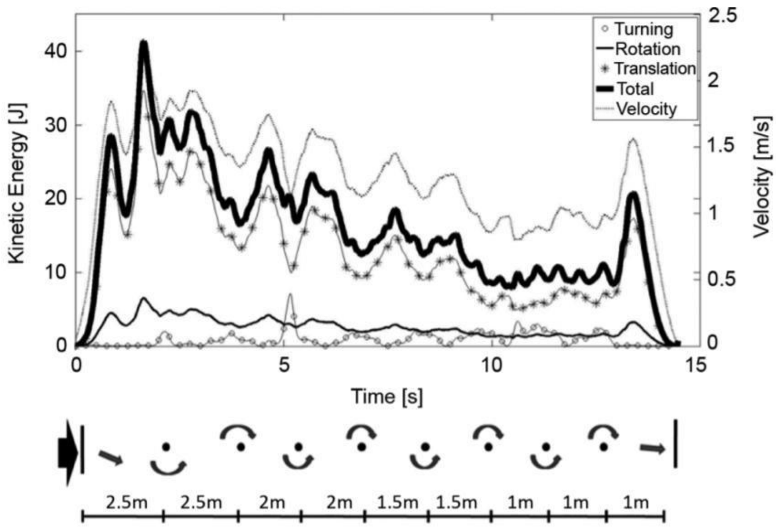


Figura 22. Comportamento dos componentes da energia cinética da cadeira de rodas em circuito (abaixo na figura) com diferentes trajetórias e acelerações. Fonte: MEDOLA et al. (2014b).

Este conhecimento dos aspectos mecânicos do movimento e suas implicações ao movimento possibilitou a fundamentação da proposta de uma cadeira de rodas manual com assistência motorizada, a partir de um único motor posicionado no centro entre as rodas traseiras (Figura 16) e atuando com o mesmo torque nas duas rodas traseiras, cujo projeto conceitual foi descrito em Medola et al. (2014d).

Esta proposta conceitual foi então implementada por meio da construção de um protótipo, para então ser submetido a testes de mobilidade. O projeto foi detalhado e depositado junto ao Instituto Nacional de Propriedade Intelectual (INPI) como Modelo de Utilidade (Número do registro: BR1020140126465). Os principais aspectos de inovação neste projeto referem-se ao sistema de transmissão de um único motor para as duas rodas traseiras, o que foi conseguido por meio da adaptação de um sistema de diferencial mecânico, o que permitiu que, mesmo com ambas as rodas recebendo torque adicional a partir do mesmo motor, o usuário tinha a possibilidade de atuar (impulsionar ou frear) de maneira assimétrica nas rodas traseiras. Esta característica permitiu condições de dirigibilidade similares à uma cadeira manual convencional e, desta forma, aprimorou um dos aspectos de limitação nos sistemas de motorização assistida para cadeira de rodas, conforme descrito no estudo de Cooper et al. (2001), que indicou dificuldades de realização de manobras em espaços restritos com o uso destes sistemas.

Um outro aspecto de inovação nesta proposta de design de cadeira de rodas foi o projeto do cubo de roda que permitiu a conexão assimétrica entre o aro propulsor e a roda. Nesta proposta, um aro propulsor ergonômico era conectado à roda de forma assimétrica, com maior espaço entre o aro e a roda na porção superior destes, de forma a oferecer maior espaço e possibilidades de encaixe (preensão) entre a mão e o aro. Na porção inferior (próxima ao solo) o aro e a roda se aproximam. Portanto, o aro propulsor mantém-se sempre em posição vertical, enquanto as rodas apresentam inclinação de 5 graus. Esta inclinação, denominada cambagem das rodas traseiras, melhora a estabilidade da cadeira ao aumentar a base de apoio no solo, assim como facilita a realização de manobras de giro. Portanto, obtém-se um favorecimento da mobilidade ao melhorar a estabilidade da cadeira, facilitar a realização de manobras de giro, e melhorar as condições para o acoplamento entre as mãos e os aros propulsores, com maior segurança e possibilidade de variação do modo de preensão (Figura 23).

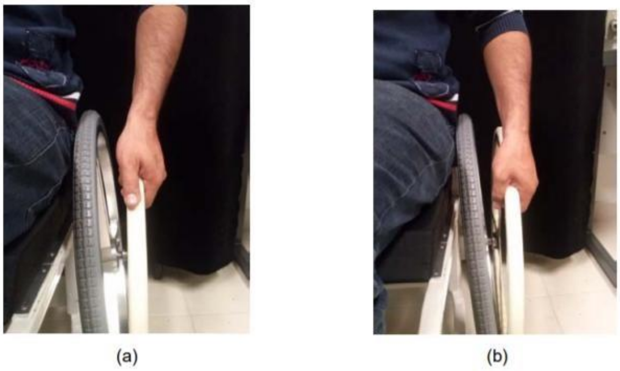


Figura 23. Encaixe da roda em cambagem com aro propulsor vertical: maior espaçamento entre roda e aro favorece o encaixe seguro e com variação da forma de preensão manual. Fonte: MEDOLA (2013).

Desta forma, a partir da pesquisa em Design e Ergonomia da Cadeira de Rodas, foi possível compreender os principais fatores determinantes para a eficiência da mobilidade, os quais foram então aplicados em um projeto inovador de cadeira de rodas manual com assistência motorizada. Em síntese, este conceito de equipamento busca aprimorar a mobilidade dos usuários de cadeira de rodas a partir das seguintes inovações:

- Assistência motorizada que complementar à propulsão manual, reduzindo desta forma a sobrecarga biomecânica nos membros superiores;
- Assistência motorizada a partir de um único motor atuando nas duas rodas traseiras, por meio de um sistema de transmissão com diferencial mecânico, o que possibilita condições de mobilidade similares a uma cadeira manual convencional;
- Aro propulsor com desenho ergonômico com maior superfície de contato e formato anatômico, o que favorece a estabilidade e conforto na preensão manual;
- Encaixe do aro propulsor verticalizado a uma roda com inclinação (cambagem) por meio de um projeto inovador de cubo de roda e transmissão das forças manuais aplicadas nos aros às rodas por meio de pinos de arraste perfurantes aos raios das rodas, o que propicia mais espaço às mãos na parte superior do aro/roda e minimiza o risco de traumas e lesões no contato das mãos às rodas em giro durante a locomoção.

Para concluir o processo de pesquisa, inovação e avaliação de protótipo, foi realizado um estudo para avaliação biomecânica da locomoção em cadeira de rodas, comparando-se o protótipo desenvolvido com uma cadeira manual convencional durante a realização de um conjunto de tarefas de mobilidade. O estudo contou com a participação de oito voluntários sem deficiência e sem experiência com o uso de cadeira de rodas. A partir de uma análise que utilizou instrumentos de avaliação de atividade muscular (eletromiografia de superfície) e de percepção de dificuldade (Escala Visual Analógica) e esforço (Escala de Borg), foi possível observar que menores níveis de atividade muscular com o uso da cadeira servo-motorizada durante a subida de rampa, o que demonstra o potencial impacto positivo na melhora da mobilidade e redução da sobrecarga biomecânica nesta condição de movimento. Ainda, os resultados de percepção de esforço e dificuldade demonstraram que os usuários reportaram menor dificuldade e esforço com uso do protótipo desenvolvido em comparação à cadeira convencional, exceto durante a descida de rampa, o que pode ser explicado pela maior massa do equipamento e, portanto, necessidade de atuação com mais intensidade de força para frear a cadeira durante a descida.

Portanto, esta abordagem investigativa com métodos de ergonomia na avaliação comparativa de um protótipo com aspectos inovadores e um produto convencional possibilitou validar o conceito de cadeira de rodas desenvolvido na medida em que demonstrou potenciais benefícios na mobilidade, por meio da maior eficiência e menor sobrecarga biomecânica durante a locomoção. Entretanto, ressalta-se que a pesquisa possibilitou identificar situações que necessitam ser consideradas em um aprimoramento do projeto, particularmente a necessidade de estabelecer soluções para a frenagem da cadeira durante a descida de rampas. Esta é uma condição relativamente frequente na mobilidade diária e, portanto, evitar sobrecarga ao usuário durante esta atividade - conforme demonstrado pelos resultados do estudo - deve ser um objetivo a ser buscado para aprimorar as condições ergonômicas do uso do protótipo.

Este estudo de avaliação comparativa do protótipo de cadeira servomotorizada e uma cadeira manual convencional foi apresentado no evento "International Symposium on Medical Robotics", realizado na cidade de Atlanta, Estados Unidos, e cuja publicação do trabalho foi disponibilizada na base IEEExplore (MEDOLA et al., 2018).

3.3 Conclusões sobre os estudos mecânicos e biomecânicos de cadeira de rodas

Estes estudos de avaliação e desenvolvimento na área de mobilidade em cadeira de rodas demonstram, inicialmente, a importância de uma abordagem interdisciplinar na condução de um projeto que é construído a partir de conhecimentos das áreas de Design, Engenharias e Saúde.

As Ciências da Saúde, mais particularmente a Fisioterapia, contribui principalmente para o entendimento do movimento humano e as questões biomecânicas e fisiológicas envolvidas na mobilidade em cadeira de rodas, assim como o conhecimento acerca das características funcionais dos usuários considerando as diversas condições de saúde que levam ao acometimento físico e funcional e ao uso da cadeira de rodas. Esta visão ampla das características e necessidades funcionais dos usuários é uma das maiores contribuições que a interdisciplinaridade com as áreas da Saúde e Reabilitação pode trazer ao desenvolvimento de projetos.

Por sua vez, a Engenharia traz o conhecimento do processo de projeto, inovação, materiais e processos de fabricação. Durante todo o projeto de pesquisa e desenvolvimento na área de cadeira de rodas, foi de grande importância a interface com as Engenharias Mecânica, Elétrica, Mecatrônica e de Materiais. Nos laboratórios de pesquisa em que desenvolvi minhas pesquisas de mestrado e doutorado, tanto na Escola de Engenharia de São Carlos (USP) quanto no *Center for Assistive Technology and Environmental Access* (CATEA) do *Georgia Institute of Technology* (Atlanta, EUA), a interdisciplinaridade entre as áreas de saúde e Engenharia foi característica muito marcante em todos os projetos de pesquisa que pude conhecer e participar. Este trabalho interdisciplinar é um aprendizado que eu trouxe destas experiências, mantenho e tento aprimorar em minha carreira acadêmica.

O Design, enquanto área do conhecimento, encaixa-se perfeitamente nesta abordagem na medida em que o diálogo com outras áreas do conhecimento é característica muito presente em sua prática. O foco na interface usuário/produto, cuja apreciação é de excelência à área do Design, traz uma perspectiva única à pesquisa e desenvolvimento de projetos ao possibilitar uma visão tanto humana quanto projetual às interações entre usuário e produto. Aqui, é de grande contribuição a ciência ergonômica e os conhecimentos, métodos de avaliação e parâmetros que permitem avaliar esta interação e torná-la, por meio de diversas abordagens, mais harmônica.

Por fim, destaca-se o papel da pesquisa na produção de conhecimento e inovação. Nos estudos aqui apresentados, a pesquisa possibilitou compreender problemas no uso de cadeira de rodas e demandas para o usuário, assim como o entendimento dos aspectos mecânicos e dinâmicos do movimento de cadeira de rodas e suas implicações para a eficiência do movimento. A partir destes estudos, foi possível fundamentar propostas de inovação no design do aro propulsor e de toda a cadeira de rodas com vistas a reduzir os problemas e melhorar as condições de uso e mobilidade para o usuário. Por fim, a pesquisa possibilitou avaliar as inovações propostas, identificar aspectos positivos e outros que demandam aprimoramento no projeto. Este processo iterativo é fundamental no desenvolvimento de projetos que agregam pesquisa e desenvolvimento, como foi o caso do conjunto de estudos aqui apresentados, todos centrados em um dos campos de grande desenvolvimento na Tecnologia Assistiva: a Mobilidade em Cadeira de Rodas.

4. ASPECTOS ESTÉTICOS, SIMBÓLICOS E O ESTIGMA ASSOCIADO A CADEIRA DE RODAS

A definição de Tecnologia Assistiva destaca o aspecto de suporte/auxílio à diminuição da incapacidade funcional, promoção de independência, participação social e qualidade de vida da pessoa com deficiência ou mobilidade reduzida. No contexto dos produtos de Tecnologia Assistiva, têm-se um aspecto simbólico muito associado a condições de incapacidade e dificuldade funcional que, em muitas situações, manifesta-se como julgamentos negativos relacionados ao uso destes produtos.

No texto “Design e Deficiência: Histórica, Conceitos e Perspectivas” (MEDOLA; PASCHOARELLI, 2014) estes aspectos são discutidos no contexto das relações entre design e deficiência a partir da perspectiva do desenvolvimento de produtos. Inicialmente, é feita uma contextualização histórica da questão da deficiência, a qual é fundamental para entender o processo que levou a um paradigma de inclusão social. Neste, destaca-se a importância de igualdade de oportunidades, sendo fundamental o acesso a serviços, ambientes e produtos.

Para se compreender as raízes desta percepção negativa relacionada aos produtos de TA, é importante conhecer a questão da deficiência ao longo da história, compreendida como o conjunto de valores - sociais, religiosos, éticos e culturais - ao longo do tempo (PACHECO; ALVES, 2007). A visão da deficiência, determinada por este conjunto de fatores, teve um processo histórico que passou por marginalização, assistencialismo, educação e reabilitação, integração e inclusão social (MAZZOTA, 1999). Estas visões não representam momentos separados, mas sim um processo contínuo de mudança gradual de tal maneira que, ainda atualmente, podem ser observadas estas diferentes posturas acerca da deficiência.

É em um cenário atual de universalidade e igualdade que o Design se impõe como um dos pilares para a inovação para inclusão social. Retomando as correlações entre os conceitos de deficiência, incapacidade e desvantagem abordadas no trabalho de Amiralian et al. (2000), tem-se que a prática do Design no contexto da Tecnologia Assistiva tem como alvo a incapacidade decorrente de uma deficiência. Ao reduzir as incapacidades e promover melhor funcionalidade e independência ao usuário, as desvantagens são então diminuídas. Portanto, o desenvolvimento de soluções em

Tecnologia Assistiva traz ao Design o desafio de explorar questões funcionais dos usuários e as incapacidades decorrentes da deficiência, com o objetivo de diminuir as limitações e favorecer e potencializar as habilidades da pessoa com deficiência. A interdisciplinaridade tem um papel fundamental no desfecho bem-sucedido de abordagens de design na área de Tecnologia Assistiva.

Além do objetivo de reduzir as incapacidades e melhorar a funcionalidade e independência do usuário de Tecnologia Assistiva, o texto (MEDOLA; PASCHOARELLI, 2014) aponta a necessidade de concepção de produtos atrativos e desejáveis, destacando a preocupação com as questões estéticas e simbólicas que podem comprometer a aceitação, satisfação e engajamento ao uso destes produtos. Idealmente, busca-se o design que promova o equilíbrio entre inclusão e não-diferenciação.

A questão estética e simbólica traz a discussão a respeito da identificação e significação do produto para o usuário. Produtos de Tecnologia Assistiva são muitas vezes associados ao aspecto prático - função primária destes produtos - de assistência para dificuldade ou incapacidade funcional. Esta "marca" negativa - aqui denominado estigma - acaba sendo estendido também aos usuários. A literatura dispõe de estudos que abordam estigma relacionado ao uso de Tecnologia Assistiva (PARETTE; SCHERER, 2004) e questões acerca do uso e abandono de Tecnologia Assistiva devido ao estigma (SCHERER, 1991; VERZA et al., 2006). De uma maneira geral, o estigma pode ser compreendido como um conjunto de preconceitos sobre uma característica específica relacionada ao papel social de um indivíduo na sociedade. De acordo com o estudo de Bispo e Branco (2008), os objetos podem provocar estereótipos e desempenham um papel na construção da imagem da pessoa com deficiência. A estética do produto é um dos aspectos que podem contribuir para a estigmatização associada à Tecnologia Assistiva (PARETTE; SCHERER, 2004), o que destaca o papel central que o Design pode desempenhar na diminuição do julgamento negativo sobre produtos assistivos. É, portanto, fundamental que o design de Tecnologias Assistivas considere não somente as questões práticas - que comunicam sua função mais imediata - do produto, mas também aspectos estéticos e simbólicos que contribuam para produtos atrativos, personalizáveis, desejáveis e que atendam às expectativas e preferências dos usuários.

Em um estudo realizado com usuários de cadeira de rodas (LANUTTI et al., 2015), foi avaliada por meio de uma escala de diferencial semântico a percepção deles sobre o significado de suas cadeiras. A escala de Diferencial Semântico, composta de pares de adjetivos opostos ancorados nos extremos de uma escala de sete pontos, foi construída a partir da realização de uma atividade - grupo focal - com usuários, terapeutas ocupacionais, fisioterapeutas, médico, usuários de cadeira de rodas e familiares. Nesta atividade, foram apresentados diversos adjetivos que poderiam estar associados ao produto cadeira de rodas. Foi uma etapa interessante e fundamental para a seleção dos adjetivos que iriam compor o instrumento de avaliação, assim como para a substituição e definição de termos familiares aos usuários, o que é importante para garantir condições adequadas de entendimento para os respondentes. Alguns achados interessantes deste estudo apontam para questões estéticas e simbólicas do design de cadeira de rodas: a maioria dos usuários considerou suas cadeiras mais "humildes" do que "sofisticadas", e mais "padrões" do que "personalizadas". Estes dois pontos indicam a necessidade de aprimoramento no design do produto e, principalmente, personalização, o que pode favorecer a aceitação e identificação com a tecnologia (Figura 24).

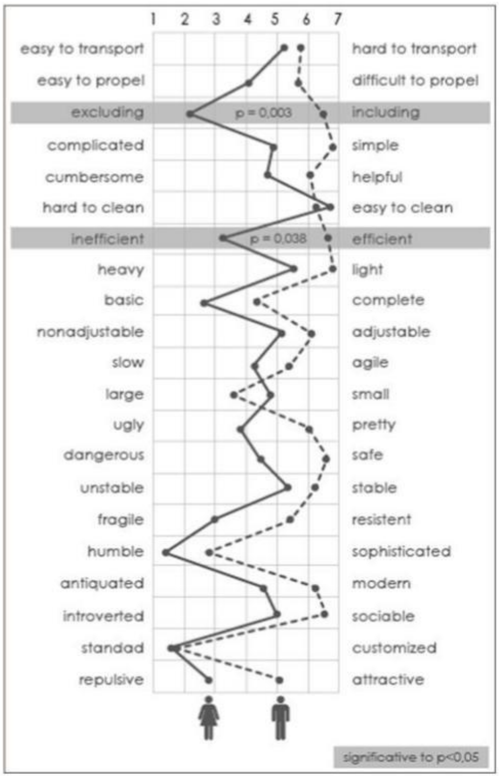


Figura 24. Percepções dos usuários sobre suas cadeiras de rodas. Fonte: LANUTTI et al. (2015).

Um outro achado interessante foi a diferença relacionada ao gênero dos respondentes encontrada entre dois pares de adjetivos: usuários do gênero masculino consideraram a cadeira mais “eficiente” e “includente”, enquanto a média das respostas dos respondentes do gênero feminino estava mais próxima do outro extremo da escala, ou seja, dos adjetivos “excludente” e “ineficiente”. Trata-se de um achado que deve ser interpretado a partir de uma perspectiva ampla e multidisciplinar, pois pode estar associado a questões tanto de ordem prática de uso, quanto estéticas e simbólicas com implicações à autoimagem e aspectos emocionais relacionados ao uso deste produto.

Sob a perspectiva do Design, chama a atenção para a necessidade de aprimorar a ergonomia no que diz respeito à eficiência e condições gerais de uso da cadeira de rodas. Além disso, ressalta-se a necessidade de conhecer não somente as necessidades funcionais do usuário, mas também suas preferências e expectativas com relação ao produto, de forma a possibilitar o desenvolvimento de produtos mais personalizados que, em última análise, podem favorecer a aceitação, satisfação e uso bem-sucedido, reduzindo o risco de abandono da tecnologia.

Em um estudo mais recente (BOIANI et al., 2019) e realizado em colaboração com a Oslo Metropolitan University (Noruega), foi avaliada a percepção de pessoas sem deficiência sobre quatro dispositivos assistivos de mobilidade: andador tradicional, andador com rodas (*rollator*), cadeira de rodas manual e cadeira de rodas motorizada (Figura 25).

(a) (b)

(c) (d)

Figura 25. Representações das imagens dos quatro dispositivos assistivos de mobilidade: (a) andador convencional; (b) andador com rodas (*rollator*); (c) cadeira de rodas manual; (d) cadeira de rodas motorizada. As imagens originais apresentadas aos participantes foram retiradas de catálogos das empresas, e por questões de direitos autorais não são apresentadas aqui, sendo estas representações de similares. Fonte: BOIANI et al., 2019.

Por meio de um questionário baseado em escala de diferencial semântico, quarenta participantes reportaram suas percepções com relação às dimensões práticas, estéticas e simbólicas dos produtos, considerando os seguintes pares de adjetivos: móvel/estacionário; feio/bonito; prático/não-prático; leve/pesado; chato/agradável; excludente/includente; seguro/inseguro; confortável/desconfortável. O questionário foi escrito em inglês e o estudo foi realizado no campus da Oslo Metropolitan University, na cidade de Oslo, Noruega.

Nas dimensões mais relacionadas com a estética, houve um padrão de percepções mais negativas associadas ao andador convencional e a cadeira de rodas manual, e mais positivas relacionadas ao andador *rollator* e a cadeira de rodas motorizada. Uma explicação possível para estes achados é que os primeiros são visualmente menos complexos, enquanto os últimos - *rollator* e cadeira motorizada - são mais elaborados.

Os resultados indicam que os respondentes que possuem pessoas próximas (familiares e/ou amigos) que fazem uso dos dispositivos de mobilidade deram respostas mais negativas em relação às características do dispositivo comparados aos respondentes sem convívio próximo com usuários destes dispositivos, sugerindo uma visão mais crítica das limitações que estes produtos impõem aos usuários.

Possivelmente o achado mais relevante refere-se ao fato de que os participantes sem proximidade com usuários de dispositivos assistivos de mobilidade perceberam a cadeira de rodas manual como mais estigmatizante em comparação aos outros respondentes. Portanto, estes achados sugerem que o convívio com usuários de produtos assistivos é um fator positivo para percepções menos estigmatizantes sobre o uso de Tecnologia Assistiva. Com base nesta observação, a discussão pode ser ampliada para a necessidade de políticas e ações de promoção de condições de mobilidade, acessibilidade e participação social da pessoa com deficiência, a partir das quais poder-se-á ter maior participação das pessoas com deficiência na sociedade, estando presente nos mais diversos setores e lugares, participando ativamente e convivendo em condições mais igualitárias. A partir destas condições, os dispositivos assistivos se tornarão mais familiares a todos, contribuindo assim para a redução de percepções negativas e estigma associado ao uso destes produtos.

O estigma relacionado ao uso de produtos de Tecnologia Assistiva é um dos aspectos que contribuem para o não-uso e abandono destes produtos. O estudo de Sugawara et al. (2018) demonstrou, a partir de um levantamento em um centro de reabilitação do estado de São Paulo, que há fatores de ordem pessoal associados ao abandono de Tecnologia Assistiva. Portanto, é importante que sejam estabelecidas estratégias baseadas na interdisciplinaridade para o enfrentamento do problema do estigma associado a produtos assistivos. O Design, enquanto área de conhecimento e de projeto de forte característica interdisciplinar em suas abordagens, tem um papel fundamental nesta questão. Mais especificamente no contexto da interação entre usuário e produto, o design deve buscar o aprimoramento do uso do produto e de sua estética, buscando promover condições mais favoráveis à aceitação e identificação do usuário com o produto.

5. CONSIDERAÇÕES FINAIS

Retomar os caminhos da construção de uma abordagem interdisciplinar aplicada à pesquisa e desenvolvimento em cadeira de rodas contribuiu para reforçar a necessidade de uma abordagem de diálogo e convergências para uma área - Tecnologia Assistiva - que cresceu sobre e a partir de múltiplos e complementares conhecimentos e competências.

Os desafios enfrentados - diariamente - por quem utiliza uma cadeira de rodas para se locomover são de tamanha dificuldade que acabam por limitar, em última análise, sua mobilidade e independência. Igualmente, os desafios são de natureza complexa e multifatorial: não é apenas uma rampa ou escada que podem representar barreiras à independência e participação social do usuário de cadeira de rodas, mas também aspectos pessoais, sociais e culturais.

O teste de produtos e protótipos de Tecnologia Assistiva traz contribuições tanto à prática em Reabilitação - ao promover evidências para indicação, seleção e adequação dos dispositivos aos usuários - quanto ao Design, ao indicar aspectos do desenho do produto que melhor atendem às necessidades, expectativas e preferências do usuário, assim como apontar demandas para a inovação. Quando o teste é realizado com protótipos, a avaliação comparativa destes aos similares comercialmente disponíveis indica os potenciais benefícios e/ou os aprimoramentos necessários no design.

A Ergonomia enquanto área do conhecimento dispõe de métodos e métricas de avaliação da interface usuário-produto de contribuição valiosa ao Design. Especificamente, os métodos de análise biomecânica - internacionalmente consagrados na pesquisa em áreas de reabilitação e ciências do movimento humano - possibilitam a avaliação de variáveis que caracterizam as interações físicas durante o processo de uso de produtos. Na área da Tecnologia Assistiva, esses métodos favorecem a avaliação de produtos principalmente utilizados por pessoas com deficiência física, tais como: cadeiras de rodas, andadores, muletas, órteses e próteses, dentre outros.

Neste texto, buscou-se sintetizar a construção de uma abordagem interdisciplinar às questões multifatoriais relacionadas à pesquisa e desenvolvimento sobre mobilidade em cadeira de rodas. De forma mais imediata, os aspectos biomecânicos foram avaliados, assim como soluções em Design propostas e suas implicações aos usuários verificadas. Adicionalmente, o design de cadeira de rodas foi explorado em suas funções estéticas e simbólicas, as quais permitem compreender aspectos das relações emocionais e de significação do usuário com o produto. Tais aspectos estão relacionados à aceitação e engajamento ao uso do dispositivo e, em última análise, são igualmente importantes para o uso bem-sucedido do produto.

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ANEXOS

Aqui estão listados e apresentados em sua versão completa as principais publicações que nortearam a construção deste texto. Representam, de modo geral, trabalhos desenvolvidos durante minha atuação acadêmica e científica, com correlação e contribuição ao tema "Tecnologia Assistiva".

ANEXO 01

BERTOLACCINI, G. D. S.; CARVALHO FILHO, I. F. P.; CHRISTOFOLETTI, G.; PASCHOARELLI, L. C.; MEDOLA, F. O. The influence of axle position and the use of accessories on the activity of upper limb muscles during manual wheelchair propulsion. **International Journal of Occupation Safety and Ergonomics,** 2018; v. 24, n. 2, p. 311‗315. doi:10.1080/10803548.2017.1294369

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BOIANI, J. A. M.; BARILI, S. R. M.; MEDOLA, F. O.; SANDNES, F. E. On the non-disabled perceptions of four common mobility devices in Norway: a comparative study based on semantic differentials. **Technology and Disability,** v. 31 n. 1-2, p. 15-25, 2019.

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ANEXO 05

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MEDOLA, F. O.; SPRIGLE, S. Avaliação da Inércia Rotacional de Cadeira de Rodas Manual: implicações para o design ergonômico. **Revista D.: Design, Educação, Sociedade e Sustentabilidade**, Porto Alegre, v. 6 n. 2, 37-54, 2014.

ANEXO 11

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ANEXO 12

SILVA, D. C.; PASCHOARELLI, L. C.; MEDOLA, F. O. Evaluation of two wheelchair hand rim models: contact pressure distribution in straight line and curve trajectories. **Ergonomics**, 2019, v. 62, n. 12, p. 1563-1571. doi:10.1080/00140139.2019.1660000

ANEXO 01

International Journal of Occupational Safety and Ergonomics (JOSE), 2018
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The influence of axle position and the use of accessories on the activity of upper limb muscles during manual wheelchair propulsion

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Introduction. Wheelchair configuration is an important factor influencing the ergonomics of the user–device interface and, from a biomechanical point of view, small changes in chair setup may have a positive influence on the demand on the upper limbs during manual propulsion. This study aimed to investigate the influence of the position of the rear wheels' axle and the use of accessories on the activity of upper limb muscles during manual wheelchair propulsion. *Methods.* Electromyography signals of the biceps, triceps, anterior deltoids and pectoralis major were collected for 11 able-bodied subjects in a wheelchair propulsion protocol with four different wheelchair configurations (differing in axle position and the use of accessories) on a straightforward sprint and a slalom course. *Results.* With accessories, moving the axle forward led to a decrease in the activity of all muscles in both the straightforward sprint (significant differences in triceps, anterior deltoids and biceps) and the slalom course (significant difference in anterior deltoids and biceps). However, when propelling the chair without accessories, no difference was found related to axle position. *Conclusion.* Changes in wheelchair configuration can influence the ergonomics of manual wheelchair propulsion. Reducing the biomechanical loads may benefit users' mobility, independence and social participation.

Keywords: wheelchairs; biomechanics; manual propulsion; ergonomics; assistive technologies

1. Introduction

Wheelchair use has been addressed in a variety of topics covering the biomechanics of manual propulsion [1–3], sports [4,5], problems related to mobility [6,7] and workplace [8–10]. Although used widely, the wheelchair has problems that prevent the user from moving with independence, safety and satisfaction. From an ergonomic point of view, such problems can be divided into two main topics: seating and mobility. While the former focuses on the interaction between the user's body and the support interfaces (seat, backrest, armrest and foot support), mobility addresses the user's actions and the resulting movement of the wheelchair.

Manual wheelchairs users have many functional difficulties in daily life. Mobility tasks as simple as climbing a sidewalk can be very hard. In this way, moving with the wheelchair for long distances is strongly limited and, as a result, the daily distance traveled and average speed are significantly lower in wheelchair mobility when compared with walking [11–14]. Manual wheelchair propulsion exposes the upper limbs to a harmful combination of load and repetition that may cause many injuries [15]. Because users occupy the chair for about 11 h/day [14], the wheelchair becomes an extension of the users' body and influences their social participation [16] and daily work.

In order to study wheelchair mobility in a closer way to how people move in their daily routine, it is important to investigate the biomechanics of manual propulsion not only in straightforward motion, but also in trajectories comprising changes in movement direction and acceleration. A previous study demonstrated that the influence of the mechanical aspects on the movement of the wheelchair is dependent on the trajectory and acceleration [17].

The wheelchair configuration is very important to determine the upper limb actions during manual propulsion. The position and camber of the rear wheels, tire and wheel types, seat and backrest angles, frame design and the use of accessories (armrest, clothing shields) are features of the equipment design that can affect propulsion forces, upper limb range of motion, rolling resistance and system stability [18]. Therefore, a proper selection regarding the wheelchair configuration can improve overall mobility performance.

Many wheelchairs have adjustable settings allowing the users to set up the wheelchair in accordance with their needs and preferences. Moving the rear wheels forward or rearward and using or removing accessories such as

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armrests and seat cover plates are two changes in configuration commonly made by users to make the equipment more suitable to them. However, the influence of the combination between axle position and use of accessories on the biomechanics of manual propulsion is still unclear. This information may contribute to improve the ergonomics of manual wheelchairs by providing objective data on how changes in the equipment configuration influence the users' actions during manual wheelchair propulsion.

This study aimed at investigating the influence of the position of the rear wheels' axle and the use of accessories on the activity of upper limb muscles during manual wheelchair propulsion.

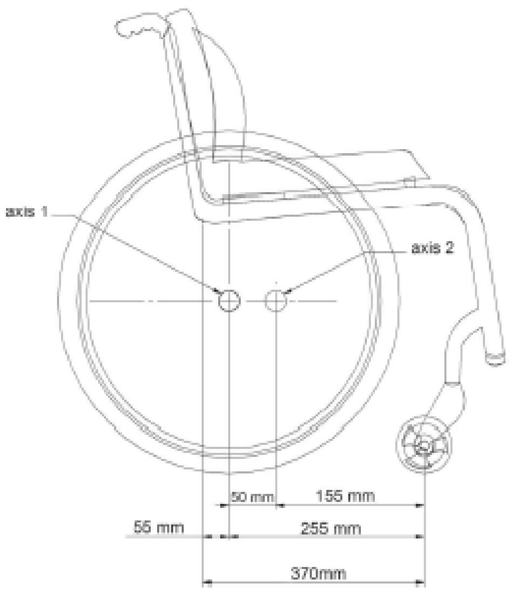

Figure 1. Relative position of the rear wheels to the user.

2. Materials and methods

2.1. *Participants*

A convenience sample of 11 participants without physical disabilities (mean age 23.82 ± 3.46 years, mean height 1.77 ± 0.06 m, mean weight 76.09 ± 11.43 kg), all male, were recruited at the São Paulo State University (UNESP, Bauru, Brazil) and voluntarily participated in this study. Participants met the following inclusion criteria: (a) minimum age of 18 years; (b) had no upper limb pain, injuries or disorders that could influence the manual wheelchair propulsion. Prior to data collection, participants read and signed an informed consent form that had been submitted and approved by the Ethics Committee of the Faculty of Architecture, Arts and Communication—UNESP (Process. N. 800.500).

2.2. *Equipment and procedure*

A manual wheelchair with a rigid frame was used in four different configurations, varying according to a relative fore–aft rear axle position to the frame of 50 mm (Figure 1) and the use or not of accessories (clothing shields and armrests), as shown in Figure 2. The total weight of the accessories was 1.95 kg.

These configurations were tested in two different trajectories: straightforward sprint (acceleration in a 15-m straight motion) and slalom course (nine cones aligned and separated by decreasing distances) (Figure 3), as proposed in a previous study [17]. For both trajectories, subjects were instructed to propel the chair as fast as possible. The sequence of trajectories and wheelchair configurations were randomized for each subject.

During the tests, surface electromyography (EMG) data of the biceps brachial, triceps brachial, anterior deltoids and pectoralis major were collected using four-channel wireless sensors (T-Sens; TEA Ergo, France) and a Datalogger module (CAPTIV; TEA Ergo, France) to register the EMG signals. Triode surface self-adhesive electrodes T3402M (Thought Technology, Canada) were placed in the

Figure 2. Wheelchairs with and without accessories.

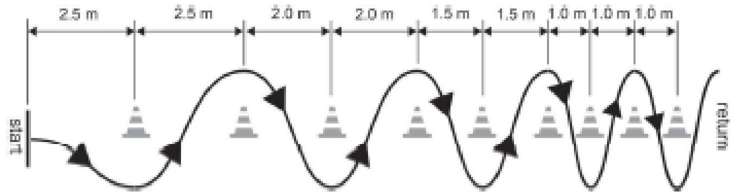

Figure 3. Slalom course.

Table 1. Mean EMG activity (mV) of the four muscles during manual wheelchair propulsion with the accessories.

Muscle	Trajectory	Rearward axle	Forward axle	p
Pectoralis major	Straightforward	101.64 (84.55)	89.36 (63.82)	0.24
	slalom	35.71 (24.10)	34.19 (28.09)	0.68
Triceps brachial	Straightforward	190.46 (161.61)	145.79 (99.81)	0.02*
	slalom	91.44 (58.42)	87.45 (45.18)	0.57
Anterior deltoids	Straightforward	281.16 (159.22)	224.37 (110.98)	0.04*
	slalom	124.23 (56.12)	98.29 (52.11)	0.01*
Biceps brachial	Straightforward	152.84 (56.42)	96.57 (48.31)	0.02*
	slalom	53.13 (37.88)	36.32 (18.59)	0.01*

*$p < 0.05$.
Note: EMG = electromyography.

respective positions for each muscle in accordance with the SENIAM project (www.seniam.org) on the dominant side of the subject's body to record the electrical activity of the muscles. Surface EMG data were sampled at 2048 Hz (which is more than double the frequency in human muscles) [19] to satisfy the Nyquist Theorem, and the root mean square (rms) value was calculated and transmitted by the T-Sens module. The frequency of the rms calculation was128 Hz, and data analysis was performed with the CAPTIV L-7000 software (TEA Ergo, France). All EMG calculation was in mV and analyzed during the complete trajectory, and the first and last pushes were discarded, in order to analyze the muscle activity in plain motion. The mean time window of the analysis was 6.52 s for the straightforward motion and 31.23 s for the slalom.

2.3. *Data analysis*

Mean values were obtained for the EMG measurements of the four muscles of all subjects. To verify statistical differences in the mean EMG of the four muscles between all of the wheelchair configurations for both trajectories, Friedman's test was applied. To verify statistical difference in paired data, the Wilcoxon test was applied, because the data did not show a normal distribution as revealed by the Shapiro–Wilk test. Significance was determined by $p \leq 0.05$. All statistical analyses were performed using SPSS version 22.0.

3. Results

The results show that wheelchair design and configuration can influence the load on the upper limbs. For the wheelchair with accessories, axle position was shown to be a factor that influences the biomechanical load on the upper limbs. In the straightforward sprint, the axle in the forward position showed lower activity than the rearward position in all of the muscles, with significant difference found in the triceps ($p = 0.02$), anterior deltoids ($p = 0.04$) and biceps ($p = 0.02$). This was also found in the slalom course, because propelling the chair with the axle in the forward position required less activity of all muscles in comparison with the rearward position, although significant difference was found only with the anterior deltoids ($p = 0.01$) and biceps ($p = 0.01$) (Table 1).

