Characterization of walking adaptations on an omnidirectional treadmill

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McGill

STATEMENT OF AUTHORSHIP

I, Smit H. Soni, certify that I am the primary author of this thesis. I claim full responsibility for the content and style of the text included herein.

STATEMENT OF ORIGINALITY

This thesis contains no material that has been published elsewhere, except where specific references are made. The study presented in Chapter 3 is original material and represents contribution to knowledge in the fields of virtual reality, neuroengineering and rehabilitation. In this study, we analyzed the spatiotemporal parameters, body kinematics and lower limb muscle activation of healthy young individuals walking at different speeds (slow, comfortable, fast) on a low-cost non-motorized omnidirectional treadmill with and without (VR) vs. overground. Most of what we know about locomotor changes on treadmill is derived from findings collected using conventional treadmill. This study thus addresses a large knowledge gap on gait adaptations while using self-pace omnidirectional treadmill, as those recently developed by the games industry. The information that emerged from this study further our understanding on whether such treadmills yield a walking pattern that is similar to overground walking. The results of this study also provide valuable information for the design of future research studies to assess the impact of a repeated exposure to omnidirectional treadmill on gait biomechanics and ensuing musculoskeletal integrity in video gamers or patient populations undergoing physical rehabilitation. The data presented in this thesis was collected at the Feil & Oberfeld Research Centre of the CISSS-Laval and Jewish Rehabilitation Hospital Site of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR), affiliated to McGill University. The study presented in this thesis was approved by the Research Ethics Board of CRIR.

DEDICATION

I dedicate this thesis to my mother, Hinaben Soni, to whom I owe everything. No words can describe your devotion and sacrifice towards my upbringing. I can’t comprehend, despite having a full-time job and against all odds, how you managed to always be there for me. To my uncle Sandip Soni, who always challenged me to push my boundaries to pursue perfection. I might not have liked it at times the pressure, but your guidance has played a pivotal role in my life and to be where I am today.

To my beautiful wife, Majory, thank you for always believing in me. I could not finish this without your support, care, and love. You have always helped me become a better person; this is the greatest gift one can receive. I love you so very much. To Arya, Oh my darling daughter! Your arrival has given me newfound motivation. Your adorable laughs and giggles have kept me going even when I felt otherwise. I will always love you.

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I thank all my fellow lab mates for the stimulating discussions, advices, assistance with the data collection and for all the fun we had together.

CONTRIBUTION OF AUTHORS

This thesis is presented in a manuscript format and includes one research manuscript which has been published in a peer-reviewed journal. I, Smit H. Soni, am the main contributor and lead author of all chapters and manuscript included in this thesis. My contribution extends to the research design, experimental set up, data collection, data analyses, statistical analyses, interpretation of findings, preparations of figures/ tables, submission for publication, revisions following peer review and writing of this thesis.

The research study and manuscript presented here was developed under Dr. Anouk Lamontagne's supervision. Dr. Lamontagne oriented the selection of the research design, experimental set up, data analysis, statistical analysis, interpretation of findings and critically reviewed and provided constructive feedback on the manuscript and this thesis.

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LIST OF ABBREVIATIONS

CoM	Center of mass
CRIR	Centre for interdisciplinary research in rehabilitation of greater Montreal
DF1	Peak ankle dorsiflexion at heel strike
DF2	Peak ankle dorsiflexion during mid stance
EMG	Electromyography
GEE	Generalized estimating equation model
HE	Peak hip extension
HF1	Hip flexion during early stance
HMD	Head-mounted display
KF1	Maximal knee flexion during stance
KF2	Maximal knee flexion during swing
MG	Medial gastrocnemius
PE	Physical environment
PF	Peak ankle planterflexion during late stance
RF	Rectus femoris
ST	Semitendinosus
TA	Tibialis anterior
TV	Television
VEs	Virtual environments
VR	Virtual reality

ABSTRACT

Treadmills are commonly used for gait retraining in rehabilitation settings. However, they have limitations when it comes to training complex locomotor tasks, as they do not allow changing the speed or direction of walking. These adaptations are essential for efficient and safe community ambulation. Self-paced omnidirectional treadmills, like those developed by the gaming industry, allow changes in speed and locomotor movements in any direction. However, it is unclear whether these treadmills yield a walking pattern similar to overground walking.

This thesis aimed to compare the spatiotemporal parameters, body kinematics, and lower limb muscle activation of healthy young individuals walking at different speeds (slow, comfortable, fast) on a low-cost, non-motorized omnidirectional treadmill with and without virtual reality (VR) versus overground.

The study found that participants achieved slower speeds on the treadmill compared to overground. On the treadmill, faster walking speeds were achieved through an increase in cadence, while overground, an increase in cadence and step length was observed. At matched speed, the study observed enhanced stance phase knee flexion, reduced late stance ankle plantarflexion, and enhanced activation amplitudes of hip extensors in late stance and hip flexors in early swing when walking on the treadmill. Adding VR to treadmill walking had no significant impact on walking outcomes.

The omnidirectional treadmill yields a different walking pattern and leads to different adaptations to speed compared to overground walking. These alterations are likely due to reduced shear forces between the weight-bearing foot and supporting surface and the perceived threat to balance on the omnidirectional treadmill. Since such treadmills are likely to be used for prolonged periods by

gamers or patients undergoing physical rehabilitation, further research should determine the impact of repeated exposure on gait biomechanics and lower limb musculoskeletal integrity.

ABRÉGÉ

Les tapis roulants sont couramment utilisés pour la réadaptation de la marche en centre de réadaptation. Cependant, ils présentent des limitations lorsqu'il s’agit d’entraîner des tâches locomotrices complexes, car ils ne permettent pas de modifier la vitesse ou la direction de la marche. Ces adaptations sont essentielles pour une marche efficace et sécuritaire dans la communauté. Les tapis roulants omnidirectionnels, tels ceux développés par l'industrie du jeu, permettent de modifier la vitesse ainsi que les mouvements locomoteurs dans n'importe quelle direction. Toutefois, il est encore incertain si ces tapis roulants produisent un patron de marche similaire à celui de la marche sur le sol.

