Université de Montréal

Étude biomécanique comparative de la propulsion en fauteuil roulant manuel à celle sur un dynamomètre motorisé

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Résumé

Introduction : Un dynamomètre peut être utilisé en clinique ou en recherche pour évaluer et entraîner la technique de propulsion du fauteuil roulant manuel (FRM) chez des individus ayant une lésion de la moelle épinière. L'entraînement sur dynamomètre pourrait augmenter les aptitudes musculaires et cardiorespiratoires et optimiser la capacité de propulsion.

Objectif : L'objectif principal de cette étude était de comparer les données spatio-temporelles, les forces appliquées aux cerceaux, la fréquence cardiaque, ainsi que les efforts mesurés et perçus entre la propulsion sur le terrain et celle sur un nouveau dynamomètre motorisé récemment développé à l'École de technologie supérieure.

Matériel et méthodes : Dix-sept adultes ayant une lésion médullaire et utilisant un FRM ont été recrutés. Ils ont complété un test de propulsion sur 20 mètres dans un couloir (2 essais) et ont propulsé pendant une minute sur le dynamomètre (2 essais). Des roues instrumentées ont permis de mesurer les paramètres spatiotemporels et les forces appliquées aux cerceaux des roues du FRM lors des poussées. Des tests de Student et des corrélations de Pearson ont été utilisés afin d'analyser les principales mesures de résultat.

Résultats: L'effort perçu, la fréquence cardiaque, la force tangentielle moyenne et maximale sont demeurés inchangés ($p>0.05$) entre les deux conditions. Une corrélation "très bonne" a été trouvée entre les conditions pour la force totale ($r=0.89$), la force tangentielle ($r=0.91$) et la puissance ($r=0.90$), et "bonne" pour l'efficacité mécanique ($r=0.76$).

Conclusion : La biomécanique de propulsion sur le dynamomètre motorisé peut être comparée à celle du terrain relativement au patron de propulsion, mais ne simule pas exactement la propulsion sur le terrain en ce qui concerne l'intensité des paramètres spatio-temporels et la force totale.

Mots-clés : biomécanique, fauteuil roulant manuel, paraplégie, propulsion, réadaptation

Abstract

Objectives: To compare propulsion biomechanics on a newly developed wheelchair simulator to overground natural propulsion.

Design: A repeated cross-sectional research design

Participants: Seventeen individuals (15 men and 2 women) with spinal cord injury between T4 and T12 who used their manual wheelchair as their primary mean of mobility.

Methods: Participants completed two 20-meter propulsion trials on a tiled surface and two 1-minute propulsion sessions on the simulator at a self-selected natural velocity. Participants and simulator wheelchair was equipped with instrumented wheels to record handrim kinetics. The main outcome measures were perceived exertion, heart rate, spatio-temporal and pushrim kinetic propulsion parameters during the push phase. T-test and Pearson correlation were generated for the main outcome measures.

Results: Perceived exertion, heart rate, tangential force and energy output were found to be similar ($p<0.05$) between overground and simulator settings at participants' self-selected natural velocity; whereas velocity, contact angle, total force and power were found to be greater ($p<0.05$) on the overground when compared to the simulator propulsion setting. Correlation between settings were found to be "very good" for the total force ($r=0.89$), tangential force ($r=0.91$) and power ($r=0.90$), and "good" for the mechanical effective force ($r=0.76$). The propulsion total and tangential forces, MEF and power intensities were found to be symmetrical without any preferential side regardless of the settings.

Conclusion: The propulsion biomechanics on the simulator and overground are similar in terms of mechanical propulsion profiles, but the simulator does not perfectly emulate overground propulsion in terms of spatio-temporal parameters and total force intensity.

Keywords: biomechanics, paraplegia, propulsion, rehabilitation, wheelchair

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AIS	ASIA Impairement Scale
ASIA	American Spinal Cord Injury Association
CIHR	Canadian Institute of Health Research
COPSE	Comité d'organisation du programme des stages d'été
CRIR	Center for Interdisciplinary Research in Rehabilitation of Greater Montreal
Dom	Dominant side
ÉTS	École de technologie supérieure
FRM	Fauteuil roulant manuel
FRQS	Fond de recherche en santé du Québec
F_{tot}	Total force
F_{tg}	Tangential force
IRGLM	Institut de réadaptation Gingras-Lindsay-de-Montréal
LMÉ	Lésion de la moelle épinière
MEF	Mechanical effective force
MWC	Manual wheelchair
Non-dom	Non dominant side
REPAR	Réseau provincial de recherche en adaptation-réadaptation
SCI	Spinal cord injury
U/L	Upper limb

Remerciements

En premier lieu, j'aimerais remercier la personne qui m'a soutenu et aidé durant tout mon parcours académique et de recherche, mon directeur de projet Dany Gagnon. Il a été mon mentor et sera un exemple à suivre dans le futur. Sa grande aide m'a permis d'assister à des conférences locales et nationales, d'obtenir des bourses d'études et de recherche, ainsi que de m'avoir donné la chance de publier plusieurs articles dans des revues scientifiques[1,23]. Merci pour tout!