Conversely, the influence of axle position appeared to be minimized when propelling the chair with the accessories removed, because there was no significant difference regarding the axle position for both the straightforward sprint and the slalom course (Table 2).

The differences in the muscle activity related to the wheelchair configurations (axle position and accessories) and trajectories can be interpreted by the ratio of the mean EMG for the forward and rearward axle positions, as presented in Figure 4. Values lower than one indicate lower demand on the upper limbs during manual propulsion with the axle in a forward position, while values higher than one indicate the opposite, i.e., lower demand with the axle in a rearward position.

4. Discussion

Wheelchair design and configuration are important factors that can influence the demand on the upper limbs during manual propulsion. This study addressed the influence of a

Table 2. Mean EMG activity (mV) of the four muscles during manual wheelchair propulsion without the accessories.

Muscle	Trajectory	Rearward axle	Forward axle	*p*
Pectoralis major	Straightforward	88.66 (71.58)	90.14 (82.33)	0.99
	slalom	31.56 (24.85)	29.39 (19.63)	0.49
Triceps brachial	Straightforward	183.35 (150.79)	192.24 (1342.43)	0.37
	slalom	91.12 (56.36)	95.07 (54.59)	0.33
Anterior deltoids	Straightforward	253.41 (131.53)	255.01 (150.73)	0.92
	slalom	105.45 (54.30)	99.93 (49.05)	0.43
Biceps brachial	Straightforward	109.78 (70.51)	123.74 (95.91)	0.30
	slalom	40.93 (25.82)	39.64 (19.73)	0.99

Note: EMG = electromyography.

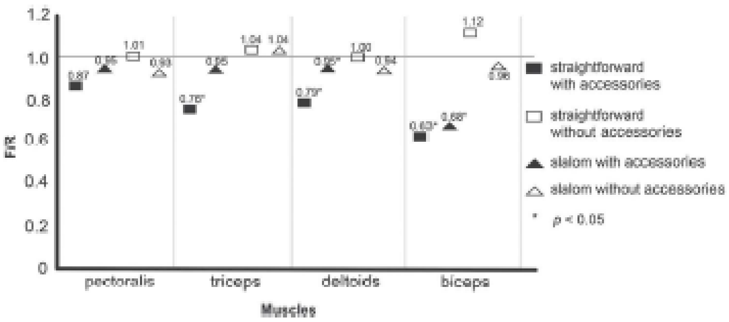

Figure 4. Ratio (F/R) of the mean EMG for the forward (F) and rearward (R) axle positions.
Note: EMG = electromyography.

slight but relevant aspect — axle position — on the activity of upper limb muscles that many times is neglected during equipment design and setup. Because some users remove the accessories (armrest and clothing shields) in order to make the chair lighter, we investigated the influence of axle position in both situations: with and without accessories.

Our results show that moving the axle position forward led to a decrease in the activity of upper limbs during manual wheelchair propulsion in both the straightforward sprint and the slalom course. However, this difference was significant only in the standard configuration (with accessories). Previous studies have highlighted the benefits of positioning the axle forward on the demand on the upper limbs [20,21]. From a mechanical perspective, moving the axle forward reduces the length of the equipment, which impacts the rotational inertia of the system. Additionally, moving the rear wheels forward may contribute to wheelchair mobility by reducing the rolling resistance, because the user's body moves toward the rear wheels [22].

Although moving the rear wheels' axle forward seems to provide an ergonomic benefit for the user in terms of facilitating manual propulsion, it must be taken into account that it has consequences on the equipment stability. In practice, the more forward the axle, the easier it is for the wheelchair to tip over. The guidelines for preserving upper limb function after spinal cord injury recommend that the rear wheels' axle must be positioned as forward as possible without compromising equipment stability [19]. This can only be set up with the participation of the user.

Although the current study produced important findings, it has limitations that must be noted. First, procedures were not performed with real users, and only men participated in the study. Additionally, tasks were conducted at the highest speed the subjects could propel. Another limitation is that we did not assess the subjects' perceptions of the efforts during manual wheelchair propulsion, which could demonstrate whether these changes in wheelchair design and configuration are perceived or not by the subjects.

5. Conclusion

The wheelchair can enhance users' mobility, independence and social participation, and small changes in its design and configuration can lead to important contributions to daily mobility. The current findings suggest that moving the rear wheels' axle forward may have a positive effect on manual propulsion by decreasing the activity of upper limb muscles, although this was only found with the chair in its standard configuration (with accessories). This shows an existing correlation between wheelchair mechanics and propulsion biomechanics. From an ergonomic perspective, adjusting the equipment mechanics (resulting from different configurations) must be seen as a strategy to reduce the loads on the upper limbs, thus benefiting users' mobility.

This information may benefit designers, manufacturers and health professionals in the design, prescription and provisioning of manual wheelchairs. Providing a wheelchair with adjustable configurations – the current study focused on the axle position – may help the user to set up the chair in accordance with his/her characteristics, needs and expectations.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Ethical approval

All the study procedures were submitted and approved by the Ethics Committee of the Faculty of Architecture, Arts and Communication – UNESP (Process. N. 800.500).

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ANEXO 02

Technology and Disability 31 (2019) 15–25
DOI 10.3233/TAD-190226
IOS Press

On the non-disabled perceptions of four common mobility devices in Norway: A comparative study based on semantic differentials

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Abstract.
BACKGROUND: Mobility devices such as walkers and wheelchairs are often associated with certain stigma. Such devices must be designed with the goal of reducing stigma to decrease the abandonment-rate. Yet there is little empirical evidence on how mobility devices are perceived.
OBJECTIVE: This study set out to explore how ($N = 40$) non-disabled individuals perceived four common mobility devices including a traditional walker, rollator, manual wheelchair and a powered wheelchair.
METHODS: A questionnaire based on semantic differential scales was designed.
RESULTS: The results show that the more elaborate devices are perceived as more aesthetical and lighter, yet more unsafe and impractical. Moreover, respondents familiar with mobility devices through family and friends gave more biased negative responses in terms of device characteristics compared to non-experienced respondents. Next, non-experienced respondents perceived the manual wheelchair to be more stigmatizing compared to experienced respondents.
CONCLUSIONS: The findings evidence that different designs of products in the same category can evoke different perceptions of non-users regarding practical, aesthetical and symbolic aspects. Insight into how different design characteristics are associated with perceptions of non-users may contribute to the comprehension of assistive technology stigma and may support design decisions that minimize negative judgments and emphasize positive perceptions.

Keywords: Assistive technology, walkers, wheelchairs, stigma, perceptions, aesthetics, operations, weight, cultural factors

1. Introduction

According to the World Health Organization [1] it is estimated that approximately 190 million adults worldwide have significant reduced function and that more than 1 billion people need one or more assistive products. The International Classification of Functioning, Disability and Health (ICF) defines disability as a broad term used to categorize activity limitations and participation restrictions. Disability is the interaction between individuals with specific needs and personal and environmental factors, in this sense the concept of disability becomes quite diverse [2].

One of the means to improve the functionality of these individuals is the use of Assistive Technology (AT). Several AT devices are used to aid mobility, such as wheelchairs, walking sticks, crutches and walkers.

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Two widely used devices for people experiencing mobility limitations are wheelchairs and walkers.

It is estimated that about 1% of the total population, that is, around 65 million people worldwide, needs wheelchairs [1]. Broadly speaking, wheelchairs can be divided into the categories of manual wheelchairs and powered wheelchairs. Electric or motorized wheelchairs are usually prescribed in cases where the functional and motor losses are large. In turn, manual wheelchairs are used by persons that can manually propel the chair by pushing the wheels in a repetitive way. The two most common designs of manual wheelchairs are foldable frame and rigid frame chairs. Wheelchair frame design [3,4], handrim design [5], propulsion system [6,7], seat-backrest configuration and accessories [6] have been shown to influence the mobility performance and the ergonomics of user-wheelchair interface.

The walker is an AT device that aims to facilitate gait, maintain balance and decrease body weight in the lower limbs with the help of the arms [8]. By having a larger support base with the surface, the walkers provide a safer support for the locomotion, increasing the balance [9].

In Brazil, the most common model is the conventional folding Walker, in which the individual must raise the walker and take steps forward to move [10]. This device is made available by the public health system.

Despite the aids available, several studies show that the abandonment of AT is common due to the stigma caused to such devices [11]. For example, Phillips and Zhao [12] found that nearly 30% of all devices are completely abandoned. The main reasons include lack of user involvement during acquisition, procurement issues, low performance and changes in users' needs and priorities. Riemer-Reiss and Wacker [13] found that device abandonment is related to relative device advantage and user involvement. To help counteract device abandonment, Denvers, Weiss-Lambrou and Ska [14] developed an instrument for measuring user satisfaction with assistive technology devices.

Stigma can be viewed as a set of preconceptions about a particular characteristic related to an individual's social role in society. Objects can provoke stereotypes associated with lifestyle [15].

People with disabilities often go through situations of prejudice caused by stigma that generates a negative perception. According to Goffman [16], this perception is usually accompanied by a social and cultural context that manifests itself in varied forms, including trying to help a stigmatized individual. Factors such as age, gender, device aesthetics, among others may contribute to stigmatization [17].

The negative cultural concept assistive products present causes users and family members to feel disappointed, provoking objections about the appearance and characteristics of the device [18]. The expectation of the family can be an important condition in the receptivity and use of the equipment, since in addition to the affective link, they usually present a global vision that results from the functioning of the device [17].

Although research into assistive technologies has gained increased focus there is still need for better design guidelines. There is particularly a lack of empirical evidence to fully understand the possible stigma associated with AT devices [17]. The study of symbolic and aesthetic elements can contribute to the understanding of non-users' perception of walkers and wheelchairs.

Several researchers have addressed perceptions of assistive technologies. Examples include Cushman and Scherer [19] who found discrepancies between the perceptions of therapists and consumers in terms of device utility and aesthetics. Stern, Mullennix and Wilson [20] studied the perception of synthetic speech in context of assistive technologies. Their results showed that non-disabled respondents preferred a natural voice over synthetic speech, while disabled the synthetic speech was perceived more positively by disabled individuals. It has also been found that the appearance and to look "cool" is as important to disabled individuals as it is to non-disabled individuals [21]. Lanutti et al. [22] found gender-related differences in users' perceptions about their own wheelchairs. In a study using semantic differentials Erler and Garstecki [23] addressed the stigma attached hearing loss and hearing aids among women. Their results suggest that younger women perceive a stronger stigma than older women. Moreover, they found that hearing loss was associated with less stigma compared to hearing aids. DeJong [24] studied how adolescent girls perceive overweight peers. The results showed that overweight girls were perceived more negatively than non-overweight peers, unless they had a valid explanation such as a glandular disorder. Shinohara and Wobbrock [25] addressed how assistive technology use is affected by social settings. Their results confirmed that 1) assistive technology marked the users as being disabled, 2) functional access trumped the feeling of self-consciousness, 3) people incorrectly perceived assistive devices as eliminating disabilities and 4) that disabled were incorrectly viewed as helpless without their devices.

The study of perceptions has also been applied to physical disability and wheelchair use [26–28]. Cahill and Eggleston [26] studied wheelchair users encounters in public spaces when receiving assistance. The results show that wheelchair users' presence in public spaces is associated with uncertainty and unsettledness. Arbour-Nicitopoulos et al. [27] addressed adolescents' perception of family members that are wheelchair users compared to other health issues. The results show that negative perceptions were lower towards wheelchair use compared to drug addition, alcohol, gambling and mental illness. The stigmatized attitudes of wheelchairs were similar to those of asthma. Taub et al. [29] studied coping strategies of physically disabled female students. Perceptions of wheelchair use has also been addressed in context of the wheelchair procurement process [30]. To the best of our knowledge there are few studies that have specifically addressed the perception of the visual properties of mobility devices and that have contrasted different mobility device categories.

The objective of this study was to evaluate nonusers' perceptions of four common mobility aids, two walker models and two wheelchair models in order to identify the existence of related stigma associated with the devices. The goal is that the empiric evidence can be used in decision making regarding the design of future assistive technologies. A four-part questionnaire was developed comprising the most common walker models in Brazil and Norway, respectively, as well as the two most common wheelchair models used in these countries. The standard walker is most common in Brazil as it is available for free via the public health system. It allows idling because the user must lift the device, take the steps and put it forward, being challenging for individuals with reduced function in the upper limbs. The rollator is common to observe on the streets of Norway. The rollator is agile, allowing a greater degree of freedom. It presents rear wheel brakes to avoid possible fall. It can carry objects and provides seating that facilitates resting.

Manual wheelchairs are usually operated though the work of the user's own upper limbs or driven by caregivers. Manual wheelchairs are classified as low complexity products and provide a reasonable range of motion for users with full upper limb functioning, being frequently used by users with manoeuvring skill who wish to be physically active.

Powered wheelchairs are used by users with severe impairment of the upper limbs' function that are not able to propel the chair manually with efficiency. Powered wheelchairs are suitable for both short and long distances.

From a Design point of view, product functions are not limited to functionality, but also connected to the significance and what it communicates about the user, that is, the symbolic function. In this context, assistive devices are of particular interest as they are often associated with stigma. The main question that this study proposes to answer is: different designs of assistive products of the same category (wheelchairs; walkers) trigger different perceptions about the users of these products?

2. Method

2.1. *Experimental design*

A mixed experiment was conducted which explored two independent variables, namely mobility device and experience. Eight semantic differential responses [31] served as the eight dependent variables. The within-groups independent variable mobility device had four levels, a walker without wheels (walker), a walker with wheels (rollator), a manual wheelchair and a powered wheelchair. The between-groups independent variable experience had two levels, namely respondents with friends or family using mobility devices and respondents without exposure to mobility devices. Measurements were acquired using a paper questionnaire.

2.2. *Respondents*

A total of 40 respondents without disabilities were recruited in Oslo, Norway, for the study, of which 27 were female (67.5%) and 13 were male (32.5%). Of these about half were students (52.5%). The age distribution of the respondents was as follows: 28 were between 18 and 39 year of age (70% young adults), 7 were in the range of 40–59 (17.5% adults) while 5 were 60 years or more (12.5%, senior).

Many of the respondents, namely 26 (65%), reported that they were familiar with wheelchairs and/or walkers. Of these 3 reported their spouse using such a device, 3 reported parents, brothers or sisters, 9 reported having a grandparent using such a device, 3 reported uncle or cousin, 2 reported a friend while 6 reported other. The participants were recruited in and around the campus of Oslo Metropolitan University. Efforts were made to solicit a sample as representative of the general population as possible.

(a) Walker

(b) Rollator (*Dirk van der Made, GNU free documentation licence 1.2*)

(c) Manual wheelchair

(d) Motorized wheelchair (*Pixabay Free use License*)

Fig. 1. Assistive devices used in the experiment (images released to the public domain or available under a creative commons licence).

2.3. *Materials*

A paper-based questionnaire was designed with the purpose of facilitating easy in-person data collection. The questionnaire comprised four sheets where each sheet addressed one of the four assistive devices, namely the traditional walker without wheels, a rollator, a manual wheelchair and a powered wheelchair. Each sheet had a similar structure. The top part of the sheet showed a colour image of the assistive device followed by the eight questions realised as 7-point semantic differentials. Each semantic differential scale comprised two adjectives that were antonyms of each other on each side of a 7-item scale. The respondents thus had the option of providing neutral responses. The two adjectives would represent a negative and a positive perception along the dimension. The order of the negative and positive adjectives varied for different questions.

The eight semantic differentials addressed practical, aesthetical and symbolic dimensions of the products: mobile versus stationary, ugly versus beautiful, practical versus impractical, light versus heavy, boring versus enjoyable, excluding versus including, safe versus unsafe and uncomfortable versus comfortable. Exploring practical, aesthetical and symbolic functions of products by means of a semantic differential scale has been reported in Product Design research [22]. The questions where randomized on each sheet and the presentation order of the sheets were also randomized for the respondents to minimize learning effects. The questionnaires were written in English.

The images used were demonstration photos without backgrounds or other disturbing elements. Note that

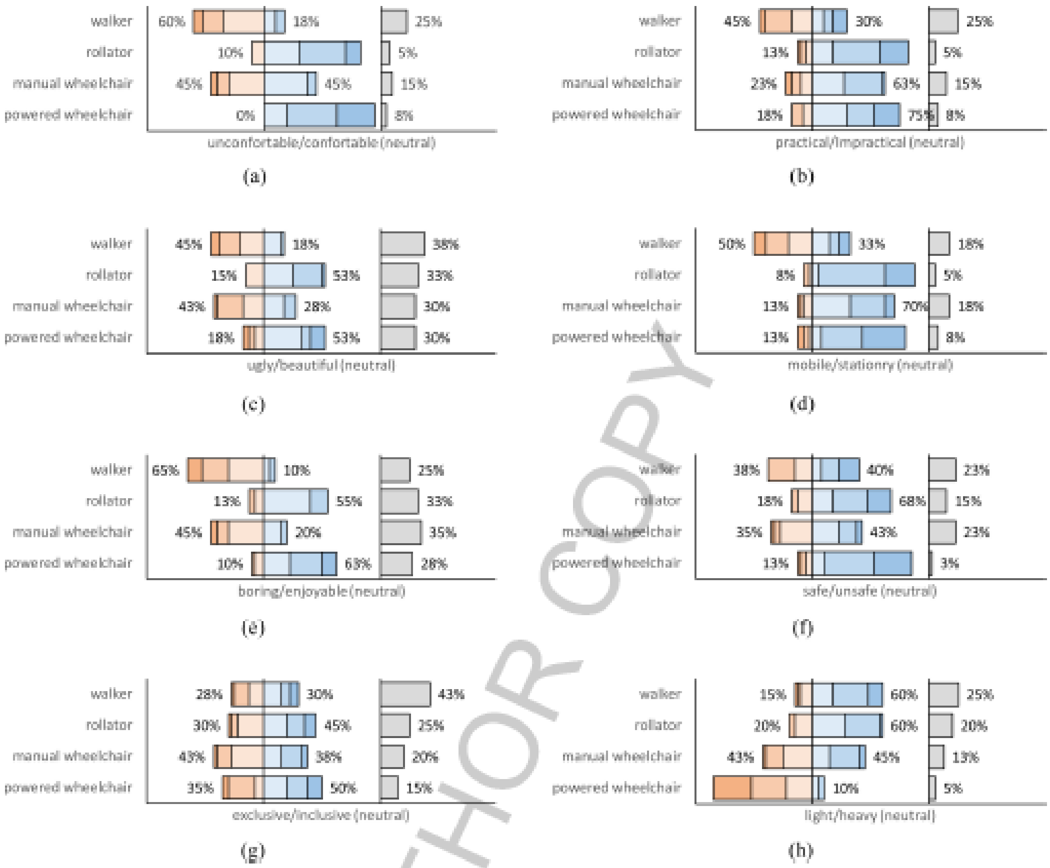


Fig. 2. Results from the semantic differential questionnaire. Responses are coded with dark orange = 1, orange = 2, light orange = 3, grey bars indicate neutral = 4, bright blue = 5, blue = 6 and dark blue = 7.

the images used are not reproduced herein as the images are copyrighted by the respective manufacturers. However, similar devices are depicted in Fig. 1.

2.4. Procedure

Respondents were recruited in person with two of the authors present while the questionnaires were completed. The participants were thus able to answer questions regarding the questionnaire. The respondents were presented with a consent form informing them of their rights to withdraw at any time and the anonymity of the results. The respondents were also asked to fill in general demographic information. Next, the respondents were asked to complete the questionnaire by observing the four pictures and rate the image in relation to the eight dimensions along the scale of the two antonyms. The data was collected during the autumn of 2017 before the introduction of the General Data Protection Regulation (GDPR).

2.5. Analysis

The questionnaire responses were manually converted into a spreadsheet and administered using Microsoft Excel. Statistical analyses were conducted using JASP version 0.9.1.0 [32]. The ordinal measurements were transformed using the Aligned Rank Transform (ART) procedure [33] allowing the data to be analysed using a parametric mixed two-way repeated measures ANOVA. This non-parametric procedure also allows the investigation of interaction effects.

(a) Mobile/stationary

(b) Safe/unsafe

(c) Exclusive/inclusive

(d) Light/heavy

Fig. 3. Dimensions with significant effects of experience.

Instances not satisfying the assumption of sphericity were corrected using Huynh-Feldt corrections as both the Greenhouse-Geisler epsilon and Huynh-Feldt epsilon were above 0.75 for all these instances. Post-hoc testing was performed using Bonferroni corrections. Questionnaire results are visualized using diverging stacked bar charts as recommended by Robbins and Heiberger [34].

3. Results

Figure 2 shows a summary of the 40 responses to the semantic differential questionnaire. The Orange and blue are used to indicate levels of preference towards one of the sides where the intensity of the colour indicates level of preference. Figure 3 shows summary of responses with significant differences due to experience.

3.1. *Uncomfortable/comfortable*

Figure 2a shows the responses to the semantic differential uncomfortable versus comfortable. The walker and the manual wheelchair were strongly tending towards uncomfortable with walker being the least comfortable, while the rollator and powered wheelchair tended towards comfortable with the powered wheelchair being considered the most comfortable. There was a significant difference between the four models (F (3, 114) = 58.748, $p < 0.001$, $\eta^2 = 0.607$). Post hoc tests reveals that all the models were significantly different to each other with high significance ($p < 0.005$), except for the walker and manual wheelchair ($p = 0.112$).

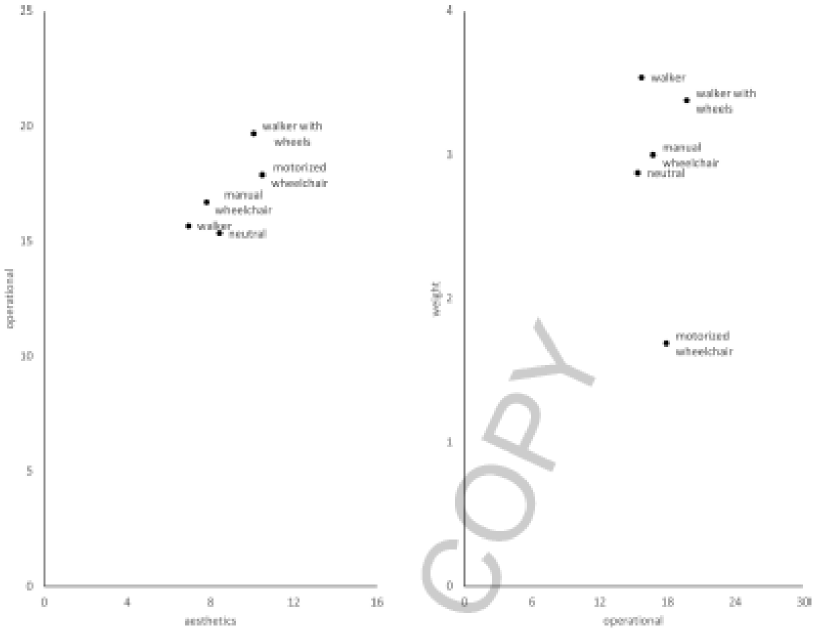
There was no significant effect of experience (F (1, 38) = 0.001, $p = 0.971$), however, there was small significant interaction effect between device type and experience (F (2.645, 100.507) = 4.479, $p = 0.006$, $\eta^2 = 0.108$).

3.2. *Practical/impractical*

Figure 2b shows the responses to the semantic differential practical versus impractical. The walker stood out tending towards practical, while the other three tended towards impractical. The rollator was perceived as the least practical, followed by the powered wheelchair and manual wheelchair considered the least impractical of the three. Again, the walker was associated with most neutral responses. There was a significant difference between the four models (F (3, 114) = 7.972, $p < 0.001$, $\eta^2 = 0.173$), however post-hoc tests reveals that only the walker and the powered wheelchair ($p = 0.007$), the walker and the rollator ($p < 0.001$) and the rollator and the manual wheelchair ($p = 0.021$) were significantly different. All the other combinations revealed p-values above the significance level of 0.05. There was no effect of experience (F (1, 38) = 0.169, $p = 0.683$) and no interaction effects (F (3, 114) = 2.089, $p = 0.106$).

3.3. *Ugly/beautiful*

Figure 2c shows how the respondents perceived the devices along the dimension of ugly versus beautiful. The walker and the manual wheelchair tended towards the ugly side with walker the ugliest, while the rollator and the powered wheelchair tended towards beautiful with the powered wheelchair being the most beautiful. There was notably also a relatively high level of neutral responses for all four models. There was a significant difference between the four models (F (2.508, 95.293) = 8.535, $p < 0.001$, $\eta^2 = 0.183$). Post hoc



(a) Aesthetics versus operational (b) Operational versus weight

Fig. 4. Mean responses for each device type plotted factor planes.

tests reveals that three pairs were significantly different to each other, that is walker and powered wheelchair ($p = 0.002$), walker and rollator ($p < 0.001$) and rollator and manual wheelchair ($p = 0.008$).

There was no effect of experience (F (1, 38) = 3.683, $p = 0.063$), but a small significant interaction effect was observed (F (2.530, 96.157) = 2.894, $p = 0.048$, $\eta^2 = 0.070$).

3.4. Mobile/stationary

The perception of mobility versus stationary is plotted in Fig. 2d. Again, the walker stands out as tending words being mobile, while the three other devices were perceived as stationary. The rollator was the most immobile, followed by the powered wheelchair and with the manual wheelchair as the least stationary of the three. The walker and the manual wheelchair were associated with more neutral responses than the rollator and powered wheelchair. The difference between the four models were highly significant (F (2.455, 93.299) = 18.892, $p < 0.001$, $\eta^2 = 0.330$) and post hoc testing reveals that only the pairs rollator and powered wheelchair and walker ($p = 1.0$) and manual wheelchair ($p = 0.063$) were not significantly different. A significant effect of experience was observed (F (1, 38) = 9.730, $p = 0.003$, $\eta^2 = 0.204$). A Mann-Whitney U test ($W = 88.5$, $p = 0.003$) showed that the experienced respondents found the rollator to be significantly more stationary ($M = 6.2$, $SD = 0.8$) than the non-experienced respondents ($M = 5.1$, $SD = 1.5$). This result is plotted in Fig. 3a. There was also a small significant interaction between device type and experience (F (2.355, 89.478) = 3.339, $p = 0.033$, $\eta^2 = 0.080$).

3.5. Boring/enjoyable

The dimension of boring versus enjoyable is plotted in Fig. 2e. The results show that the walker and the manual wheelchair were considered boring with the walker being the most boring while the rollator and the powered wheelchairs were considered enjoyable with the powered wheelchair being the most enjoyable. There were many neutral responses with the manual wheelchair having the most neutral responses of the four models. The differences were highly significant (F (2.736, 103.968) = 18.434, $p < 0.001$, $\eta^2 =$

0.375) and again post hoc testing reveals that only the pairs rollator and powered wheelchair ($p = 0.578$) and walker and manual wheelchair ($p = 0.614$) were not significantly different. There was no effect of experience (F (1.38) $= 0.331$, $p = 0.569$) and no interaction effect (F (3, 118) $= 0.916$, $p = 0.436$).

3.6. *Safe/unsafe*

A similar pattern was observed for what was perceived as safe versus unsafe (see Fig. 2f). The walker and the manual wheelchairs were considered neutral, also with most neutral responses, while the rollator and powered wheelchair were considered unsafe with the powered wheelchair being perceived as the most unsafe device. The differences were significant (F (3, 114) $= 15.870$, $p < 0.001$, $\eta^2 = 0.293$). Post hoc testing reveals that all the devices were significantly different apart from the rollator and powered wheelchair ($p = 0.063$) and the walker and manual wheelchair ($p = 1.0$). There was an effect of experience (F (1, 38) $= 4.400$, $p = 0.043$, $\eta^2 = 0.104$). Figure 3b shows that both the powered wheelchair ($W = 99.5$, $p = 0.014$) and rollator ($W = 92.5$, $p = 0.010$) are perceived differently by the experienced and novice participants. In both cases the experienced respondents viewed the devices as more unsafe, namely powered wheelchair: experienced respondents ($M = 6.1$, $SD = 1.3$) and non-experienced respondents ($M = 5.0$, $SD = 1.7$) and rollator: experienced respondents ($M = 5.6$, $SD = 1.4$) and non-experienced respondents ($M = 4.4$, $SD = 1.3$). There was also an interaction effect (F (3, 114) $= 5.075$, $p = 0.002$, $\eta^2 = 0.117$).

3.7. *Exclusiveness/inclusiveness*

No significant differences (F (2.588, 98.387) $= 0.712$, $p = 0.528$) were observed across the four models with respect to exclusiveness versus inclusiveness (see Fig. 2g). The responses were balanced with especially a large portion of neutral responses for the walker. However, there was a significant effect of experience (F (1, 38) $= 6.111$, $p = 0.018$, $\eta^2 = 0.139$). Figure 3c shows that the experienced respondents found the manual wheelchair more inclusive ($M = 4.5$, $SD = 1.6$) than the non-experienced respondents ($M = 3.2$, $SD = 1.1$). This difference is significant ($W = 88.0$, $p = 0.007$). There was no interaction effect (F (2.560, 97.280) $= 1.470$, $p = 0.232$).

3.8. *Light/heavy*

The perception of light versus heavy (see Fig. 2h) was highly significantly different across the four models (F (3, 114) $= 33.350$, $p < 0.001$, $\eta^2 = 0.463$). The powered wheelchair was considered light, the manual wheelchair was neutral while the two walkers were considered heavy with the walker being the heaviest. The level of heaviness also corresponded with a higher degree of neutral responses. All the pairs were statistically significantly different apart from the walker and the rollator ($p = 1.0$). There was also an effect of experience (F (1, 38) $= 7.643$, $p = 0.009$, $\eta^2 = 0.167$). Figure 3d shows that the dimension of light versus heavy was perceived differently by the two groups for three devices, namely walker ($W = 96.50$, $p = 0.013$), manual wheelchair ($W = 102$, $p = 0.021$) and rollator ($W = 273.0$, $p = 0.008$). In all three cases the experienced respondents viewed the devices as heavier than the respondents without experience. Walker: experienced respondents ($M = 5.3$, $SD = 1.4$) and non-experienced respondents ($M = 4.2$, $SD = 1.3$), manual wheelchair: experienced respondents ($M = 4.6$, $SD = 1.6$) and non-experienced respondents ($M = 3.4$, $SD = 1.5$) and rollator: experienced respondents ($M = 5.0$, $SD = 1.2$) and non-experienced respondents ($M = 4.1$, $SD = 1.3$). There was no interaction between device and experience (F (3, 114) $= 0.874$, $p = 0.457$).

Table 1
Factor analysis

	RC 1	RC 2	RC 3	Uniqueness
Boring/enjoyable	0.639	...	...	0.375
Exclusive/inclusive	...	...	...	0.846
Light/heavy	...	...	0.719	0.474
Mobile/stationary	...	0.818	...	0.511
Practical/impractical	...	0.579	...	0.500
Safe/unsafe	...	0.508	...	0.676
Ugly/beautiful	1.049	...	...	0.197
Uncomfortable/comfortable	0.420	0.401	...	0.381

3.9. *Factor analysis*

A factor analysis was also conducted on the responses to the questionnaire as it is sometimes used in analysis of semantic differential data [35,36]. The results listed in Table 1 shows that there were three significant factors (X^2 (7) $= 15.294$, $p = 0.032$). The first factor comprises the dimension of ugly versus beautiful with a strong loading (1.049), boring versus enjoyable (0.639) and uncomfortable/comfortable (0.420). We termed this factor *aesthetics* as beauty and enjoyable are related to aesthetics. The second factor is composed of the dimensions mobile versus stationary (0.818), practical versus impractical (0.579), safe versus unsafe (0.508) as well as uncomfortable versus uncomfortable (0.401) which is shared with the first factor. We thus termed this factor *operational*. The dimension of light versus heavy is the only semantic differential assigned to the third factor that we termed weight. The dimension of exclusion versus inclusion was not included in the model which correspond well with the neutral responses observed. The results suggest that the walkers and wheelchairs are perceived according to the factors aesthetics, operationality and weight.

Figure 4 shows the mean responses for each device type plotted for the factor pairs aesthetics versus operational and operational versus weight. An all neutral response is also plotted for reference. In terms of aesthetics the walker and manual wheelchair is below neutral while rollator and powered wheelchair are above neutral. The plots show that all devices are above neutral in the following sequence: walker, manual wheelchair, powered wheelchair and rollator with the highest operational value. In terms of weight the walker is regarded the heaviest, followed by the rollator and manual wheelchair. The powered wheelchair is the only one below neutral standing out from the other three perceived as the lightest.

4. Discussion

The dimensions associated with aesthetics, namely, ugly versus beautiful, boring versus enjoyable and uncomfortable versus comfortable all showed a similar pattern, namely that the walker was perceived most negatively followed by the manual wheelchair while the powered wheelchair was perceived most positively followed by the rollator. One may expect the walker to be perceived as the least aesthetic and the more elaborate powered wheelchair as the most aesthetic. However, it is somewhat surprising that the rollator is perceived as more aesthetical than the manual wheelchair. A reasonable explanation for this finding is that manual wheelchairs and walkers are visually less complex and have simpler design than powered chairs and rollators.

In terms of operational issues, the results are divided, namely that the walker is perceived as the most practical while the powered wheelchair is perceived as the least practical. This could perhaps be explained by the dimension of mobile versus stationary where the walker is considered the most mobile device and the other devices immobile. Hence the small and light small frame of the walker may give the impression that the walker is easier to move around and takes less space compared to the other devices. However, walking with the assistance of a walker demands attention from the user as it requires synchronized actions from the upper (lift, move forward and place the walker on the floor) and lower limbs (steps). According to the study of Bateni and Maki [37], walkers can demand excessive strength and affect the balance maintenance in certain situations. Furthermore, as the current study was carried out in Norway, where rollators are popular assistive walking device [38], it can be inferred that it is associated with situations of functional limitations and dependence. In turn, conventional walkers are not commonly seen in the community as rollators are in Norway. This may explain the more positive perceptions about walkers in comparison to rollators. There were no differences in terms of aesthetics in relation to experience.

It is also interesting to observe that the walker was considered the safest device while the powered wheelchair is considered the most unsafe device. Perhaps respondents feel that few things can go wrong with the stationary walker which does not move on its own, while things can get out of control with the powered wheelchair as it moves by itself. Open ended follow up questions could shed more light on these responses.

Experienced respondents also gave more strongly biased responses compared to the non-experienced respondents in terms of safety as they considered both the powered wheelchair and rollator more unsafe. Next, experienced respondents responded more negatively than the non-experienced respondents in terms of the mobility of the rollator. Again, these differences could possibly be explained by these respondents' knowledge of these device properties. The literature documents benefits for the mobility of elderly people when using rollators. The study of Hoenig et al. [39] compared rollator, manual and powered wheelchairs in a community mobility task, and found that rollator allowed fastest mobility, while manual wheelchairs were most associated with fatigue.

In terms of weight the powered wheelchair was considered the lightest and the walker the heaviest. Clearly, this does not refer to device mass as the powered wheelchair clearly has the largest mass and the walker the smallest mass. Thus, the weight refers to the weight of handling from the perspective of the user, that is, the walker is associated with heavy work as it must be lifted and carried, while the powered wheelchair can be easily moved using gentle finger movements.

The weight factor was also associated with most differences across experienced and non-experienced respondents. The experienced respondents rated the three non-powered devices negatively, while the non-experienced respondents rated these more neutrally. This result indicates that the experienced users are more aware of the actual effort involved operating the three non-powered devices compared to the non-experienced respondents who are more ignorant of the actual work involved.

Although no differences were found across the devices in terms of exclusiveness versus inclusiveness, this dimension revealed a difference in terms of experience for the manual wheelchair. The non-experienced respondents ranked the manual wheelchair negatively in terms of inclusiveness suggesting a cultural stigma associated with the manual wheelchair, while the experienced respondents rated the manual wheelchair as inclusive, perhaps knowing that the manual wheelchair adds greatly to the quality of life for the user and inclusion in society compared to not being able to move around.

Generally, the walker ends up at the lower end of most scales while the rollator is generally perceived more favourably. One possible explanation for this trend is that respondents probably are more familiar seeing the rollator as the rollator is the most common walker device in Norway and most respondents probably have never seen a traditional walker. It would have been interesting to observe if the perception of these two devices would be different in a different environment such as Brazil where the traditional walker is more common than the rollator.

It is possible that the respondent sample was somewhat biased as it was solicited in and around the University Campus located in the city centre where people may be more open to diversity than in smaller more rural places. An extended study with participants from a wider geographical area with different socio-economic and educational backgrounds may give somewhat different results.

Although there are limitations that must be observed, this study provides some insight on the perception of non-users about practical, aesthetical and symbolic aspects of two widely used assistive mobility devices, thus contributing to the investigation of factors associated with stigma in assistive technology usage. From the perspective of Product Design, the information gained from the visual judgement of people without disabilities about two different designs of products of the same category – namely wheelchairs and walkers – may support the identification of features in the design of these products that are associated with negative and positive judgements. Ultimately, this knowledge may support innovative design proposals aiming to minimize the stigma related to assistive devices.

5. Conclusions

A questionnaire based on semantic differentials was developed to measure non-disabled individuals' perceptions of four of the most common mobility devices. The results show that the responses can be explained by three factors namely aesthetical, operational and weight. The more elaborate devices are perceived as more aesthetical. Moreover, experienced respondents seem to have a more realistic, yet negative view of the actual properties of the devices, weight in particular. The results also show that respondents without experience with people using such mobility devices associate manual wheelchairs with certain stigma, while this was not found for respondents familiar with mobility devices. Future work should solicit responses from other cultural context such as Brazil.