Cette thèse avait pour but de comparer les paramètres spatiotemporels, la cinématique corporelle et l'activation des muscles des membres inférieurs d’individus jeunes et en bonne santé marchant à différentes vitesses (lente, confortable, rapide) sur un tapis roulant omnidirectionnel non motorisé et peu coûteux, avec et sans réalité virtuelle (RV), par rapport à la marche au sol.

L'étude a démontré que les participants atteignaient des vitesses plus lentes sur le tapis roulant que lors de la marche au sol. Sur le tapis roulant, une augmentation de la cadence permettait d'augmenter la vitesse de marche tandis qu’au sol, une augmentation de la cadence et de la longueur des pas a été observée. Cette étude a révélé qu’à vitesse égale, une augmentation de la flexion du genou en phase d'appui, une réduction de la flexion plantaire de la cheville en fin d'appui ainsi qu’une augmentation des amplitudes d'activation des extenseurs de la hanche en fin d'appui et des fléchisseurs de la hanche en début d'appui étaient présents lors de la marche sur le tapis roulant. L'ajout de la RV à la marche sur tapis roulant n'a pas eu d'impact significatif sur les résultats de la marche.

Le tapis roulant omnidirectionnel produit un patron de marche différent et entraîne des adaptations différentes de la vitesse par rapport à la marche au sol. Ces modifications semblent principalement dues à la réduction des forces de cisaillement entre le pied et la surface d'appui ainsi qu’à une perception d’une difficulté accrue à maintenir l'équilibre sur le tapis roulant omnidirectionnel. Étant donné que ces tapis roulants sont susceptibles d'être utilisés pendant des périodes prolongées par des joueurs de jeux vidéo ou des patients en processus de réadaptations, des recherches supplémentaires devraient déterminer l'impact d'une exposition répétée sur la biomécanique de la marche et l'intégrité musculo-squelettique des membres inférieurs.

THESIS ORGANIZATION AND OVERVIEW

The organization of this manuscript-based thesis adheres to the guidelines for thesis preparation published by McGill Graduate and Postdoctoral Studies. Chapter 1 includes a literature review and rationale for the MSc project. Chapter 2 outlines the objectives and hypothesis of the MSc project. Chapter 3 presents a research manuscript which includes an abstract, an introduction, the methodology, the results, and a discussion of results. Chapter 4 summarizes the findings of the study and discusses the contribution of these findings to rehabilitation and future research. The last chapter of this thesis (Chapter 5) provides references of all studies cited in the thesis.

CHAPTER 1: INTRODUCTION

1.1 BIPED WALKING

Walking is a primary mode of locomotion in domestic or public environments among the human species. Thus, it has been widely studied since antiquity. Biped walking, which is absent in other primates, results from a complex evolutionary strategy, with one of its major requirements being the ability to maintain postural equilibrium or balance (Pavcic, Matjacic, & Olensek, 2014). During upright stance, postural stability is ensured provided that the vertical projection of the center of mass (CoM) falls within the base of support (A. Patla, 2003). During walking, however, the body's center of mass travels outside of the base of support for about 80% of each stride (Frank & Patla, 2003), causing inherent instability. Furthermore, two-thirds of the body mass which includes the arms, trunk and head are balanced over the moving lower limbs, thus adding to this inherent instability (Winter, 1991, 1995b). This rather precarious posture benefits one by freeing the upper limbs for the other tasks (e.g., opening doors or carrying parcels); however, these simple looking tasks frequently challenge our balance.

Walking is essential to the completion of many activities of daily living (A. Patla & Shumway-Cook, 1999) and has been identified as an important determinant of participation (Danielsson, Willen, & Sunnerhagen, 2011), quality or life (Lord, McPherson, McNaughton, Rochester, & Weatherall, 2004) and health (Fritz & Lusardi, 2009). For these reasons, there is abundant research that describes the characteristics of walking (primarily level walking along a straight line) in both healthy and pathological populations across different age groups.

Walking is characterized by cyclical movements of the lower limbs. A typical gait cycle or stride cycle is defined as the period of time between any two identical events in the gait process (Gage

& Novacheck, 2001). Generally, these two nominally identical events correspond to the instant where one foot strikes the ground (referred to as heel strike (HS) or initial foot contact) and ends when the same foot strikes again the ground. During the gait cycle (see Figure 1-1), each lower limb alternates between a stance phase, where the foot in contact with the ground (about 60% of gait cycle), and a swing phase, where the foot is without ground contact (about 40% of the cycle) (Winter, 1991). The stance phase can further be divided in sub-phases, which are the double support phase (both the limbs are in stance phase) and single support phases (when the limb of interest in stance phase but the other is swinging). Others (e.g. Perry and colleagues (1992)) have proposed a description of the gait cycle according to functional sub-phases occurring in the following sequence: initial contact, loading response, midstance, terminal stance and preswing, all of which are part of the stance phase. The swing phase is then divided into three functional and consecutive sub-phases referred to as initial swing, mid-swing, and terminal swing.