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1. Introduction

1.1 Problématique

Au Canada, environ 155 000 individus se propulsent en fauteuil roulant manuel (FRM) comme principal moyen de locomotion, et dans le monde, ce chiffre se situe à plus de 100 millions d'individus[4]. L'utilisation de FRM peut être la conséquence de diverses conditions cliniques, dont une lésion de la moelle épinière (LMÉ)[5]. Ces individus doivent se propulser en FRM comme moyen de mobilité principale afin de se déplacer en communauté et garder leur autonomie [6,7], ce qui les contraint à de très grands efforts journaliers. Ils pousseront et lâcheront la roue en moyenne 3500 fois par jour [8]. L'utilisation extensive des membres supérieurs a été corrélée avec une haute prévalence de blessures: durant leur vie, entre 30% et 60% des utilisateurs de FRM ayant une LMÉ sont susceptibles de développer de la douleur à l'épaule, entre 5% et 16 % de la douleur au coude et entre 15% à 48% de la douleur à la main ou au poignet[9-11].

En milieu clinique, des programmes d'entrainement spécifiques pour augmenter les capacités cardiorespiratoires, l'endurance et la puissance musculaire ainsi que la technique de propulsion, sont utilisés afin de réduire les risques de blessure aux membres supérieurs. Afin de maximiser l'accessibilité et la gestion du temps des cliniciens, certains milieux se sont dotés d'un dynamomètre de FRM, tels des ergocycles, des dynamomètres ou des tapis roulants adaptés aux FRM, comme moyen d'entrainement spécifique à la propulsion en FRM.

1.2 Objectifs de l'étude

L'objectif principal de cette étude était de comparer la propulsion sur un nouveau dynamomètre motorisé récemment développé à l'ÉTS à la propulsion au sol sur une surface de tuiles, à une vitesse sélectionnée par l'utilisateur pour un même effort perçu. La comparaison était basée sur les données spatio-temporelles, les forces appliquées aux cerceaux, la fréquence cardiaque, ainsi que les efforts mesurés et perçus parmi des utilisateurs de FRM expérimentés ayant une LMÉ. La finalité de cette étude était de savoir si ce dynamomètre de FRM pouvait simuler la réalité de manière adéquate et ainsi être utilisé afin d'entrainer des individus ayant une LMÉ lors de leur programme de réadaptation intensive.

1.3 Hypothèses

Notre hypothèse était que le dynamomètre simulerait la propulsion en FRM au sol de manière efficace au niveau des principales mesures de résultats à une vitesse sélectionnée par l'utilisateur pour un même effort perçu. Il était aussi anticipé que les forces appliquées aux roues seraient symétriques pour les deux conditions.

2. Revue de la littérature

2.1 Simulateurs de fauteuil roulant manuel

Un grand nombre d'études sur des programmes d'entrainement spécifique à la propulsion utilisent des simulateurs de FRM, tels des ergocycles, des dynamomètres ou des tapis roulants adaptés aux FRM, pour simuler la réalité dans un environnement contrôlé [12-26]. Ces études, ainsi que plusieurs revues de littérature[27-29] et des guides de pratique clinique spécifiques aux individus ayant une LMÉ[30-32], font état de bénéfices quant à l'augmentation de la qualité de vie des participants, ainsi que de leurs capacités cardiorespiratoires, leur force, leur puissance et de leur technique de propulsion. Par conséquent, l'utilisation d'un simulateur de FRM peut être utile autant en milieu clinique comme moyen d'entrainement qu'en milieu de recherche afin d'objectiver les changements suite à des programmes d'entrainement spécifiques.

Par contre, peu d'études ont évalué si ces simulateurs peuvent réellement reproduire la réalité. Une étude a comparé la propulsion au sol à celle sur un dynamomètre[33], et deux autres études ont comparé la propulsion au sol à celle sur tapis-roulant[34,35]. La conclusion générale est que même si les simulateurs n'imitent pas parfaitement la propulsion au sol, les utilisateurs de FRM restent constants dans leur biomécanique de propulsion, telle que l'angle et la fréquence de poussée, la direction et l'amplitude des forces appliquées aux roues.