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Conflict of interest

None to report.

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ANEXO 03

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The significance of manual wheelchairs: a comparative study on male and female users

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Abstract

As one of the most representative assistive technology devices, the wheelchair has many peculiar aspects in its daily usage. Therefore, the wheelchair cannot be thought of only as a mobility device, and ergonomic investigation should include also aesthetics and symbolic aspects. This study was aimed at investigating the influence of gender on the users' perceptions about the significance of their own wheelchair. The sample comprised ten manual wheelchair users, being five men and five women. Subjects were asked to rate in a seven-point scale their perceptions about each pair of opposite adjectives, taking into account their experience with their own wheelchairs. The mean and standard deviation values were obtained for each pair of adjectives and then compared between the two groups of subjects by using parametric and non-parametric tests, according to the normality of the data. The results show that, in general, men's perceptions about their wheelchairs were more positive than women's in both practical and symbolic functions. Significant difference between gender was found with the pairs of adjectives including/excluding ($p=0.003$) and efficient/inefficient ($p=0.038$). Such differences may reveal underlying problems that female users experience in daily wheelchair usage and, ultimately, reflect the social consequences of this. Knowledge about the significance of assistive devices is important to provide a view not only on practical, but also aesthetic and symbolic aspects of the product, thus benefiting designers in developing products that best meet the users' needs and expectations.

Peer-review under responsibility of AHFE Conference

Keywords: Wheelchairs; User's perceptions; Semantics; Ergonomics; Assistive technologies

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1. Introduction

The wheelchair is an assistive technology device aimed to promote and/or improve the mobility of subjects with problems that limit or prevent them from moving independently. From an ergonomic point of view, the wheelchair has problems that, ultimately, impact the user's functionality, comfort, independence and satisfaction. Such issues may lead to serious consequences to the users in terms of his / her social inclusion. Indeed, a study demonstrated that the wheelchair itself was considered by the users as the main factor affecting their community participation [1].

Although improving locomotion is the most representative function of a wheelchair, it should not be seen only as a mobility device, since the users occupy the wheelchair about eleven hours per day [2]. Interestingly, in only one hour the user is in motion [2]. Taking into account the prolonged daily user-device interaction, the wheelchair should be seen also as a product socially representing the user. In this context, it is therefore important to study the significance of the wheelchair for both users and non-users.

The aspects of significance have been investigated in a variety of products, aptly called the semantic object, a term that was first used by Krippendorf and Butter, in 1984, and defined as "the study of the symbolic qualities of man-made objects in the context of their use and the application of this knowledge to industrial design" [3].

Krippendorf points out that the concept has only made sense because of the vast application in researches that discussed the industrial product beyond the aesthetic issues, addressing what the product may represent to the users, as well as what it communicates and means [4].

The Semantic Differential (SD) scale is a tool widely used to address the significance of objects that was created in 1957 by Charles Osgood. From a factorial analysis of a large data set, the author found three recurrent attitudes that people use to evaluate words and sentences: evaluation or judgement (for example, "good" or "bad"), intensity (for example, "strong" or "weak") and activity (for example, "passive" or "active") [5]. However, besides measuring the connotation of words and concepts, the SD technique has been used in many fields of research as a means of evaluating a variety of aspects of the human-technology interface. According to Santa Rosa and Moraes, the SD is a tool for "elucidating the perceptual and attitudinal aspects" [6].

The SD has already been used in studies addressing subjects with disability. The perception by able-bodied subjects of aspects of wheelchair users was investigated in terms of communicability, competence, attractiveness and popularity [7]. By using pictures, the authors found it to be a valid and reliable instrument for the analysis of social perception of disability and attitudes related to disabled people. Additionally, the perceptions of health-care professionals about the persons with a visible physical disability were assessed [8]. The study was carried out with videos of job interviews with wheelchair users, and the main finding was that the wheelchair itself influences judgements about social adjustment, general competence and the ability of the user. Another study investigated the perceptions of able-bodied subjects about children with disabilities at preschool and primary school age [9]. The authors found that the able-bodied children have positive and inclusive attitudes toward children who use a wheelchair.

In a comparative study between young and elderly, was used the SD to assess the perception of comfort in wheelchairs, and found that the backrest angle is directly related to the perceived comfort in a wheelchair [10]. Similarly, the SD was also used to investigate the relation between the wheelchair mobility, body posture and the perception of comfort [11].

It can be noted that the use of SD in wheelchair studies, in most cases, is related to the perception of able-bodied (non-users) or as a complementary analysis of practical aspects of wheelchair usage. Furthermore, the studies did not show a concern for how the users feel about their wheelchairs and perceive themselves when using the chair.

This study was aimed at evaluating the influence of gender on the significance of the wheelchair to the users. This information may contribute to the knowledge about the complex interaction between user and the wheelchair in the practical, aesthetic and symbolic aspects.

2. Methods

A sample of 10 manual wheelchair users (five men; five women, mean age of 39 ± 8.3 yr) was recruited from SORRI Rehabilitation Center, Bauru, SP, Brazil.

A Semantic Differential protocol was built up by twelve specialists from SORRI, comprising 21 sets of opposing pairs of adjectives related to the practical, aesthetic and symbolic functions of the product (Table 1).

Table 1 - Pairs of adjectives (in portuguese) used in the Differential Semantic instrument and the correspondent terms in English.

English	Portuguese	X	English	Portuguese
adjustable	*ajustável*		nonadjustable	*não ajustável*
basic	*básica*		complete	*completa*
light	*leve*		heavy	*pesada*
efficient	*eficiente*		inefficient	*ineficiente*
easy to clean	*fácil de limpar*		hard to clean	*difícil higienização*
cumbersome	*dificultosa*		facilitating	*facilitadora*
complicated	*complicada*		simple	*simples*
including	*inclusiva*		excluding	*eliminadora*
easy to ride	*fácil de 'tocar'*		tough to ride	*fácil de 'tocar'*
easy to transport	*fácil transporte*		hard to transport	*difícil transporte*
repulsive	*repulsiva*		attractive	*atrativa*
standard	*padrão*		customized	*personalizada*
introverted	*introvertida*		sociable	*sociável*
modern	*moderna*		antiquated	*antiquada*
sophisticated	*sofisticada*		humble	*humilde*
fragile	*frágil*		robust	*resistente*
unstable	*instável*		stable	*estável*
dangerous	*perigosa*		safe	*segura*
ugly	*feia*		pretty	*bonita*
large	*grande*		small	*pequena*
slow	*lenta*		agile	*ágil*

Prior to data collection, subjects read and signed an informed consent form that had been approved by the Ethics Committee of the Faculty of Architecture, Arts and Communication -FAAC/UNESP (Process n. 800.500/2014).

For the data collection, subjects were asked to rate in a seven-point scale their perceptions about each pair of opposite adjectives, taking into account their own wheelchairs. The pairs of adjectives were presented in a randomized sequence.

Mean and standard deviation values were obtained for each pair of adjectives. To verify significant difference ($p<0.05$) between the mean values of men and women for each pair of adjectives, Student's t -test was applied, given the assumptions of normality (Shapiro-Wilk's test). The non-parametric Wilcoxon's test was used for the samples (19 pairs of adjectives) that did not meet the assumption of normality.

3. Results

The sample was comprised of ten manual wheelchair users, being five men (mean age of 37.2+7.2 years) and five women (mean age of 40.8 + 9.8 years). All the users make use of a manual wheelchair with folding-frame. Table 2 summarizes the subjects' characteristics.

Table 2 - Subjects Characteristics.

Subject	Gender (years)	Diagnosis	Time of wheelchair usage (months)	Time using the current wheelchair (months)
1	Male	Traumatic Brain Injury	8	6
2	Male	Tetraplegia	15	1
3	Male	Tetraplegia	120	8
4	Male	Paraplegia	48	6
5	Male	Lower-limb amputation	36	24
6	Female	Muscular Dystrophy	30	30
7	Female	Paraplegia	32	32
8	Female	Lower-limb amputation	24	24
9	Female	Hemiplegia	60	60
10	Female	Polio	96	12

For the majority of the pairs of adjectives, men's perceptions were more positive than women's about their own wheelchairs (Figure 1). Statistical significant differences between genders was found when compared the average SD score of the adjectives efficient/inefficient ($p = 0.038$) and excluding/including ($p = 0.003$).

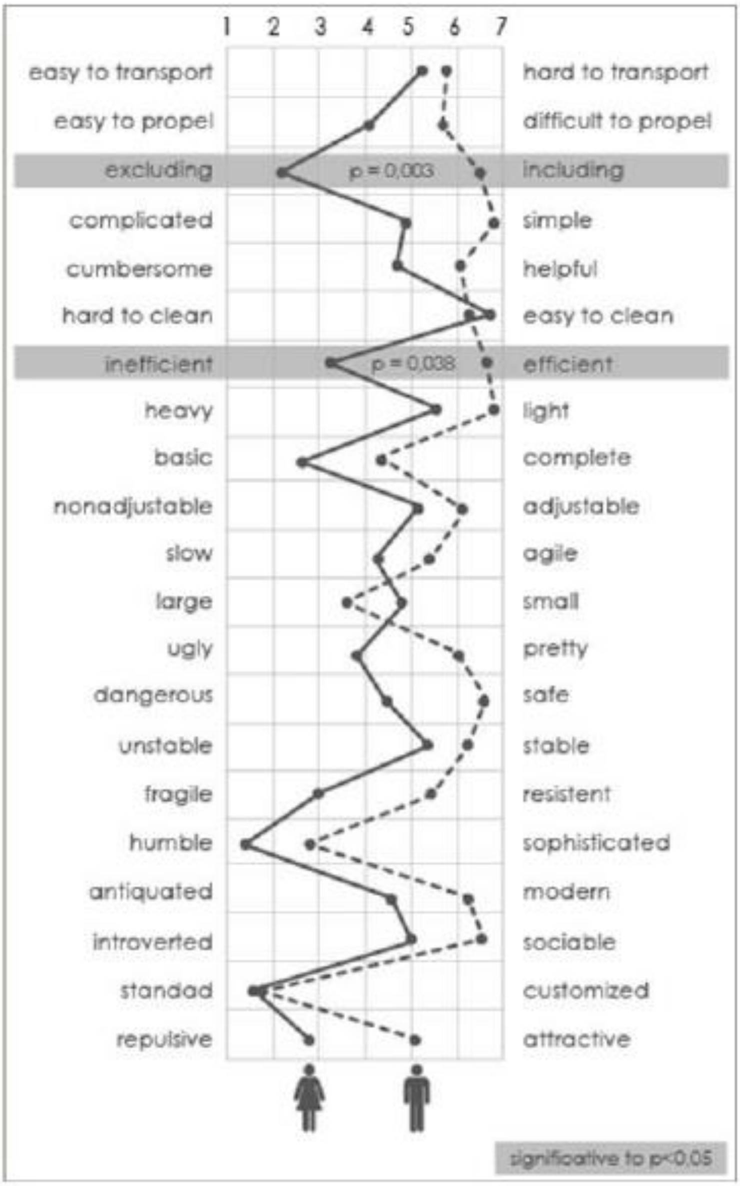

Fig. 1. Comparison between men's and women's perceptions about their own wheelchairs.

In only two cases the women's evaluation about their wheelchairs were slightly more positive in comparison to men's, but no significant difference was found. The wheelchairs were indicated by women as being a little larger and easier to clean in comparison to men's report.

4. Discussion

The current study addressed the semantic aspects of the wheelchair as a product of personal use. By using the Semantic Differential assessment tool, it was possible to explore the significance of the wheelchair not only from a practical point of view, but also the aesthetic and symbolic aspects.

The results reveal some interesting differences regarding the evaluation of men and women about their wheelchairs. In general, the men tended to evaluate the wheelchair in a more positive way than the women did.

The fact that statistical significant difference was found in the pair of adjectives inclusive/exclusive and efficient/inefficient (women reporting the wheelchair as exclusive and inefficient) can be understood as a reflection of the limited mobility, which ultimately impacts the users' social participation and the effective use of the device. This is a relevant finding, considering that there are no major differences between the wheelchairs of male and female users that participated in this study (all subjects use a folding frame wheelchair). In fact, men's evaluation on the easiness to propel the chair was greater than women's, although with no significant difference. Taking into account that manual propulsion is a highly extenuating and inefficient means of mobility [12], this result is somehow expected, since men may tend to be more apt to perform such action, because of their greater physical capacity, and less likely to express an implied weakness.

Besides the practical aspects of the wheelchair usage, there are interesting findings regarding both aesthetic and symbolic functions of the device. In adjectives more related to these aspects, women evaluated in a more negative way in comparison to men's. This happened for pairs of adjectives such as ugly/pretty, humble/sophisticated, antiquated/modern, introverted/sociable, and repulsive/attractive, among others.

Although this finding does not allow one to explore deeply the reasons of such difference, it certainly reveals that the meaning of the wheelchair to the user depends on many factors, with the user gender being one of great importance. Designers and manufacturers must consider these gender-related differences, in order to design wheelchairs that best meet the users' preferences and expectations. In fact, both men and women perceived their own wheelchairs as more standard than customized. Taken into account gender-related differences and users' preferences in the design of wheelchairs would, ultimately, benefit the users' self-identification and acceptance to the assistive device.

While important information was gained from this study, it has some limitations that need to be noted. First, the small sample size limits the statistical analysis, therefore the results are not representative and cannot be extended to the population of wheelchair users. Additionally, the subjects' diagnosis and time of wheelchair usage were not the same between the subjects, which might have influenced the results. Future studies should use a larger sample size, in order to allow the investigation of the possible influence exerted by specific aspects such as diagnosis and experience in wheelchair usage on the significance of wheelchairs.

5. Conclusion

The wheelchair research has been focused mainly on the practical functions. However, besides the practical aspects of the user-wheelchair interface, there are subjective aspects that influence the users' perceptions on the device and the experience of usage.

User's acceptance or rejection of an assistive device may not be totally related to practical functions of the product, but also associated to the product's significance, which reflects what it communicates socially and emotionally. Not only referring to how able-bodied subjects perceive and evaluate the user and the wheelchair from a semantic point of view, but also – and mainly – to how the users themselves perceive the product that is part of their interaction with the world.

Although this is a preliminary study, it revealed that the significance of manual wheelchairs to their users is different between male and female subjects. In general, women's evaluation about their own wheelchairs is more negative than men's.

Probably the main finding refers to the two pairs of adjectives that showed significant difference: women considered the wheelchair as excluding and inefficient, while men considered it as including and efficient. This is a relevant finding and may reveal, ultimately, social consequences of the problems experienced with wheelchair usage. Understanding the significance of wheelchairs to the users may benefit designers and manufacturers in the development of products that best meet the users' needs, preferences and expectations.

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ANEXO 04

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DEVICE/PRODUCT

A new design for an old concept of wheelchair pushrim

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Purpose: Report on the development of an ergonomic manual wheelchair pushrim and evaluate the user's perception of the quality of the device. *Method*: Based on anthropometric features and ergonomic concepts, a new wheelchair pushrim was designed, and a prototype was manufactured in polyurethane, using the rapid prototyping technique and serial production of parts by molding. The prototype was tested by a sample of wheelchair users, who rated the perceived quality of the device after testing both the new and conventional pushrims in a wheelchair propulsion experimental protocol. *Results*: The new ergonomic pushrim was found to be, in general, better than the conventional round tube pushrim. Specifically, experienced wheelchair users found the new wheelchair pushrim better in terms of easy and comfortable propulsion, braking and maneuvering of the wheelchair, and appearance. *Conclusions*: The new wheelchair pushrim provides a proper fit for the hands due to its ergonomic design and its polyurethane composition, making wheelchair propulsion easier and more comfortable than the conventional wheelchair pushrim. Assistive technology devices should be design based on ergonomic concepts that involve less effort and offer greater comfort for the user.

Keywords: Human engineering, rehabilitation, self-help devices, wheelchairs

Implications for Rehabilitation

- Manual wheelchair propulsion has been related with upper limb injuries that may potentially limit functionality.
- The conventional pushrim does not meet the need for a firm and stable grip, requiring further effort to hold the pushrim during manual propulsion that may cause discomfort, pain and contribute for developing upper limb injuries.
- In a relatively small sample of wheelchair users, this study shows that an ergonomically designed pushrim makes manual propulsion easier and more comfortable compared to the conventional pushrim.

Introduction

Recent technological advances in equipment for people with special needs are aimed at promoting full social inclusion. One of the most important devices for social inclusion is the wheelchair, which, in its simplest design with manual propulsion, is the focus of this study. Focusing on the interface between the hand and the pushrim, we search for a simple but efficient innovation for the manual propulsion by improving the design of the wheelchair pushrim.

Manual wheelchair propulsion is still the primary source of mobility for many disabled people, and has been associated with a high prevalence of upper limb injuries, which can be explained by the combination of repetitive movements and heavy loads imposed on the upper extremities during this activity [1]. Carpal tunnel syndrome has been commonly diagnosed in wheelchair users, and there is a correlation between the function of the median nerve and the rate of propulsion. Major cadence and higher forces applied to the pushrim are correlated with impaired median nerve function [2]. The application of excessive force has been associated with greater physiological cost and also heavier loads on shoulder joints [3]. Boninger et al. [4] suggest that the direction or effectiveness of the resultant force on the pushrim can influence the load on the upper limbs. Forces exerted by the hands on the pushrim during manual wheelchair propulsion can be divided into radial, axial and tangential components. The relationship between tangential and resultant forces indicates the effectiveness of propulsion from a mechanical standpoint. A major tangential component for the same

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magnitude of strength increases the moment about the axis, and theoretically reduces the effort required for the same power. Moreover, the application of excessive force has been associated with greater physiological cost and also the heaviest loads on shoulder joints [3].

The majority of manual wheelchairs have pushrims made of circular metal tubes located at a distance of 20 mm from wheel. These pushrims have a tube diameter of 20 mm, which is too small for individuals whose hand length is approximately 180 mm [5]. In the first place, it reduces the contact area between the hand and the rim, which increases the pressure on the contact points of the hand and the forces transmitted to the delicate structures of the hand. Secondly, the inability to hold the rim with the entire palm and fingers reduces the mechanical efficiency by recruiting muscles to stabilize the hand on the rim instead of promoting power for propulsion of the wheelchair [6]. It is both notable and surprising that this pushrim design has existed since the middle of the twentieth century, whereas the design of grip tools, appliances, car steering wheels and other devices underwent enormous changes. Therefore, the wheelchair pushrim is a strong candidate for potential changes aimed at relieving pain in the upper limbs and prolonging the independent use of manual wheelchairs [7].

Many wheelchair users report that the design of the pushrim does not meet their needs during wheelchair propulsion. In a survey of 117 wheelchair users, only 39% reported using solely the pushrim for propulsion, 54% stated they hold the pushrim and tire simultaneously, and only 7% use the tire [8]. In addition to propulsion, braking is also an important element of the relationship between the hands and the pushrim. There have been personal reports of slipping or overheating, thermal discomfort and unpleasant smell due to the chemical reaction between sweat and metal, which also causes wear of the paint on the pushrim.

Considering the wheelchair pushrim as the handle of a manual instrument, it is believed that if the shape and dimensions are ideal it can be used more efficiently [9]. The hand/tool interface consists of hand, tool and task. In fact, these three components interact with each other, directly affecting the user's effectiveness, safety and health. The hand/handle can be considered an important part of the power transmission that is generated directly by humans on any instrument.

This study reports on the development of a manual wheelchair pushrim based on anthropometric and ergonomic concepts, whose shape and size are ideal for the function of manual wheelchair propulsion. In addition, the study evaluates the user's perception of the overall quality of the wheelchair equipped with the new pushrim.

Materials and methods

This study involves a technological innovation within the field of assistive technology, in which a wheelchair pushrim model was developed with emphasis on anthropometric features and ergonomic concepts, creating a virtual prototype that was manufactured in polymer. The pushrim prototype was tested by several wheelchair users, who rated the perceived quality of the wheelchair device.

Conceptual creation

Taking as reference the approximate hand's length of 180 mm for adults [5], and based on the principle of ergonomic design of maximizing contact area, the new design of wheelchair pushrim aimed at providing the user a functional and comfortable grip. The design was developed using CAD Solid Edge ST2 software (Siemens PLM Software, Plano, TX, USA) to create a virtual model of the wheelchair pushrim.

The handles of manually operated devices must be designed to avoid the frequent use of a finger or thumb, distributing physical demands to all the fingers. The distribution of pressure across the palm and fingers of the hand reduces the need for efforts at specific points, especially the thumb. This reduces the activity of the small muscles of the hand [10]. According to Shimada et al. [11], a significant part of the forces applied to the pushrim do not contribute to the forward movement, but are required to provide friction between the hand and the rim, which explains why some wheelchair users wear gloves. A larger contact surface for the hands may reduce the demand for muscle strength to hold the pushrim, resulting in less muscle work and increasing the efficiency of the movement.

Based on the virtual model designed with the Solid Edge ST2 software, a polymer wheelchair pushrim prototype was produced by the rapid prototyping technique, followed by a serial production of the parts using a silicone mold. These pushrims were assembled and installed on the rear wheels of the wheelchair in place of the original pushrims.

Evaluation of the wheelchair pushrim

Participants

The study involved six independent users of manual wheelchairs who are patients with spinal cord injuries treated at the physical therapy service of the Lucy Montoro Rehabilitation Institute in Ribeirão Preto, São Paulo, Brazil. These patients were invited and signed a consent form agreeing to participate in the study. This study was approved by the Ethics Committee of the Clinical Hospital of the Faculty of Medicine of Ribeirao Preto, Unievrsity of Sao Paulo.

The activities were based on the Wheelchair Circuit proposed by Kilkens et al. [12]. The participants performed the same activities with a wheelchair in two situations: wheelchair with the conventional pushrim; and wheelchair with the new pushrim, with 20 minutes of rest between the two activities, when the wheels were swapped. All subjects performed the activities in a standard design Freedom Plus wheelchair ((Freedom, Pelotas, RS, Brazil) (width of the back: 420 mm; height: 400 mm; seat: 420 mm wide and deep; pressure of the rear tires: 4.5 bar). The wheelchair used had the same technical specifications regarding seat measures and the standard type of pushrim of the subjects' wheelchairs. The order of pushrims used during data collection was randomized, and no blinding procedure was done, due to the clear difference in appearance of the devices. All the activities, which were performed on flat terrain, involved:

Three minutes of straight propulsion at a comfortable speed, repeating a course of 15 meters;

Two minutes of figure-eight-shaped propulsion around three markers placed on the floor at a distance of 1.5 meters;
One minute of maneuvers with the wheelchair, with only the rear wheels in contact with the ground, then moving forward, backward and turning.
Fifteen meters at full speed in a straight line.

Instrument of assessment

Upon completion of the above activities, the users answered a questionnaire containing nine questions, in order to register and evaluate their perception of the quality of the new device compared to that of the conventional pushrim. The questions involved mainly aspects of manual propulsion, focusing on the pushrim, with five comparative alternatives (a– much better; b– slightly better; c– no difference, d– slightly worse, e– much worse). This questionnaire was designed by the researchers for use in the present study and, thus, is not a validated tool (Appendix 1).

The results of the development and evaluation of the pushrim are described below.

Results

Conception and virtual model of the wheelchair pushrim

The new pushrim replaces the geometric design (cylindrical) of the original round tube pushrim with an ergonomic design aimed at providing a larger contact area without increasing the wheelchair's dimensions, and a secure and comfortable fit for the hands during both pushing and braking. To this end, the new device features a slightly curved upper surface on which the thumb, the thenar eminence and the base of the hypothenar eminence can rest; a lateral surface to support the distal half of the palm and proximal phalanges of fingers II, III, IV and V; and a lower surface to support the medial and distal phalanges of the fingers. Figure 1 illustrates the development of the concept of the new ergonomic pushrim.

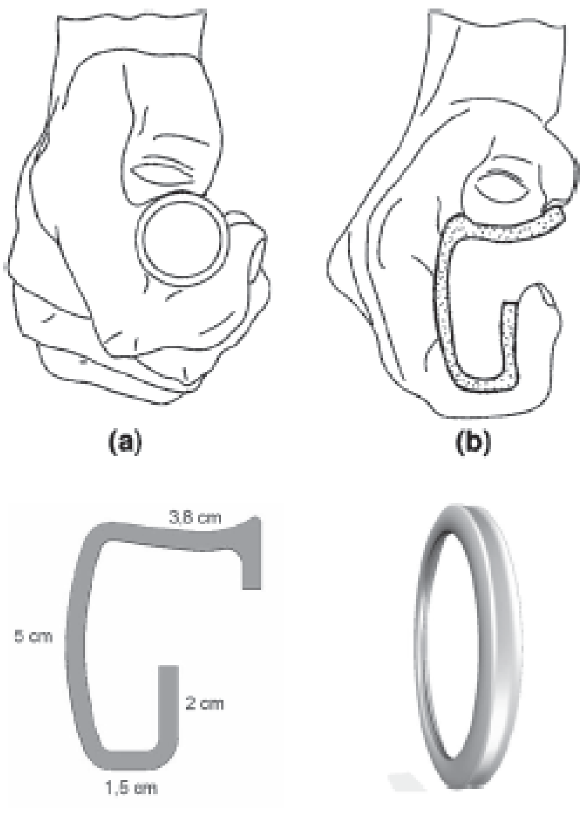


Figure 1. Conceptual development of the new ergonomic pushrim: (a) cross-section of the conventional pushrim; (b) idealization of the cross-section of the new pushrim; (c) final project: shape and measurements of the cross-section the new pushrim; (d) 3D image of the new pushrim.

Physical model of the pushrim

The rapid prototyping technique (inkjet print in plaster - PRINTER Z 310 - Z CORPORATION, Burlington, Massachusetts, USA) was chosen to produce the model due to its curve and asymmetric geometry. Due to the limited dimensional capacity of the conventional 3D printers, the design of the pushrim with the CAD software was divided into eight equal segments, which required an additional design of a part to connect a pair of segments internally (Figure 2). Each segment has a tab to attach it to the bottom surface of the rim, which supports the wheelchair tire. Both the segment and the connecting piece are designed for removal in a specific direction from the mold, i.e., after removal from the mold, each segment should be contained within the segment removed immediately before it.

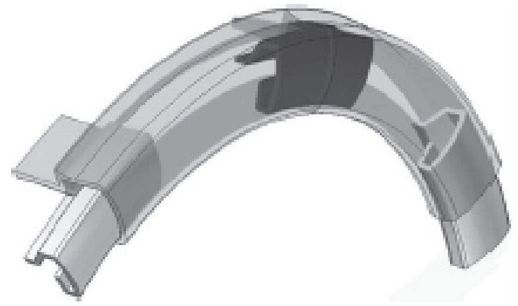


Figure 2. Mounting system of the pushrim segments for assembling with internal parts.

Manufacture– casting

A silicone mold (shore 35A hardness) was produced from the prototype model (Fig 3a). The polymer was then cast inside the mold cavity to mold the pushrim's segments and connecting pieces. Each pushrim of the wheelchair consists of eight segments and eight connecting pieces. Using plastic glue, these segments and connecting pieces were glued together inside a 525 mm diameter circular wooden template whose diameter was equivalent to that of the wheel on which the prototype would be installed (Fig 3b). Two wheelchair pushrims were assembled as described.

The pushrims were sanded and painted before testing. After removing the conventional pushrims, the new pushrims were screwed onto the rear wheels using the wheelchair's original installation system.

Material selection

For the design of a hand operated device, it is important that the material provides a firm grip for the hands, thermal comfort and adequate friction [13]. Also, the material selection had to be based on the requirements of manufacturing a single prototype, i.e., that the material had to be suitable for the production of parts using the technique of rapid prototyping followed by replication in silicone mold. Polymers of medium hardness (Shore D 70–90 hardness) appear to meet the demand, based on the concept of car steering wheel coating that replaced bakelite for more flexible polymers. In addition, in terms of total manufacturing cost, the polymer used in this study allows for casting at room temperature.

According to Smith [14], thermoset polymers for engineering design applications offer the following advantages: high thermal stability, high stiffness, dimensional stability, resistance to deformation under load, and good thermal and electrical insulation properties. Two casting systems– epoxy and polyurethane– were tested. Polyurethane (PU RP50 - Oligomtec) was selected, which presented a pot life of 40 minutes, preparation viscosity of 300–400 cPs, hardening time of 4 hours and cure time of 1 day. After curing, the material presented a Shore-D hardness of 83. The part presented a good fit to the silicon mold, with easy removal, less adherence to the mold and therefore good preservation of the mold, enabling the serial production of parts. In contrast, despite its low viscosity (2800–3300 cPs), the charged epoxy resin was very brittle, leading to fractures during removal and chemically attacking the silicone mold. Moreover, the composition of the charged epoxy system was more viscous, making it difficult to fill the mold.

Human skin is more sensitive to heat or cold in comparison with other parts of the body. The fingertips are good heat receptors and consequently are sensitive to heat conduction [15]. Therefore, at room temperature, steel feels colder than wood. Thermal comfort can be influenced not only by skin sensitivity but also by the thermal properties of materials, through differences in thermal conductivity. Polymers are known to have a very low thermal conductivity when compared to that of metallic materials, i.e., the thermal conductivity of polyurethane plastic is approximately 370 times lower than that of carbon steel [16,17]. The lower thermal conductivity of polymers compared to metals may represent a gain in comfort during wheelchair use by reducing the sensation of heat on the user's hands.

Hand contact with the pushrim

During preliminary tests the new wheelchair pushrim showed satisfactory coupling with the hands, also providing a firm grip, large surface contact and less flexion posture of the fingers than the conventional pushrim (Figure 4).

Figs 5a and b illustrate the differences with respect to coupling of the hand on the two different pushrims.

Equipment evaluation

Six experienced wheelchair users, with diagnosis of paraplegia due to traumatic spinal cord injury (ASIA A-B, levels of injury between T1 and T6), were invited to test the new wheelchair pushrims. All of them were men who used wheelchairs to move independently, with mean age of 33 ± 9.6 years. The mean time since injury was 4 ± 4.3 years, and the referred time of independent use of the wheelchair was 4 ± 2.6 years.

It is noteworthy that, after the tests with the two types of wheelchair pushrim, all the participants considered the new pushrim, in general, much better than the conventional one. Figure 6 describes the perception of users regarding the comfort in pushing, braking and maneuvering, coupling with hands, and force required to propel the wheelchair.

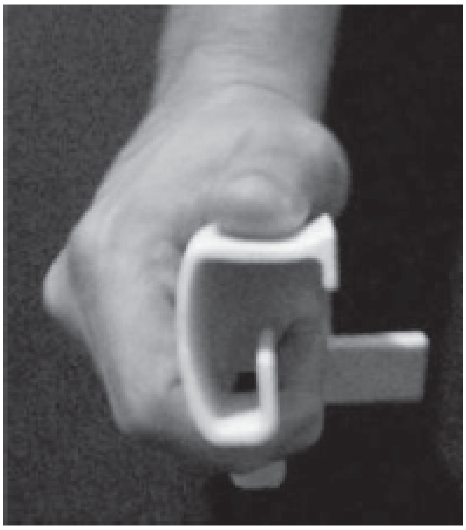
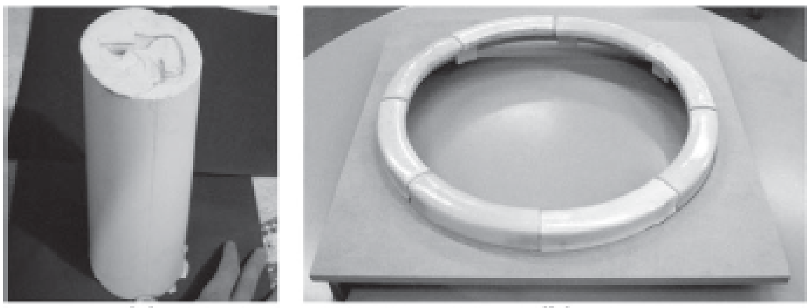


Figure 4. Hand fit to the new pushrim: cross-section image.



(a) (b)

Figure 3. (a) Silicon mold from which the pushrim segments were produced in Polyurethane; (b) assembly of the pushrim.

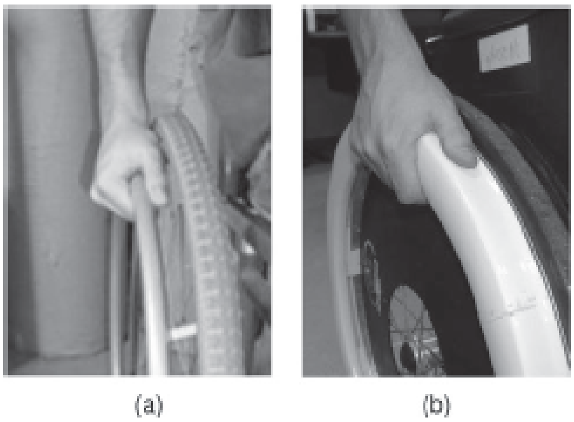


Figure 5. Hand fit to: (a) a conventional pushrim; (b) the new pushrim.

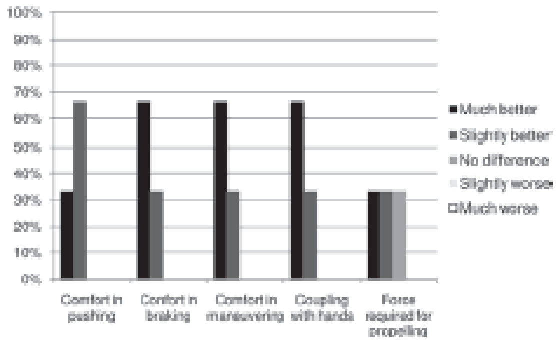


Figure 6. Wheelchair users' perception of the quality of the new wheelchair pushrim compared to the conventional pushrim. Vertical axis referring to the percentage of participants.

The users' perception about the appearance of the device was also verified. Most of the participants (67%) considered the appearance of the new pushrim better, and 33% indicated "no difference". Moreover, locomotion in a wheelchair with the new pushrim was considered easier (67% of the participants stated it was "very easy" and 33% claimed it was "somewhat easier").

Discussion

The new pushrim provided a functional grip, since the wrist joint remained in slight extension, positioning the superficial and deep flexor muscles of the fingers in a favorable condition for their action. This synergism between the finger flexors and extensor carpi muscles is essential for gripping. The extension of the wrist is considered functionally more important than flexing, since it enhances the action of the finger flexor tendons, increasing the grip strength [18,19]. The positioning of the finger joints can favor functional gripping when the force they exert is directed towards the palm of the hand, which increases the contact force of the entire palm against the pushrim, thus increasing its stability [20]. Therefore, by holding the pushrim, the fingers increase the pressure in the region of the palm against the lateral surface of the device, whose size and shape adequately accommodate the entire surface of this region of the hand.

In the design of hand tools, the diameter of the handle is one of the key points to maximize its performance, since it reduces the stress on the forearm muscles and tendons of the fingers during the use of hand tools. The cross-section of the conventional pushrim (20 mm diameter) provides 68.8 mm of contact surface, which is insufficient to support the entire hand, considering the length of the hand of approximately 180 mm [5]. Kong and Lowe evaluated five cylinders of varying diameters (25, 30, 35, 40, 45 and 50 mm) and observed that the highest strength and efficiency (greater torque with less muscle effort) were obtained from the handle with a diameter of 50 mm [21]. Shih and Wang demonstrated that the increase in maximum torque stabilizes at a plateau when the diameter of the grip increases above 50 mm [9]. Thus, these studies show that the diameter of 50 mm, with a contact surface of 157 mm in cross section, is able to provide firmer and more stable grip, with greater efficiency in the application of forces. These findings, applied to the analysis of the wheelchair propulsion, expose the limitations in the design of the conventional pushrim as a hand-operated device. In addition to the ergonomic design developed considering the best posture of hands for the proper management of the wheelchair, the ergonomic pushrim described here has approximately 123 mm of surface for hand's contact, supporting most of the hand, as required for a stable, firm and functional grip.

It is worth noting that torque is a function of the tangential force of the radius of a handle. In their study, Kong and Lowe [19] demonstrated that muscle efficiency increases when the diameter of the handles increases. In this case, the torque depends on the radius of the cylindrical handle, since it is generated by rotating the cylinder about its axis. However, in the present study, the radius on which the torque depends does not involve the fitting of hands on the pushrim, but on the axis of the wheelchair's rear wheel. However, the findings of Kong and Lowe [19] can be employed in the analysis of the present study, considering that a manual instrument with increased diameter of the handle (and hence, also an increased contact surface area) provides higher muscle efficiency and greater stability of the hand, thus meeting the objectives proposed in the ergonomic design of the new pushrim.

Improvements in the upper extremity symptoms and in the ability to perform functional tasks had already been reported with the use of the Natural-Fit (Three Rivers Holdings, Mesa, AZ, USA) [22,7], a product designed to provide an improved fit to the hand and relieve stress and pressure on the carpal tunnel. Although both the new pushrim described here and the Natural-Fit are based on ergonomic design, important differences can be observed. Concerning the size and shape of the devices, the ergonomic pushrim has greater vertical diameter (50 mm compared 38 mm from Natural-Fit), and its lateral surface has slightly convex shape proper to support the entire palm during grip. We believe that, during manual wheelchair propulsion, hands need not fully involve the rim, and therefore the largest vertical diameter associated with the convex contour of the lateral surface are sufficient to provide a firm and stable coupling to the brief but highly repetitive contact of hands on the pushrims. The design of the cross section is not, therefore, internally closed. Furthermore, while the Natural-Fit pushrim is an assembly of two separately coated components (a smooth for the palm of the hand and a higher friction surface for the thumb) for propulsion and braking, the ergonomic pushrim is made entirely of a single material: polyurethane. As a result, the contact of the hands on the pushrim can be kept the same either for pushing or to brake the wheelchair.