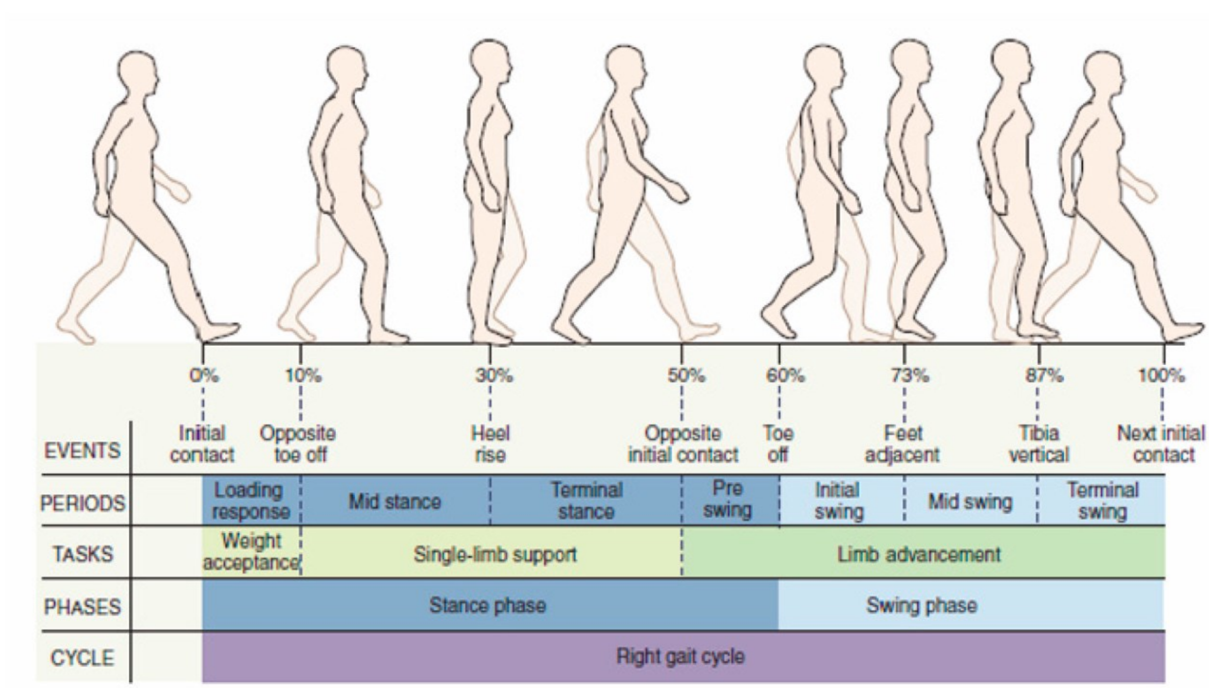

Figure 1-1. Phases of normal gait cycle. From: (Di Gregorio & Vocenas, 2021).

As for the movements or kinematics of the lower limbs while walking, they are characterized by reciprocal movement patterns in flexion and extension, which are driven by the flexor and extensor muscles of the lower limbs (see Figure 1-2 for lower limb kinematics). This alternate pattern in terms of leg movement and muscle activation, which is reminiscent of that elicited by central pattern generators in several animal species (MacKay-Lyons, 2002), is robust and consistent across human individuals, given that maturation is achieved, that there are no pathologies affecting locomotion, and that no volitional gait adaptations are required (e.g. slope, obstacle, change of direction).

In the following sections, I will further discuss the gait adaptations that are required for community ambulation, mechanisms for speed adaptations, as well as the tools that are available in a laboratory setting to assess and train these locomotor adaptations.

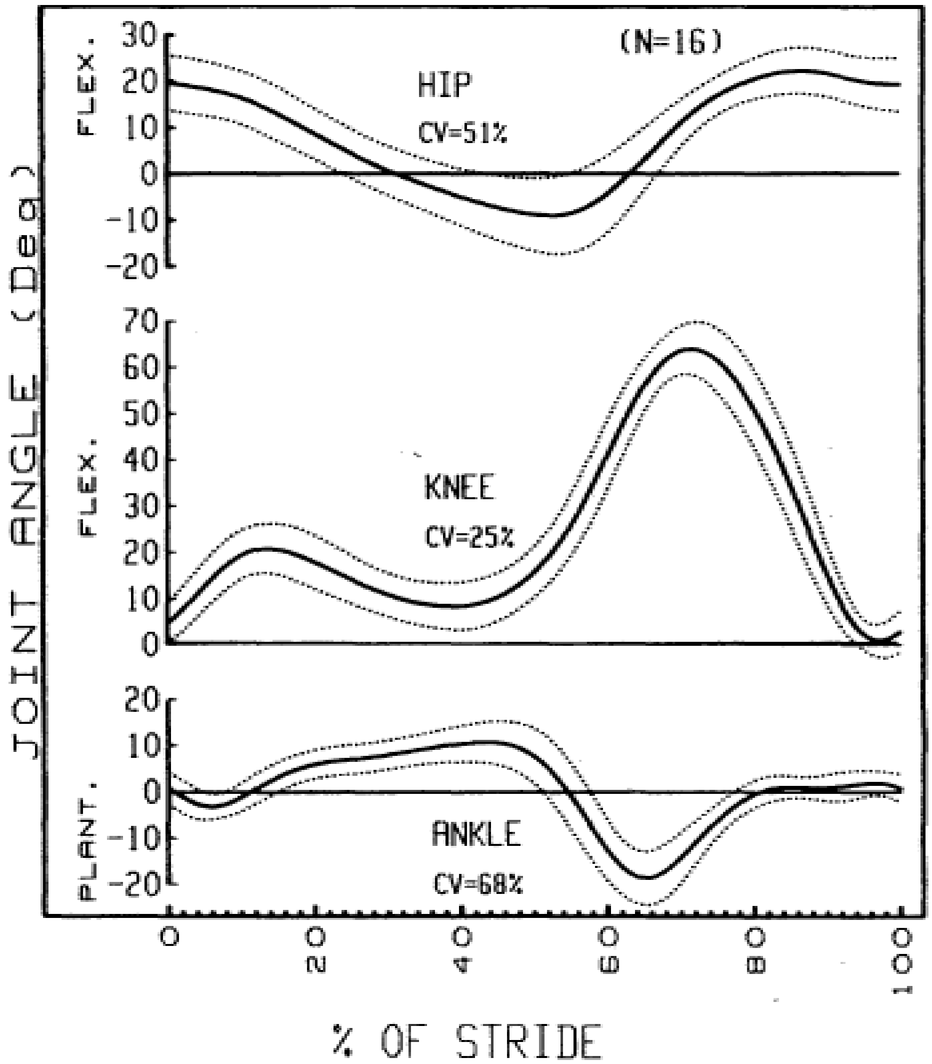

Figure 1-2. Average of joint angles over stride period for natural cadence. Standard deviation (dotted line) is plotted on either side of mean (plain line). From: (Winter, 1983a).