Contrairement aux autres simulateurs de FRM, le dynamomètre développé par l'équipe de l'ÉTS utilise des rouleaux motorisés contrôlés en temps réel par un ordinateur[36]. Des roues instrumentées calculent les forces appliquées aux roues, et des rouleaux motorisés accélère ou décelèrent les roues en fonction des effets recherchés. L'ordinateur simule le comportement d'un FRM virtuel dans son environnement naturel (c.-à-d. changement de vitesse et de pente)[37], et peut être configuré pour simuler l'inertie réelle et la résistance au sol de l'utilisateur et du fauteuil. Ce dynamomètre de FRM pourrait éventuellement être utilisé afin d'entraîner spécifiquement l'endurance et la puissance musculaire, le patron de propulsion par biofeedback haptique ou visuel, ainsi que les changements de directions et de vitesse fonctionnels à la vie réelle par un système d'immersion virtuelle.

2.2 Recommandations générales d'entrainement

Un guide pratique de recommandations cliniques[31] a statué que les individus ayant une LMÉ devraient faire au moins deux fois 20 minutes par semaine d'exercice aérobique d'intensité modérée à intense, soit en s’entraînant sur un ergomètre pour les membres supérieurs ou en propulsant en FRM. En complément, ils recommandent un entrainement en force musculaire deux fois par semaine, consistant en 3 séries de 8-10 répétitions pour les groupes de muscles principaux utilisés lors de la propulsion. Un autre guide conseille de personnaliser le programme d'exercice chez les individus ayant une LMÉ en fonction de leur niveau ASIA de lésion et de leurs complications (dysréflexie autonomique, spasticité, diminution de la densité osseuse contractures articulaires et dérèglements du contrôle thermal)[32]. Par contre, le guide conclut que les recommandations ne devraient pas différer énormément de celle pour les individus sains en cas d'absence de problèmes spécifiques.

2.3 Recommandations spécifiques au patron de propulsion

Un guide de pratique clinique visant à préserver l’intégrité des membres supérieurs chez les individus présentant une LMÉ suggère d’utiliser une basse cadence, de longues poussées et le déploiement progressif des forces lors de la propulsion, tout en permettant aux mains de revenir lentement vers le bas et l'arrière lors de la phase de récupération[30]. Malheureusement, très peu d'utilisateurs de FRM reçoivent ces informations caractérisant une technique de propulsion efficace. Les interventions des professionnels de la réadaptation se concentrent habituellement davantage sur la sélection d'un coussin fessier adéquat et d'un positionnement au FRM à la fois optimal et adapté à chaque individu[38]. Afin de réduire le risque de blessure aux membres supérieurs, un programme d'entrainement spécifique aux techniques de propulsion en FRM devrait être enseigné durant le programme de réadaptation fonctionnelle intensive chez les individus ayant une LMÉ.

Quelques programmes d'entrainement pour améliorer les techniques de propulsion en FRM ont été proposés [12-19], mais aucun consensus n'a été admis quant aux modalités d'enseignement et aux paramètres à prioriser. La plupart de ces études se sont concentrées principalement à améliorer l'efficacité mécanique de la force appliquée au cerceau de la roue en utilisant une rétroaction visuelle continue lors de changements à divers paramètres de propulsion (Intensité, vitesse, durée)[12-14,16-19]. Les entraînements avec ou sans rétroaction visuelle et/ou vocale proposés dans les études précédentes se sont montrés plutôt efficaces pour augmenter l'angle de poussée et diminuer la cadence[12,13,17-19], alors que d'autres ont montrés aucune ou peu de différence sur leur qualité de propulsion [14,16]. C'est pourquoi il est impératif de trouver une méthode efficace pour enseigner un patron de propulsion optimal personnalisé à chaque condition.

Le nouveau simulateur de propulsion en FRM qui a été développé à l'ÉTS, lequel peut fournir une rétroaction haptique en temps réel en utilisant le sens du toucher pour optimiser l'efficacité mécanique, pourrait conférer une alternative novatrice aux moyens conventionnels de rétroaction (auditif et visuel) sans nécessiter un haut niveau d'attention puisqu'aucune rétroaction visuelle n'est offerte.

3. Méthodologie et résultats

La méthodologie et les résultats de ce mémoire sont présentés sous la forme d'un article scientifique. Sa version abrégée à été soumise à la conférence de la société RESNA (Rehabilitation Engineering and assistive technology Society of North America) qui aura lieu en juin 2014 à Indianapolis, aux États-Unis.

To what extent are spatiotemporal and handrim kinetic parameters comparable between overground and wheelchair simulator propulsion among long-term manual wheelchair users?

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Abstract

Objectives: To compare propulsion biomechanics on a newly developed wheelchair simulator to overground natural propulsion.

Design: A repeated cross-sectional research design

Participants: Seventeen individuals (15 men and 2 women) with spinal cord injury between T4 and T12 who used their manual wheelchair as their primary mean of mobility.