The results indicate that the new pushrim was well accepted by the wheelchair users, who stated that it facilitated wheelchair propulsion and who considered it, overall, an improvement over the conventional pushrim still in use today on all known wheelchair models. Several factors should be considered to understand these findings. As mentioned previously, the new device provides a high contact surface for hands and fingers and allows for optimal posture, with no overload at specific points of contact, since the entire palm and fingers are supported. The design of the new wheelchair pushrim is based on ergonomic concepts involving the anthropomorphic and anthropometric characteristics of the hand. As a result, it is comfortable and facilitates the propulsion of manual wheelchairs, according to the participants, thus embodying the concept of comfortable usability.

The appearance of the new pushrim was best assessed by comparing it to the conventional pushrim. Concern about the appearance of the device reveals the user's desire for a less stigmatizing and obsolete round design, which is characteristic of the classical model in use for many decades. This classical design does not consider the individual, and contributes to the continued image of a wheelchair as a negative symbol of physical disorders, disabilities and handicaps [23]. Thus, the design of accessories for wheelchair users should be guided not only by functional aspects but also by innovative features that minimize the individual's limitations and strengthen his abilities. This requires significantly changing the visual concepts of equipment used so far.

Another aspect that may have positively influenced the assessment of the device was the material it is made of– polyurethane. In the manufacture of handles, metallic materials should be avoided because they mechanically compress the tissues of the hand and increase the transmission of cold, heat and vibration. Moreover, metal pushrims have a relatively high heat transfer, causing discomfort in cold weather. On the other hand, rubber coated metal pushrims, which provide good traction, greatly increase the temperature of the hand during braking, making them uncomfortable [24]. Thus, the polyurethane pushrim appears to offer a better option for the user's mechanical and thermal comfort than the metal pushrim.

Finally, it should be emphasized that the strength of grasp applied to a hand tool increases significantly with increasing weight of the equipment or resistance to movement [25]. Thus, a primary objective in the design of equipment for manual wheelchairs should be weight reduction, since this is related to lower risk of injury during its use [26].

Limitations

Although important information was gained from this investigation, several limitations need to be noted. First, the small number of subjects and the sample not selected randomly to test the wheelchair pushrims limits the generalization of the findings. Our sample, therefore, represents a group of adults with paraplegia due to spinal cord injury, who independently uses the wheelchair. Due to the need to create a survey tool specific for the purposes of this study and, therefore, not a validated tool, the comparison with previous studies is limited. Furthermore, potential limitations in the design of the pushrim must be taken into account. The use of only one size of prototype may limit the extension of the results to others populations with differences in anthropometric measures. Moreover, despite the good technical characteristics of the polyurethane used, it does not present the same resistance to impact and deformation of the metallic materials, and thus may be broken in cases of high-intensity impact.

Conclusions

The design of the new wheelchair pushrim presents innovative features that provide a proper fit and greater comfort for the hands, allowing for a hand and wrist posture that favors a functional grip. The product provides the user with a larger contact surface and improved thermal comfort due to the lower heat transfer coefficient of polyurethane than that of the conventional metal pushrim. The wheelchair users referred that the new ergonomic pushrim provided greater comfort in propelling, braking and maneuvering of the wheelchair, better coupling to the hand, less force required to propel, easier locomotion and a more attractive look than the conventional pushrim. The promising initial results presented in this study encourage further investigation of the kinetics and kinematics of manual wheelchair propulsion with the new pushrim. In addition, further studies involving a larger number of participants should be conducted to evaluate their acceptance and satisfaction with the device, thus obtaining more conclusive data to justify the production of the new pushrim and to recommend its use in wheelchairs. The application of innovative concepts in the design of assistive technology products, a characteristic that defines the essence of this study, indicates a trend for the development of increasingly advanced products and solutions, including customization for people with special needs. Furthermore, it helps to do away with negativistic paradigms in favor of positivist ones that focus on the potential of the disabled person. In this sense, the device should not only meet the user's needs and help him overcome difficulties, but also maximize his potential and provide new opportunities.

Acknowledgement

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Declaration of Interest

The authors report no conflict of interest.

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Appendix 1. Comparative questionnaire of two types of wheelchair pushrim

1. With respect to driving comfort of the wheelchair, you consider the new pushrim (as compared to conventional pushrim):
   a) Much better
   b) A little better
   c) Same
   d) Somewhat worse
   e) Much worse

2. With regard to the comfort to brake the wheelchair, you consider the new pushrim (as compared to conventional pushrim):
   a) Much better
   b) A little better
   c) Same
   d) Somewhat worse
   e) Much worse

3. In your opinion, the coupling of your hands to the new pushrim is, compared to the conventional pushrim:
   a) Much better
   b) A little better
   c) Same
   d) Somewhat worse
   e) Much worse

4. To maneuver the wheelchair and transpose some obstacles (like small steps, for example), you consider the new pushrim, compared to conventional pushrim:
   a) Much better
   b) A little better
   c) Same
   d) Somewhat worse
   e) Much worse

5. With regard to the force needed to propel the wheelchair, how do you evaluate the new pushrim, compared to the conventional pushrim?
   a) Much less force
   b) A little less force
   c) Same
   d) A little harder
   e) Much harder

6. To hold the new pushrim, compared to the conventional pushrim, how much force did you need to do?
   a) Much less force
   b) A little less force

c) Same
d) A little harder
e) Much harder

7. What is your perception regarding the appearance of the new wheelchair pushrim, comparing with the conventional pushrim?
a) Much better
b) A little better
c) Same
d) Somewhat worse
e) Much worse

8. You consider that the wheelchair locomotion with the new pushrim, compared to the conventional pushrim, became:
a) Much easier
b) a little easier
c) Same
d) A little harder
e) Much more difficult

9. What is your overall evaluation of the new pushrim, in comparison with the conventional pushrim?
a) Much better
b) A little better
c) Same
d) Somewhat worse
e) Much worse

Biomechanical and Perceptual Evaluation of the use of a Servo-Controlled Power-Assistance System in Manual Wheelchair Mobility

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***Abstract*—This preliminary study investigated the effect of the implementation of a servo-controlled power assisted mechanism in a manual wheelchair on the demands of the upper limb muscles and the subjects' perception about the effort and difficulty to perform mobility tasks. The electromyographic activity of four upper limb muscles (pectoralis major, anterior deltoids, triceps and biceps) and the rate of perceived exertion and difficulty in six different wheelchair mobility tasks performed by eight subjects were analyzed comparatively with the use of two different wheelchairs: a standard manual device and a prototype of a servo-controlled power assisted wheelchair. The results show that the subjects considered easier and less strenuous to perform most of the wheelchair mobility tasks with the use of the power-assisted chair, in comparison to the manual wheelchair. Data from muscles' activity showed that moving on an ascent ramp with the servo-assisted wheelchair reduced the biomechanical demand on the upper limbs, in comparison with the standard wheelchair. However, the other five mobility tasks did not have the same results, suggesting that the servo-controlled mechanism still needs to be improved to provide consistent benefits for the users in terms of reducing the biomechanical loads during manual propulsion.**

Keywords*—*Wheelchairs, Mobility, Propulsion, Robotics, Biomechanics.

I. Introduction

An increased amount of research has shown that manual wheelchair propulsion is a very inefficient and strenuous mean of mobility [1-3]. As a result of the long-term use of manual wheelchairs, users tend to develop pain and injuries that, ultimately, may affect their independent and safe mobility. Studies have shown a high prevalence of problems related to the biomechanical overload that the upper limb' muscles are exposed when repetitively pushing the handrims to move with a wheelchair [1,4]. As maintaining the integrity of the upper limbs' function is a key factor for independence, reducing the demand on the upper limbs and improving mobility efficiency is therefore important to benefit user's participation and quality of life.

Ergonomic solutions for the design of the wheelchair and its components have been reported in previous studies [5-8]. Robotic systems for wheelchairs have also been proposed to address conditions and barriers that users find in daily mobility and transfers [9,10].

When it comes to improving manual propulsion efficiency, pushrim-activated power assisted wheelchairs (PAPAWs) have been proposed to provide complementary torque for the user's forces applied to the handrims, in an attempt to reduce the biomechanical demand as well as to improve mobility efficiency. Such systems comprise in hub sensorial and motor system that detect and increase the user's actions on each rear wheel separately. While studies have found positive results of reduced demand on the upper limbs and increased distance travelled [11-12], problems with maneuverability have also been reported [13]. It is possible that the independent action of the motors on each rear wheel result in some difficulty in maneuvering the chair as it alters the turning radius originally intended by the user. Therefore, reducing the biomechanical demand on the upper limbs while maintaining similar drivability to a manual wheelchair may benefit user's mobility.

This study aimed to investigate the effect of the implementation of a servo-controlled power assisted mechanism in a manual wheelchair on the demands of the upper limb muscles and the participants' perception about the effort and difficulty to propel the wheelchair in different mobility tasks.

II. Material and Methods

A. Participants

A sample of eight subjects without disabilities, all male (average age of 28±16.33 years, average weight of 74.5±10.74 kg and average height of 1.7±0.05m) were recruited at Sao Carlos School of Engineering (University of São Paulo, São Carlos, Brazil), and voluntarily participated in this study. Participants met the following inclusion criteria: (1) minimum age of 18 years; (2) had no upper limbs pain, injuries or disorders that could influence the activity of manual wheelchair propulsion. Prior to data collection, participants read and signed an informed consent form that had been submitted and approved by the Ethics Committee of the Faculty of

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Architecture, Arts and Communication - UNESP (Process. N. 800.500).

B. *Wheelchairs and procedures*

Two wheelchairs were used to compare biomechanical and perceptual data from the subjects: a standard manual wheelchair with foldable frame (AVD Alumínio Reclinável, ORTOBRAS), total mass of 17 kg (Fig. 1); and a prototype of a servo-controlled power assisted wheelchair (Fig. 2).

Fig. 1. Standard foldable-frame manual wheelchair.

(a) (b) (c)

Fig. 2. Servo-assisted wheelchair prototype: (a) front view; (b) perspective view; (c) mechanical and electronic components under the seat.

The servo-assisted wheelchair prototype, model 2017, is an evolution of 2014 model [7], consisting in a hybrid model with a single central DC motor, model EC 45 brushless from Maxon, with a 4-Q-EC DEC 70/10 Maxon driver with setup in current mode. Between the wheels and the motor, there are two gears: the first is the motor output, being a planetary gear model Maxon GP 62 A with reduction ratio changed to 3.65:1; the second, between the planetary output and wheels, a differential transmission with 6:1 reduction ratio. The maximum linear speed reached by this configuration was 2.8 mph without any user input. For the control logic and data acquisition, it was implemented a National Instruments NI-DAQ USB 6009 board connected to a Microsoft Surface tablet running an executable Labview program. An operational amplifier with gain equals to two was also used once the maximum driver input was 10 V and the maximum NI-DAQ output was 5V, meaning that the motor was being underused. Currently, this model has fixed current output with three different options: 35%, 70% and 100% maximum current characterizing a proportional gain controller. In this configuration, the wheelchair weights 33 kg equipped with 24V lithium battery with 10AH charge that supplies the whole system.

Fig. 3 displays the block diagram proposal, where the user specifies the desired current options, leading to a reference current (*Iref*). This way, the Maxon driver tries to follow this current with a manufacturer internal control loop, which is simplified by the blocks inside the dotted block: a current error (*Ierr*) is the result between the reference current and the actual current (*Iact*), obtained via internal circuitry and sensors. As a result, the motor gives an output torque (*Tact*), helping the user input on the wheelchair (*Tuser*). The wheelchair, then, displays a linear translational velocity. It works open loop for the user input, only closed in the motor internal current tracking.

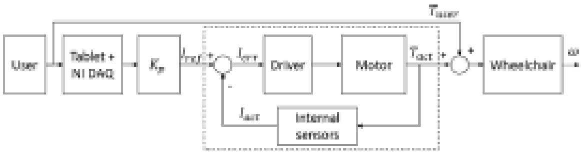

Fig. 3. Block diagram for the wheelchair control system

The test consisted of performing, with both wheelchairs, six different mobility tasks: 15-meters forward propulsion at self-selected speed; 15-meters forward sprint as fast as possible; circular trajectory (two-meters radius) in anti-clockwise direction; slalom course (15 meters course with aligned cones separated by decreasing distances of 2.5 m, 2.5 m, 2 m, 2 m, 1.5 m, 1.5 m, 1 m, 1 m, 1 m) as proposed in a previous study [3]; descent ramp; and ascent ramp. During the tests, surface electromyography (sEMG) data of *anterior deltoids, pectoralis major, triceps brachii* and *biceps brachii* were collected using wireless sensors and a Data Logger module (T-Sens, TEA Ergo, France) to register the EMG signals. Triode surface self-adhesive electrodes T3402M (Thought Technology, Canada) were placed in the respective positions for each muscle in accordance with the SENIAM project (www.seniam.org) on the dominant side of the subject's body to record the electrical activity of the respective muscles.

Surface EMG data were sampled at 2048 Hz with RMS frequency calculation of 128 Hz. EMG data analysis was performed with the CAPTIV L-7000 software (TEA Ergo, France). All EMG calculation was in mV and analyzed during the complete trajectory, and the first and last pushes were discarded, in order to analyze the muscle activity in plain motion. After each trajectory, subjects were asked to rate their perceived exertion (RPE) and the difficulty to perform each task in a Borg's Scale [14] and a ten-point analog visual scale, respectively. Data analysis of subjects' perception was performed using descriptive statistics with mean and standard deviation, and Students' T-test was applied to verify statistical difference between the subjects' perception with the two wheelchairs. For the EMG analysis, mean values were obtained for the four muscles of all subjects and presented descriptively by the means of the percentage of the activity relative to the maximum voluntary contraction (MVC). Significance level was determined by $p<0.05$. All statistical analyses were performed using the software SPSS version 22.0 (SPSS Inc., Chicago, IL, USA).

III. Results

The results show that both the biomechanical load on the upper limbs muscles as well as the subjects' perception of exertion and the difficulty to perform the six different mobility tasks are influenced by the wheelchair type (standard manual wheelchair and servo-controlled power assisted wheelchair). Surprisingly, the results of the EMG showed that, in most of the situations investigated in this study, there were higher levels of muscular activity when moving with the servo-controlled power-assisted wheelchair prototype, except when moving on ascendant ramp (for the triceps, deltoids and biceps), as shown in Tables I to VI.

TABLE I. EMG ACTIVITY IN FORWARD PROPULSION.

	Forward propulsion			
	Pectoralis	*Triceps*	*Deltoids*	*biceps*
Manual wheelchair % mve	4.28 (3.77)	3.49 (1.63)	10.9 (7.21)	2.7 (1.84)
Servo assisted wheelchair % mve	8.3 (5.43)	3.98 (1.05)	10.68 (4.64)	3.31 (3.6)
difference	4.02	0.49	-0.22	0.61
Variation of the Mean (%)	68.34	26.56	-4.40	18.76

TABLE II. EMG ACTIVITY IN FORWARD PROPULSION SPRINT.

	Forward propulsion max			
	Pectoralis	*Triceps*	*Deltoids*	*biceps*
Manual wheelchair % mve	12.67 (7.9)	9.76 (4.39)	18 (9.73)	4.63 (2.83)
Servo assisted wheelchair % mve	19.21 (7.79)	13.81 (6.27)	16.06 (5.83)	6.95 (4.41)
difference	-6.54	-4.05	1.94	-2.32
Variation of the Mean (%)	51.61	41.49	13.22	3.84

TABLE III. EMG ACTIVITY IN CIRCULAR TRAJECTORY.

	Circular			
	Pectoralis	*Triceps*	*Deltoids*	*biceps*
Manual wheelchair % mve	6.18(2.9)	3.66(1.53)	10.56(4.29)	3.79(2.71)
Servo assisted wheelchair % mve	10.8(10.77)	4.12(1.91)	11.04(4.5)	3.57(2.61)
difference	-4.62	-0.46	-0.48	0.22
Variation of the Mean (%)	64.42	19.98	-2.76	-6.64

TABLE IV. EMG ACTIVITY IN ASCENT RAMP.

	Ascent ramp			
	Pectoralis	*Triceps*	*Deltoids*	*biceps*
Manual wheelchair % mve	8.74 (4.54)	10.16 (3.96)	15.01 (3.56)	4.08 (2.28)
Servo assisted wheelchair % mve	13.97 (14)	8.03 (2.67)	13.85 (5.39)	3.73 (2.58)
difference	-5.23	2.13	1.16	0.35
Variation of the Mean (%)	52.85	-22.54	16.11	-16.11

TABLE V. EMG ACTIVITY IN DESCENT RAMP.

	Descent ramp			
	Pectoralis	*Triceps*	*Deltoids*	*biceps*
Manual wheelchair % mve	2.44 (0.76)	1.81 (1.36)	8.86 (4.09)	4.21 (3.56)
Servo assisted wheelchair % mve	3.78 (2.91)	3.05 (1.08)	10.15 (4.75)	2.82 (2.62)
difference	-1.34	-1.24	-1.29	1.39
Variation of the Mean (%)	40.32	68.42	13.47	-40.23

TABLE VI. EMG ACTIVITY IN THE SLALOM COURSE.

	Slalom course			
	Pectoralis	*Triceps*	*Deltoids*	*biceps*
Manual wheelchair % mve	9.29 (6.93)	3.87 (1.85)	9.87 (4.11)	4.05 (4.07)
Servo assisted wheelchair % mve	8.53 (5.93)	4.51 (1.84)	10.56 (4.11)	3.77 (3.58)
difference	0.76	-0.64	-0.69	0.28
Variation of the Mean (%)	-4.74	21.32	3.19	-9.2

In contrast to the EMG findings, the participants' RPE was lower when performing mobility tasks with the servo-assisted wheelchair compared to the standard manual wheelchair (Fig. 4). Significant differences were found in the forward propulsion at self-selected speed ($p=0.01$), forward sprint ($p=0.01$) and slalom course ($p=0.03$). Although not statistically significant, the only situation with higher average of RPE was moving down on a ramp, suggesting that the torque provided by the motor enhancing the inertia lead to an increased effort to decelerate the chair. Similar results were found in the participants' perception of difficulty with lower rates with the use of the prototype of the servo-controlled power-assisted wheelchair, with statistical difference found in the following mobility tasks: forward propulsion at comfortable self-selected speed ($p=0.03$), circular (2-meters radius) trajectory ($p=0.02$), slalom course ($p=0.03$) and ramp ascent ($p=0.02$), as shown in Fig. 5.

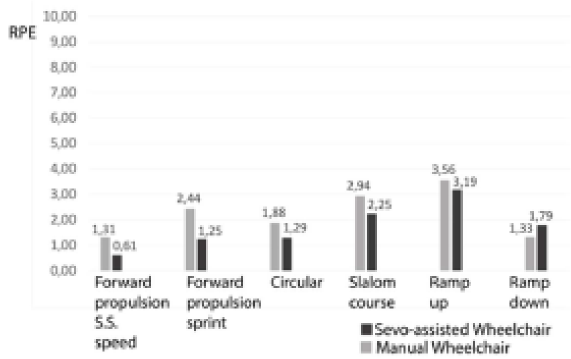

Fig. 4. Perceived effort during different mobility tasks with the two wheelchairs. * $p<0.05$.

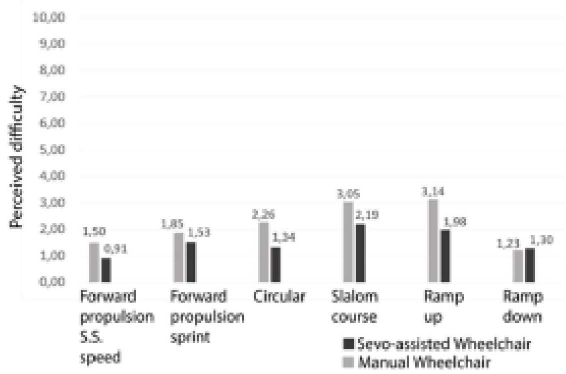

Fig. 5. Subjects' perception of difficulty in performing mobility tasks with the two wheelchairs. * $p<0.05$.

To illustrate the comparison of the results of the EMG measurements during the mobility tasks with the two wheelchairs, Fig. 6 presents the ratio between the standard manual wheelchair and the servo-controlled assisted wheelchair (MW / SCAW) in terms of the mean EMG activity of all muscles for all the trajectories. Values above the 1-line means that the biomechanical demand was higher with the manual wheelchair in comparison to the servo-controlled wheelchair. In turn, values below the 1-line reveals the opposite: higher demand on the upper limb muscles when propelling the servo assisted wheelchair.

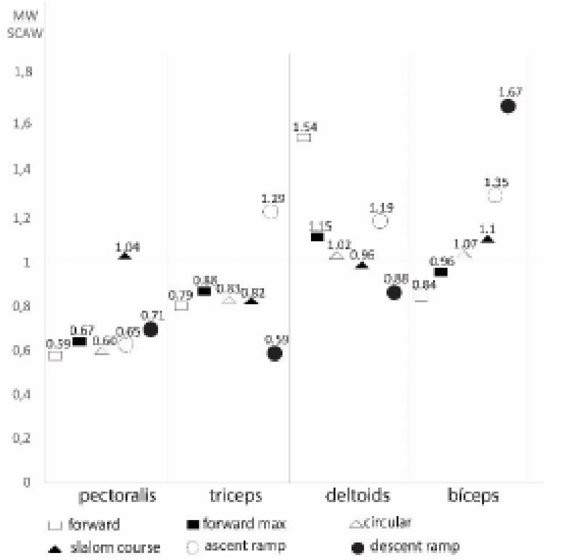

Fig. 6. Ratio (MW/SCAW) of the mean EMG for the manual wheelchair (MW) and servo-controlled assisted wheelchair (SCAW).

IV. DISCUSSION

This study found that providing power assistance complimentary to manual propulsion influences the biomechanical demand on the upper limbs' muscles and the subjects' perception of effort and difficultness in performing different mobility tasks. However, the EMG findings and the subjects' perceptions have some controversial results: while the perceived effort and difficulty was higher with the manual wheelchair in most of the mobility tasks, the measurements of muscular activity were lower with the manual wheelchair in comparison to the servo assisted device in many of the situations. A possible reason for the increased EMG activity with the power assistance may be the resistance that the motor transmits to the rear wheels axle that, ultimately, results in a slight resistance for the user to start pushing the handrims. Also, the increased mass (33 kg) of the prototype may have influenced, and future work should focus on reducing the mass of the prototype. However, EMG findings indicate that when moving up on a ramp - a problematic mobility situation for wheelchair users - the demand on the upper limbs muscles was reduced in comparison to the manual wheelchair.

Based on the results presented in Figure 5, it can be noted that both pectoralis and triceps muscle had lower activation with the use of the manual wheelchair compared to the power-assisted one, while the ratio for the anterior deltoids and biceps are close to the 1-line and above it in some tasks. For ascending a ramp - one of the most challenging mobility task to perform with a manually propelled wheelchair – the muscle activity was lower with the use of the power-assisted device for three (anterior deltoids, triceps and biceps) of the four muscles investigated, suggesting that power-assistance may facilitate moving on ramps and incline terrains.

Subjects considered easier and less strenuous to move with the power assisted chair in comparison to the standard manual one in all the mobility tasks, except in one situation. This is a positive finding, considering that problems in maneuvering PAPAW's have been reported [13]. Improving the drivability and maneuverability is an important issue for manual wheelchairs with power-assistance system.

This study has limitations that need to be noted. First, the sample size is relatively small and only subjects without disabilities participated. Therefore, the results may not be fully representative of a wheelchair user. Furthermore, it is possible that the knowledge of using an automated wheelchair may have influenced the perception of the participants. Future studies with larger sample size and real wheelchair users may provide a clearer view on the influence of the use of the servo-controlled power assisted wheelchair on the biomechanical demands and subjects' perceptions.

Additionally, the proportional controller is not the solution that will be implemented in future works, due to the fact of low assistance to the user: it may be another cause of the high efforts by the user. Interaction control, such as impedance controller [15], is a good candidate to aid the user in the process of maneuvering the wheelchair. The gear friction and other effects due to unmodeled dynamics can be minimized using other compensators [16], giving the user the sensation of transparency of the motor [17].

V. CONCLUSION

The current study found that the prototype of a servo controlled power assisted wheelchair has the potential to benefit the users' mobility by reducing the perceived effort and difficultness in performing different wheelchair mobility tasks, as well as reducing the biomechanical load on the upper limbs muscles when ascending a ramp. However, electromyography data showed an increased demand on the upper limbs in forward propulsion at comfortable speed, forward sprint, circular trajectory and slalom course. Besides the increased mass of the prototype, another possible explanation for these findings is that the motor acting on the rear wheels' axle adds a resistance to the initial phase of pushing the handrims forward. Future work should focus on reducing the total mass of the power-assisted system as well as minimizing the resistance of the motor in the wheels movement resulted from the user's pushes on the handrims, and on implementing other control techniques for user aid and transparency of the system.

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ANEXO 06

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Review

Aspects of Manual Wheelchair Configuration Affecting Mobility: A Review

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Abstract. Many aspects relating to equipment configuration affect users' actions in a manual wheelchair, determining the overall mobility performance. Since the equipment components and configuration determine both stability and mobility efficiency, configuring the wheelchair with the most appropriate set-up for individual users' needs is a difficult task. Several studies have shown the importance of seat/backrest assembly and the relative position of the rear wheels to the user in terms of the kinetics and kinematics of manual propulsion. More recently, new studies have brought to light evidence on the inertial properties of different wheelchair configurations. Further new studies have highlighted the handrim as a key component of wheelchair assembly, since it is the interface through which the user drives the chair. In light of the new evidence on wheelchair mechanics and propulsion kinetics and kinematics, this article presents a review of the most important aspects of wheelchair configuration that affect the users' actions and mobility.

Key words: Wheelchairs, Rehabilitation, Ergonomics

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INTRODUCTION

The use of a manual wheelchair suitable for a user's individual characteristics and needs can improve their independence, sense of participation and quality of life[1–3]. Changes in the wheelchair configuration can affect propulsion forces, the range of motion (ROM) of the upper limb joints, rolling resistance and system stability. Ultimately, all these aspects determine how easy or difficult it is to propel a wheelchair in everyday mobility. System stability and mobility performance are two inter-related variables: improving one has an impact on the other. Accordingly, healthcare professionals have to find the best balance between stability and performance when prescribing a wheelchair. Consequently, understanding how the changes in wheelchair configuration impact a user's work and system stability is important for minimizing the demand on the upper limbs during manual propulsion and optimizing the user's mobility.

Although a widely used assistive technology device, the wheelchair has been cited by many users as the main factor limiting their community participation[4]. Indeed, the daily distance traveled and the average speed of wheelchair users are significantly lower than those of individuals without disabilities[5–9]. Although quantifying the specific contribution of the equipment to this limited mobility is not possible, it is reasonable to state that the wheelchair design and mechanics play an important role in it. Furthermore, the distance traveled should not be thought of as the only variable representing daily mobility, since it does not reflect how people move but only how far people go. However, it does illustrate the existing gap between walking and wheelchair mobility.

Manual wheelchair propulsion exposes the upper limbs to a harmful combination of load and repetition, resulting in a high prevalence of shoulder abnormalities among wheelchair users[10–12]. Since wheelchair users rely on their upper limbs for most daily activities, the presence of pain and injuries limits their mobility, independence and quality of life[13]. Therefore, minimizing mechanical loads during manual propulsion and optimizing mobility efficiency must be addressed by researchers, manufacturers and clinicians in an attempt to improve overall mobility. In this context, the appropriate prescription is important in the provision of the most suitable equipment for a user's needs and expectations. Somewhat surprisingly, a recent study found that

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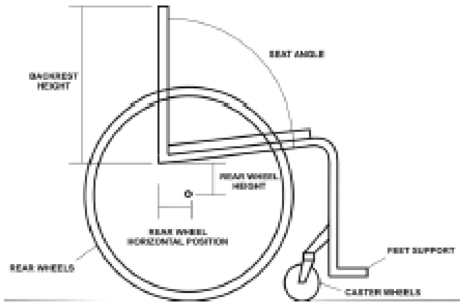

Fig. 1. Wheelchair configuration: factors that affect manual mobility

Fig. 2. Rear wheel camber (front view)

68% of the evaluated wheelchairs were not suitable for their users, and this may be interpreted as a result of prescription errors[14)].

Many studies have investigated how different wheelchair configurations impact the biomechanics of manual propulsion. Seat angle and dimensions, rear wheels' vertical and horizontal position, and wheel size and camber have been shown to affect propulsion efficiency and wheelchair drivability[15–22)]. In an effort to preserve upper limb function among wheelchair users, the Paralyzed Veterans of America Consortium of Spinal Cord Medicine[23)] provided some guidelines for prescribing and adjusting a wheelchair in order to reduce the risk of developing injuries in to the upper extremities. However, recent studies have brought to light new evidence on the role of wheelchair configuration in wheelchair mechanics[24–26)].

This review paper discusses the evidence on the aspects of wheelchair configuration affecting users' work and mobility. The review covers the most relevant aspects of the interaction between wheelchairs and users, updating current knowledge on wheelchair mobility with valuable information about research, development and innovation on wheeled mobility. Ultimately, clinicians, manufacturers and users may benefit from this study when prescribing, designing and selecting a wheelchair that provides the best mobility performance, comfort and functionality for the user.

WHEELCHAIR COMPONENTS AND CONFIGURATION

The most common aspects of wheelchair components and configuration indicated as affecting manual mobility are those related to the geometry of the system assembly, as shown in Figs. 1 and 2. In other words, the relative position of each component related to the others, and to the user, determines wheelchair mechanics, stability and the biomechanics of manual propulsion. The evidence related to each of these aspects affecting wheelchair mobility are presented and discussed below.

BACKREST HEIGHT

The backrest configuration influences the trunk support and upper limbs' ROM. These aspects are counterposed when one considers the two extreme situations: while a higher backrest provides greater support, it limits shoulder extension, which is particularly undesirable, since it is necessary to posteriorly grip the handrims of the wheel when starting to push a wheelchair. On the other hand, lower backrests allow the upper limbs to move freely, but back support and posterior stability are limited. Based on our clinical experience, most lightweight manual wheelchairs have backrests with a standard height of 400 mm.

A study by Yang et al.[27)] found that a lower backrest (200 mm, versus the highest 406 mm) allowed greater shoulder ROM and greater push angle and push time, thus reducing push frequency. However, backrest height did not significantly affect the forces applied to the handrim. According to Cherubini and Melchiorri[14)], users with impaired trunk control would benefit from higher backrests, which should be positioned 20 mm below the scapulae inferior angle. Those with intact trunk control should use lower backrests, taking the top of the lumbar spine as a reference. Since the seat configuration depends on the user's physical characteristics, the use of anatomical references seems to be the most appropriate approach, with the backrest height ranging from 200 mm to 406 mm, as proposed by Yang et al.

SEAT AND BACKREST ANGLE

Reclining the seat angle is a common procedure used to improve a user's sitting balance and functional reach, but it also affects the biomechanics of manual propulsion. The use of straight seat angles is related to the development of shoulder pain[28)]. However, in terms of propulsion efficiency, the optimal seat inclination is still not known. Desroches et al.[29)] showed that altering the seat angle (0°, 5° and 10°) and backrest angle (95°, 100° and 105°) did not influence the shoulder loads during manual propulsion by elderly wheelchair users.

The pressure on the seat interface is also an important concern for therapists when configuring the seat and backrest angles. The study by Park and Jang[30)] did not report

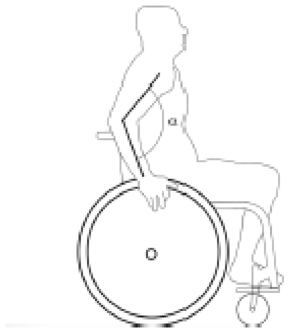

Fig. 3. Elbow angle (α) as a reference for the optimal vertical position of the rear wheels

definitive findings supporting the hypothesis that a reclined backrest (with an angle wider than 90° in relation to the horizontal line) reduces the pressure on the seat interface. Although a reduction in the pressure on the ischial tuberosity was found, there was an increase in the peak pressure on the sacrococcygeal region. Furthermore, the study of Maurer and Sprigle[31)] found no indication that increasing seat angle implies in increased seat interface pressure. Their results showed that less pressure was concentrated under the ischial tuberosities with increasing seat inclination, which seems to load slightly more body weight under the thighs and away from the ishcial tuberosities.

ANTERIOR–POSTERIOR AXLE POSITION OF THE REAR WHEELS

The anterior–posterior position of the rear wheels influences two important aspects of wheelchair mobility: stability and manual propulsion. While positioning the wheels rearward improves stability, it limits the user's ability to reach the handrims in this rearward position, thus reducing the push angle. Alternatively, moving the wheels forward improves propulsion biomechanics but reduces stability. The optimal position of the rear wheels is a client-dependent decision, based on the user's perception of stability and ease of chair propulsion. However, there are some objective guidelines to support this decision. The rear wheels should be positioned in the most forward position that does not compromise system stability[23)]. Gorce and Louis[16)] showed that, when moving the rear wheels forward, push angle and shoulder ROM are increased, thus reducing both push frequency and handrim forces, minimizing the risk of upper limb injuries[32)]. In addition to the biomechanical benefits, moving the rear wheels forward diminishes the wheelchair length and, as a result, facilitates turning maneuvers by reducing the rotational inertia of the system[24)].

VERTICAL POSITION OF THE REAR WHEELS

The vertical distance between the rear wheels and the seat greatly influences the biomechanics of manual propulsion. Having a lower seat benefits manual propulsion because it results in increased push angle. However, it results in increased upper limbs' ROM, which is potentially harmful if physiological limits are exceeded[33)]. On the other hand, when the user is too high above the wheels (i.e. in a higher seat), he/she can only push the handrims over a short distance (small push angle), and to maintain the desired speed, the user has to increase push frequency[34)], which may lead to muscular fatigue[32)]. The relation between seat height, push angle and push frequency has been investigated by Richter et al.[35)] and Wei et al.[36)]

The optimal seat height is determined by the elbow angle when the user holds the handrim at its top position (Fig. 3). Previous studies have shown that elbow angles ranging from 100° to 120° are related to improved propulsion efficiency and lower energy expenditure[37–39)]. Lower seat heights (elbow angles ranging from 80° to 90°) have been shown to be less efficient in terms of handrim forces and cardiorespiratory parameters[37)]. Therefore, in order to preserve upper limb function, it is recommended to set up the chair with the seat positioned at such a height that the elbow angle ranges from 100° to 120°[23)].

CAMBER OF THE REAR WHEELS

Stability is enhanced with wheel camber, especially when moving over lateral slopes. In addition, the hands are better protected against trauma because the wheels touch the floor spanning a wider area than the hands have in contact with the handrims. Maneuverability is also enhanced by wheel camber, which facilitates turning maneuvers.

Previous studies have investigated the effects of wheel camber on propulsion biomechanics. Camber angles wider than 15° increase the elbow ROM, reduce wrist radial deviation and increase wrist ulnar deviation[15)]. The changes in wrist kinematics are a consequence of the contact and release positions of the handrim happening in a more forward position. Camber angles ranging from 0° to 9° have been shown not to affect the cardiopulmonary parameters of manual propulsion[40)]. In addition, the average acceleration of the wheelchair is greater with 15° of camber, compared to cambers ranging from 0° to 9°[15)]. This finding is related to the increased rolling resistance generated by angles greater than 9°, which require the user to increase angular acceleration in an effort to maintain the average velocity[41)]. Rolling resistance is reduced by cambers up to 9°, compared to wheels with no camber[42)]. Perdios et al.[40)] indicate that 6° is the optimal angle for rear wheel camber, in terms of lateral stability in inclined planes, comfort during handrim propulsion, maneuverability and the general preferences of manual wheelchair users. However, rear wheel camber increases the system's overall width, which may lead to problems when moving in tight spaces.

FRAME MATERIAL

The frame mass plays an important role in the mechanics of a manual wheelchair. Ultra-light chairs are most appropriate for those users who have an active lifestyle, since the reduced mass helps with the preservation of upper limb function by reducing the handrim forces during manual propulsion[23]. Aluminum is widely used in wheelchairs, since it has a better strength-to-weight ratio than steel and does not require special manufacturing techniques[43]. More recently, titanium and carbon fiber have been used to make wheelchair frames. Titanium has advanced properties in terms of absorbing shocks and vibration, and a better strength-to-weight ratio than aluminum[44]. Similarly, carbon fiber has an improved strength-to-weight ratio, and the fibers can be molded in a way that increases the strength in one direction while increasing flexibility in another direction. However, both titanium and carbon fiber are significantly more expensive than aluminum, and they also require specialized manufacturing techniques[44].