The prerequisites for walking include the strength and balance to stand, the ability to generate the cyclic pattern of lower leg movement responsible for forward progression, and the cardiovascular endurance to reach one's destination (A. Patla, 2001). While the ability to walk along a straight, leveled, uncluttered, and well-lit path provides the basic foundation for independent mobility, they are not synonymous (A. Patla, 2001). Indeed, physical requirements associated with daily life environments such as community settings (e.g. shopping malls, streets, etc.) are complex and modulated by environmental demands (A. Patla & Shumway-Cook, 1999). To that effect, Patla and Shumway-Cook (1999) proposed a conceptual model where they grouped eight attributes of the physical environment referred to as "dimensions", as a way of capturing the interaction between the individual and the environment during community walking (Figure 1-3). These dimensions capture the external demands that must be met for an individual to be mobile within a given community. The various dimensions identified were (1) minimum walking distance, (2) time constraints, (3) ambient conditions, (4) terrain characteristics, (5) external physical load, (6) attentional demands, (7) postural transitions and (8) traffic level.

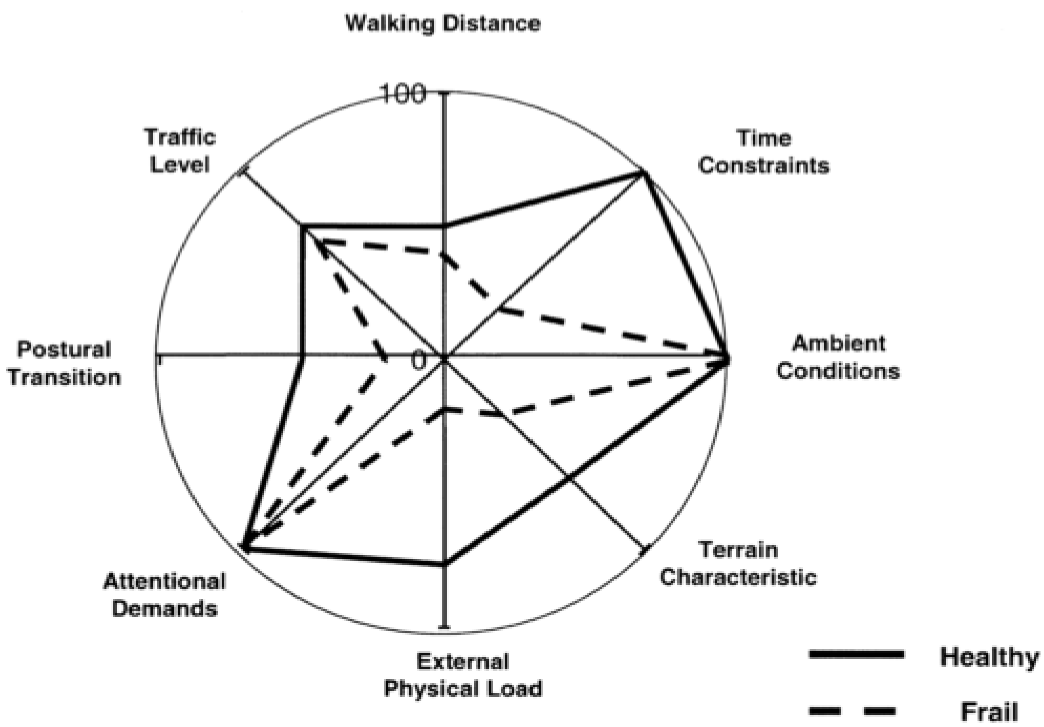

Figure 1-3. Dimensions of mobility in complex environments, as experienced during community ambulation (from: (Frank & Patla, 2003). The two sets of lines represent, respectively, the 'operating range' of an older adult with and an older adult without walking disability. Measures for these dimensions are obtained from observational analysis.

Of the dimensions mentioned above, time constraints are especially of interest in the context of this MSc research project, as these lead to one of the gait adaptation mechanisms essential to independent community walking: changing the walking *speed*. Additionally, as shown in Figure 1-3, the operating range for this dimension can be severely compromised not only in older adults but also for several other populations with a physical disability.

The most obvious example of time constraint is that imposed by traffic lights, since street crossing has to be carried out within a set time (Hoxie & Rubenstein, 1994; Langlois et al., 1997). In this example, a minimum speed of walking- shopping ~1.1m/s (Lord et al., 2004), street crossing ~1.2 m/s (Cohen, Sveen, Walker, & Brummel-Smith, 1987) in major cities is needed to ensure that the task is completed within the required time frame.

Another dimension of interest in the context of a study that involves an omnidirectional treadmill is that of postural transitions, which include initiating gait from various postures, terminating gait, and more specifically changing the direction of walking (Hollands, Sorensen, & Patla, 2001). These transitions are an integral part of mobility and impose demands on the balance control system over and beyond those encountered during steady-state walking (Winter, 1995a). For example, gait initiation requires going from a stable standing posture to essentially falling (where center of mass is moved outside the base of support), followed by recovery with the positioning of the swing limb (A. Patla et al., 1999).