Methods: Participants completed two 20-meter propulsion trials on a tiled surface and two 1-minute propulsion sessions on the simulator at a self-selected natural velocity. Participants and simulator wheelchair was equipped with instrumented wheels to record handrim kinetics The main outcome measures were perceived exertion, heart rate, spatio-temporal and pushrim kinetic propulsion parameters during the push phase. T-test and Pearson correlation were generated for the main outcome measures.

Results: Perceived exertion, heart rate, tangential force and energy output were found to be similar ($p<0.05$) between overground and simulator settings at their self-selected natural velocity; whereas velocity, contact angle, total force and power were found to be greater ($p<0.05$) at overground propulsion when compared to the simulator propulsion setting. Correlation between settings were found to be "very good" for the total force ($r=0.89$), tangential force ($r=0.91$) and power ($r=0.90$), and "good" for the mechanical effective force ($r=0.76$). The propulsion total and tangential forces, MEF and power intensities were found to be symmetrical without any preferential side regardless of the settings.

Conclusion: The propulsion biomechanics on the simulator can be compared to those overground in terms of mechanical propulsion profiles, but that the simulator does not perfectly emulate overground propulsion in terms of spatio-temporal parameters and total force intensity.

Keywords: biomechanics, paraplegia, propulsion, rehabilitation, wheelchair

Background

Individuals with spinal cord injury (SCI) who have lower limb paralysis generally use a manual wheelchair (MWC) as their primary means of mobility[7]. The extensive use of the upper limb (U/L) for locomotion such as repetitive propulsion patterns have been previously correlated to a high prevalence of U/L injury in this population [9]. Between 30% and 60% of MWC users are likely to develop shoulder pain during lifetime, between 5% and 16 % elbow pain, and between 15% and 48% hand and wrist pain [9-11]. In clinical practice, MWC simulators such as dynamometers have been used for a long time for task specific training programs [15,17,20-22]. Similarities between overground and dynamometer propulsion have already been highlighted [33]. The general conclusion is that, even if dynamometers do not perfectly emulate overground propulsion, manual wheelchair users are consistent in their propulsion patterns, such as push angle, stroke frequency, direction and amplitude of forces applied at the handrim and timing.

Looking at the promising results from other SCI training programs that resulted in improved function, quality of life, propulsion mechanical efficiency, muscular endurance and cardiorespiratory capacity[28], a new motorized simulator was developed[36]. Unlike other dynamometers, this simulator uses motor-driven rollers controlled by a real-time computer. The computer simulates the behaviour of a virtual wheelchair in its natural environment (e.g. velocity and slope changes) [37]and thus can be configured to simulate the real inertia and rolling resistance of the user and wheelchair.

Purpose

The goal of this study was to compare the propulsion of this newly developed simulator to overground propulsion on a tiled surface at a self-selected natural velocity. The comparison was based on spatio-temporal and biomechanical parameters as well as perceived exertion and heart rate among a group of experienced MWC users with SCI. It was hypothesized that the simulator would emulate overground wheelchair propulsion key outcome measures at self-selected natural velocity. It was also anticipated that symmetrical handrim force applications would be generated for both propulsion settings.

Method

Participants

Seventeen individuals (15 men and 2 women) with a spinal cord injury located between T4 and T12 were contacted by phone or email from an internal subject database and accepted to participate in this study. Mean ± s.d. age was 43.5 ± 13.9 years, height was 1.73 ± 0.21 meters, weight was 79.4 ± 15.3 kg, and time since their injury was 14.0 ± 9.2 years. Inclusion criteria were having been diagnosed with SCI at least one year prior to the study, using a manual wheelchair as a primary means of mobility (>4hours/day) and having no or minimal pain at the shoulder which could limit the ability to propel their wheelchair (WUSPI[39] mean score=1.87±4.39/150). Participants were excluded if they had associated neurological or musculoskeletal impairments or any other disability that could have hindered their ability to carry out the experimental tasks. They were also excluded if they could not properly fit in the wheelchair simulator due to their weight, height or cushion width. Ethical approval was obtained from the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR) and the École de Technologie Supérieure (ÉTS) Research Ethics Committees. Participants reviewed and signed informed consent forms and the PAR-Q form (www.csep.ca) before entering the study.

Overground propulsion setting

Participants first performed a MWC propulsion trial over a distance of 20 meters in a corridor (tiled surface) with their own wheelchair at a self-selected natural velocity. The trial was done twice, unless there was a velocity variation exceeding 10%, in which case a third trial was completed. The time needed to travel the required distance was measured with a stopwatch, which was started when the front wheels began to move and stopped when the wheels crossed the finish line. A rest period was allowed before each trial as required.

Simulator propulsion setting

The participants were transferred from their own wheelchair to a manual wheelchair customized to fit on the simulator (seat width=44 cm, seat height from ground= 57 cm, diameter of wheels = 24", Figure 1).