FRAME DESIGN

Currently, two types of frame design are commercially available: folding and rigid frames. When selecting the frame type, one should consider the user's functional and physical features and lifestyle. For a less active user, wheelchairs with folding frames may be the best choice, since they are, in general, larger and therefore more stable, and allow disassembly of components that may facilitate transportation. Moreover, Liu et al.[43] showed that folding-frame wheelchairs are more stable in the forward direction, and they suggested that this may be a consequence of the footrest position being more forward in folding chairs than in rigid-frame wheelchairs. Rigid frames, in turn, are generally lighter and provide improved mobility performance, but stability is affected.

WHEEL TYPE

The design of the rear wheels plays an important role in the system's mass and vibration transmission. From a mechanical standpoint, heavier wheels make it harder to start moving from a standing position; lighter wheels allow users to accelerate faster[45]. Furthermore, because the rear wheels are located on the outer side of the chair, the mass greatly influences the rotational inertia of the system[24]. Although users have reported improved comfort in manual propulsion with lighter wheels, Hughes et al.[45] found no influence of the wheels' weight on energy expenditure during manual propulsion using two pairs of wheels differing by 0.6 kg.

Traditionally, rear wheels have been produced in either plastic or steel. More recently, carbon fiber has been used to produce lighter wheels. In addition to weight reduction, carbon fiber wheels minimize the transmission of vibration to the user's body[44], which is highly beneficial since vibration may cause discomfort, nausea, dizziness, fatigue and even exacerbate muscular hypertonicity and pain[45].

TIRE TYPE

When selecting rear wheel tires, two options are available: pneumatic and solid tires. Pneumatic tires provide good impact and vibration absorption, thus improving users' comfort[46]. Solid tires, however, are still commonly used because they require almost no maintenance, and pose no risk of emptying due to punctures[25].

An important aspect of the tire type affecting wheelchair mobility is the force opposing the movement of the tire rolling on a surface. This force, known as rolling resistance, is dependent on the tire design, material composition, mass of the tires, and interactions with the surface. Pneumatic tires have been shown to significantly reduce rolling resistance compared to solid tires[25], and this facilitates manual propulsion by keeping the wheels rolling for a longer distance until another push is need, thus contributing to mobility efficiency.

CASTER WHEELS

Caster wheels are important components of the system, influencing the system's stability, rolling resistance, maneuverability and users' comfort. Similar to the rear wheels, pneumatic and solid caster wheels are commercially available. Although pneumatic wheels have been shown to reduce rolling resistance, they do require extra attention regarding pressure control and maintenance. Therefore, solid casters are still the most commonly used type of caster in manual wheelchairs.

Caster wheels and stem assembly can influence a wheelchair in motion in many aspects. First, the diameter of the caster wheels affects rolling resistance: smaller wheels increase rolling resistance, thus requiring the user to push harder to maintain an average velocity. The position of the caster assembly in the wheelchair geometry is also an important aspect of wheelchair mechanics. The shorter the distance between the rear wheel and caster, the lower the rolling resistance due to the increased weight upon the rear wheels[44]. Furthermore, more mass is located near the center of the system and, therefore, rotational inertia is reduced, making turning maneuvers easier. However, this requires reduced wheelchair length, which may have an impact on system stability.

Finally, the transmission of shock and vibration is an important aspect of the casters' size and composition. Smaller casters with solid tires have limited shock and vibration absorption and, therefore, the user's comfort is affected. In an effort to reduce vibration and improve user's comfort, damping materials may be used inside the casters' stem[44]. Similarly, the use of suspension in the casters' assembly is an efficient way of reducing vibration transmission to the user[47].

LEG AND FOOT SUPPORT

The consequences of inappropriate positioning of the leg and foot support are felt in relation to the pressure on the seat interface, the user's comfort and stability, maneuverability, and the mechanical parameters of the wheelchair. When the foot support is too low, the pressure on the seat interface tends to increase, since the weight of the legs and feet pushes the thighs down, compressing them against the seat. Because the feet are not properly supported, gravity makes the ankles bend down, facilitating the shortening of the calf muscles. In addition, without proper anterior support for the feet, reaching forward becomes an unstable and dangerous task[48]. In turn, when the foot support is too high, the thighs are not completely supported by the seat, which may increase the pressure on the buttocks.

The horizontal distance between the leg and foot support and the rear wheels determines mass distribution and the overall length of the wheelchair and, in consequence, the inertia of the system. The variables directly affected by the positioning of the leg and foot support are the system's center of mass, stability, rolling resistance and moment of inertia, with all these variables influencing wheelchair stability and maneuverability[3, 26].

The angle of the knees can be used as a reference for positioning of the foot support. In general, the foot support is positioned in such a way that the angle of the knees ranges from 90° to 120°[49]. MacPhee et al.[26] investigated the effect of two extreme angles of the knees – totally extended (0°) and totally flexed (120°) – on the mechanics of the wheelchair. When the knees were totally flexed, the wheelchair length was reduced by 39%, the center of mass moved backwards 38% and rolling resistance was reduced by 21%. MacPhee et al.[26] suggested that the rolling resistance is reduced by the center of mass being moved backwards, which increases the mass upon the rear wheels, thereby reducing the mass upon the casters. Furthermore, the moment of inertia of the system was reduced by 42% when the knees were totally flexed. This is a relevant finding, since the moment of inertia directly influences wheelchair maneuverability. Indeed, the angular velocity increases by 40% when turning on its own axis (i.e. a zero radius turn), and subjects found it easier to turn the wheelchair with their knees totally flexed.

HANDRIM DESIGN

As the interface through which the user drives manual wheelchairs, the handrims play an important role in terms of both the comfort and efficiency of manual propulsion. In the majority of manual wheelchairs, the handrims are two metallic round tubes of 20 mm diameter, located on the outer side of the wheels. The small size of conventional handrims leads to two main problems: increased pressure on the areas of the hands' surface where contact with the handrim occurs; and reduced mechanical efficiency due to inability to hold the handrim with the entire hand, which requires additional muscle contraction to stabilize the hands on the rim[50]. Not surprisingly, many wheelchair users hold the handrim and tire simultaneously when propelling the wheelchair[51].

Previous studies have proposed different handrim designs in order to optimize propulsion comfort and efficiency. Van der Linden et al.[52] found that handrims with a greater tube diameter showed greater efficiency and lower physiological costs. Improvements in upper limb symptoms were found with the use of the Natural-Fit (Three Rivers Holdings, Mesa, AZ, USA), a commercially available product designed to provide an improved fit to the hand and relieve stress on the carpal tunnel[53]. Richter et al.[54] found reduced finger and wrist flexor activity during manual propulsion with the use of a flexible handrim, a metallic tube connected to the wheels through a flexible rubber membrane that reduces peak forces during initial contact. In a recent study, wheelchair users reported improved comfort and maneuverability with an ergonomic handrim that offers an increased surface for hand contact based on human anthropometric features[55].

CONCLUSION

Improving the mobility efficiency of wheelchair users has been a challenging goal for researchers and professionals. Manual wheelchair mobility is affected by factors that are intrinsically related to wheelchair design and configuration. This paper collated the evidence on how different configurations influence the extent to which the wheelchair meets the needs of users. By changing the wheelchair configuration, it is possible to optimize the biomechanics of manual propulsion, system stability, pressure on the seat interface and the user's perception of comfort and wheelchair drivability. However, manual propulsion is still very demanding on users and much less efficient than normal gait. Further studies should investigate how wheelchair configuration affects the biomechanics of manual propulsion during different maneuvers, trajectories and situations most representative of mobility in daily life. This knowledge may help both manufacturers and clinicians when designing and prescribing wheelchairs that are more appropriate to users' functional features, needs and expectations, thus benefiting users' social participation, independence and quality of life.

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ANEXO 07

Partitioning Kinetic Energy During Freewheeling Wheelchair Maneuvers

Fausto O. Medola, Phuc V. Dao, Jayme J. Caspall, and Stephen Sprigle

***Abstract*—This paper describes a systematic method to partition the kinetic energy (KE) of a free-wheeling wheelchair. An ultralightweight rigid frame wheelchair was instrumented with two axle-mounted encoders and data acquisition equipment to accurately measure the velocity of the drive wheels. A mathematical model was created combining physical specifications and geometry of the wheelchair and its components. Two able-bodied subjects propelled the wheelchair over four courses that involved straight and turning maneuvers at differing speeds. The KE of the wheelchair was divided into three components: translational, rotational, and turning energy. This technique was sensitive to the changing contributions of the three energy components across maneuvers. Translational energy represented the major component of total KE in all maneuvers except a zero radius turn in which turning energy was dominant. Both translational and rotational energies are directly related to wheelchair speed. Partitioning KE offers a useful means of investigating the dynamics of a moving wheelchair. The described technique permits analysis of KE imparted to the wheelchair during maneuvers involving changes in speed and direction, which are most representative of mobility in everyday life. This technique can be used to study the effort required to maneuver different types and configurations of wheelchairs.**

***Index Terms*—Kinetics, mobility, rehabilitation, wheelchair propulsion, wheelchairs.**

I. Introduction

MANUAL wheelchairs provide independent mobility for people with disabilities. However, wheelchairs have been identified as limiting community participation [1]. A number of factors influence the extent to which manual wheelchairs meet the needs of individual users including the effort required to maneuver the wheelchair. Previous studies have addressed the efficiency of handrim propulsion, the most common means of wheelchair locomotion. Time to perform locomotive activities [2], effective handrim forces [3], [4], and metabolic cost have been used to determine efficiency of manual propulsion [5], [6]. From a mechanical design standpoint, the effort required to propel is dependent on wheelchair design and configuration and how these parameters impact wheelchair propulsion. Investigating the kinetics of the wheelchair during freewheeling maneuvers is, therefore, important to understand mechanical efficiency and performance. This knowledge may serve as guidance for wheelchair users, clinicians, and manufacturers when selecting or developing wheelchairs that meet the needs and expectations of users.

Maneuvering a manual wheelchair requires applying forces on the handrims in a repetitive motion that, in long term, may cause upper limb overuse injuries, impacting independence and quality of life. Several studies have shown high prevalence of upper limb injuries among manual wheelchair users [7], [8], and the importance of muscular strength and endurance, proper biomechanics, and the use of suitable wheelchairs have been highlighted as important factors affecting mobility performance [9]–[11]. While most wheelchair propulsion research has focused on user biomechanics, little is known about how the mechanical characteristics of the equipment influence the dynamics of the entire system, comprised of the user and the chair. Furthermore, manual wheelchair mobility in real life has been shown to be composed of relatively short bouts of mobility [12]. Studying wheelchair mobility in a manner that reflects daily wheeling is therefore important to understand the mechanical interaction between the equipment and user.

The overall propulsion efficiency of a wheelchair is based on a combination of factors, both biomechanical and mechanical. Most research has focused on the biomechanical factors of propulsion, using physiological, kinetic, and kinematic variables. Previous studies have shown the impact of changing wheelchair configurations on the kinematics of handrim usage [13], muscle activity [14], [15], velocity and acceleration [16], forces applied on the handrim [17]–[19]. In addition, surface type [17], [20], tire type [21], tire inflation [22], and fore-aft distribution of the total mass [23] have been identified as factors influencing rolling resistance, and therefore, increased effort in propulsion. Only few of these studies [16], [17], [19], [23] used over ground motion rather than stationary propulsion, i.e., treadmill or roller system. Studies incorporating free-wheeling wheelchair movement are more representative of propulsion in real life, but these free-wheeling studies have been limited to straight maneuvers.

From a mechanical perspective, two factors greatly influence manual wheelchair movement: friction and inertia. These factors are manifested as rolling resistance, bearing friction, overall

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system (chair + occupant) mass and mass distribution, among others. Wheelchair dynamics during typical everyday wheelchair motion are influenced by inertia changes during starting, stopping and turning. Studies limited to straight maneuvers, especially during steady state velocity, are not able to discern the accelerations due to changes in speed and direction. Measuring the kinetic energy (KE) during more representative maneuvers will provide a fuller understanding of wheelchair dynamics.

A few studies have described energy measurement during over ground wheelchair mobility. Coutts [24] investigated the dynamics of a moving wheelchair, describing wheelchair propulsion in terms of acceleration, drag force, propulsion power and work, as a function of wheels' rotation and wheelchair inertial properties. Guo *et al.*, [25] investigated the energy of the musculoskeletal system and power flow over the upper limb segments based on a kinematic model of manual propulsion. The study of De Saint Remy and Vaslin [26] showed the KE variations during straightforward displacement, with a method combining the measurement of the acceleration and the breaking force. Supporting this finding, a recent study confirmed that the user's mechanical actions during the propulsion cycle modify both the rolling resistance and the stability of the wheelchair [27]. Although these studies increased the knowledge on the dynamics of a moving wheelchair, their analyses were restricted to straightforward displacements. Therefore, measuring KE of wheelchairs moving through different trajectories, as happens in real life, has not yet been described.

The objective of this study was to develop a systematic method to measure, calculate and analyze the KE as the output of wheelchair movement. This technique is capable of partitioning the KE of a wheelchair during a free rolling state, including accelerating and braking in either straight or turning motion. The ability to measure and partition KE of a free-wheeling wheelchair will permit the objective comparison of different types and configurations of wheelchairs over a variety of maneuvers that represent real world mobility. Objective comparisons of performance would be useful for both clinicians and wheelchair users during the wheelchair evaluation and selection process.

II. Methods

A. Design Criteria

In order to achieve a usable and sensitive technique, several design criteria were defined: 1) the measurement equipment should be compatible with most commercially available wheelchairs; 2) data collection must permit KE measurement during freewheeling maneuvers that include changes in speed and direction; 3) the equipment should not impact wheelchair propulsion and have minimal influence on overall system mass and inertia. Performance considerations included the ability to determine: 1) the KE of the whole system (wheelchair + equipment); 2) the energy of each rigid body in the wheelchair assembly; 3) the KE components based on the trajectory. Plotted as a function of time, the KE at a certain time should reflect the mechanical features of the wheelchair moving over a certain trajectory at a certain speed.

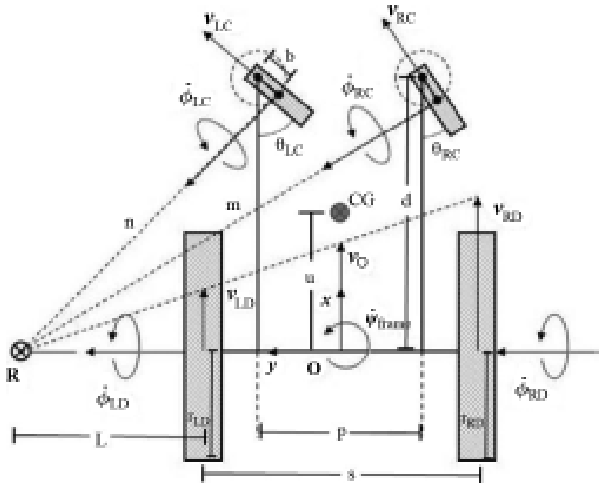

Fig. 1. Schematic of wheelchair for use in deriving wheelchair kinematics over ground.

B. Theoretical Approach

In essence, the wheelchair can be viewed as an assembly of seven rigid bodies: frame, left and right drive wheels, left and right caster forks, and left and right caster wheels. The total energy of a wheelchair in motion is comprised of the sum of the kinetic and potential energy of all these components. However, potential energy effects can be neglected when the motion is on flat ground. A kinematic description of the wheelchair in motion is the first step in the KE partitioning approach. Maneuvering the wheelchair over ground, or freewheeling, requires force input to both drive wheels. Characterizing the motion of the drive wheels during freewheeling enables the determination of all other kinematic variables, except for caster orientation in some special cases. These kinematic variables include the following.

v_o	Velocity of the wheelchair at the center of mass.
$\dot{\Psi}_{\text{frame}}$	Yaw rotation rate of chair.
$\dot{\Psi}_{\text{LC}}, \dot{\Psi}_{\text{RC}}$	Yaw rotation rates of the left and right casters relative to frame.
$\dot{\phi}_{\text{LD}}, \dot{\phi}_{\text{RD}}$	Left and right drive wheel spin rate.
$\dot{\phi}_{\text{LC}}, \dot{\phi}_{\text{RC}}$	Left and right caster spin rate.

The theoretical approach to determine the aforementioned kinematic variables is as follows. By measuring the drive wheels' rotation rates, the turning radius, velocity of the center of mass as well as the yaw rotation rate of the chair can be determined, assuming the wheelchair rolls without slipping. The mechanical model of the wheelchair with all pertinent kinematic variables and chair parameters used in the derivation are shown in Fig. 1. This model assumes zero rear wheel camber to simplify the analysis. The origin is placed at the midpoint of the rear axle with the x, y, and z-axis representing roll, pitch, and yaw, respectively. Rear wheels spacing is denoted as s, front wheels spacing as p, caster trail as b, and distance of caster stem forward of rear axle is d. The model also assumes left-right symmetry in the chair such that the center of gravity (CG) is located at the midline, forward from the rear axle at a distance, u.

The yaw rotation rate of the chair $\dot{\Psi}_{\text{frame}}$ is dependent on the drive wheels' rotation rates, and that dependence is expressed as

$$\dot{\Psi}_{\text{frame}} = \frac{(\dot{\phi}_{\text{RD}} r_{\text{RD}} - \dot{\phi}_{\text{LD}} r_{\text{LD}})}{s}. \quad (1)$$

The velocity of the CG is based upon two parameters as shown in (2): the velocity of the origin which is based upon the rotation rates and diameters of the drive wheels, and the product of the frame's yaw rate and the distance between the origin and CG

$$v_G = \sqrt{\left[\frac{(\dot{\phi}_{\text{RD}} r_{\text{RD}} + \dot{\phi}_{\text{LD}} r_{\text{LD}})}{2}\right]^2 + |\dot{\Psi}_{\text{frame}} u|^2}. \quad (2)$$

Similar application of the kinematics equation for rigid bodies would yield a relation between the known velocity of the origin O, to the velocities of the left and right casters. Assuming the casters roll without slipping, dividing the velocities by their respective radii yield the left and right caster rotation rates, (3) and (4), where V_0 is the velocity of the origin given as the first parameter in (2)

$$\dot{\phi}_{\text{LC}} = \frac{V_O}{r_{\text{LC}}}\cos\theta_{\text{LC}} - \frac{\dot{\Psi}_{\text{frame}}}{r_{\text{LC}}}\left(\frac{p}{2}\cos\theta_{\text{LC}} - d\sin\theta_{\text{LC}}\right) \quad (3)$$

$$\dot{\phi}_{\text{RC}} = \frac{V_O}{r_{\text{RC}}}\cos\theta_{\text{RC}} - \frac{\dot{\Psi}_{\text{frame}}}{r_{\text{RC}}}\left(\frac{p}{2}\cos\theta_{\text{RC}} - d\sin\theta_{\text{RC}}\right). \quad (4)$$

Caster yaw rates were derived based on geometrical relations present during turning. When the wheelchair turns, every point in the wheelchair follows a curvilinear path which, at any moment in time, can be fitted to a circle. This circle has a center located at point R in Fig. 1 and a turning radius measured to the point of interest. The following radii were derived: distances from R to left and right caster stems, $r_{\text{stem}L}$ and $r_{\text{stem}R}$, respectively, distances from R to left and right caster centers, n and m

$$r_{\text{stem}L} = \sqrt{d^2 + \left(L + \frac{s}{2} - \frac{p}{2}\right)^2} \quad (5)$$

$$r_{\text{stem}R} = \sqrt{d^2 + \left(L + \frac{s}{2} + \frac{p}{2}\right)^2} \quad (6)$$

$$n = \sqrt{r_{\text{stem}L}^2 - b^2} \quad (7)$$

$$m = \sqrt{r_{\text{stem}R}^2 - b^2}. \quad (8)$$

Caster angle relative to the frame, and caster yaw rotation rates via derivative, can be determined from geometry when the wheelchair moves in either forward or reverse directions. The presence of the caster trail complicates the calculation of caster swivel when the chair switches from forward to reverse motion. To circumvent this limitation, we further constrain the freewheeling motion to avoid caster reversal. It then follows that the angles the casters make relative to the wheelchair frame can be computed using (9) and (10), where θ_{LC} and θ_{RC} correspond to left and right caster angle relative to the frame

$$\theta_{\text{LC}} = \cos^{-1}\left[\frac{L + \frac{s}{2} - \frac{p}{2}}{r_{\text{stem}L}}\right] - \cos^{-1}\left[\frac{r_{\text{stem}L}^2 + n^2 - b^2}{2r_{\text{stem}L}n}\right] \quad (9)$$

$$\theta_{\text{RC}} = \cos^{-1}\left[\frac{L + \frac{s}{2} - \frac{p}{2}}{r_{\text{stem}R}}\right] - \cos^{-1}\left[\frac{r_{\text{stem}L}^2 + m^2 - b^2}{2r_{\text{stem}R}m}\right]. \quad (10)$$

Differentiation of the caster angle equations yield $\dot{\Psi}_{\text{LC}}$ and $\dot{\Psi}_{\text{RC}}$

$$\dot{\Psi}_{\text{LC}} = \frac{d}{dt}(\theta_{\text{LC}}) \quad (11)$$

$$\dot{\Psi}_{\text{RC}} = \frac{d}{dt}(\theta_{\text{RC}}). \quad (12)$$

The KE of the wheelchair in freewheeling on flat ground is the summation of the KE of its parts (13), which is

$$\begin{aligned}\text{KE} = &\frac{1}{2}m_{\text{sys}}v_G^2 + \frac{1}{2}I_{ZZ,\text{sys}}^G\dot{\Psi}_{\text{frame}}^2 + \frac{1}{2}I_{YY,\text{LD}}\dot{\phi}_{\text{LD}}^2 \\ &+ \frac{1}{2}I_{YY,\text{RD}}\dot{\phi}_{\text{RD}}^2 + \frac{1}{2}I_{YY,\text{LC}}\dot{\phi}_{\text{LC}}^2 + \frac{1}{2}I_{YY,\text{RC}}\dot{\phi}_{\text{RC}}^2 \\ &+ \frac{1}{2}I_{ZZ,\text{LFLC}}\dot{\Psi}_{\text{LC}}^2 + \frac{1}{2}I_{ZZ,\text{RFRC}}\dot{\Psi}_{\text{RC}}^2. \end{aligned} \quad (13)$$

m_{sys}	Mass of the whole chair.
$I_{ZZ,\text{sys}}^G$	Yaw moment of inertia of the wheelchair about its center of mass.
$I_{YY,\text{LD}}, I_{YY,\text{RD}}$	Moment of inertia of the left and right drive wheels about their axles.
$I_{YY,\text{LC}}, I_{YY,\text{RC}}$	Moment of inertia of the left and right caster wheels about their axles.
$I_{ZZ,\text{LFLC}}, I_{ZZ,\text{RFRC}}$	Yaw moment of inertia of the left and right caster forks about their stems.

During freewheeling motion, the KE terms in (1) can be partitioned into three broad categories of energy: translational KE, rotational KE and turning KE. Translational energy, the first term in (1), represents the energy of linear motion. Rotational energy represents the energy of all four wheels spinning on their axes and is calculated by the sum of the four terms using drive and caster wheel velocities. Finally, turning energy is embodied by the terms containing the yaw rate $\dot{\Psi}$, which includes the yaw rate of the whole chair and the caster fork assembly.

In addition to the kinematic variables, the necessary parameters to estimate the KE of the wheelchair in freewheeling are the mass and the moments of inertia. It is understood that the movement of masses in a system changes the moments of inertia. The wheelchair in motion invariably has nonconstant $I_{ZZ,\text{sys}}^G$ because of the swivel of the casters. Because it is impractical to know exactly how $I_{ZZ,\text{sys}}^G$ changes over time, our analysis assumes one value of $I_{ZZ,\text{sys}}^G$ that is representative of a chair with casters facing forward such as when moving forward.

Both mass and its distribution affect how the energy is partitioned from a systems standpoint. Clearly, energy components containing the chair mass and chair yaw moment of inertia dominate the remaining terms because they are measured at the systems level as opposed to the component level. However, the rotational energy terms become more important at high speeds or high rotation rates even with their relatively small moments of inertia. Because of the interplay between mass and mass distribution (moment of inertia) and their variable influences across different speeds, it is logical to measure wheelchair energy using maneuvers that highlight different energy components. Maneuvers that require changes in speed and direction will be able to reflect the varying influences of each type of energy.

Algorithm

Wheelchair kinematic analysis begins with measuring the rotation of both drive wheels. The angular velocities of the wheels were then computed using a finite difference derivative of the two-wheel rotation data. Wheel angular velocities were low-pass filtered using a second-order Butterworth filter at 2-Hz cut-off frequency. Using published data on daily wheelchair usage, we defined 2 m/s as an acceptable speed during wheelchair maneuvers [12]. This corresponds to 1 Hz (1 wheel rotation per second), hence the 2-Hz cut-off frequency. Logically, it then follows that other kinematic variables discussed in the theoretical analysis are computed using rigid body kinematic relationships. These kinematic variables together with inertia parameters feed into the system KE formulation. The formulation gives the total energy of the wheelchair in freewheeling, which can be partitioned into translational, rotational and turning energy.

C. *Validation*

1) Hardware: The TiLite Aero Z ultra lightweight wheelchair (K0005 class) was used for all the tests. The unloaded chair weighed 12.1 kg and was configured with spoke wheels, pneumatic tires, and side guards and no other accessories such as armrests or anti-tip bars. Inertial parameters of the wheelchair and its components were measured by two separate devices. Rotational inertia measurements of the drive wheels, caster wheels, and caster forks were taken using a system based on the established Trifilar Pendulum [28], [29], which measures the rotational inertia based on the mass and the frequency of oscillation. To do so, each wheelchair component was positioned in the center of a flat triangular plate that was suspended by three wires on its vertices. The plate was then manually rotated and a camera (Canon Powershot S5 IS, Canon, Ōita, Japan) that is capable of high speed video recording (60 fps) recorded fifty complete cycles which was then used to determine the frequency of oscillation. The rotational inertia of the entire wheelchair was measured by a device designed for this purpose, the iMachine. It consists of a platform supported by load cells on a spring-damped rotational axle. A complete description of the system and its validation were reported elsewhere [30].

In order to obtain accurate measurements of wheel velocities, two high-precision M-260 optical encoders (Encoder Products Co., Sandpoint, ID, USA) were mounted on each drive wheel Fig. 2. The encoders were connected to the LabJack U6 (Labjack Corp., Lakewood, CO, USA) data acquisition device, positioned on a plastic plate under the seat, located at the wheelchair's center of mass. A Q1u tablet (Samsung, Samsung Town, Seoul, South Korea) served as storage for all data collected from the encoders and provided power for the Labjack. The instrumentation of the wheelchair was configured to minimize influence of the system's mass and inertia. This data acquisition hardware added 1.86 kg to the wheelchair's mass and increased its rotational inertia by 5.9%.

(a)

(b)

Fig. 2. Data acquisition components: (a) side view showing axle-mounted encoders; (b) rear view showing processing and storage unit (Labjack and Tablet).

2) Participants and Protocol: To validate the analysis method over different conditions of wheelchair mobility, two able-bodied volunteers (male, ages 30 and 27), experienced in propelling wheelchairs, propelled through different maneuvers. The methods used in this study were reviewed and approved by the Georgia Institute of Technology's Institutional Review Board. Four maneuvers were defined to assess the methodology's sensitivity in distinguishing different types of energy within movements comprised of translation, turning and changes in speed. The four maneuvers were as follows.

a) Straight Run: Starting from rest the subject accelerated in a straight line as fast as possible reaching maximum speed using six consecutive pushes within 15 m.

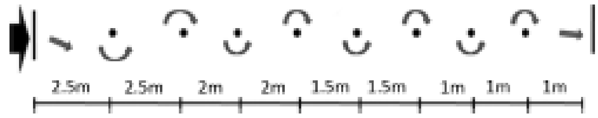

Fig. 3. Slalom course: cones positioned at progressively decreasing distances apart.

TABLE I
AVERAGE COMPONENT AND TOTAL KE OVER DIFFERENT COURSES

	Translational KE Avg (J) (% of Total KE)	Rotational KE Avg (J) (% of Total KE)	Turning KE Avg (J) (% of Total KE)	Total KE Avg (J)
Straight Motion	33.03 (84.22%)	6.18 (15.76%)	0.01 (0.03%)	39.22
Zero Radius Turn	1.23 (16.52%)	0.98 (13.24%)	5.23 (70.20%)	7.45
Finite Radius Turn	14.61 (81.72%)	2.81 (15.69%)	0.49 (2.74%)	17.90
Slalom Course	11.45 (78.15%)	2.27 (15.49%)	0.92 (6.28%)	14.64

b) Zero Radius Turn: Starting from rest the subject performed a 360° turn by rotating the drive wheels in the opposite directions as fast as possible.

c) Finite Radius Turn: Starting from rest the subject propelled completely around a 2-m-radius circle as fast as possible.

d) Slalom: Starting from rest the subject traversed, as quickly as possible, a 15-m course with cones aligned in straight line and progressively decreasing separation distances Fig. 3.

3) Data Analysis: All data were analyzed using custom codes in MATLAB R2011a (Mathworks Inc., Natick, MA, USA). Specifically, MATLAB codes written for this procedure performed wheel rotation rate computations, data filtering, KE estimation, and plotting based on input wheel rotation data from the wheel-mounted encoders. A descriptive analysis of the data is presented whereby both the peak and average energy values are used as basis for comparing across courses, and also as evidence of changing in energy partitioning in different energy components.

III. RESULTS

To compare how the energy was partitioned in different courses, mean and peak values from were calculated. For the Straight run, Zero Radius Turn, and Finite Radius Turn courses, data consisted of three trials for each of the two subjects. Slalom course data consisted on only one trial by each subject. Tables I and II report the average and peak KE values for each component as well as the total KE. Figs. 4–7 depict the energy-time relationships of one representative trial of each maneuver to illustrate its unique energy features. Detailed discussion of each maneuver is presented separately.

TABLE II
PEAK COMPONENT AND TOTAL KE OVER DIFFERENT COURSES

	Translational KE Peak (J) (% of Total KE)	Rotational KE Peak (J) (% of Total KE)	Turning KE Peak (J) (% of Total KE)	Total KE Peak (J)
Straight Motion	63.22 (84.23%)	11.83 (15.76%)	0.06 (0.08%)	75.06
Zero Radius Turn	2.69 (21.49%)	1.70 (13.62%)	8.86 (70.98%)	12.49
Finite Radius Turn	23.81 (82.79%)	4.52 (15.72%)	4.13 (14.35%)	28.77
Slalom Course	31.38 (84.03%)	5.88 (15.76%)	8.77 (23.49%)	37.34

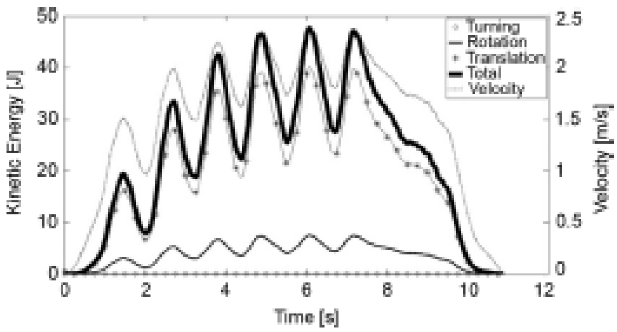

Fig. 4. Partitioned KE of six consecutive pushes in a straight forward motion.

A. Straight Run

The KE partition of a straight motion test run is shown in Fig. 4. A straight maneuver highlights the close relationship between speed and KE and the cyclical oscillations of each that result from the propulsion strokes Fig. 4.

As expected, the translational KE component was dominant, with a lesser contribution of rotational KE from the wheels and casters, and virtually no contribution from the turning KE component. Note that in both the peak and average KE values for the straight run shown in Tables I and II, the percentage of total KE represented by the translational and rotational components were about 84% and 15%, respectively, with the remaining 1% accounted for by the slight turning during the maneuver. This stems from the fact that the chair speed and wheel rotation speed are kinematically linked, and this ratio remains true whenever the chair moves straight. Starting from rest, the speed increased dramatically during the first three pushes and reached a plateau of approximately 2.3 m/s that was maintained until the last push.

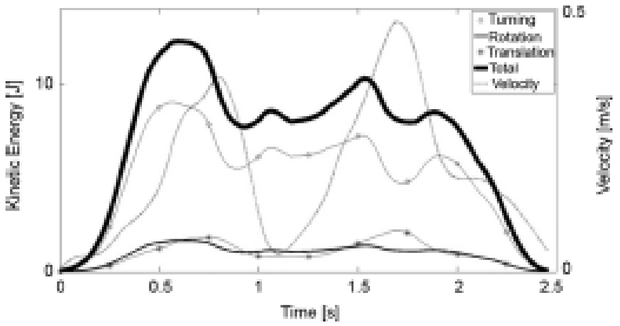

Fig. 5. Partitioned KE during a zero radius turn.

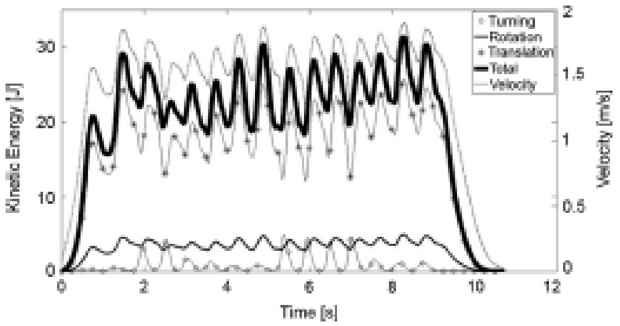

Fig. 6. Partitioned KE during a 2 m radius turn.

B. Zero Radius Turn

The KE partition of a wheelchair performing a zero radius turn shows a markedly different energy partition than the straight run Fig. 5. The turning KE component contributes the greatest percentage of the total KE, with the translational and rotational KE components contributing smaller and relatively equal amounts. As with the straight maneuver, one KE component is dominant. However, in a zero radius turn, the total KE was about seven times less in magnitude. This result is not surprising, however, given that the rectilinear inertia of the chair far exceeds the turning inertia. In the execution of this maneuver, the chair spins approximately at the midpoint of the rear axle instead of at the center of mass.

Because the center of mass is offset forward from the axle, any zero-radius turn would result in the center of mass moving slightly which resulted in a finite but nonzero translational KE. The bimodal shape of the velocity curve shown in Fig. 5 was the result of performing two pushes in the course of a turn.

C. Finite Radius Turn

Executing a finite radius turn requires a combination of both translation and turning movements. Since the movement started from rest, a rapid rise in speed quickly elevated the KE of the system Fig. 6. Afterward, total KE stabilized to a level and an interchange of energy between translational and turning components was observed. Drops in translational KE component occurred at the same time as peaks in turning KE. This pattern results from the fact that the user can only make the wheelchair turn when pushing the handrims. When the hands are released from the handrims during the recovery stroke, the wheelchair tends to travel tangent to the circular path until another push is initiated. The velocity in finite radius turn was much less as compared to going straight (1.7 m/s versus 2.3 m/s), and that is reflected in the lower average and peak total KE. Rises and falls in velocity for this maneuver were not as dramatic as compared to the straight runs because of shortened propulsion strokes needed to follow the curved path.

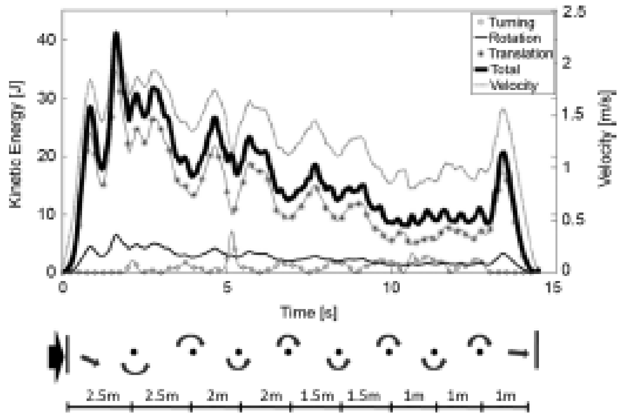

Fig. 7. KE partition in a slalom course going as fast as possible.

D. Slalom Course

When moving through a slalom course, the translational and turning KE varied greatly due to variations in speed and turning radii throughout the course Fig. 7. Wider cone spacings at the beginning allowed for higher speeds and less pronounced turns, hence the high levels of translational KE and low levels of turning KE. Toward the end of the course, a decrease in translational KE from more demanding turns that required a slower speed. An important characteristic of the velocity plot that is worth mentioning is the rough, jagged-looking velocity curve that was not present in other maneuvers. The slalom course requires a lot of control to maneuver the chair around the cones. Maneuverability is made possible by braking and/or accelerating the handrims in a specific way in order to speed up, slow down and turn the chair. The unevenness of the velocity is an indication of control or lack thereof, during the run.

IV. Discussion

This is the first study to present a systematic method to partition the KE of a wheelchair during freewheeling. Since the wheelchair is an assembly of distinct components, partitioning the KE allows better understanding of the energy interchange among them. Wheelchair maneuvers that include acceleration/deceleration and straight/turning movements reflect the varying contributions of each type of energy to the total KE. This method permits a powerful means to study the efficiency of wheelchair propulsion by considering how work input by the user is converted into KE.