This thesis focused specifically on speed adaptation as a first step toward the understanding of the impact of a new, passive omnidirectional treadmill technology on locomotion. For this purpose, we studied spatiotemporal parameters, body kinematics, and lower limb muscle activation of healthy young individuals, while comparing how these vary depending on the mode of locomotion, that is while performed overground vs. on a self-pace omnidirectional treadmill.

1.3 SPEED ADAPTATION

One of the major requirements of community walking is speed adaptation. Gait speed, considered as a “sixth vital sign”, directly correlates with functional ability (J. Perry, Garrett, Gronley, & Mulroy, 1995) and balance confidence (Mangione, Craik, Lopopolo, Tomlinson, & Brenneman, 2008). It has the potential to predict future health status (Studenski et al., 2003), functional decline and mortality (Hardy, Perera, Roumani, Chandler, & Studenski, 2007). Walking speed reflects both functional and physiological changes and is a discriminating factor in determining potential for rehabilitation (Goldie, Matyas, & Evans, 1996). It further aids in prediction of falls and fear of falling (Maki, 1997). Furthermore, progression of walking speed has been linked to clinical meaningful changes in quality of life as well as in home and community walking behavior (Schmid et al., 2007).

As previously explained and besides the obvious constraints on the speed imposed by traffic lights, there are other subtle pressures to adjust speed while walking in the community, such as slowing down or speeding up to avoiding an approaching obstacle (Huber et al., 2014). Thus, one needs the ability to both increase and reduce walking speed to safely move around within the community. For these reasons, my thesis focused on the ability to walk at different speeds, including not only comfortable walking speed but also walking faster and slower walking speeds.

The effect of speed on locomotion has been studied by many investigators. Studies that investigated the effect of walking speed on the various temporal-distance factors of walking found that fast walking is accomplished by decreasing the step duration (e.g. increasing cadence) and by increasing the step length, up to certain point after which only cadence can be increased (Murray, Kory, Clarkson, & Sepic, 1966). It was also found that faster walking speeds are accompanied by decreases in the duration of phases of the walking cycle such as stance, swing and double-limb support phases (Murray et al., 1966; Smith, Mc, & Shideman, 1960; Winter, 1991). The time of swing phase as a percentage of the gait cycle, increases at faster speeds, which is caused by the swinging limbs that moves forward through a greater distance in a shorter time to achieve the longer step length needed for faster walking (Y. Liu et al., 2014; Murray et al., 1966; Smith et al., 1960).

Although the patterns of lower limb joint movements do not change significantly with faster speeds, greater step length is achieved by increasing the magnitude of joint excursion (Fukuchi et al., 2019; Murray et al., 1966). Longer step lengths are primarily associated with increased hip flexion of the leading (forward-reaching) lower limb, as well as increased ankle extension of the trailing (rear) lower limb. At heel strike, the knee position of both the leading and trailing lower limb are in greater flexion for fast walking than for comfortable speed (Winter, 1983b). This increased knee flexion would not serve the purpose of augmenting the step length, but rather that of providing shock absorption for the more forceful fast gait (Murray et al., 1966). At heel strike, the trunk is also in a lower vertical position at faster walking speed compared to comfortable speed. This probably is due to the increased obliquity of the outstretched lower extremities with the faster waking speed. In addition to the changes in the excursions depicted above, the amplitude of transverse rotation of the thorax and pelvis increases in the faster walking speed (Wagenaar & Beek, 1992). The increase in transverse rotation of the pelvis with faster walking would contributes substantially to the increase in step length (Murray et al., 1966).

Recent modeling studies of walking at self-selected speeds have identified how individual muscles work in synergy to satisfy the demands of forward propulsion and body weight support during locomotion (Anderson & Pandy, 2003; M. Q. Liu, Anderson, Pandy, & Delp, 2006). They showed that the plantarflexor muscles (soleus and gastrocnemius) and hip extensors (gluteus mediius), which play a role in supporting the body against gravity, are also main contributors to the forward progression of the body during locomotion. As a result, and not surprisingly, the level of activation of these muscles is typically increased at faster speeds (Neptune, Sasaki, & Kautz, 2008). At faster walking speeds, muscles that contribute mainly to vertical support (e.g. knee extensors) (Orendurff et al., 2004), as well as muscles that are contributing to the larger leg swing (e.g. hip flexors), typically associated with fast walking also show larger activation levels (Doke, Donelan, & Kuo, 2005). Conversely, walking slower is generally associated with reduced activation amplitudes of lower limb muscles (Franz & Kram, 2012). However, as slow walking may be mechanically less efficient and less conducive to the storage and recovery of elastic energy in the musculotendon complex compared to comfortable walking, this may cost some additional muscle recruitment (Neptune et al., 2008).

1.4 TRAJECTORY ADAPTATION

The ability for trajectory adaptation or steering is another essential dimension for independent mobility. In the context of community ambulation, it allows circumventing an obstacle or an undesirable surface as well as aligning heading towards the desired direction. Unlike other adaptive strategies such as step length and step width regulation which are successfully implemented within a step cycle, direction change must be planned and initiated during the previous step to reduce the acceleration of the CoM without stopping the ongoing locomotion (A. E. Patla, Prentice, Robinson, & Neufeld, 1991).

Steering at its most basic level requires reorientation of the body in the direction of intended travel. Online control of steering (without termination of ongoing locomotion) will require the control of body reorientation embedded within other modifications of the structure of the ongoing step cycle. As Hase et al. (1999) explained, there are two turning strategies: (1) step turn and (2) spin turn. The *Step turn* strategy consist of the trunk being remained in a more posterior position. Elevation of the opposite side of the pelvis as well as inversion of the ankle can contribute to moving the CoM toward the turning direction. This strategy is easier and more stable compared to the spin turn because the base of support while changing direction that is much wider. The *Spin turn is* a strategy that allows the body to spin on the forward leg while producing a braking force (axial leg). The torso is kept behind the axial leg presumably to balance the centrifugal force caused by rotating the body and to step toward the new direction. As a result, the person cannot use this strategy after the CoM passed the stance foot.