The wheelchair was completely stabilized by a front wheel and rear axle locking device. The backrest angle was adjusted to fit the specifications of the participants' wheelchairs and, if desired, the participants could use their own cushion. A familiarization period, consisting of 5 three-minute propulsion periods followed by two minutes of rest, was completed. Then, 2 one-minute propulsion trials were conducted on the simulator at the participants' self-selected natural velocity, corresponding to the same perceived effort as that reported during overground propulsion. After each task, the participant expressed their perceived exertion using the modified BORG scale[40] ranging from 0 (no effort) to 10 (maximum effort). Heart rate was calculated at the end of every task by a cardiometer located below the xiphoid process and read by a watch (POLAR FT40).

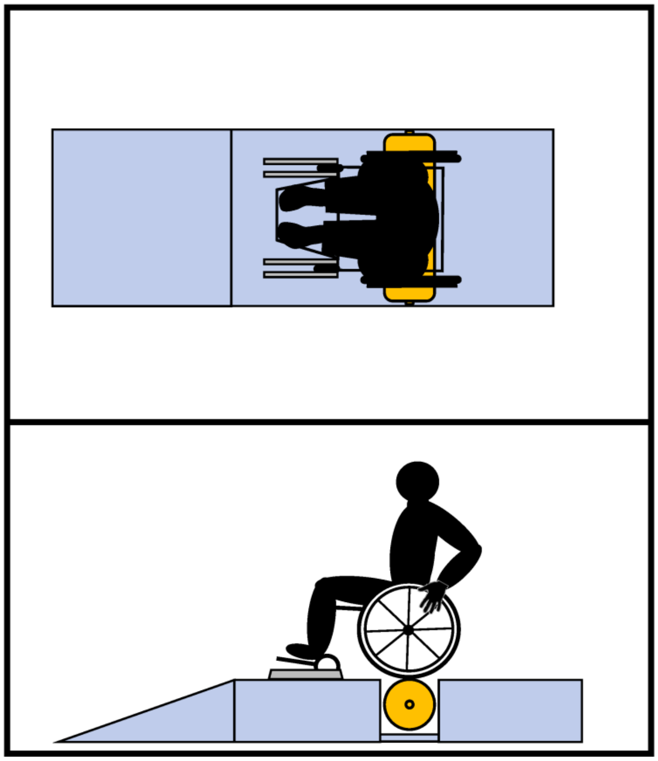

Figure 1: Superior and lateral view of a schematic representation of the simulator setting

Handrim kinetics

In both settings, the wheelchairs were equipped with two instrumented wheels to record the forces and moments applied at the handrims at 240 Hz equipped with instrumented wheels (SmartWheel; wheels diameter=24"; Out-Front, Mesa, Az, USA). Once installed on the participant's wheelchair, these instrumented wheels did not significantly alter the wheelchair's characteristics (width, position, size and orientation of the wheels) aside from the overall weight of the wheelchair (SmartWheel=4.9 kg/wheel) and additional rolling resistance due to the different tire construction (SmartWheels were fitted with solid tires whereas most participants used inflatable tires). The instrumented wheels allowed us to calculate the spatio-temporal variables and force applied to the MWC pushrim bilaterally.

Force and moment data were filtered using a zero-lag eighth-order low-pass Butterworth filter with a cut-off frequency of 30 Hz.

Main outcome measures

To facilitate data analysis, MWC propulsion cycle was divided into two distinct phases: push and recovery phases[41]. Thresholds of 15 N and 5N were applied on the total force to respectively detect the beginning and the end of the push phase. The kinetic data collected during the push phase were analyzed and normalized over the push angle between 0% and 100%.

The total force (F_{tot}) was determined by computing the vectorial sum of the individual forces (F_x, F_y, F_z) measured at the handrims bilaterally. The tangential force (F_{tg}) was obtained using the ratio between the wheel's axial moment (M_z) and the wheel's radius [10]. The mechanical effective force (MEF), which is the proportion of the force applied to the pushrim directly contributing to the forward rotation of the wheel expressed as a percentage, was calculated using $[F_{tg}^2 / F_{tot}^2]*100$[42]. The moment M_z was obtained directly by the SmartWheels sensors; the power was calculated using $M_z*\omega$, where ω is the angular velocity in radian per second. Energy output was measured by integrating power by time. F_{tot}, F_{tg}, MEF and power measures were time-normalized (0%-100%) over the push phase of each trial for each participant. These main outcome measures were selected as they are likely related to the development of secondary musculoskeletal impairments affecting the U/Ls among wheelchair users [9,43].