Previous studies addressed wheelchair propulsion efficiency in terms of muscle activity, handrim forces and metabolic cost [3]–[6] using stationary propulsion or straight maneuvers. These studies greatly contributed to the understanding of how muscles work during manual propulsion, the forces applied on the handrims and how cardio respiratory system responds to increasing speeds. Similarly, previous work seeking to calculate work and energy during wheelchair propulsion was limited to straight motion [31]–[34]. Straight trajectories best demonstrate the effects of system mass (translational inertia) and friction. Because these are dominant influences, these previous studies are useful in reporting those influences. However, limitations in instrumentation prevented the previous studies to fully characterize the energy response. One advantage of having wheel rotation data is to determine the freewheeling trajectory, which reports a complete picture of what actually happens when there are energy exchanges between components. The approach described here has the resolution to measure the rise and fall in KE corresponding to a propulsion cycle Fig. 4. Rising KE is attributed to the increase in speed during the propulsion stroke with the subsequent decrease in KE occurring during the recovery phase when speed decreases due to energy dissipation from rolling resistance and other frictional influences. Characterizing this energy dissipation is one way to evaluate the mechanical efficiency of manual wheelchairs. Greater energy loss can be attributed to a less efficient wheelchair.

V. Conclusion

Wheelchair mobility comprises an interaction of factors related to the user, equipment and environment. When addressing mechanical efficiency, the wheelchair can be considered as an assembly of components whose interaction influences the effort required to move about. This is the first study to objectively partition KE as the output of a wheelchair during freewheeling maneuvers. The approach can be applied to a variety of commercially available wheelchairs with minimal influence on mass and inertia. The method showed proper sensitivity to differentiate KE over maneuvers with different speeds and trajectories. In particular, the slalom maneuver highlights the continuous interchange of translational and turning KE components and underscores the need of using maneuvers endowed with accelerations and decelerations when investigating manual wheelchair propulsion efficiency. Future research should apply this KE partitioning technique to investigate the differences in wheelchair types and configurations. This will help clinicians and manufacturers to prescribe and develop the most suitable equipment that meets users' needs and expectations.

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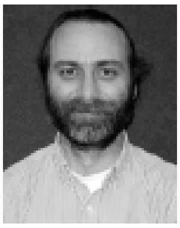

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ANEXO 08

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The influence of handrim design on the contact forces on hands' surface: A preliminary study

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A B S T R A C T

This study is aimed at investigating how contact forces are distributed over the hand's surface during manual wheelchair propulsion with two different designs of handrim. Twenty able-bodied subjects performed a wheelchair propulsion protocol comprising five consecutive pushes: start-up, straight motion and braking. The protocol was repeated twice, each time with a handrim type: the standard round metallic tube handrims, and a prototype of an ergonomic handrim. During all the tests, contact forces over the users' hand surfaces were measured through a pair of gloves instrumented with ten force sensors each. The average values of each sensor were used to compare both handrims, and statistical tests were used to verify significant differences. The results indicate that the handrim design influences the magnitude of contact forces on hands' surface. There was a reduction in the magnitude of the contact forces in both regions – metacarpals and distal phalanges – during the three propulsion phases with the use of the ergonomic handrim. Among all ten sensors, the distal phalange of the third finger registered the greater forces during start-up, forward motion and braking. The reduction on the contact forces with the use of the ergonomic handrim is possible due to the increased surface and the anatomical shape. Improving handrim design can contribute the ergonomics of manual propulsion, thus benefiting users' comfort and safety in wheelchair mobility.
Relevance to industry: This study contributes to the knowledge of the ergonomics of manual wheelchair propulsion, with the main focus on the hand-handrim interface. Thus, it can benefit designers and manufacturers in developing handrims with ergonomics features, as well as improve the users' comfort and safety during manual wheelchair usage.

1. Introduction

Manual propulsion, the main means of wheelchair ambulation, exposes the upper limbs to high loads and repetitive task, and as a consequence there is an increased risk of overuse injuries (Gellman et al., 1988; Curtis et al., 1999; Subbarao et al., 1994). Since wheelchair users rely on their upper limbs for mobility and most of the activities of daily living, pain and upper limb injuries can impact functionality, independence, and quality of life (Finnerup et al., 2001; Jensen et al., 2005; Ehde et al., 2003; Alm et al., 2008). Therefore, reducing workload and improving the comfort of the users' hands during propulsion is an important goal for both rehabilitation practice and engineering.

As the interface through which the user controls a manual wheelchair, the handrim plays a key role on the manual propulsion technique. van der Woude et al. (2003) highlighted the need of a stable coupling between the hands and the handrims on both propulsion and navigation of the wheelchair. Because wheelchair propulsion requires the hands to hold and push a rotating handrim quickly, the standard handrim — a round metallic tube located on the outer side of the wheel — have no ergonomic features, requires a pinch grip and was not designed for variations in upper limb

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function (Dieruf et al., 2008). The cross-sectional diameter (18–20 mm) is insufficient to provide proper support to the entire hand's surface. Consequently, increased muscular effort is needed to stabilize the hand on the handrim, concentrating contact forces over small areas (mainly the distal phalanges), thus exposing the delicate structures of the hand to a harmful condition.

Alternative designs for wheelchair handrims have been proposed aiming to make manual propulsion easier and more comfortable (Dieruf et al., 2008; Richter et al., 2006; Gaines and La, 1986). More recently, an ergonomic handrim designed based on hand's anthropometrics was developed with the main purpose of increasing the surface area in order to properly support both the palm and fingers. When using this handrim prototype, wheelchair users reported improved comfort during manual propulsion when pushing, braking and maneuvering (Medola et al., 2012). Although the ergonomic handrim and the other proposed devices are aimed to improve hand-to-rim interaction and benefit user's comfort, the first differs from the others in terms of its material composition, larger size and shape.

An important outcome used in ergonomic research on hand tools is the distribution of contact forces on hands. During manual tasks, the distribution of forces is not uniform across the surface of the hand. Therefore, the relative risk of mechanical trauma (such as blisters and hairline fractures) is also not uniform across the hand surface (Muralidhar et al., 1999). While there has been considerable research investigating pressure on hands with the use of a number of hand-tools (Kong and Freivalds, 2003; Lu et al., 2008; Kong and Lowe, 2005), to our knowledge, no study has quantified the contact forces on the hand-rim interface.

The comparison of different handrims had been addressed with the use of objective outcomes and users' responses. Dieruf et al. (2008) and Gaines and La (1986) investigated users' responses to compare alternative design of handrims with the standard cylindrical handrim. In both studies, users reported their preference for an alternative contoured design of handrim rather than the standard cylindrical handrim. The study of van der Woude et al. (2003) compared different types of handrim in terms of oxygen uptake, gross mechanical efficiency, handrim propulsion forces and participants' subjective ratings, and found significant difference only in the subjective ratings. Outcome measures such as propulsion forces and physiological parameters may be not sensitive enough to detect differences between handrims types. In this way, measuring hand contact forces may be a more appropriate method to identify such differences. The objective of this study was to investigate how contact forces are distributed over hand's surface during manual propulsion with two different handrims. Two main hypotheses are investigated: (i) the distribution and magnitude of the contact forces on the hands' surface differs according to the handrim design; (ii) the ergonomic handrim can reduce the magnitude contact forces on hands' by optimizing the distribution of contact forces through the entire surface of the hand.

2. Materials and methods

2.1. Participants

Twenty able-bodied subjects were recruited at the São Paulo State University (UNESP, Bauru, Brazil) and voluntarily participated in the study. The sample consisted of ten men and ten women, with a mean age of 42.5 ± 9.2 yr, mean height of 1.76 ± 0.08 m, and mean mass of 84.0 ± 18.3 kg. Participants met the following inclusion criteria: (1) 18 years or older and (2) had no upper limb pain, injuries, or deformities that could influence both manual propulsion and/or force sensor data acquisition.

Prior to data collection, volunteers read and signed an informed consent form that had been approved by the Ethics Committee of the Faculty of Medicine of Ribeirão Preto, University of São Paulo.

2.2. Materials

A standard design Star Lite Ortobras® wheelchair (seat width of 400 mm, backrest height of 400 mm, and pressure of the rear tires at 4.5 bars) was used during data collection for all the subjects. This configuration was acceptable for the participants to perform all the propulsion tests, and did not influence the subjects' ability to propel the chair.

In addition to the pair of standard handrims (circular metallic round tube with 20 mm of diameter) already present on the wheelchair used, it was used an extra pair of an updated version of the ergonomic handrim prototype (Fig. 1). With the same design concepts of the handrim developed by Medola et al. (2012), the new version of the ergonomic handrim was designed with an upper surface to support the first metacarpal and the thumb (width of 38 mm), a lateral convex surface to support from the second to the fifth metacarpal (vertical diameter of 48 mm), and a lower surfaces with smooth grooves (width of 22 mm each depression) to support the medial and distal phalanges of the fingers, allowing a firm and comfortable grip (Fig. 2).

When pushing the handrim, the fingers fit to the smooth grooves and the protrusions provide extra support to the fingers, facilitating the push phase. Both handrims (the standard and the ergonomic) had the same radius from their top to the center of the wheel, differing only in their shape and size of the grip.

To evaluate how contact forces act on the users' hand surfaces, we used an instrumented glove system equipped with ten Force Sense Resistors (FSR) sensors (Interlinks Electronics, Inc., USA, Part No Model 402, 0.5 inch diameter) on the palm side of the glove (Fig. 3). The FSRs force sensitivity range varies from 0.1 to 100 N, which is adequate to most of hand held instruments or hand tools. The sensors have low sensitivity to noise and vibration and a good force resolution, better than 0.5% of full scale. Their rise time output is 3 ms and the force repeatability is about 2% (Interlink Electronics 2014). However, FSRs exhibit considerable hysteresis, which makes the unloading forces smaller than the loading ones in about 10%.

The instrumented glove system is an evaluation tool for ergonomic research, allowing the investigation of the mechanical interaction between the hand and a hand tool during a manual task (Silva and Paschoarelli, 2009). Also, we used a data acquisition system for FSR sensor signal conditioning (sampling rate of 10 Hz), a multifunction module (DAQ – National Instruments – NI USB 6210, 16 bit, M Series), and the SADBIO software developed using the Labview® 7.0 software (National Instruments, Austin, TX, USA). Prior to the study, each of the ten sensors was calibrated separately.

2.3. Experimental procedures

Before starting the data collection, the participants had about ten minutes to practice manual propulsion with both handrim models, in order to become familiar with wheelchair propulsion. All subjects performed a four-meter propulsion protocol on a flat and smooth floor, repeated twice, using each pair of handrims in a randomized order. Starting with the chair stopped, participants were instructed to push the handrims five times consecutively over a straight forward trajectory (a straight line was drawn on the floor with adhesive tape), at comfortable speed, trying to keep the same propulsion pattern for both conditions. Thus, each single trial comprised three different phases: one start-up push to start moving the wheelchair forward, three pushes to keep forward motion, and a braking contact with the handrim to stop the chair. The

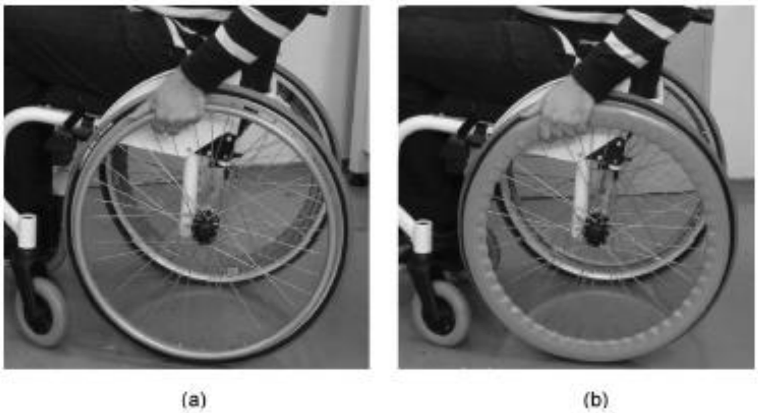

Fig. 1. Wheelchair handrims: (a) standard; (b) ergonomic.

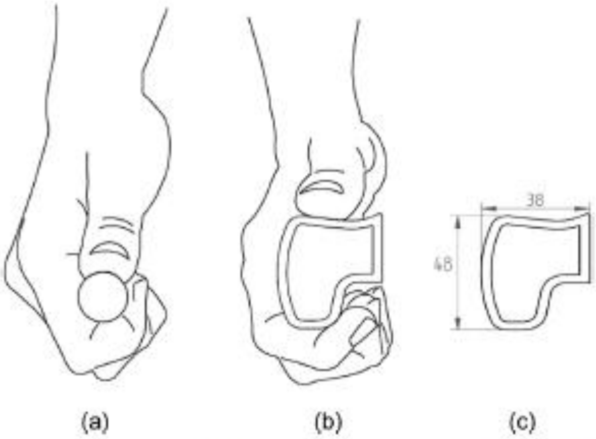

Fig. 2. Cross-section view: (a) 20 mm diameter standard handrim; (b) ergonomic handrim; (c) ergonomic handrim measures (millimeters).

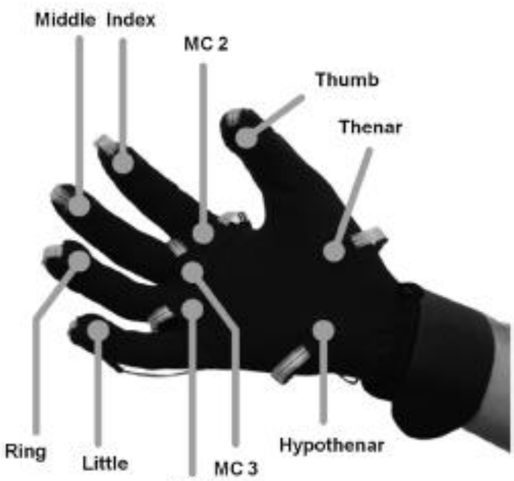

Fig. 3. Location of the ten force sensors on the palm side of the glove. MC: metacarpal.

protocol was performed two times for each type of handrim, with a ten-minute rest interval during which the pairs of handrims were switched. During the protocol, data from instrumented gloves system were collected. The wires and connectors were attached to the chair in a way that it did not interfere with the users' upper-limb movement during manual propulsion (Fig. 4).

2.4. Data analysis

The average value of each sensor was obtained from the two trials of each subject, and then the average force of the 20 subjects was calculated for each sensor. The average force on the two areas of the hand - metacarpals and distal phalanges – was obtained by the sum of the average forces of the five respective sensors of each area. The condition of normality (Shapiro–Wilk's W test) and homogeneity (Levene's test) of data were verified. Student's t-test was applied to normal and homogeneous data to compare both devices. On the data sets that did not meet these conditions, the Wilcoxon's

Fig. 4. Wheelchair set up with the data acquisition components.

test was applied. All results were considered significant at a *P* value of 0.05 or less.

3. Results

The method allowed the comparison of how contact forces act on hands' surface when propelling a wheelchair with two different handrim designs. The behavior of contact forces as a function of time can be appreciated by looking at the data of a single trial of one subject (Fig. 5). In order to simplify the graphic and facilitate the understanding, the sensors were grouped as follow: distal, comprising the five sensors positioned in the distal phalanges; and metacarpals, comprising the five sensors on the palm of the hand.

For both regions – metacarpals and distal phalanges – there was a reduction in the magnitude of the contact forces during the three propulsion phases with the use of the ergonomic handrim (Fig. 6). The percentage of reduction on the contact forces was greater in the metacarpals than in the distal phalanges: start-up (metacarpals 56.6%, distal phalanges 17.2%); forward motion (metacarpals 55.2%, distal phalanges 24.4%); and braking (metacarpals 30.1%, distal phalanges 17.4%).

By looking individually to each sensor, it is possible to identify areas of the hand where the contact with the handrim was more intense (Table 1). In all the propulsion phases and for both handrims, the distal phalange of the third finger registered the greater forces among all sensors. In the metacarpal region, the greater forces were concentrated in the bases of the second and third fingers. The vast majority of the ten areas of the hands showed a reduction on the contact forces with the use of the ergonomic handrim during all the five propulsion cycles. Although statistical significant difference between the two handrims was found in many areas, only the thumb showed a significant reduction in the three phases with the ergonomic handrim. Only the second metacarpal (basis of the second finger), during the braking phase, showed a significant increase in the contact force with the ergonomic handrim. Finally, the total force (sum of the forces measured by the ten sensors) reveals that, for both handrims, forces of greater magnitude occurs during the start-up and braking phases.

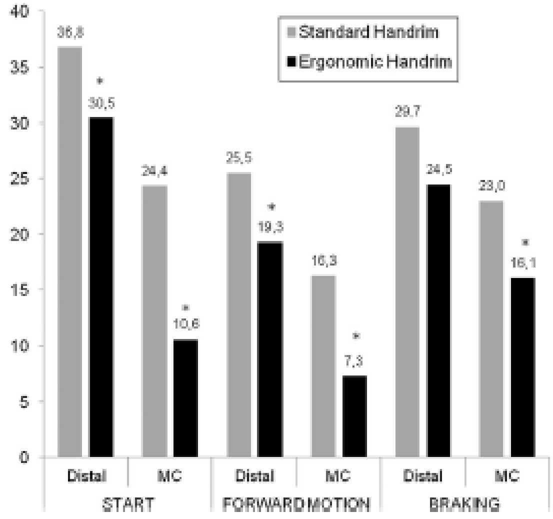

Fig. 6. Contact forces (average) on distal phalanges and metacarpals during start, forward motion and braking (Forces expressed in Newton). *significant difference ($p \leq 0.05$).

4. Discussion

This study showed that different handrim designs influences the distribution of contact forces on hands' surface. Additionally, the results indicate that propelling a wheelchair with an ergonomically designed handrim reduces the forces on user's hands, in comparison with a standard round tube handrim. This is most likely because of the greater surface of contact and anatomical shape provided by the ergonomic handrim. Similar results were found by previous studies that investigated forces on hands with the use of handles and other hand tools (Kong and Freivalds, 2003; Lu et al., 2008). As a result of the greater surface, there is a more equitable distribution of contact forces on hands, reducing the forces measured by each sensor.

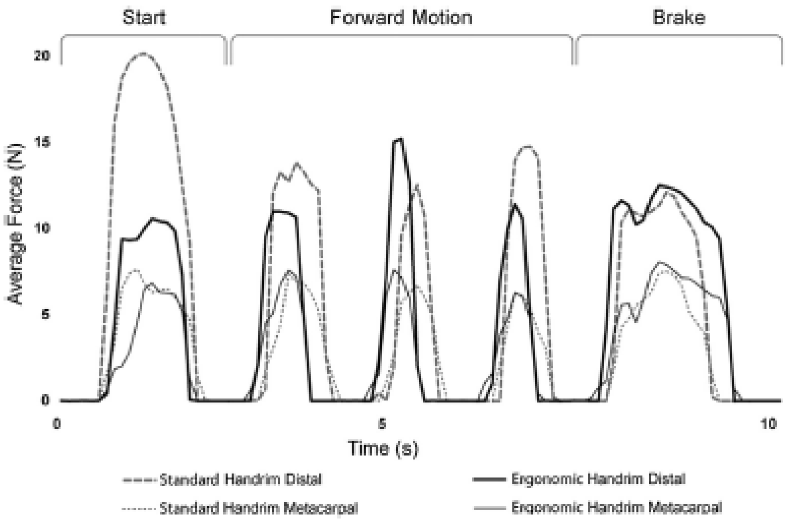

Fig. 5. Contact forces in five consecutive pushes of a single subject.

Table 1
Average forces for each sensor during the three propulsion phases.

		Start-up		Forward motion		Braking	
		N.H.	C.H.	N.H.	C.H.	N.H.	C.H.
Distal phalanges	Thumb	5.41	7.30[a]	2.91	5.25[a]	3.44	7.32[a]
	Index	3.28	5.02[a]	1.35	3.23[a]	1.12	1.77
	Third	9.10	10.13	7.19	8.07[a]	9.74	10.89
	Fourth	6.43	7.42[a]	4.42	4.61	5.02	5.65
	Fifth	6.23	6.91	3.41	4.36[a]	5.17	4.04
Metacarpals	Thenar	0.95	1.95[a]	0.51	1.12[a]	0.7	0.74
	MC2	5.44	7.91[a]	4.01	4.66	6.13	4.21[a]
	MC3	1.39	7.62[a]	0.68	5.43[a]	2.33	8.80
	MC4	0.85	5.14[a]	0.47	3.53[a]	2.02	4.14
	Hypothenar	1.94	1.75	1.63	1.55	4.93	5.11[a]
	TOTAL	41.02	61.15	26.48	41.81	40.6	52.67

[a] Significant difference ($p < 0.05$).

The current findings can be related with the study of van der Linden et al. (1996), which showed lower physiological parameters (oxygen consumption and respiratory exchange ratio) and higher gross mechanical efficiency when propelling the wheelchair with the use of handrims of larger tube diameter (oval shaped tube with a cross section of 25 by 30 mm) compared to a handrim with 18 mm tube diameter. The decrease in the physiological parameters might be explained by the decreased need for stabilization by the larger muscle groups at the elbow and shoulder (van der Linden et al., 1996). In contrast with this, van der Woude et al. (2003) found no difference in oxygen uptake, gross mechanical efficiency and forces applied on the handrim when comparing four different handrim profiles. It is possible that the differences between the handrims might not be enough to promote changes in physiological parameters and propulsion forces. Thereby, the contact forces on the hand-to-rim interface appear to be more sensitive to detect differences between handrim. Although the physiological and kinetic parameters not show significant differences among the handrim models, the subjective ratings of the participants showed a clear preference for the round foam rubber-coated handrim. This is an interesting finding since it evidences the importance of the increased friction (provided by the foam rubber coating) to hold and push the handrim.

As expected, contact forces of greater magnitude occurred during both the start-up and braking phases. From a mechanical point of view, this finding reflects the inertial challenges to, respectively, put a stationary chair in motion and stop it from moving. In contrast, propelling a rotating wheel requires less force to maintain the wheelchair in motion.

Because the contact forces on the hand do not act directly to move the wheels, but only in holding the handrim, they cannot be interpreted in terms of mechanical effectiveness. The reduction of contact forces impacts pressure on the hands, which is directly related to comfort in handling hand tools. Thus, measuring contact forces on the hand's surface might provide more reliable information related to comfort than effectiveness. When addressing propulsion efficiency, it is important to study the relationship between energy expenditure and muscular activity pattern (Spaepen et al., 1996). Therefore, future studies should investigate how the handrim design affects physiological parameters as well as upper limbs kinetics and kinematics during manual propulsion.

Contact forces on hands' surface have already been addressed in previous studies on the ergonomics of hand tools (Kong and Freivalds, 2003; Lu et al., 2008; Kong and Lowe, 2005). The study of Aldien et al. (2005) investigated the interface pressure by sensoring the handle with a flexible capacitive pressure sensing grid. The authors found that the handle diameter influences the magnitudes and distribution of hand–handle interface forces in a gripping and pushing task. Also of interest, the study showed that the average peak interface pressure for a given handle size can be expressed as a linear combination of grip and push forces. Although not used in studies addressing forces on hand surface, other studies have investigated interface pressure distribution by using different measurement systems (Marenzi et al., 2013; Lampe and Mittemacht, 2010).

As happens in manual wheelchair mobility, pushing forces are present in several user–product interactions of daily life. The forces involved in manual activities (coupling forces) can be divided them into two main components: gripping force and push force or pull force (Malinowska-Borowska and Grzegorz, 2013). These force components are also present in manual propulsion in the repetitive act of holding, pushing and releasing a rotating handrim. In a recent study, Garg et al. (2014) discussed the factors affecting pushing forces in daily and work activities (such as pushing carts and other objects). Among many user-product-environmental factors that may affect pushing force, those of interest to manual wheelchair mobility are: friction, handle design, slope of the terrain, wheels, weight on the chair, among others.

When addressing biomechanics of manual propulsion, it is important to consider that the velocity can affect propulsion technique. According to the study of Spaepen et al. (1996), as velocity increases, the push time is decreased, resulting in a decrease in cycle time. Additionally, both start and end angles are shifted to the front of the handrim (Spaepen et al., 1996). Therefore, when moving faster, the activity of repeated holding, pushing, and releasing the handrim may expose the hands to the risk of traumas from the wheels. By providing greater surface for a firm grip, the ergonomic handrim aims to provide a safe and stable support for the hands.

This study may contribute to innovations in the design of wheelchair handrims. In order to enhance the ergonomic features manual wheelchairs, it is important to use both anatomical and biomechanical information of wheelchair users when designing wheelchairs and accessories (such as handrims). Furthermore, the anthropometrics of wheelchair users was shown to vary between different groups of this population (Paquet and Feathers, 2004), which requires designers and producers to be aware of it when developing wheelchairs and accessories.

One concern of this study was related about the influence of shear force on the measured force, as it may happen when holding and pushing the handrim. According to Hall et al. (2008), the presence of shear force may overestimate up to 36% the compression force measured by the FSRs sensors. However, the authors found that prolonged use significantly reduces the influence of shear loading on the measured force to 2.8%.

Although the current study showed important findings, it has limitations that must be noted. First, only able-bodied subjects participated in this study, and thus, the findings of this study are not fully representative of wheelchair users. The experience in wheelchair use is related to a decrease in energy expenditure (Croft et al., 2013) and an increase in gross mechanical efficiency (Brown et al., 1990; de Groot et al., 2002; Lenton et al., 2008). These improvements may be the result of adaptations in propulsion pattern and muscle activity and coordination. Studying wheelchair users could provide important information on the mechanical interaction between hand and handrim among a variety of groups of different levels of upper limb function. Additionally, the sensors did not cover the entire palm surface of the glove, and the forces registered are only valid for the limited area of each sensor. The investigation of the electromyography of the forearms during manual propulsion could provide additional information on the relation between handrim design and muscular work, improving the analysis of the current results. Finally, due to equipment and space limitations, only straight forward motion was performed and, as a result, we do not have data from turning maneuvers, which would best mimic wheelchair propulsion in daily life.

5. Conclusions

This study showed that the handrim design influences the magnitude of contact forces on hands' surface during manual wheelchair propulsion. Compared to the standard round tube handrim, the use of an ergonomic handrim with increased surface and anatomical shape reduces the contact forces on hands in both metacarpal area and distal phalanges during start-up, forward motion and braking the wheelchair. Additionally, this study showed that the magnitude of contact forces on hands are greater during the start-up and braking the chair, which is related to the inertial challenges to put the chair in motion and make it stop. Improving the comfort and safety in manual wheelchair usage must be targeted by designers and manufacturers in order to benefit both product usability and users' satisfaction.

Conflict of interest

The authors declare that they have no conflict of interests.

Acknowledgments

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Conceptual Project of a Servo-Controlled Power-Assisted Wheelchair*

Fausto O. Medola, Benedito M. Purquerio, Valeria M.C. Elui, Carlos A. Fortulan

***Abstract*— Manual and powered wheelchairs have been widely used as assistive technologies to improve users' mobility. However, both types of wheelchairs have problems that limit the users' ability in moving independently, thus impacting social participation, health and quality of life. This paper report on the conceptual development of a manual wheelchair equipped with a servo-controlled power-assisted system. The development process comprised the design of a wheelchair frame properly designed to receive the components of the power-assistance system; the measurement and integrated processing (with an onboard computer) of the user's forces applied to the handrim and rear wheels angular velocity. The integrated processing of these data generates an order to the motor driver, according to an algorithm of conditions that specifies the state (activation or deactivation) and magnitude of operation of the servo-motor. The output torque of the servo-motor (located below the seat and between the rear wheels) is distributed to both rear wheels via mechanical differential, thus allowing similar drivability to a standard manual wheelchair. The implementation of the innovative and ergonomic characteristics of the servo-controlled power-assisted wheelchair may improve users' ability to move longer and with comfort and safety, thus benefiting social participation and quality of life.**

I. Introduction

Wheelchairs are widely used as assistive technologies aimed to promote independent mobility and improve users' social participation. However, propelling manual wheelchairs is a very extenuating and inefficient mode of ambulation [1], which may be related to a very curious and controversial finding: many users referred that the wheelchair is the main factor limiting their community participation [2]. Improving wheelchair mobility may benefit users' independence and quality of life and, to do so, both scientific and technological advances must be targeted by an interdisciplinary point of view between health sciences and engineering.

From the users' perspective, the two most common types of wheelchair – manual and powered – do not provide full independence in locomotion. Quantifying daily mobility evidences the gap between normal gait and wheeled mobility: while walkers move a mean of 6 to 7.5 km a day [3], wheelchair users move only 1.5 to 2.5 km [4, 5]. These findings suggest that the wheelchair, even being an assistive device, plays an important role on users' mobility limitation.

Manual propulsion, the most common mode of operating a wheelchair, is characterized by the combination of loads and repetition [6]. As a result, long term use of manual wheelchairs has been related to the high incidence of upper limb injuries [7, 8]. Due to the high demand on upper limbs, many mobility situations become difficult or even impossible for the users to perform, such as moving on uneven terrains, ramps, uphill and long distance displacements. On the other hand, motorized wheelchairs, the immediate solution for most of the problems associated to manual propelled chairs, have limitations that, ultimately, do not fully benefit users' mobility. Indeed, the daily distance traveled of power-wheelchair users is similar to those who move with manual wheelchairs [9]. Furthermore, motorized chairs expose the user to a passive condition in his/her locomotion, which is important to consider since inactivity may contribute to obesity and cardiovascular problems. Other aspects such as total mass, cost, battery autonomy and maintenance contribute to the limited acceptance of power-wheelchairs among users.

In an attempt to improve users' mobility, alternative devices were developed based on hybrid systems, whose concept is based on the association of motorized assistance complementary to manual propulsion, with the objective of minimizing the users' workload during locomotion and keeping the manual propulsion as the mode of operation. The assisted propulsion systems currently available are based on a sensing and motorizing system for each of the two rear wheels [10-12]. In commercially available power-assisted wheelchairs, the two motors are coupled to the respective wheels hub and supplied by a single battery attached to the frame of the chair. In general, these systems increase from 15 to 24 kg in the mass of manual chairs, a significant increase considering the weight of most manual wheelchairs ranging from 12 to 17 kg.

Previous studies have shown the benefits of motorized assistance for manual wheelchairs. From the perspective of functionality, the use of assisted propulsion systems improved the mobility of tetraplegic subjects on ramps, uneven terrain and carpeted surfaces [13]. The benefits for

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tetraplegic subjects also comprise the reduction on energy expenditure, propulsion frequency and upper limbs range of motion [14]. For users with upper limbs symptoms, the use of power-assisted systems proved to be beneficial, with decreased energy expenditure and perceived exertion, as well as significant increase in distance travelled [15]. In addition, Arva et al. [16] demonstrated that power-assisted wheelchairs provide greater mechanical efficiency and lower energy consumption compared to manual equipment.

Despite the above mentioned benefits, power-assisted systems are still not widely used among wheelchair users. Possibly, the main limitation of these devices is related to the difficulty in performing maneuvers in areas locals of reduced space [12]. Once each rear wheel is independently motorized, applying asymmetric forces on the handrims – commonly used to move on curves, turn the chair and perform short displacement maneuvers - result in asymmetric amplification of the torques on the wheels, thus altering the turn radius from the primarily intended by the user. From this perspective, power-assisted systems work satisfactorily only when moving straight or the trajectory is not constantly changed, which does not represent how people move with wheelchairs in their daily routines.

This way, although the biomechanical benefits have been demonstrated, up to date, the use of power-assisted wheelchairs does not find definitive support for unequivocal prescription. Furthermore, the independent motorization for each rear wheel represents an increase in system's cost, weight and complexity. This study aims to present a proposal for a conceptual project of an intelligent power-assisted system for manual wheelchairs. Scientific and technological challenges inherent to this project involve the development of mechanical and electronic solutions for sensoring the handrim forces, motorizing and transmission of torque to the rear wheels, in order to provide optimal propulsion assistance and similar drivability to manual wheelchairs.

II. Experimental Procedure

The current study was carried out in the Laboratory of Tribology and Composites (LTC) at School of Engineering of Sao Carlos, University of Sao Paulo. Firstly, it was designed a wheelchair with an original project in order to enable a power-assisted system to be properly installed to the wheelchair. The wheelchair was design with ergonomic characteristics, in order to provide the most appropriate conditions for a safe, comfortable and efficient use.

After designing the wheelchair, the components of the power-assisted system were defined in terms of sensoring, acquiring and processing the data from user's actions on the wheels. The most appropriate sensors for each data were then selected, and an algorithm for data processing was developed to determine the specific conditions for activating, working and deactivating the power-assisted system. Finally, it is presented the implementation of the system, that is, the prototype of the servo-controlled power-assisted wheelchair.

III. Results

The current results are consequence of a multidisciplinary approach and include issues of: ergonomic design; propulsion and assistance; algorithm for data processing and power-assistance; and a build of a prototype to qualitative evaluation.

A. Equipment Design

An original project of wheelchair frame and wheels was designed, in order to receive the components of the power-assistance system. Ergonomic features were applied on the design of the handrim interface: an improved hand-to-rim coupling was provided by a handrim with greater surface and anatomical shape for hand's contact. The handrim was connected asymmetrically to the wheel hub, resulting in more space between the wheel (with camber) and the vertical (orthogonal) handrim, as shown in Figure 1. Besides protecting the hands against traumas with the wheels, this increased space allows the user to push the handrim in variable grip positions, thus benefiting propulsion comfort and safety. Because the handrim and the wheel are connected asymmetrically, the handrim forces are transmitted to the wheels by drag pins connecting the inner face of the handrim to the outer face of the wheel.

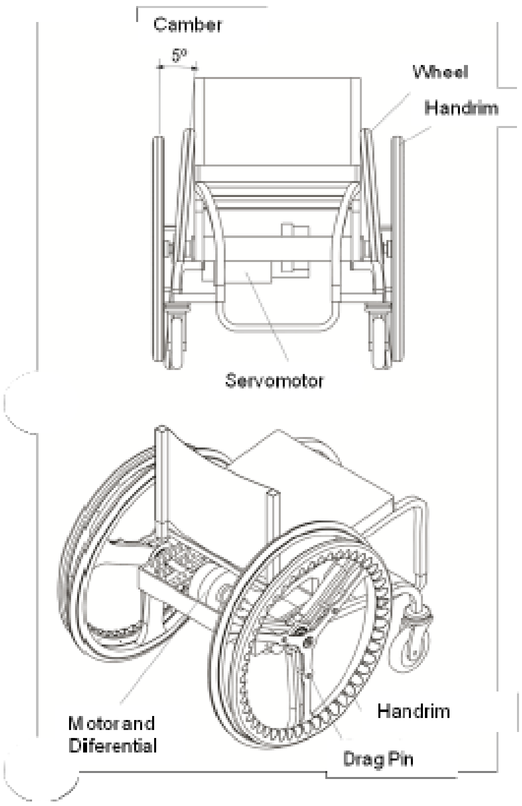

Figure 1. Schematic drawing of assistive wheelchair: front view (above) and isometric rear view (below).

The power-assisted system comprised a servo-motor (EC45 Maxon Motor, brushless, 250 Watt, planetary

Gearhead GP62A and Driver 4-Q-EC Amplifier DEC 70/10). The output torque of the servo motor was distributed to the rear wheels through a mechanical differential system. The components of the motor system were positioned inside a box – here called motor box – positioned in the center of the wheelchair, under the seat. This is an important feature that distinguishes this prototype from the current commercially available power-assisted chairs, because most of the added mass is located in a centered position of the system (between the rear wheels) and, therefore, close to the wheelchair center of mass. Theoretically, it minimizes the effect of the added mass on the wheelchair rotational inertia [17], thus ensuring similar drivability to conventional manual wheelchairs.

B. *Propulsion and assistance*

During manual propulsion, the system recognizes the user's intention to move and provides complementary power proportional to the handrim forces. To combine the manual force with the torque provided by the motor under a certain condition of locomotion, three types of information were used: (i) user's forces on the handrim, measured with strain gauges; (ii) rear wheels rotation, measured with optical encoders; and (iii) slope of the terrain, measured with a triaxial accelerometer. A scheme of the position of the force sensors is presented in Figure 2. To process and use these data during real time propulsion, a data acquisition system collect (DAQ NI USB 6009®, National Instruments) and processes it (with a program develop in Labview®, National Instruments) onboard (with a portable computer with Windows Operational System). Figure 3 shows a scheme of the electric power supply and system's operation.

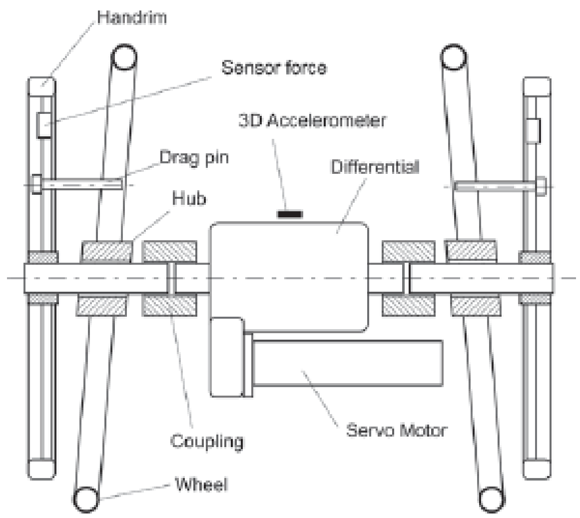

Figure 2. Acquisition of force and motor system scheme.