When using a step turn strategy, the change in body orientation in the new direction of travel is accomplished through appropriate foot placement (step width regulation) and trunk roll motion (A. E. Patla, A. Adkin, & T. Ballard, 1999) that precede or concur with a top-down sequence of horizontal reorientation (yaw) of the head, followed by the thorax and pelvis, towards the new travel direction (Gibson, 2009; Grasso, Glasauer, Takei, & Berthoz, 1996; A. E. Patla et al., 1999). The fact that the head yaw motion is initiated before trunk yaw motion suggests that reorientation of gaze takes precedence (A. E. Patla et al., 1999), a finding that was confirmed by others (A. Lamontagne & Fung, 2009). During the spin turn, trunk roll change would precede all other changes.

Before understanding turning strategy, however, it’s important to study straight line walking, thus the focus of this thesis was to understand speed adaptations while walking straight on self-paced omnidirectional treadmill compared to overground walking.

1.5 VIRTUAL REALITY BASED TREADMILL TRAINING

In the previous sections, I have described the demands of community ambulation and how one achieves gait speed and trajectory adjustment to safely and efficiently adjust to environmental demands. Unfortunately, mobility can be compromised by older age as well as by the presence of a neurological disorder such as stroke. A commonly used approach for gait rehabilitation is treadmill training, which allows the repeated practice of stereotyped, cyclical leg movements. This technology occupies a relatively small space and provides reliable speed control, sometimes with integrated body weight support system that facilitates stepping. Gait rehabilitation gains achieved through treadmill training, however, do not completely transfer to overground gait (Barbeau, Norman, Fung, Visintin, & Ladouceur, 1998). Further, conventional treadmill, which runs at fixed speeds, does not allow training important gait adaptations for community ambulation such as online *speed adaptations*.

In the last decade, virtual reality (VR)-based training approaches for gait rehabilitation were proposed as a mean to allow training in meaningful and ecological environments that mimic the demands of everyday life, with the premise that such an approach would lead to better gait adaptation strategies and a better transfer of gains to everyday life (Darekar, McFadyen, Lamontagne, & Fung, 2015). Nowadays, VR systems for gait training normally consist of a visual display (e.g. rear-projection screen (Powell, Stevens, & Simmonds, 2009), helmet mounted display (A. Lamontagne, Fung, McFadyen, Faubert, & Paquette, 2010) or 3D television (Rizzo & Kim, 2005) coupled with a self-pace treadmill that allows the participant to adjust speed at will. These self-pace treadmills provide the main advantage of allowing training gait speed adaptation, which is otherwise not possible on a conventional treadmill (A. Lamontagne, Fung, McFadyen, & Faubert, 2007). Coupled to a movable platform, one can also walk at self-selected speed while going up or down a hill, or while experiencing postural perturbations (Fung, Richards, Malouin, McFadyen, & Lamontagne, 2006). This technology remains limited, however, by the fact that it does not allow one to change direction during gait. For this reason, researchers as well as the games industry are currently working on the development of omnidirectional treadmills that allow not only changes in walking speed but also changes in the walking trajectory. Coupled with the VR technology, omnidirectional treadmills provide visual motion information (optic flow) as experienced during overground locomotion, something that is not possible without VR given that users are stepping on the spot. This optic flow, which provides information about the direction and speed generated by the relative motion between a participant's eye and the immediate surroundings (Pailhous, Ferrandez, Fluckiger, & Baumberger, 1990), plays an important role in adjusting one's walking speed (A. Lamontagne et al., 2007; Prokop, Schubert, & Berger, 1997) and walking trajectory (Sarre, Berard, Fung, & Lamontagne, 2008; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). More research is needed, however, to determine the extent to which the gait pattern elicited on omnidirectional treadmills resembles that observed during everyday life, that is during overground locomotion. The latter consideration is important to ensure an optimal transfer of training gains to situations of everyday life, and to avoid unwanted gait movements that would ultimately lead to pain and injury.

In the following sections, I will thus be reviewing the state of knowledge concerning differences in the walking pattern on conventional and self-pace treadmills vs. overground (section 1.5) and differences in the walking pattern when walking in virtual environments (section 1.6). I will further be reviewing the very few studies that have examined the walking pattern of participants walking on recently developed omnidirectional treadmills (section1.7).

1.6 WALKING ON A TREADMILL VS. OVERGROUND

1.5.1 Conventional treadmill vs. overground

A number of previous studies have compared temporal-distance gait parameters (Alton, Baldey, Caplan, & Morrissey, 1998; Molen & Rozendal, 1966; Murray, Spurr, Sepic, Gardner, & Mollinger, 1985; P. O. Riley et al., 2008), joint kinematics (Alton et al., 1998; Strathy, Chao, & Laughman, 1983) and muscle activation patterns (Lee & Hidler, 2008) in healthy young individuals walking on a conventional treadmill vs. overground. While there exist numerous similarities between the two modes of locomotion, subtle but significant differences also emerge, even when controlling for walking speed. For instance, Murray et al. (1985) concurred with Strathy et al. (1983) that cadence and double support time were higher with consequent shorter stride lengths and shorter swing time on the treadmill compared to overground. Murray and colleagues (1985) also proposed that the faster cadence on the treadmill could result from a sense of urgency to get the foot of the swinging limb onto the ground as the supportive limb was automatically driven behind the body. It could also be that the finite length of the treadmill influenced the users to shorten their step lengths, which in turn required a faster cadence in order to maintain the given walking speed. The shorter swing duration on the treadmill may relate to both the faster cadence and the shorter step length. Relatively longer double limb support periods on the treadmill, also found by Molen and Rozendal (1966) and Riley et al. (2008), may be an attempt to minimize the duration of an unsteady single-limb stance on the moving treadmill surface.