The symmetry between the dominant (Dom) and non-dominant (Non-Dom) side were analysed for the main outcome measures. A symmetry index was calculated using a ratio method[44],

$$\text{Symmetry Index}\,(/100) = \frac{\text{Dom}}{Dom + Non - Dom},$$

where Dom is the absolute dominant side value and Non-Dom is the absolute non-dominant side value[45]. A value of 0.5 indicates symmetry; a value ≤0.45 was taken as asymmetry to the non-dominant side, meaning the force at non-dominant side was greater than the dominant, and a value ≥0.55 was taken as asymmetry to the dominant side. Note that all participants were dominant on their right side.

Statistical analysis

Mean and standard deviations (SD) were calculated for the participants' demographic and clinical characteristics (Table 1) as well as for all outcome measures at the dominant side (Table 2). For each of the simulator and overground settings, 2 trials were evaluated, with 5 propulsion cycle considered for each trial (total=10 propulsion cycles). The propulsion cycles were selected as strokes 4 to 9 of each trial. Energy output was measured for the fifteen meters where the velocity was the most stable for each test. After confirming the normality of the data distribution by a Shapiro-Wilk test, paired t-tests were used to verify whether differences existed between simulator and overground propulsion main outcome measures.

Pearson correlation coefficients (*r*) were used to analyze similarity between time-normalized profiles of F_{tot}, F_{tg}, MEF and power were achieved overground and on the simulator for each participant and a group mean was calculated. The group mean *r* value obtained for each outcome measure was interpreted according to the guidelines proposed by Altman [46]: poor agreement ($r \leq 0.20$), fair ($r=0.21-0.40$), moderate ($r=0.41-0.60$), good ($r=0.61-0.80$) and very good ($r \geq 0.81$). Statistical significance level was set to $\alpha=0.05$ for all tests. Statistical analyses were performed with SPSS v.20 software.

Results

Comparison between simulator and overground propulsion

Group mean (s.d.) spatio-temporal parameters, handrim kinetic parameters and BORG exertion scale value were calculated on the simulator and overground settings at the participant's self-selected natural velocity (Table 1). The handrim kinetics time-normalized profiles with mean and maximal values are presented in Figure 2.

Table 1: Mean (SD) main outcome results

	Natural velocity			
Variables	**Overground**	**Simulator**	**Differences**	
Mean velocity (m/s)	1.57(0.31)	1.20(0.19)	-23.8%	***
Peak velocity (m/s)	1.66(0.30)	1.24(0.19)	-25.2%	***
Contact angle (°)	87.42(15.47)	74.17(16.83)	-15.2%	**
Mean F_{tot}(N)	43.40(12.15)	38.11(9.00)	-12.2%	*
Peak F_{tot}(N)	70.63(22.15)	56.28(15.84)	-20.3%	**
Mean F_{tg}(N)	26.26(8.95)	23.92(6.17)	-8.9%	
Peak F_{tg}(N)	44.79(15.81)	39.36(10.85)	-12.1%	
Mean MEF	0.40(0.11)	0.43(0.11)	7.7%	
Peak MEF	0.71(0.14)	0.79(0.12)	11.8%	*
Mean Power (W)	36.90(16.30)	26.14(8.65)	-29.2%	**
Peak Power (W)	67.54(29.61)	49.04(16.60)	-27.4%	*
Energy output (J / 15 meters)	196.72(31.71)	197.54(40.77)	-0.42%	
Energy per mass (J/kg)	2.50 (0.16)	2.50 (0.32)	0.11%	
BORG exertion (/10)	2.46(0.82)	2.79(1.21)	13.8%	
Heart rate (bpm)	90.78 (11.65)	91.85 (15.93)	1.2%	

* Significant difference(* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$) between overground and simulator setting.

Spatio-temporal parameters

Velocity and contact angle were found to be significantly different between overground and simulator propulsion at a self-selected natural velocity (Table 1).

Pushrim kinetics and BORG exertion scale and heart rate

Mean and peak F_{tot}, power, and peak MEF were found to be significantly different, whereas mean and peak F_{tg}, mean MEF, energy output, perceived exertion and heart rate were found to be similar between simulator and overground propulsion at their self-selected natural velocity (Table 1).