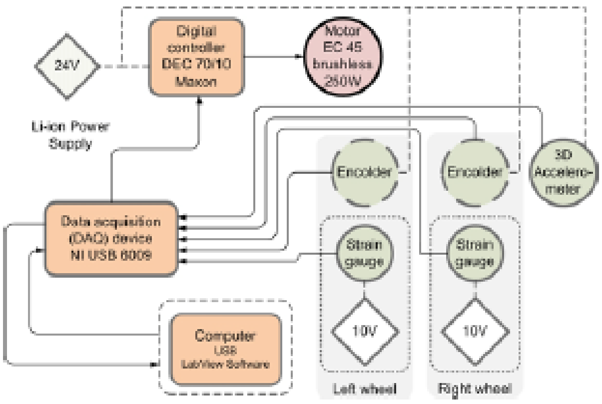

Figure 3. Electric power supply and system's operation.

C. *Algorithm for the Power-Assistance System*

In order to properly match the power-assistance to user's needs and intention to move, an algorithm of conditions and actions was developed (Figure 4). To activate the assistance system, the most important answer to respond is:"Does the user want to move?" Two conditions need to be satisfied in order to activate the system: (i) a second push; and (ii) a minimal wheel angular rotation of 180°. If these two conditions happen simultaneously, then the motor is activated with a certain torque (T1) and velocity (V1, wheel rotation), both dependent on and proportional to the measured handrim force and rear wheels angular rotation. To maintain the motor assistance, another force must be applied on the handrim before the wheels stop moving. If this force (F2) is of similar strength to F1, then both torque and velocity are kept the same as T1 and V1. On the other hand, forces of greater or lesser strength activate mode of acceleration or deceleration, respectively. The deactivation of the power-assistance is triggered if two applied forces of lesser strength are measured consecutively or no push is detected after a decrease in the measured force.

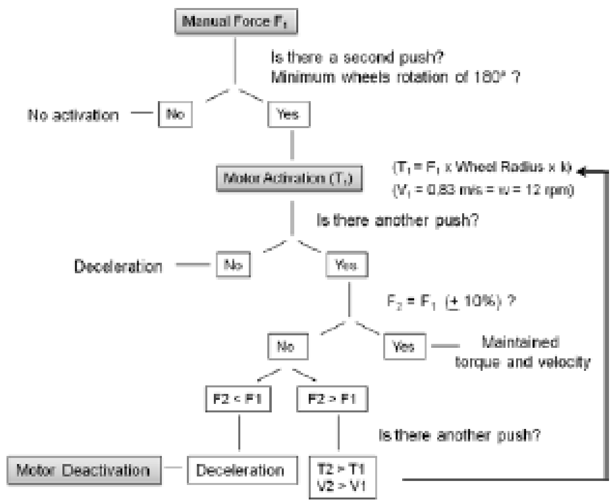

Figure 4. Algorithm for the activation and deactivation of the power-assistance.

D. Prototype of the Servo-Controlled Power-Assisted Wheelchair

The development of the wheelchair prototype comprised: the design and production of an original wheelchair frame; design and production of a pair of rear wheels with original designed wheel hub; a pair of two ergonomic handrims; a pair of two commercially available casters. All these components were mounted as a wheelchair prototype, and then instrumented with the power-assistance system, as shown in Figure 5.

(a)

(b)

(c)

Figure 5. Prototype of the servo-controlled power-assisted wheelchair: (a) isometric front view; (b) isometric rear view; (c) user and chair interaction.

IV. Conclusion

This paper reported on the conceptual project of a servo-controlled power-assisted wheelchair. The system comprised a number of technologies applied for: sensoring and processing real-time measurements of handrim forces, wheel rotation velocity and slope terrain; controlling of a single motor and transmission of torque and velocity to the rear wheels through a mechanical differential system. Furthermore, the wheelchair prototype was designed with ergonomic features in the handrim interface, in order to provide a stable, safe and comfortable grip when pushing the handrims. The preliminary tests showed promising results in terms of power-assisted system and mechanical operation. The system configuration is currently being adjusted to improve its operation. Future tests will investigate propulsion biomechanics, wheelchair drivability and users' perception on the servo-controlled power-assisted wheelchair.

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The authors would like to thank the National Council for Scientific and Technological Development (CNPq, Process N. 484153/2011-0, Brazil) and Coordination for the Improvement of High Education Personnel (CAPES, Process N. BEX 0810/12-6, Brazil), for the financial support.

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Revista D.: Design, Educação, Sociedade e Sustentabilidade

Avaliação da Inércia Rotacional de Cadeira de Rodas Manual: implicações para o design ergonômico

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Avaliação da Inércia Rotacional de Cadeira de Rodas Manual: implicações para o design ergonômico

Resumo

No design de uma cadeira de rodas manual, o desempenho na locomoção é um dos aspectos de maior preocupação, em vista da importante limitação de mobilidade à qual os usuários estão expostos. O desempenho na mobilidade é resultante, basicamente, do equacionamento entre os esforços do usuário, os aspectos inerciais da cadeira de rodas e a resistência ao movimento (principalmente no atrito entre as rodas e a superfície). O designer é capaz de intervir nesta equação - e desta forma no desempenho da mobilidade - abordando os aspectos inerciais do equipamento. Para deslocamentos em trajetória retilínea, a massa total da cadeira de rodas é o principal componente inercial. Por outro lado, para movimentos em trajetórias curvas ou mistas, bem como para manobras de giro da cadeira, assume grande relevância a inércia rotacional do sistema. Neste sentido, o objetivo deste estudo é avaliar a influência da adição de massa (e sua localização) e do uso de dois diferentes conjuntos de aro-roda na inércia rotacional de uma cadeira de rodas manual. Uma plataforma construída com sensores de força e encoder óptico foi utilizada para avaliação da inércia rotacional da cadeira de rodas. As medidas foram realizadas em três situações, em todas sendo utilizada a mesma cadeira de rodas: (i) adição de pesos nas rodas e no centro do assento da cadeira; (ii) dois diferentes conjuntos de rodas e pneus traseiros comercialmente disponíveis; (iii) duas posições - anterior e posterior - do eixo das rodas traseiras. Os resultados demonstram que, para uma mesma configuração de cadeira de rodas, a adição de corpos de pouca massa (0,25 kg e 0,4 k) junto aos eixos das rodas traseiras provoca maior aumento da inércia rotacional do que a adição de 5,5 kg em posição centralizada. Similarmente, o conjunto de rodas de maior massa resultou em maior inércia rotacional, assim como a posição posterior das rodas (consequentemente maior comprimento da cadeira). Este estudo contribui com duas diretrizes projetuais para cadeira de rodas: a massa do equipamento deve estar concentrada, o máximo possível, próximo ao centro de massa da cadeira; as medidas de comprimento e largura devem ser as menores possíveis, de modo a diminuir as distâncias dos extremos (e suas massas) anterior, posterior e lateriais para o centro de massa do equipamento. Designers devem, no processo de desenvolvimento de cadeiras de rodas manuais, considerar os aspectos inerciais do equipamento, de forma a favorecer o desempenho da mobilidade de seus usuários e, assim, sua funcionalidade, independência e qualidade de vida.

Palavras-chave: Cadeira de rodas, Mobilidade, Design, Tecnologia Assistiva.

Evaluation of Rotational Inertia of Manual Wheelchair: implications for ergonomic design

Abstract

In the design of a manual wheelchair, the performance during mobility is one of the aspects of great concern, due to the important limitation in the mobility among users. The mobility performance results, basically, from the equation between user's manual efforts, wheelchair inertial properties and rolling resistance (mainly the friction between the wheels and the surface). The designer can intervene in this equation - and thus in the mobility performance - by addressing the inertial aspects of the equipment. For straight-forward displacements, wheelchair total mass is the main inertial component. In contrast, for turning trajectories and maneuvers, rotational inertia of the system plays an important role. The aim of this study was to evaluate the influence of adding mass (and its location) and the use of two different sets of rear wheels on the rotational inertia of a manual wheelchair. A platform instrumented with force sensors and optical encoder was used to measure the rotational inertia of the wheelchair. Measurements were taken in three different situations (all them with the same wheelchair): (i) addition of mass in the wheels and in the center of the seat; (ii) two different sets of commercially available rear wheels; (iii) two positions - rearward and forward - of the rear wheels' axle. The results show that, for the same wheelchair configuration, the addition of low weight bodies (0.25 kg e 0.4 k) in the rear wheels led to a greater increase in the rotational inertia of the system than adding 5.5 kg in the center of the seat. Similarly, the heavier set of rear wheels resulted in greater rotational inertia, as well as the rearward position of the rear wheels axle. This study contributes with two ergonomics guidelines for the design of manual wheelchairs: the equipment mass should be concentrated, as possible, close to the center of mass of the chair; the wheelchair length and width should be as small as possible, in order to reduce the distances to the wheelchair center of mass. In the design process of manual wheelchairs, designers should consider the inertial aspects of the equipment, in order to improve mobility performance and, thus, benefiting users' functionality, independence and quality of life.

Keywords: Wheelchairs, Mobility, Design, Assistive Technology.

1 INTRODUÇÃO

A locomoção é uma característica essencial do ser humano, necessária para o desempenho da maioria das atividades de vida diária. Para muitas pessoas com limitação da mobilidade, a cadeira de rodas é o dispositivo de assistência através do qual a locomoção pode ser desempenhada. No entanto, comparada a outras formas de locomoção, a propulsão manual de cadeira de rodas é um modo altamente ineficiente de locomoção (VAN DER WOUDE et al., 2001).

Em sua forma mais tradicional, a cadeira de rodas manual, o usuário se locomove por meio da aplicação de forças (impulsões) nas rodas traseiras de forma rítmica, e a intensidade, simetria e frequência com as quais tais forças são aplicadas determinam a velocidade e trajetória do movimento. A partir de uma perspectiva mecânica, o movimento resultante representa o equacionamento entre as ações do usuário, os aspectos inerciais do equipamento e a resistência ao movimento das rodas (SPRIGLE, 2009). Neste sentido, o design e configuração da cadeira de rodas assumem grande relevância, pois afetam os aspectos inerciais e, como resultado, a atuação do usuário na locomoção.

Este estudo tem como objetivo avaliar a influência do design e configuração de cadeiras de rodas manuais na inércia rotacional (IR) do sistema. Este conhecimento possibilita, em última análise, compreender de que forma a atuação do usuário pode ser influenciada pelo design e configuração do equipamento. Contribui, portanto, para a atividade de designers, fabricantes e demais profissionais que trabalham diretamente com o projeto e produção de cadeira de rodas, a fim de que os produtos desenvolvidos ofereçam melhores condições de mobilidade aos usuários.

2FUNDAMENTAÇÃO TEÓRICA

2.1 Problemas ergonômicos na mobilidade em cadeiras de rodas manuais

Estudos apontam alta prevalência de dor nos membros superiores entre usuários de cadeira de rodas manual, especialmente nos ombros e punhos (ALM et al., 2008; CURTIS et al., 1999; SUBBARAO et al., 1994). A natureza repetitiva da atividade de propulsão manual tem sido apontada como um dos fatores de sobrecarga nos membros superiores de usuários de cadeira de rodas (MIYAHARA et al., 1998; AMBROSIO et al., 2005; BONINGER et al., 2004).

Para um usuário de cadeira de rodas manual, as consequências das lesões de membros superiores podem ser incapacitantes, uma vez que a locomoção, transferências da cadeira e a maioria das demais atividades da rotina diária são desempenhadas com os braços e mãos. a preservação da função dos membros superiores é condição essencial para a independência funcional dos usuários de cadeira de rodas (PARALYZED VETERANS OF AMERICA CONSORTIUM FOR SPINAL CORD MEDICINE, 2005). Desta forma, é importante que o design de cadeiras manuais busque reduzir ao máximo a sobrecarga biomecânica na propulsão manual e aprimorar a eficiência na locomoção.

Possivelmente devido à elevada carga biomecânica relacionada à atividade de propulsão manual, os usuários de cadeira de rodas têm importantes limitações na locomoção independente por longas distâncias, rampas e em terrenos com aclives. Nestas situações, mover-se sem a ajuda de terceiros representa um desafio extenuante, difícil e, por vezes, impossível de ser superado. Recentes estudos possibilitam a compreensão do impacto da limitação de mobilidade na rotina diária: a média de distância percorrida em um dia, através da marcha normal, por adultos sem deficiência é de 6 a 7,5 km (BOHANNON, 2007), enquanto que usuários de cadeira de rodas percorrem de 1,5 a 2,5 km (KARMARKAR et al., 2010; LEVY et al., 2010; TOLERICO et al., 2007).

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Para os profissionais que trabalham com o design, configuração e fabricação de cadeira de rodas, talvez mais importante do que saber o quanto as pessoas se movem seja entender como se movem. Esta questão é essencial para se compreender de que forma o design da cadeira de rodas pode afetar a mobilidade de seu usuário, assim contribuindo para o desenvolvimento de produtos mais adequados ao modo de utilização, necessidades e expectativas dos usuários. Embora o tempo de ocupação diária da cadeira seja relativamente longo (aproximadamente 11 horas/dia), em apenas aproximadamente 10% do tempo os usuários estão efetivamente em movimento (Sonenblumet al., 2012). Sonenblumet al. (2012) estudaram a mobilidade em cadeira de rodas, e encontraram que a locomoção na rotina diária dos usuários é caracterizada principalmente por pequenos e numerosos "episódios de movimento" (aproximadamente distância de 8,6 metros, duração de 21 segundos e velocidade de 0,43 m/s)

2.2 A locomoção em cadeira de rodas manual

A dinâmica de uma cadeira de rodas durante a locomoção diária é influenciada pelas mudanças inerciais durante o início, a frenagem e as curvas. A partir de uma perspectiva mecânica, dois fatores influenciam de forma importante o movimento de uma cadeira de rodas manual: o atrito e a inércia. Tais fatores são manifestados como resistência ao rolamento das rodas, atrito dos rolamentos, massa total e a distribuição de massa, entre outros (SPRIGLE, 2009). Desta forma, as forças manuais aplicadas pelo usuário nos aros propulsores interagem com o atrito e as forças inerciais, e o resultado desta equação de forças é o movimento da cadeira de rodas que, fisicamente, é representado pela sua energia cinética.

Uma cadeira de rodas manual pode ser entendida como a composição de sete corpos rígidos distintos conectados de tal forma a possibilitarem a mobilidade: o quadro, as duas rodas traseiras, as duas pequenas rodas dianteiras (casters) e os dois garfos que suportam, respectivamente, as rodas dianteiras (Figura 1). O desempenho da cadeira de rodas durante a locomoção depende, em grande parte, dos aspectos inerciais de cada componente e da configuração destes no sistema (cadeira de rodas).

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FIGURA 1
Sete componentes essenciais de uma cadeira de rodas: (a) quadro; (b) rodas traseiras; (c) rodas dianteiras (*casters*); (d) suporte ou "garfo" dos *casters*.
Fonte: Elaborado pelo autor, com base na pesquisa realizada.

Do ponto de vista mecânico, para movimentos em trajetória retilínea, o aspecto inercial mais importante é a massa total do sistema. Neste sentido, quanto maior a massa total da cadeira, tanto maior será a dificuldade do usuário em impor acelerações e desacelerações - tais como ao iniciar e frear - no movimento. Por outro lado, quando a trajetória é curvilínea ou mista (alternância de direções do movimento), a inércia de cada um dos componentes e suas posições relativas ao centro de massa na geometria do sistema assumem papel importante, pois determinam a inércia rotacional (IR) do sistema (MEDOLA et al. 2014a). A IR (ou momento de inércia) é uma medida da resistência que um corpo oferece ao movimento de rotação, sendo o análogo rotacional da massa no movimento linear. Desta forma, é dependente da massa e do raio do objeto, conforme demonstrado abaixo:

$$I = m.r^2$$

Na prática, isto sugere que quanto maior a massa das rodas traseiras, maior será o esforço do usuário para impor à cadeira uma trajetória curva. Considerando que a locomoção em cadeira de rodas na vida diária compreende pequenos deslocamentos e constante alternância de direção da trajetória (Sonemblumet al., 2012), a distribuição de massa no equipamento é um fator tão ou mais importante do que a massa total do sistema.

A atuação do usuário sobre a cadeira de rodas manual ocorre por meio das forças aplicadas ao aro propulsor (tubo cilíndrico metálico acoplado às rodas traseiras), em um padrão rítmico que define duas fases: toque (quando o usuário tem suas mãos em contato com os aros propulsores); e fase de recuperação, quando o usuário libera as mãos dos aros e as balanceia para trás, com o objetivo de alcançar novamente os aros e iniciar novo ciclo propulsor.

Portanto, o usuário consegue alterar a direção do movimento somente quando aplica nestes forças assimétricas. Durante a fase de recuperação, quando as mãos são liberadas dos aros, a cadeira de rodas assume trajetória retilínea. Pode-se concluir, a partir do exposto acima, que a locomoção em trajetória curva compreende a alternância entre trajetória curva e retilínea. Para manter a cadeira em uma trajetória curva, o usuário "luta" para alterar a direção do movimento de uma cadeira cuja tendência é deslocar-se em linha reta. Nesta situação, tanto a massa das rodas traseiras quanto a distância destas para o centro de massa do equipamento determinam a dificuldade do usuário em girar a cadeira ou mover-se por uma trajetória curva.

O presente estudo tem como objetivo avaliar a influência da massa, distribuição de massa e configuração da cadeira de rodas na inércia rotacional do sistema. Este conhecimento pode contribuir no entendimento dos aspectos inerciais de uma cadeira de rodas, bem como a importância de se considerar esta visão mecânica e ergonômica no design, configuração e fabricação de cadeira de rodas.

3MATERIAIS E MÉTODOS

Este estudo foi realizado no Rehabilitation Engineering Applied Research Laboratory (REAR Lab), Center for Assistive Technology and Environmental Access (CATEA), GeorgiaInstituteof Technology, Atlanta, Estados Unidos.

3.1Materiais

A cadeira de rodas utilizada no estudo permite o ajuste da posição horizontal (na direção anterior-posterior) do eixo das rodas traseiras em 44,5 mm. Este ajuste é comumente presente em cadeiras de rodas manuais, e possibilita ao usuário ajustar a posição das rodas de acordo com a estabilidade desejada. Quanto mais à frente as rodas, melhor o alcance das mãos durante o contato com os aros propulsores, porém a cadeira tem menos estabilidade traseira. Uma vez que este ajuste altera o comprimento da cadeira, também foi avaliado no que diz respeito aos efeitos na IR do sistema.

A avaliação da IR de cadeira de rodas foi realizada com a plataforma iMachine (EICHOLTZ et al., 2012), que é um equipamento composto de uma plataforma giratória instrumentada com três células de carga dispostas triangularmente e equidistantes umas às outras e ao centro da plataforma, onde há um encoder ótico (Figura 2). As informações dos sensores de massa (células de carga) e de rotação da plataforma (encoder ótico) são coletadas por um dispositivo de aquisição de dados conectado a um computador, onde os dados são analisados em programa desenvolvido em ambiente Labview 7.0 (NationalInstruments, Austin, TX, USA).

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FIGURA 2
iMachine - equipamento para medição da inércia rotacional de cadeira de rodas: oscilação da plataforma em eixo normal à intersecção das coordenadas *x* e *y*.
Fonte: Elaborado pelo autor, com base na pesquisa realizada.

3.2 Métodos

O procedimento de avaliação consiste em posicionar a cadeira de rodas sobre no centro plataforma, o que é facilitado pela visualização em tempo real das massas registradas pelas três células de carga, permitindo assim ao operador ajustar a posição da cadeira até que a condição ideal seja atingida.

Após garantir o posicionamento da cadeira de rodas no centro da plataforma, uma alavanca é acionada para produzir um deslocamento na plataforma que, após liberada, oscilada em torno de um eixo que cruza verticalmente o centro da plataforma, em rotação com frequência aproximada de 1,25 Hz. A partir das medidas de massa e período de oscilação da plataforma, obtém-se a inércia rotacional do sistema. Paracada medida, este procedimento foi repetido por cinco vezes, e a média dos valores medidos foi então calculada.

Em todos os testes, foi utilizada a mesma cadeira de rodas (modelo Aero Z, TiLite). No entanto, com o objetivo de comparar os efeitos de diferentes configurações de cadeira de rodas na IR do sistema, dois diferentes pares de rodas traseiras foram utilizados (Figura 3). Os efeitos da posição horizontal do eixo das rodas também foi investigada, pois a cadeira utilizada permiteo ajuste horizontal (anterior-posterior) das rodas traseiras em 44,4 mm. Ainda, foi avaliado o efeito da adição de corpos de diferentes pesos em nas rodas e no centro do assento na IR do sistema.

(a)

(b)

FIGURA 3
Dois modelos de conjunto pneu-roda: (a) pneu com enchimento a ar e roda multi-raios; (b) pneu maciço e roda com raios largos.
Fonte: Elaborado pelo autor, com base na pesquisa realizada.

Para apreciação dos resultados, são apresentadas as médias das cinco medidas realizadas da IR para cada configuração da cadeira de rodas.

4RESULTADOS

A análise dos efeitos do acréscimo de corpos de diferentes pesos nas rodas ou em posição central do assento da cadeira de rodas demonstra que, de uma forma geral, a distribuição de massa é mais determinante para a IR da cadeira de rodas do que propriamente sua massa total. Conforme demonstraa Tabela 1, o acréscimo de 0,25 kg no eixo de cada roda traseira resultou em maior aumento da IR (5,9%) do que o acréscimo de 5,5 kg (2,36%) no centro do assento.

TABELA 1
Efeitos da adição de corpos de diferentes massas em diferentes posições na IR do sistema

Configuração da Cadeira de Rodas	Massa Total (kg)	IR média (kg.m2)	Porcentagem de aumento em relação à configuração original
Cadeira de rodas com configuração original	12,15	1,101	-
Cadeira de rodas + 0,25 kg no eixo de cada roda traseira	12,65	1,166	5,9 %
Cadeira de rodas + 0,4 kg no eixo de cada roda traseira	12,95	1,201	9 %
Cadeira de rodas + 1,2 kg no centro do assento	13,35	1,102	0,09 %
Cadeira de rodas + 5,5 kg no centro do assento	17,65	1,127	2,36 %

A mudança de configuração de uma mesma cadeira de rodas, ou seja, a posição do eixo das rodas traseiras e o conjunto roda/pneu utilizado - também afetou a IR do sistema (Tabela 2). Enquanto a posição do eixo das rodas traseiras modifica a geometria mantendo-se a massa total da cadeira, o conjunto pneu/roda altera a distribuição de massa, em uma mesma geometria. Considerando ambas as situações, o menor valor de IR foi encontrado com a configuração que combinou a posição anteriorizada do eixo das rodas traseiras e os pneus a ar / rodas multi-raios (1,073 kg-m^2). Por outro lado, a combinação entre posição posteriorizada do eixo das rodas traseiras e pneus maciços / rodas raio largo apresentou a maior IR, 11% maior em relação à configuração de menor IR.

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Posição do eixo das rodas traseiras	Conjunto Pneu / roda	Massa (kg)	IR Média (kg.m²)	Porcentagem de aumento em relação à menor IR
Anterior	Pneus a ar / Rodas multi-raios	12,15	1,073	-
Posterior	Pneus a ar / Rodas multi-raios	12,15	1,101	2,6 %
Anterior	Pneus maciços / Rodas raio largo	13,30	1,169	8,94%
Posterior	Pneus maciços / Rodas raio largo	13,30	1,191	11%

TABELA 2
Influência do conjunto pneu / roda e da posição das rodas traseiras na IR do sistema

5 DISCUSSÃO

O presente estudo demonstrou que o design e configuração de cadeiras de rodas manuais determinam a inércia rotacional de um equipamento e, portanto, afetam as cargas impostas ao usuário durante a locomoção e a dirigibilidade da cadeira. Ainda, os resultados demonstram que a distribuição de peso na geometria da cadeira de rodas exerce maior influência na IR da cadeira de rodas do que sua massa total sendo, portanto, um aspecto de atenção para designers e fabricantes de dispositivos de mobilidade sentada.

Os resultados deste estudo devem ser compreendidos a partir da perspectiva das implicações do design e configuração da cadeira de rodas na mobilidade do usuário. Especificamente, a IR do sistema afeta a dirigibilidade do dispositivo, em especial a realização de manobras de giro sobre o próprio eixo e a locomoção e trajetórias curvas ou mistas. Os movimentos em trajetória curvilínea merecem destaque, uma vez que são caracterizados pela alternância entre giro da cadeira e movimento retilíneo. Durante o deslocamento em trajetória curva, o usuário consegue fazer com que a cadeira gire apenas quando aplica forças assimétricas nas duas rodas. A partir do momento que libera as mãos do aro (movimento necessário para iniciar um novo ciclo propulsor), a cadeira assume movimento retilíneo, conforme demonstrado em um recente estudo (MEDOLA et al., 2014a). Portanto, nesta situação, quanto maior a IR do sistema, maior a dificuldade do usuário em retirar a cadeira de um movimento retilíneo e assumir trajetória curva.

Os resultados do presente estudo podem ser correlacionados com o estudo de MEDOLA et al. (2014a), que demonstraram que, para movimentos em trajetória retilínea, o principal componente inercial da energia cinética é a massa total da cadeira e sua velocidade em deslocamento translacional. Em outras palavras, para deslocamentos em trajetória retilínea, a energia cinética em rotação (giro da cadeira ou movimento curvilíneo) é desprezível e, portanto, a massa total da cadeira é o principal componente inercial. Por outro lado, para manobras de giro da cadeira sobre o próprio eixo, o principal componente inercial da energia cinética refere-se à inércia rotacional do sistema que, conforme demonstrado no presente estudo, decorre diretamente e é mais dependente da distribuição de massa na geometria do sistema do que de sua massa total.

O processo de desenvolvimento de uma cadeira de rodas manual, no âmbito do design ergonômico, envolve a concepção de um dispositivo de mobilidade para pessoas com deficiência, de forma a reduzir as cargas biomecânicas e aumentar a eficiência da locomoção e, desta forma, favorecer a funcionalidade e independência do usuário. Os diversos aspectos do design e configuração de cadeira de rodas manual que afetam a mobilidade foram discutidos em um recente estudo (MEDOLA et al., 2014b). É também objetivo do designer conceber um produto cujo uso proporcione conforto e satisfação. No entanto, implementar todas estas qualificações em um único projeto representa um desafio de difícil resolução plena durante a prática projetual. Um exemplo: para melhorar o conforto na postura sentada do usuário de cadeira de rodas, a solução mais imediata seria aumentar as dimensões das superfícies de suporte (assento, encosto, apoio para os pés, apoio para os braços), de modo a distribuir o peso do corpo por uma maior área e, desta forma, reduzir a pressão em pontos específicos da interface usuário-cadeira. No entanto, tal solução implica em aumento da massa e alteração da distribuição de massa do sistema. O uso de apoio de braços, em vista de sua localização nos extremos laterais do assento, aumenta a concentração de massa nesta região e, portanto, implica em maior IR do sistema, conforme demonstrado no presente estudo. Além disso, um estudo demonstrou que a posição do apoio dos pés influencia a IR do sistema e está diretamente relacionada ao desempenho na realização de manobras de giro da cadeira de rodas (MACPHEE et al., 2001).

As implicações práticas para o design e configuração de cadeiras de rodas manuais podem ser resumidas em três recomendações: (i) a massa total da cadeira de rodas deve ser a menor possível; (ii) a distribuição de massa na geometria da cadeira deve buscar concentrar a maior parte da massa próxima ao centro de massa do sistema; (iii) a cadeira de rodas deve possuir menores medidas de comprimento e largura possíveis (medidas nas direções anteroposterior e látero-lateral), reduzindo assim a distância dos extremos da cadeira para o centro do equipamento. É importante ressaltar que designers e fabricantes devem considerar que estas recomendações não podem ser compreendidas como regra geral para um projeto de cadeira de rodas, uma vez que influenciam outros aspectos da interação entre usuário e equipamento, tais como a estabilidade, segurança e conforto do usuário. No entanto, se consideradas como diretrizes, podem contribuir de forma importante no desenvolvimento de um produto que ofereça condições ótimas de desempenho na mobilidade.

Apesar dos resultados demonstrarem o impacto das alterações na configuração da cadeira de rodas na IR do sistema, os mesmos não indicam a extensão com a qual a mobilidade do usuário é afetada. Apenas a partir de testes que avaliem os aspectos fisiológicos e biomecânicos da locomoção em cadeira de rodas manual e a percepção de esforço do usuário nas diversas trajetórias e manobras, será possível verificar as correlações objetivas entre a configuração do equipamento e as reais implicações à demanda de trabalho do usuário.

6CONCLUSÃO

Este estudo demonstrou que o design e configuração dos componentes de uma cadeira de rodas manual afetam a inércia rotacional do sistema e, desta forma, sua dirigibilidade. Os resultados apresentados permitem destacar duas conclusões principais: a distribuição de massa na geometria da cadeira de rodas é mais determinante para a inércia rotacional do que a massa total; a posição anterior-posterior das rodas traseiras determina o comprimento da cadeira e, portanto, a inércia rotacional. A partir destas conclusões, podem ser destacadas duas diretrizes para o design de cadeira de rodas, no que diz respeito ao desempenho na mobilidade: concentrar maior parte da massa em posição centralizada, próximo ao centro de massa da cadeira de rodas; reduzir o máximo possível - sem comprometer a estabilidade - as medidas de comprimento e largura da cadeira de rodas. As implicações ao usuário relacionam-se, principalmente, aos desafios inerciais nas diversas situações de mobilidade diária, que compreendem os movimentos de partida, frenagem, acelerações, manobras de giro e deslocamentos em trajetórias mistas (com frequentes mudanças de direção). Futuros estudos devem buscar investigar, sob a perspectiva do usuário, as correlações entre o design e configuração de cadeira de rodas e as implicações biomecânicas e fisiológicas ao usuário. As informações aqui apresentadas contribuem para a atuação de designers no desenvolvimento de equipamentos que priorizem o melhor desempenho na mobilidade, de forma a favorecer a independência, participação comunitária e qualidade de vida dos usuários de cadeira de rodas.

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ANEXO 11

DESIGN E DEFICIÊNCIA
História, conceitos e perspectivas

O uso bem-sucedido de um produto depende essencialmente da adequação de sua interface tecnológica com as características físicas, cognitivas e funcionais do usuário. A partir de uma perspectiva ergonômica, a inadequação destes aspectos resulta em ruído na interação entre usuário e produto.

(...)

FAUSTO ORSI MEDOLA
LUIS CARLOS PASCHOARELLI

1 Este texto adota o termo "pessoas com deficiência", com base em sua utilização na Convenção sobre os Direitos das Pessoas com Deficiência da Organização das Nações Unidas (ONU). Mais informações são disponibilizadas pela Secretaria dos Direitos da Pessoa com Deficiência do Estado de São Paulo (http://www.pessoacomdeficiencia.sp.gov.br/usr/share/documents/ConvencaoONUsobre%20DireitosPcD.pdf)

Para uma parcela significativa da população, o design de produtos concebidos para atender a população geral não é capaz de satisfazer as necessidades e expectativas dos usuários. Destacam-se, dentre estes, as pessoas com deficiência[1], que experimentam limitações funcionais em muitas atividades da rotina diária.

De acordo com o Censo Demográfico de 2010 (BRASIL, 2010), dos mais de 190 milhões de pessoas que residem no Brasil, 23,9% apresentam algum tipo de deficiência, podendo esta ser visual, auditiva, motora ou mental/intelectual. Isto demonstra o potencial mercadológico em se aplicar design para esta parcela da população.

Para este grupo de usuários / consumidores, o design desempenha um papel essencial na qualidade de vida, através de seu potencial para favorecer a funcionalidade, independência e participação social. No entanto, para a grande maioria dos produtos de uso comum, a diferenciação dos mesmos ainda não contempla as reais necessidades das pessoas com limitações funcionais que, como resultado, continuam a experimentar as dificuldades, limitações e frustrações no uso de produtos.

É, portanto, função do designer conhecer as relações entre deficiência e funcionalidade nas atividades cotidianas e implementá-las no desenvolvimento dos diversos produtos e sistemas. Desta maneira, torna-se viável oferecer àqueles com deficiência interfaces tecnológicas que representem, efetivamente, alternativas funcionais para o desempenho adequado de suas atividades diárias. O presente texto tem como propósito discutir os conceitos e as relações entre design e deficiência a partir da perspectiva do desenvolvimento de produtos.

DEFICIÊNCIA: ASPECTOS HISTÓRICOS

A compreensão do processo histórico relacionado à forma como se "vê" a pessoa com deficiência é importante para o entendimento das razões pelas quais, aparte toda a política de inclusão social, há ainda uma desvalorização social. Para o designer, é importante entender a atual questão da deficiência, pois a partir deste entendimento pode-se conceber produtos e soluções verdadeiramente inclusivas e condizentes com o contexto atual.

O processo histórico sobre a questão da pessoa com deficiência reflete o conjunto de valores sociais, morais, filosóficos, éticos e religiosos de diferentes culturas em diferentes momentos históricos (Pacheco; Alves, 2007). Todos estes fatores determinaram a forma com a qual as pessoas com deficiência eram vistas, passando da marginalização ao assistencialismo, educação, reabilitação, integração e inclusão social (Mazzotta, 1999). Em uma perspectiva histórica, estas etapas não podem ser entendidas como separadas. Segundo Amaral (1995), mesmo nos dias de hoje as diferentes posturas convivem e direcionam práticas e políticas públicas. É importante que o designer compreenda a evolução histórica das questões da pessoa com deficiência na sociedade, de forma a inserir sua abordagem projetual em um contexto inclusivo moderno.

A marginalização da pessoa com deficiência, segundo Silva (1986), estava relacionada à ideia de que as deficiências, assim como uma parte das doenças, eram manifestações de espíritos, demônios ou formas de punição por pecados cometidos. Desta forma, as pessoas com deficiência eram postas à margem da sociedade. O crescimento do Cristianismo trouxe uma nova visão de homem – criação e manifestação divina – e, os deficientes passaram a ser vistos como pessoas que necessitam de ajuda, abrindo espaço para uma abordagem assistencialista, a qual vinha sobretudo das famílias e da igreja (Aranha, 1997). Entretanto, tais cuidados não garantiam a inclusão e integração dos deficientes na sociedade.

Os avanços da medicina trouxeram uma visão biológica e científica da deficiência, afastando-a da visão teológica (Aranha, 1997). Mais adiante, a revolução industrial trouxe a necessidade de formar cidadãos produtivos, com o objetivo de aumentar a mão-de-obra, e os deficientes passaram a ser vistos como potencialmente capazes de desempenhar atividades dentro de um sistema produtivo industrial (Aranha, 1997). Surge, assim, um período (a partir da segunda metade do século XIX) voltado para a educação da pessoa com deficiência como resultado da preocupação com o potencial de trabalho, quando passam a ser criadas organizações específicas para esta finalidade (Pacheco; Alves, 2007).

A visão reabilitadora da pessoa com deficiência ganha força após as Grandes Guerras Mundiais, devido ao elevado número de soldados feridos de guerra. A crescente preocupação com a responsabilidade social para com as pessoas com deficiência induziu à integração de especialistas de diversas áreas – da saúde, sociais e engenharias - em equipes multidisciplinares, em busca de soluções para a reabilitação destas pessoas (Salimeni, 1996). Neste sentido, é importante destacar que a deficiência deve ser entendida como um fenômeno biopsicossocial e, portanto, a reabilitação da pessoa com deficiência em seus aspectos biológicos, psíquicos e sociais é também objeto do processo de design de produtos e sistemas, de forma a melhorar a qualidade de vida da pessoa com deficiência.

O paradigma da inclusão social vai além da integação, uma vez que requer que ambos – pessoa com deficiência e sociedade – sejam partes atuantes das mudanças necessárias para a inclusão plena (Pacheco; Alves, 2007). Na prática, para que a inclusão social seja garantida, é fundamental que as oportunidades sejam equiparadas a fim de que todas as pessoas – com ou sem deficiência – tenham acesso a todos os serviços, ambientes e produtos na busca da realização de seus sonhos e objetivos (Sassaki, 1997). É neste universo que o design deve desenvolver sua abordagem projetual, buscando conceber produtos e sistemas que satisfaçam as necessidades, expectativas e desejos de toda a diversidade de usuários, de forma a garantir a independência, funcionalidade, segurança e satisfação no processo de uso dos produtos.

DEFICIÊNCIA, INCAPACIDADE E DESVANTAGEM

A "Classificação Internacional de deficiências, incapacidades e desvantagens: um manual de classificação das consequências das doenças" (CIDID) foi publicada em 1989 como a tradução do documento originial (ICIDH – International Classification of Impairments, Disabilities and Handicaps) criado durante a IX Assembléia da Organização Mundial de Saúde, em 1976. A proposta de classificação da conceituação de deficiência representa um referencial unificado aplicável a vários aspectos da saúde e da doença.

De acordo com Amiralian et al. (2000), a CIDID estabelece com objetividade, abrangência e hierarquia três importantes conceitos: deficiência, como sendo a perda ou anormalidade de estrutura ou função psicológica, fisiológica ou anatômica, temporária ou permanente refletindo, portanto, um distúrbio ou perturbação de caráter orgânico; incapacidade, como a restrição, resultante diretamente de uma deficiência, da habilidade para desempenhar uma atividade tida como normal do ser humano; e desvantagem, como sendo o prejuízo para o indivíduo, resultante de uma deficiência ou uma incapacidade, que limita ou impede o desempenho de suas habilidades de acordo com a idade, sexo, fatores sociais e culturais, refletindo assim a socialização da deficiência.