Murray and colleagues (1985) also identified a significantly greater maximum hip flexion angle during treadmill walking compared to overground walking. They proposed that this was caused by or was a consequence of an increased rise distance of the foot, which was shown to occur during treadmill ambulation. Another finding of this study was a smaller maximum hip extension and ankle dorsiflexion angle during the stance phase in treadmill walking, which they attributed to reduced step length.

In addition to above mentioned changes in temporal-distance factors of gait sagittal lower limb joint kinematics, differences were also found in muscle activation patterns particularly in the tibialis anterior throughout stance where EMG activity during treadmill walking was of lower amplitude (Lee & Hidler, 2008). As further described by Lee and Hidler (2008), an interesting pattern among the hamstrings, vastus medialis, and adductor longus muscles emerged between the two conditions. Here, throughout early swing and midswing, there were higher activity levels during overground walking in each of these muscles. Yet, at terminal swing, this observation reversed (e.g., significantly more activity during treadmill walking). The difference and reversal of activation arises because treadmill walking involves a fixed speed and path, reducing the need for anticipatory muscle activation, unlike the variable conditions of overground walking. Additionally, during treadmill walking, there is no work required to move the body forward with respect to the ground, which might also explain lower energy requirement and therefore reversal of activation. Specifically, during the final phase of the swing in treadmill walking, there is an increase in muscle activity. This is likely to control the limb movement as it prepares to touch the treadmill, in contrast to the earlier phases where the motion of the treadmill reduces the need for active muscular control. The finding demonstrates the adaptation of walking through muscle activity based on the environment, especially in key muscles like the hamstrings, vastus medialis, and adductor longus, which are crucial for stabilizing the lower limb.

The literature suggests that differences between treadmill and overground walking may be due to several factors such as the fixed, imposed treadmill speed (Sloot, van der Krogt, & Harlaar, 2014b), lack of optical flow during treadmill walking (Sheik-Nainar & Kaber, 2007), differences in belt surface (Dingwell, Cusumano, Cavanagh, & Sternad, 2001), or small intra- stride variations in belt speed (P. Riley, Paolini, Della Croce, Paylo, & Kerrigan, 2007; Savelberg, Vorstenbosch, Kamman, van de Weijer, & Schambardt, 1998). These differences possibly limit the transfer of gait analysis and training outcomes on a treadmill to overground walking.

1.5.2 Self-pace treadmill vs. overground

The drawbacks of an imposed walking speed could possibly be solved by a feedback-controlled treadmill that adapts treadmill speed to the user, i.e., that allows for self-paced walking. This self-pace walking would allow the users to apply their natural way of controlling and varying walking speed, presumably leading to a more natural gait. Additionally, the ability of self-pace systems to support smooth transitions from standing to walking has been demonstrated (Fung et al., 2006; Minetti, Boldrini, Brusamolin, Zamparo, & McKee, 2003).

Only 2 studies that compared self-pace treadmill and overground gait were found. Amongst these studies, one compared gait speed overground and on a self-pace treadmill with and without exposure to VR (Plotnik et al., 2015). The study summarized that walking on a self-pace treadmill is not fully identical to overground walking in terms of gait speed development in the absence of VR because the required walking distance to reach a steady state level of gait speed is longer while walking on the treadmill. However, an interesting finding of the study was that steady state walking on the self-pace treadmill was achieved earlier in the presence of VR, presumably because of the addition of optic flow. Additionally, gait speed control, in the presence of optic flow simulated by VR, showed greater similarity to that generated by natural overground walking. Yet another study done by Van der Krogt and colleagues (2014) compared kinematics and spatiotemporal parameters while walking on a self-pace treadmill with VR vs. overground and found that participants walked with shorter strides on the treadmill. However, no significant differences in lower limb joint kinematics were found between the two locomotor conditions. In this study, however, the researchers collected the treadmill data only in the presence of VR, thus making it difficult to dissociate the effects of the self-pace treadmill mode vs. VR.

Sloot and colleagues (2014) compared 70 parameters (temporal-distance factors, kinematics, kinetics) in healthy adults walking on a self-pace treadmill with VR vs. on a conventional fixed speed treadmill and found differences in only 15 parameters. The latter were of small magnitude and considered to be 'not clinically meaningful'. They also reported more stride variability in the self-pace treadmill walking condition. When walking on the self-pace treadmill, people were also able to select and change their own preferred walking speed, resulting in long-term stride fluctuations that resemble those seen during overground walking. This stride variability on the self-pace treadmill could also be the result of participants being unsure of how the treadmill was going to respond and thus they speed up so as not to drift too far backwards and prevent fall (Zhao, 2014).

1.7 INFLUENCE OF VR ON THE GAIT PATTERN

Sheik-Nainar and Kaber (2007) compared walking on a treadmill with and without VR vs. walking overground in healthy young participants. Their results indicate that adding optic flow through VR to the treadmill walking yields a walking pattern that is more similar compared to overground walking compared to treadmill walking without VR, thereby adding to the observation made by (Plotnik et al., 2015). Namely, with the introduction of VR to treadmill walking, speed and cadence increased toward values observed during overground gait, but still remained different. This difference in walking speed and/or cadence while walking on self-paced treadmill with VR vs. while walking overground was also confirmed by Powell and Colleagues (2009), as well as Plotnik and colleagues (2015).

Another study by Sloot and Colleagues (2014) compared the effects of combining VR to a self-pace treadmill and a conventional treadmill and found that adding the VR caused the gait pattern of the participants to become 'more cautious', i.e. participants adopted a shorter stride length and stride time, an increased step width and reduced hip and knee joint excursions. Hollman and colleagues (2006) also found an increased variability in stride velocity with the addition of VR while waking on a self-pace treadmill.