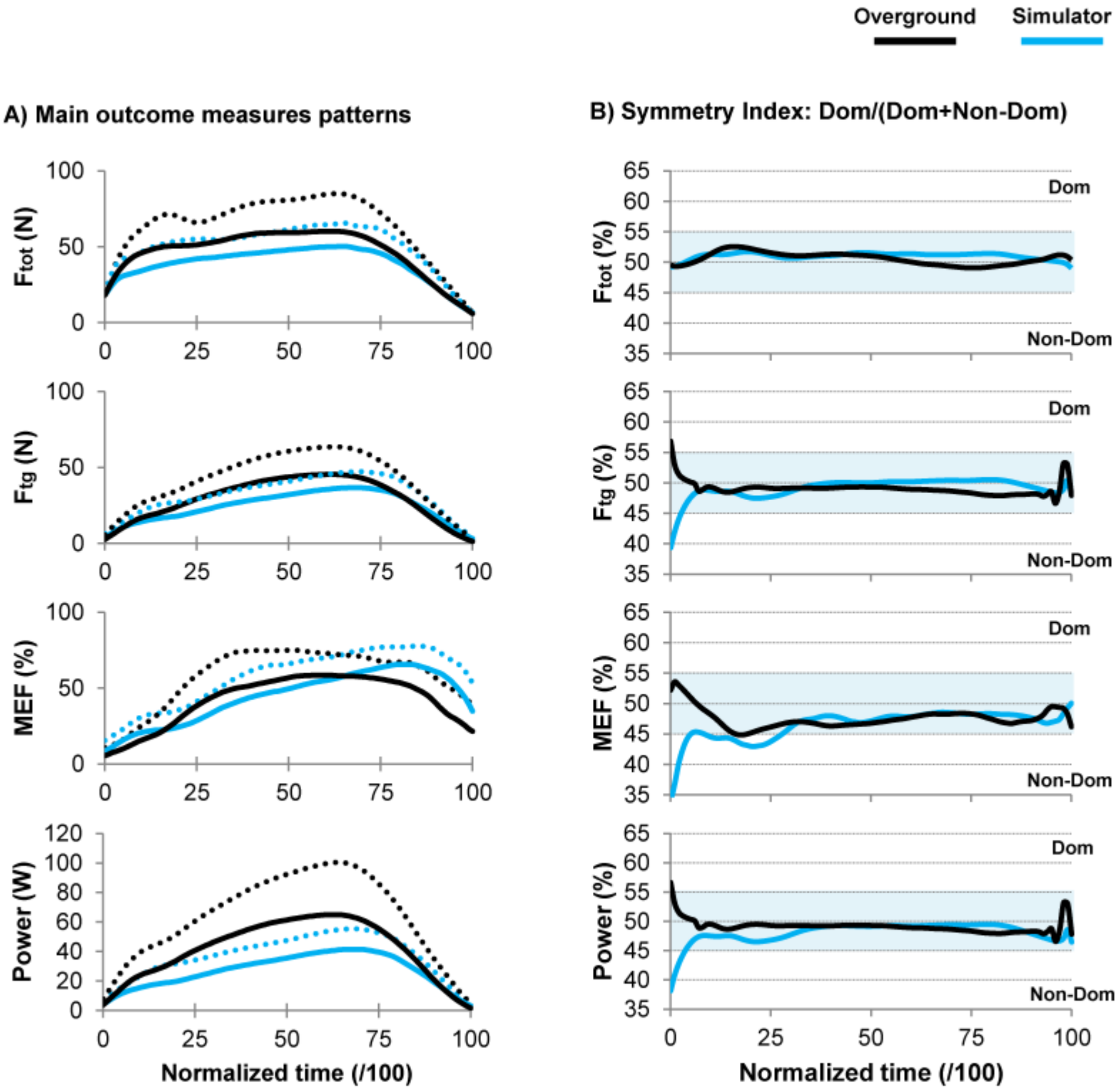

Figure 2: A) Mean (solid lines) + s.d. (dotted lines) of the main outcome measures patterns for overground (black line) and simulator (light blue line) propulsion settings. B) Symmetry index patterns of the main outcome measures for overground and simulator propulsion settings. Areas highlighted in light blue represents a zone of symmetry. Dom = Dominant side, Non-Dom = Non-Dominant side

.

As shown in Figure 2A, the general trends show similar profiles between simulator and the overground handrim kinetics with peak values occurring between 50% and 75% of the push phase for F_{tot}, F_{tg} and power. MEF peak occurred between 50% and 75% of the push phase in the overground setting and between 75% and 100% in the simulator setting. Correlation was found to be "very good" for F_{tot}(r=0.89), F_{tg}(r=0.91) and power (r=0.90), and "good" for the MEF (r=0.76) value.

Intensity of symmetry indices

The symmetry index patterns for F_{tot}, F_{tg}, MEF and power intensities are summarized in Figure 2B. Overall, these patterns highlight comparable force application at the dominant and non-dominant handrims during propulsion on both settings. Due to relatively low intensities at the beginning and the end of the push phase, asymmetry was seen in the first and last 10% of the push phase.

Discussion

Velocity was lower on simulator than overground

Adoption of a lower self-selected natural velocity on simulators compared to the overground has already been noticed and documented in other studies on gait locomotion using treadmills [47], and was explained by the lack of visual flow, which contributes to the calibration of propulsion mechanical and energetic aspects. The absence of visual flow could alter the control of the locomotive behavior and influence the velocity of the wheelchair displacement seen in this study [47].