Há ainda, um grupo de pessoas que apresentam limitações funcionais para a mobilidade mas que não se enquadram no conceito de pessoa com deficiência. De acordo com a Norma Brasileira ABNT NBR 14022 (2009), são aquelas pessoas que possuem, por qualquer motivo, dificuldade em movimentar-se, em caráter temporário ou permanente, resultando em uma redução efetiva da mobilidade, flexibilidade, coordenação motora e percepção. Se enquadram neste conceito idosos, gestantes e obesos, por exemplo.

É no âmbito das incapacidades e desvantagens que a práxis do design se concretiza. Cabe ao designer compreender as implicações funcionais e as incapacidades e desvantagens decorrentes da deficiência, para então propor soluções projetuais que busquem eliminar ou reduzir as limitações e potencializar a funcionalidade do indivíduo. Para tanto, o design deve ser concebido a partir de uma perspectiva holística, integrando o indivíduo, a deficiência e a incapacidade no desempenho de uma(s) função(ões).

Tecnologia assistiva

O design é capaz de intervir no processo deficiência-incapacidade-desvantagem através do desenvolvimento de produtos, sistemas e ambientes que favoreçam a funcionalidade da pessoa com deficiência em uma certa atividade. O produto ou recurso tecnológico cujo objetivo é assistir, ou seja, promover assistência ou ajuda, à pessoas com dificuldades funcionais é chamado de dispositivo de assistência, ajuda técnica ou, mais comumemente, Tecnologia Assistiva (TA).

O Ministério da Ciência e Tecnologia (MCT) define a TA como aquela desenvolvida para permitir o aumento da autonomia e independência de idosos, de pessoas com deficiência ou com mobilidade reduzida em suas atividades domésticas ou ocupacionais de vida diária (MCT, 2009 apud Rodrigues et al., 2010). A Classificação Internacional de Funcionalidade, Incapacidade e Saúde (CIF), propõe uma definição mais ampla para os produtos de TA: "qualquer produto, instrumento, equipamento ou tecnologia adaptada ou especialmente projetado para melhorar a funcionalidade de uma pessoa incapacitada" (OMS; OPAS, 2003).

De forma geral, os produtos de TA são organizados em 14 categorias, que abordam situações específicas, conforme demonstra a Figura 1. É possível observar, desta forma, que a TA tem inserção e aplicação para uma grande diversidade de problemas, condições e situações que levam a incapacidades e desvantagens. Consequentemente, há um grande potencial – e portanto oportunidades - de atuação do designer no desenvolvimento de produtos e sistemas para pessoas com deficiências.

Design e deficiência: desafios e perspectivas

Os avanços tecnológicos e científicos têm contribuído para que, de uma forma geral, as pessoas com deficiência consigam viver mais e com melhor qualidade de vida. Isto representa uma parcela da população com potencial para participar ativamente da sociedade. Portanto, é essencial que estas pessoas tenham condições adequadas para realizar suas

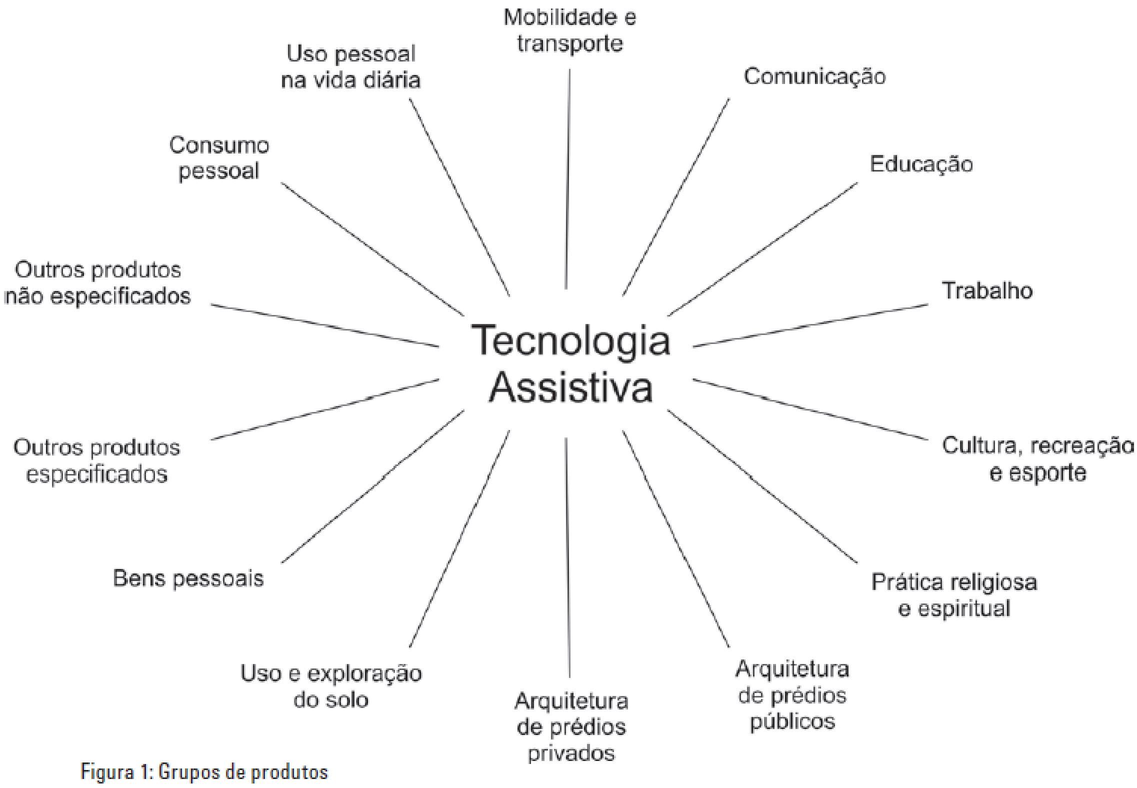

Figura 1: Grupos de produtos e tecnologias para a pessoa com deficiência segundo a CIF (OMS; OPAS, 2003).
Fonte: Autores.

atividades com desempenho, segurança e conforto satisfatórios.

Até pouco tempo, a inclusão social poderia resumir-se a simplesmente adequar produtos, ambientes e sistemas às necessidades e características das pessoas com deficiência. Atualmente, é necessário ainda oferecer oportunidades e condições atrativas para que estas pessoas participem de modo ativo nas diversas atividades humanas. Neste sentido, é importante considerar que, em muitos aspectos da vida cotidiana, a inclusão não está ao alcance de grande parte das pessoas com deficiências, permanecendo ainda distante o ideal de sociedade inclusiva.

Neste sentido, a questão central e norteadora da práxis do design, sob a perspectiva inclusiva, refere-se ao projeto de produtos, sistemas e ambientes para uso igualitário e indiscriminado. Em outras palavras, o desafio é projetar para incluir sem, entretanto, diferenciar. Embora esta perspectiva possa parecer de certa forma antagônica e ainda muito distante de ser implementada, é válido considerar que a velocidade dos avanços tecnológicos permite a criação de tais expectativas. Assim, cabe ao designer acompanhar a evolução dos recursos a que dispõe e conceber projetos para uso igualitário e indistinto para o maior número de pessoas possível.

O ponto de partida pode ser projetar o produto de modo a considerar não apenas sua funcionalidade, mas também sua estética seja atrativa para todas as pessoas. Neste sentido, é válido retomar a concepção de design proposta por Lobach (2001), que descreve três funções principais do produto: prática, estética e simbólica. No design para pessoas com deficiências, a função prática refere-se aos aspectos funcionais no processo de uso, ou seja, maximizar a funcionalidade e reduzir ou mesmo eliminar as incapacidades. Entretanto, no atual quadro dos meios de consumo globalizado, os aspectos estéticos e simbólicos dos produtos devem ser necessariamente explorados. Em um produto projetado para uso igualitário e indistinto por todas as pessoas, os aspectos estéticos e simbólicos devem assumir grande relevância, uma vez que necessitam tornar o produto atrativo a todos e, ao mesmo tempo, não transmitir significado de "assistência" que ressalte a deficiência.

Pensar o design para pessoas com deficiência abordando a dualidade – inclusão e não-diferenciação – de forma indissociável parece ser o desafio emergente para uma nova visão de produtos assistivos. Para tanto, é necessário que se conheça - com profundidade - as interações físicas, sensoriais e perceptuais que ocorrem entre usuário, produto, atividade e ambiente. O design assume, desta forma, papel definitivo como uma ferramenta essencial para a implementação dos princípios da inclusão social e universalidade, através de sua prática projetual aplicada às interfaces tecnológicas dos diversos produtos, ambientes e sistemas que compõem a vida cotidiana.

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ANEXO 12

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ARTICLE

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Evaluation of two wheelchair hand rim models: contact pressure distribution in straight line and curve trajectories

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ABSTRACT
Manual wheelchairs are essential for people with disabilities or limited mobility. However, manual propulsion causes biomechanical loads, including contact pressures on the palms of the hands. The hand rim design has received little attention over time, remaining almost unchanged since its creation. This study investigated how two different designs of such devices – one standard and another with a contoured design – influence the contact pressure on the surface of the hands. The procedures included a figure-of-eight shape propulsion task on a regular floor, using both models on a wheelchair. A pressure-mapping system coupled with a pair of fabric gloves recorded the data. The results show that the contoured hand rim provides lower pressure in most of the analysed regions. Considering that manual propulsion is performed during a considerable part of the day as a routine activity, improving the hand rim interface may benefit the user's comfort and safety during wheelchair use.

Practitioner summary: The design of the hand rim used in wheelchair propulsion influences the contact pressure on the hands. Conventional round tube rims tend to concentrate high levels of pressure on the distal phalanges and metacarpal regions. A contoured design generally provides better stability and promotes the distribution of pressure.

Abbreviations: AT: assistive technology; kPa: kilopascal

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Wheelchair; hand rim; disability ergonomics; contact pressure; product design

Introduction

Manual wheelchairs are assistive technology (AT) devices that promote and/or improve the mobility of people with disabilities or limited mobility (Medola 2010). Medola (2010) also defines manual propulsion as the technique of rhythmic application of pushes on the wheels for the user to control the movement of the wheelchair. Although wheelchair propulsion allows independent mobility, it has been related to biomechanical overloads on the upper limbs which, in the long term, may lead to the incidence of pain and injuries. Dieruf, Ewer, and Boninger (2008) point out that most lesions occur in individuals between the ages of 16 and 30, which implies a long duration of use and is evidence of the importance of a suitable design for this type of device. Nevertheless, manual propulsion requires high force on the rear wheels to start motion, sustain the movement, and brake or turn the wheelchair (Medola, Elui, et al. 2014).

Such activity has a low mechanical efficiency (van der Linden et al. 1996). Studies indicate that the efficiency of manual propulsion is approximately 10%, with only 50% of all forces exerted by the user being applied in a forward direction (Arthanat and Strobel 2006). Although there are alternatives which promote greater efficiency, such as propulsion by levers or cranks (Arnet et al. 2013), manual propulsion is widely diffused, reaching up to 90% of use among the available types of propulsion (Rifai Sarraj et al. 2011). In addition to the cost, the reasons for this wide use include greater flexibility in manoeuvring and mobility for everyday situations.

Considering that a user stays in their wheelchair for about 11 h per day (Sonenblum, Sprigle, and Lopez 2012), the interface between the hand and the rims occurs many times. It is estimated that a user propels the hand rim once per second during the propulsion, which characterises a highly repetitive activity (less than a 30-sec cycle). Assuming 40 min of movement, there are around 2500 propulsions per day (Koontz et al. 2006). Hence, the characteristics of these devices, such as size and shape, determine the stability of movements,

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and the comfort and efficiency of the task (van der Linden et al. 1996; Medola, Elui, et al. 2014).

Studies have also addressed how changes in wheelchair mass, configurations, and accessories influence the propulsion torque and the demand on the upper limbs (Bertolaccini et al. 2018; Sprigle and Huang 2015). Additionally, manual propulsion involves high force peaks, because there is always a short interval of force application and a recovery period (Arnet et al. 2013). These peaks generally occur with extreme wrist postures, which increase the incidence of upper limb injuries associated with the use of this device (Arthanat and Strobel 2006; Zukowski et al. 2017; Mandy, Redhead, and Michaelis 2014).

Most of the standard hand rims are characterised by a round metal tube with a 20 mm cross-sectional diameter, located on the posterior side of the wheels (Medola, Silva, et al. 2014; Dieruf, Ewer, and Boninger 2008). This configuration has been widely used for at least 50 years, mainly because of its simplicity and low manufacturing and maintenance costs (Koontz et al. 2006). However, this configuration does not offer ergonomic features, often requiring distal phalange grips, exposing sensitive regions of the hands to potentially damaging conditions. Because this requires extra muscular activity to stabilise the hands, the force is concentrated in a few regions of the hand, increasing the contact pressure (Medola, Silva, et al. 2014).

Commonly, the users of these devices end up adopting strategies to relieve the contact pressure. Among these strategies is the technique of simultaneously holding the hand rim and the tire or even holding only the tire (Koontz et al. 2006). Modifying the design of such a propulsion device is an appropriate approach to improving the mobility and independence of its users (Dieruf, Ewer, and Boninger 2008). Small changes in design are enough to modify mechanical efficiency (van der Linden et al. 1996). Thus, some studies have addressed changes in the design of the hand rims, concluding that larger tube diameters or anatomical contours are evaluated as being better by their users (Koontz et al. 2006; Dieruf, Ewer, and Boninger 2008; van der Linden et al. 1996; Medola et al. 2011). In addition, the hand rim diameter itself seems to be determinant of the contact pressure with the hand (Kabra et al. 2015).

Medola et al. (2012) proposed a hand rim design based on greater contact surface and anatomical shape for a comfortable, stable and efficient coupling with the hands during manual propulsion. This design distributes the contact pressure on an outer surface for the palm of the hand. Also, it provides an upper surface for the positioning of the thumb, as well as a bottom side with smooth depressions that help the index finger to push the wheel forward. The hand rim designed by Medola et al. (2012) was expected to reduce the manual forces applied to hold the hand rim, thus enhancing the hand rim force component that effectively moves the wheels forward.

However, even in an interaction with relatively low forces, relatively high levels of pressure may occur during the use of a product as a result of a concentration in a small area. High contact pressures on the skin result in discomfort, pain and ischaemia. Uneven pressure distribution on a palmar grip can lead to pressures of up to 80 kPa in the distal phalanges (Harih and Dolšak 2014).

Goossens et al. (2000) emphasise that the combination of pressure and shear is responsible for the total mechanical load on the skin. The authors mention studies in which it was possible to interrupt the blood flow in the palm with a pressure of 9.8 kPa. In their study, the authors reproduced the same shear force under the skin, varying the pressure parameters applied on the skin. Their findings demonstrate that the reduction of blood flow was the same in all combinations.

Armstrong (1985) also emphasises the effect of exposure time. The author points out that constant pressures of 10.5 kPa are enough to damage the skin. Also, it is notable that the proportional effect of the product between pressure and time – i.e., a pressure of 10 kPa applied for four hours – has the same effect on the skin as a pressure of 400 kPa applied for one hour. Aldien et al. (2005) discussed pain and discomfort thresholds according to the regions of the hand. The authors indicate a 188 kPa discomfort threshold, while Fransson-Hall and Kilbom (1993) indicate a value of 104 kPa. The differences found in studies on the subject indicate that although there is a connection between contact pressure and discomfort, it is still not well defined (Harih and Dolšak 2014).

Thus, the analysis of contact pressure levels between hands and the hand rims during propulsion activities with manual wheelchairs can provide important information about the ergonomic characteristics of this interface. The aim of this paper is to evaluate the contact pressure distribution on the palms during wheelchair propulsion with two types of hand rims.

Materials and methods

Subjects

Thirty-one able-bodied subjects participated in this study. All were male and young adults, aged between

18 and 29 years old. Because we had only one pair of gloves, reducing the range of hand sizes to fit the gloves was essential in order to keep the sensors correctly positioned during the activities. The mean age of participants was 21.2 years old ($\sigma = 2.4$ years) and the mean body mass was 72.8 kg ($\sigma = 12.2$ kg). The average laterality coefficient was 66.1 ($\sigma = 29.1$), obtained using the Edinburgh Handedness Inventory, originally developed by Oldfield (1971), suggesting moderated right-hand dominance throughout the sample.

Among the participants, there were four ambidextrous individuals and all the others were right-handed. Because the wheelchair propulsion task is a bimanual activity with symmetrical characteristics, there was no grouping factor, regardless of hand dominance. Only one subject reported previous experience in wheelchair propulsion. All volunteers signed an informed consent form prior to their participation. The research methods were submitted and approved by the Research Ethics Committee of the School of Architecture, Arts and Communication – FAAC/UNESP/SP-Brazil (Technical Appraisal 800.424).

Experimental setup

The Grip VersaTek Wireless System (Tekscan Inc.) recorded the contact pressure data. The pressure sensors had been previously equilibrated, calibrated and conditioned according to the manufacturer's instructions. In addition, to facilitate the sensors' positioning during the activities, they were coupled to a pair of fabric gloves. The two-hand rim models of this study were the same as those used by Medola, Silva, et al. (2014): a standard model, characterised by a cylindrical handle, with a metal tube of 20 mm in diameter; and a contoured model, developed by Medola et al. (2012) to provide support for more hand regions and greater stability in the movement transmission. The contoured hand rim is made of polymer and was constructed by rapid prototyping.

The activity consisted of moving along a path in the shape of a figure of eight, starting with a straight line motion, followed by a right curve, a second straight line section and, lastly, a left curve. The activity room had a regular and flat floor, and was air-conditioned. Prior to data collection, the researcher demonstrated the wheelchair mobility task and instructed the participants to: use smooth and long pushes; keep the drive steady and avoid stopping the wheelchair; not rush, but instead get around comfortably; push with both hands simultaneously (except in curves); and keep the path line centred to the chair during propulsion.

After the demonstration, each participant had three minutes to familiarise themselves with the use of the product and the activity. Then, the participant was taken to the starting point of the route, the software recording was initiated, and the subject started the activity. The subject moved uninterruptedly throughout until he reached the starting point again. A video camera, positioned above the head of the subject, recorded the activity. Figure 1 shows additional specifications and the activity schematic.

After completing a lap, the subject stood to the side of the chair, so the researcher could switch the hand rim model. After changing this, the process was repeated. The sequence of the models was random.

Analysis

We exported the pressure records via Research Software®, according to the hand rim models, each hand, and the 17 sensitive regions of the system. The treatment and initial analysis was carried out in spreadsheets (LibreOffice Calc 4), and resulted in the determination of pressure peaks and the removal of inconsistencies (spikes or noise). Thus, the video recording was also important to verify and to dismiss any irregular behaviour during the subject's activity (e.g. hand slips). The number of peaks at each path segment varied due to the subject's abilities. First and last peaks (start and brake) were discarded, because they might have contained high values that were not representative of the activity. The analysis included conditional means for the pressure peaks at the distal, middle and proximal phalanges of the fingers, and for the metacarpal, thenar and hypothenar regions. These procedures brought more consistency to the collected data, reducing the variability due to the users' inexperience.

We made tests for normality (Shapiro–Wilk's test) and homogeneity (Levene's test) assumptions. For comparisons with normal and homogeneous datasets, we used the Student's t-test for dependent samples. For those that didn't match those criteria, we used the Wilcoxon signed-rank test. The statistical analyses were performed using IBM™ SPSS 22® software.

Results

The results are presented according to the path segments. Comparisons between the conventional and

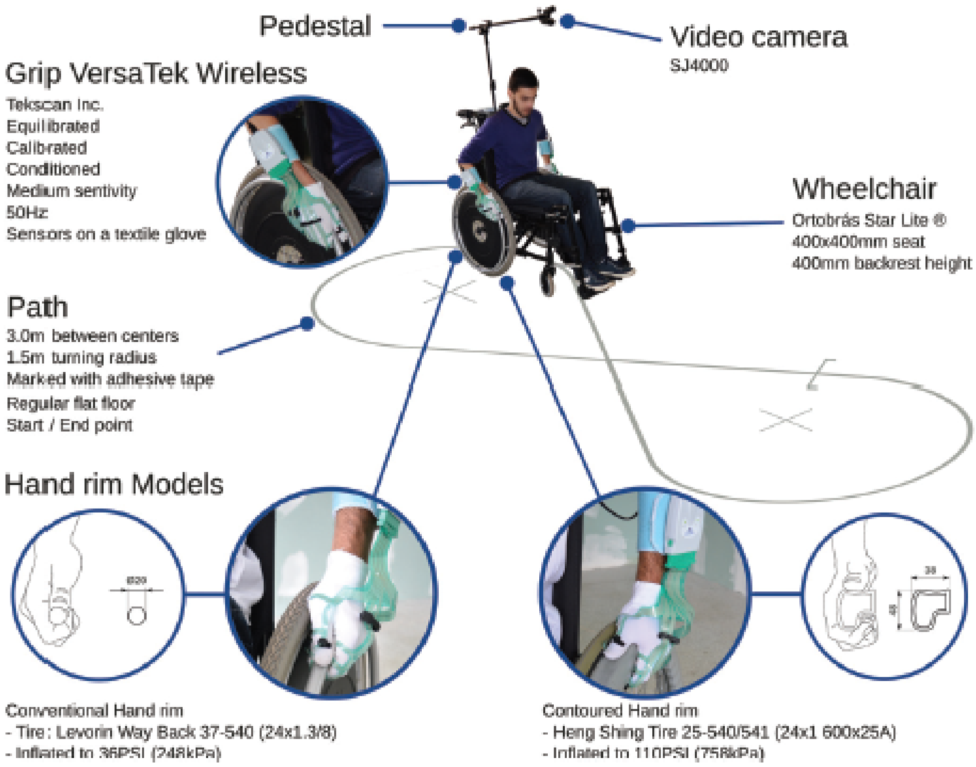

Figure 1. Activity schematic showing the parameters and procedures of the task. Source: Authors.

contoured hand rims were performed on the right and left hands individually.

Straight line motion

During straight line motion, the use of the contoured hand rim provided significantly lower contact pressures for the right hand in the distal (t-test, $t(30) = 3.502$, $p < .01$), proximal (t-test, $t(30) = 8.253$, $p < .01$), metacarpal (Wilcoxon, $Z = -4.194$, $p < .01$) and thenar regions (Wilcoxon, $Z = -3.586$, $p < .01$). In the medial regions, there was a significantly higher contact pressure using the contoured device (Wilcoxon, $Z = -4.684$, $p < .01$). There was no significant difference for the hypothenar region.

The pressure levels for the left hand presented similar results: significantly lower levels of contact pressure with the use of the contoured device in the distal (t-test, $t(30) = 2.765$, $p = .010$), proximal (t-test, $t(30) = 4.617$, $p = .000$) and metacarpal regions (t-test, $t(30) = 8.068$, $p = .000$). The medial regions showed significantly higher levels of contact pressure using the contoured model (t-test, $t(30) = -5.671$, $p < .01$), and no significant difference was found for the thenar and hypothenar regions. Figure 2 exhibits the average pressure levels observed on the left and right hand for each model during the straight line motion.

Right curve

In the right curve, the use of the contoured hand rim resulted in significantly lower contact pressures for the right hand in the proximal (t-test, $t(30) = 3.104$, $p < .01$), metacarpal (Wilcoxon, $Z = -3.341$, $p < .01$) and thenar regions (Wilcoxon, $Z = 2.802$, $p < .01$). As in the previous situation, the contoured model provided significantly higher contact pressure in the medial region (Wilcoxon, $Z = -4.782$, $p < .01$). For the distal and hypothenar regions, there were no significant differences.

The pressure levels behaved in a fairly similar manner on the left hand, because the contoured device provided lower contact pressure levels in the distal (t-test, $t(30) = 5.697$, $p < .01$), proximal (t-test, $t(30) = 4.119$, $p < .01$) and metacarpal regions (t-test, $t(30) = -4.801$, $p < .01$). A significantly higher contact pressure also occurred in the medial regions when using the contoured model (t-test, $t(30) = -4.670$, $p < .01$). No significant differences were observed for the thenar and hypothenar regions. Figure 3 exhibits

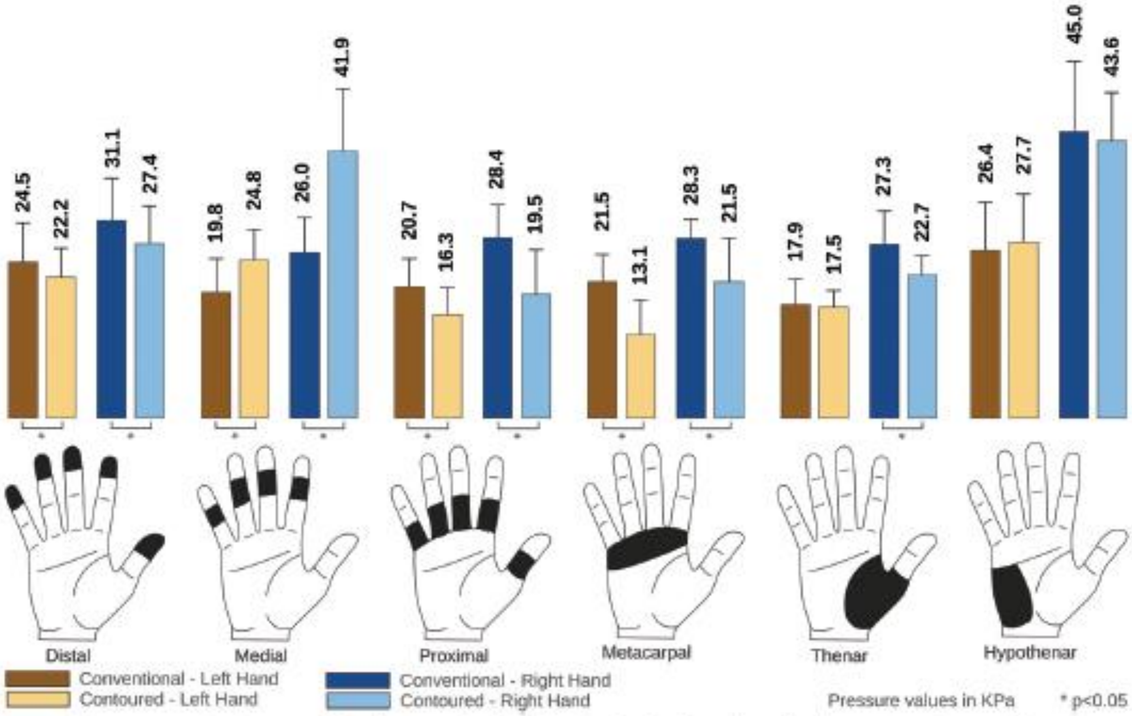

Figure 2. Mean pressure levels at each hand region for the left and right hand and straight line motion. Source: Authors.

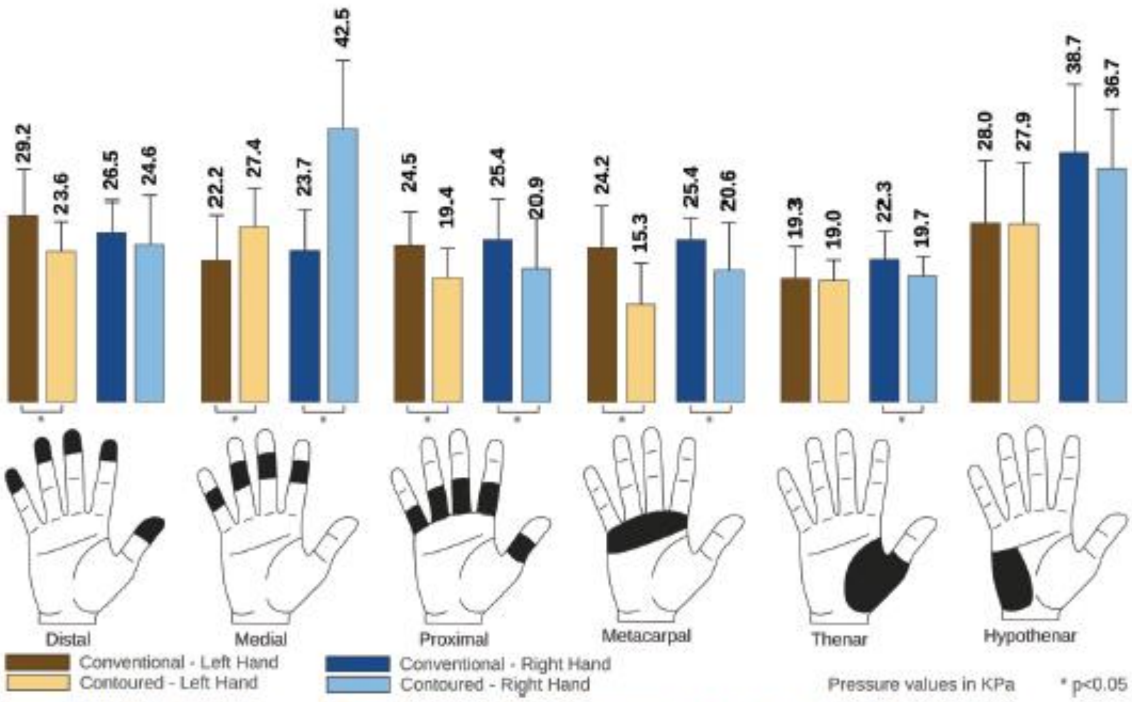

Figure 3. Mean pressure levels at each hand region for the left and right hand in the right curve. Source: Authors.

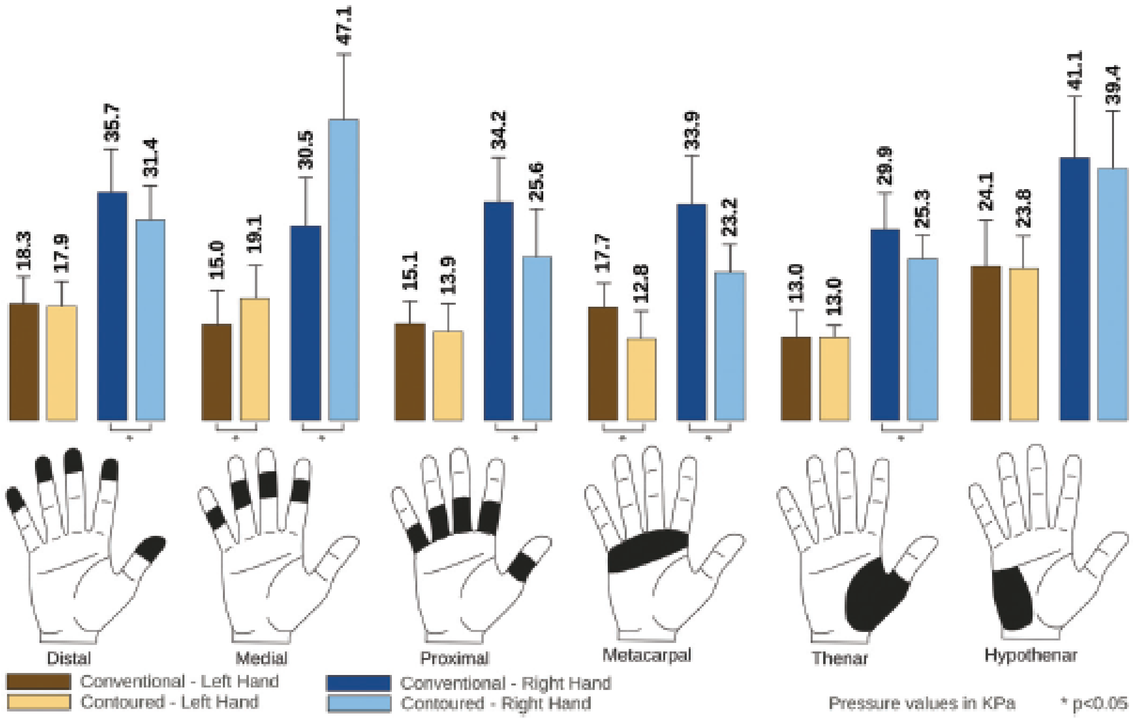

Figure 4. Mean pressure levels at each hand region for the left and right hand in the left curve. Source: Authors.

the average pressure levels observed on the left and right hand for each model during the right curve.

Left curve

During the left curve, the contoured hand rim provided significantly lower levels of contact pressure for the right hand in the distal (*t*-test, $t(30) = 3.209$, $p < .01$), proximal (*t*-test, $t(30) = 6.488$, $p < .01$), metacarpal (Wilcoxon, $Z = -4.840$, $p < .01$) and thenar regions (Wilcoxon, $Z = -3.782$, $p < .01$). Like the previous situations, the contoured model provided significantly higher contact pressure in the medial region (Wilcoxon, $Z = -4.684$, $p < .01$). There was no significant difference for the hypothenar region.

Conversely, on the left hand, the contoured hand rim provided significantly lower contact pressures only in the metacarpal region (Wilcoxon, $Z = -4.057$, $p = .000$). Like the previous situation, in the medial region there was a significantly higher contact pressure using the contoured model (*t*-test, $t(30) = 2.907$, $p < .01$). For all other regions, there were no significant differences. Figure 4 exhibits the average pressure levels observed on the left and right hands for each model during the left turn.

Discussion

This paper addresses the contact pressure in the hand and hand rim interface during manual propulsion, considering different designs and movement trajectories. Thus, this study contemplates movement in straight lines and curves on a regular and flat floor. We observed lower contact pressures in the distal, proximal, metacarpal and thenar (only for the right hand) regions with the contoured model. However, that device showed higher pressures in the medial region.

On the other hand, the conventional round tube hand rim concentrated pressure on distal phalanges and the thenar and metacarpal regions of the hand. This may be related to the small dimensions of this interface, which favour a grip with the fingers' extremities. This is particularly relevant because the finger tips are more sensitive and tendon forces are two to three times greater when forces are applied to the distal regions compared with the medial phalanges (Aldien et al., 2005; Hwang et al. 2011).

A small contact surface necessitates greater muscle activity to stabilise the hand on the device, impairing the use of muscle activity for propulsion. This may explain why users of this type of device simultaneously hold the hand rim and the tire to obtain a more suitable grip for propulsion (Medola, Elui, et al. 2014).

Also, the levels of contact pressure found are close to 50 kPa in the hands, which may lead to injuries. Pressure levels around 10 kPa in some circumstances are enough to interrupt blood flow or cause damage to the skin (Armstrong 1985; Goossens et al. 2000). Because the effects of contact pressure are also proportional to the exposure time (Armstrong 1985) and manual wheelchair propulsion is a repetitive routine activity, it should be considered that pressure levels of such magnitude may lead to discomfort or even pain.

However, this study has limitations that need to be highlighted. First, the hand rim models were based on similar wheels, but different types of tires, which may have affected the rolling resistance (Medola, Elui, et al. 2014). It is also important to consider that the contact forces during manual wheelchair propulsion may have been overestimated, mainly because of the shear forces and their influences on the sensors, which can affect the contact pressure as well.

Hand size is another important factor that affects the pressure distribution in such activities. However, because we had only one pair of gloves, measuring hand size would have been time-consuming; thus, we decided not to evaluate hand anthropometry. As a palliative measure, we restrained the sample characteristics to improve data consistency. Also, we checked the sensors' positions before each trial to make sure they were in the correct place.

It is also important to note that only able-bodied subjects participated in this study and, therefore, the current findings may not be fully extended to 'real' wheelchair users. Indeed, there are differences in manual propulsion patterns and efficiency between experienced and inexperienced wheelchair users (Croft et al. 2013; Lenton et al. 2008; de Groot et al. 2002). However, the novice users do not have some of the habits experienced users do, such as holding the hand rim and the tire simultaneously, which may affect the results.

Lastly, we expect that there would have been considerable learning effects on the pressure distribution and pressure values if the volunteers repeated the propulsion, following the path. Novice users may propel the wheelchair more erratically, creating pressure peaks that do not represent 'real' values. That should be highlighted, even considering our data treatment. Experienced users should participate in a future stage of this study.

Conclusions

The current findings are useful to assess the contact pressure distribution on hands during some propelling tasks, such as straight line motion and turns on a regular flat floor. Such data are valuable for ergonomists and practitioners in order to analyse how pressure is distributed during such manoeuvres for both conventional and contoured hand rims. In general, our results indicate that propelling a wheelchair is an activity that exposes users to a high-risk factor regarding hand contact pressures.

The contoured hand rim design was related to reduced levels of contact pressure on most hand regions in comparison with the conventional round tube device. Significantly less pressure was found in distal and proximal phalanges of the fingers and in the head of the metacarpals. However, we cannot recommend our current contoured design, because it concentrated a high level of pressure on the medial phalanges.

It is possible that this finding is due to the smooth depressions at the inner edge of the device, for which the medial phalanges are thought to provide a firm and stable hand and hand rim coupling. While this feature plays an important role in the stability of the hands, it may result in higher pressure levels. We currently do not recommend this feature, because it can harm the pressure distribution during manual propulsion. A texture on the inner edge of the hand rim might provide additional support, although it might not significantly affect the pressure distribution. Further studies are needed to support this claim.

Although the current study contributes additional knowledge about the mechanical interaction between hands and the hand rim in straightforward and turning motions, these trajectories do not fully represent the variety of manoeuvres that characterise wheelchair mobility in daily living. Therefore, future investigations should address the mechanical aspects of the interface of the hand and the hand rim in manoeuvres such as zero radius turns, acceleration, braking, ramp ascent and descent, and wheelie manoeuvres, among others. Also, the pressure distribution on hands is only one of several aspects involved in the mobility of wheelchair users. Additional studies may clarify the importance of measuring contact pressure and its relation with other aspects of manual propulsion.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data that support the findings of this study are openly available in Mendeley Data at http://dx.doi.org/10.17632/hv4yzz7vk9.1

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