Also, the velocity difference could have been influenced by the change in wheelchair design, as it could have altered the participants' propulsion biomechanics. When propelling on the simulator, participants could have increased muscular efforts (increased muscular co-contractions) resulting in increased perceived effort for similar velocities. As participants were asked to propel with similar perceived effort, velocity on the simulator was decreased to comply with the instructions. The increased overground velocity was associated with increased forces (F_{tot}, F_{tg}) and power output, as previously described during manual wheelchair propulsion [48-50], even if perceived effort and heart rate were found to be similar

Propulsion patterns comparable between simulator and overground propulsion settings

Mean curve profiles were found to be similar for total force, tangential force, power and MEF. The "good" to "very good" correlation between simulator and overground propulsion could be associated with similar propulsion technique, which could be associated with similar neuromuscular behaviour when comparing both conditions. On the other hand, total force intensity and velocity were found to be different between the simulator and overground setting, indicating that the simulator does not perfectly emulate overground propulsion. These differences need to be taken into account when combining practical guidelines based on ergometers and dynamometers studies with real life propulsion situations [9]. To optimize rehabilitation, protocols could include hybrid training involving propulsion on both dynamometers and overground. Propulsion training on dynamometers can be useful during intensive rehabilitation to minimize some risks associated with outdoor propulsion, such as being stuck in snow or on ice. It can also contribute to train wheelchair user propulsion techniques and cardio-respiratory conditioning during longer periods.

Symmetrical intensities during propulsion

This study shows that both propulsion overground and on a wheelchair simulator involve symmetrical bilateral efforts. This goes in the same direction as Hurd et al.[51] who have already stated for overground propulsion in straight line that it requires a symmetrical effort. Regarding clinical implications, it means that both sides need to be trained during rehabilitation. As for research concerns, it implies that only one side can be analysed when doing propulsions experiments, as the other side is likely to be similar.

Study limitations

The most significant limitation of this study was that participants did not use their own wheelchair on the simulator, which may have altered their mechanical behavior and output measures. Furthermore, because of the increased weight compared with most wheelchair wheels, instrumented Smartwheels may have altered rolling resistance and consequently modified participants' usual overground performance.

Conclusion

This study compared manual wheelchair users' propulsion biomechanics when propelling on a novel wheelchair simulator versus overground. The results confirm that the propulsion biomechanics on the simulator can be compared to those overground in terms of mechanical propulsion profiles, but that the simulator does not perfectly emulate overground propulsion in terms of spatio-temporal parameters and total force intensity. Current developments are being made to improve the simulator, including the integration of a more immersive way of propulsion with visual feedback, and development of a mechanical system to fit the participants' own wheelchair on the simulator.

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4. Conclusion

Cette étude comparait la biomécanique de propulsion d'utilisateurs de fauteuil roulant manuel sur un dynamomètre à la propulsion sur le terrain. Ce nouveau dynamomètre motorisé, développé par l'équipe de Rachid Aissaoui de l'ÉTS en collaboration avec l'équipe de Dany Gagnon du laboratoire de pathokinésiologie de l'IRGLM, semble être une technologie prometteuse qui permet de simuler une propulsion symétrique chez les usagers de FRM au niveau des profils biomécaniques de propulsion. Par contre, des différences au niveau des intensités des données spatio-temporelles, de la force totale et de la puissance montrent qu'une certaine divergence existe entre les conditions étudiées.

La vitesse plus basse sur le dynamomètre par rapport à la propulsion au sol pourrait être expliquée par le fait que le fauteuil intégré sur le dynamomètre était différent de celui du participant. Cela pourrait avoir amené un recrutement musculaire différent, soit une plus grande quantité de co-contractions musculaires, augmentant ainsi l'effort perçu pour une même vitesse. Par contre, puisque les consignes étaient de garder le même effort perçu, la vitesse aurait été diminuée. Enfin, la diminution de la vitesse sélectionnée sur le dynamomètre pourrait être expliquée par l'absence de flux visuel qui contribuerait à la calibration mécanique et au contrôle du comportement locomoteur [47].

Deux systèmes sont présentement en cours de développement pour améliorer le dynamomètre , soit un mécanisme qui permettrait d’installer le fauteuil roulant des participants sur le dynamomètre et un système de réalité virtuelle qui augmentera l’immersion des participants lors de leur propulsion.

En conclusion, ce dynamomètre offrira la possibilité de développer des protocoles d’évaluation et d'entrainement spécifiques visant à améliorer la force, l'endurance et l'efficacité mécanique chez les usagers de FRM. Il pourra être utilisé autant dans le milieu clinique pour permettre l'entraînement d'utilisateurs de FRM, qu'en recherche pour développer et étudier l'effet de différents programmes d'entraînement spécifiques aux individus utilisant un FRM.

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