Collectively, the studies presented above suggest that the presence of VR itself influences the locomotor pattern, sometimes making it closer to what is being observed during overground gait, but sometimes leading to a more cautious and variable gait pattern. Given the impact of VR itself on locomotion, and while self-pace and omnidirectional treadmills were so far designed to be used in combination with VR, it would be warranted to test individuals both with and without VR in order to get a better understanding of where differences from overground walking arise from.

1.8 WALKING ON AN OMNIDIRECTIONAL TREADMILL

To our knowledge, and given that omnidirectional treadmills are fairly recent, only one study carried out by Pavcic and colleagues (2014) has examined the influence of an omnidirectional treadmill (in this case motorized) on the walking pattern when turning while walking. Body kinematics, especially the pelvis and torso rotation in the transverse plane, as well as stride length, were compared while walking and turning on the treadmill vs. overground. The authors found that the movements of the pelvis in the transverse plane are almost identical in both walking conditions. In the first 20% of the gait cycle the pelvis rotation was aligned in both conditions, however, in the middle of the gait cycle a difference of no more than 5° became evident. Later, the pelvis rotation accelerated to catch up with the direction of turning at the end of the gait cycle. The authors also found that the stride length of the outer leg was longer than the stride length of the inner leg while walking on the omnidirectional treadmill, as observed overground.

While this study by Pavcic and colleagues (2014) suggests that omnidirectional treadmill may yield similar turning strategies compared to overground walking, there are still many aspects, including those related to speed adaptations strategies, that were not examined. Furthermore, the type of treadmill employed (motorized) differs from newly developed, commercially available, low-cost omnidirectional treadmills developed by the games industry which are ‘passive’ (i.e., non-motorized, such as the Cyberith Virtualizer and the Virtuix Omni). Further research is thus needed to determine the extent to which omnidirectional treadmills influence strategies for walking adaptations, including speed and direction changes.

As a first step, this MSc thesis focused on walking speed adaptations while on a self-pace omnidirectional treadmill as compared to walking overground. Findings will help appraise the impact of omnidirectional treadmills, as currently utilized by gamers, on the pattern of locomotion, which is an essential step prior to their use as assessment or training tools in rehabilitation.

CHAPTER 2: RATIONALE AND RESEARCH OBJECTIVES

2.1 RATIONALE

Walking, a fundamental human locomotion skill, has been a subject of extensive research within the field of biomechanics. The complexity of bipedal walking lies in the delicate balance between maintaining postural stability and generating forward propulsion. The mechanisms governing these aspects of human locomotion have implications not only in understanding fundamental biomechanics but also in applications related to rehabilitation and assistive technology.

Traditionally, gait analysis has been conducted on overground walking, providing valuable insights into the kinematics, kinetics, and muscle activation patterns involved. However, recent advancements in technology have introduced novel training methods and assessment tools, such as treadmills and virtual reality (VR).

Treadmill training has become a cornerstone of gait rehabilitation, offering controlled conditions for repetitive leg movements. This approach has been of great importance in investigating walking pathologies and quantifying the effects of various treatments on locomotion due to its advantage of providing a controlled environment. However, conventional treadmills have their limitations, particularly in replicating the dynamic conditions of overground walking, including speed adjustments and directional changes.

The integration of VR technology into treadmill training has opened new avenues for gait assessment and rehabilitation. VR-based treadmill training aims to bridge the gap between traditional treadmill training and real-world overground walking by providing more immersive and ecologically valid training environments.

This thesis focuses on examining the differences in walking patterns between overground walking and walking on an omnidirectional treadmill, both with and without the use of VR. By investigating how these factors influence gait characteristics and speed adjustments, this research seeks to contribute valuable insights into the field of locomotion and its applications in rehabilitation.

2.2 OBJECTIVES AND HYPOTHESIS

Objectives

The main objective of this research was as follows:

1. To compare spatiotemporal parameters, body kinematics and lower limb muscle activation patterns while walking at different speeds on the omnidirectional treadmill with and without VR vs. overground.

A secondary objective was:

2. To assess how VR influences gait patterns during treadmill walking and whether it brings the treadmill-walking patterns closer to those observed during overground walking.

Hypothesis

The following hypotheses were proposed.

1. As participants adapt their speed on the omnidirectional treadmill, they show the following changes compared to when walking overground:

   1.1 Faster cadence and a shorter step length

1.2 Smaller sagittal lower limb joint excursion

1.3 Higher amplitudes of muscle activation

2. The addition of VR to treadmill walking will yield a walking pattern that more closely resemble that observed during overground gait compared to when walking on the omnidirectional treadmill without VR.

Please note that the hypotheses, as presented in the published manuscript, were simplified or abridged, following the peer review process.

PREFACE

The general objective of this study presented here was to determine the extent to which spatiotemporal parameters, body kinematics, and lower limb muscle activation of healthy young adults differs while walking on omnidirectional treadmill compared to overground.

Walking is essential for completion of many activities of daily living, and one needs to adjust gait speed to fulfill contextual demands (e.g., crossing a street within the time allotted by traffic lights) to achieve and safe and efficient community ambulation. Unfortunately, mobility can be compromised by older age as well as the presence of neurological disorders. A commonly used approach for gait rehabilitation is conventional treadmill training which allows the repeated practice of stereotyped, cyclical leg movements. While there has been numerous research done to assess the effectiveness of treadmill training with or without VR, the conventional treadmills traditionally used cannot be used to train adaptations in walking speed and direction. These drawbacks can be addressed by using a newly developed omnidirectional treadmill.

The following study, presented in Chapter 3, explores the extent to which a recently developed self-pace omnidirectional treadmill allowing speed and direction changes yields walking speed adaptations that are similar to those observed while walking overground. As the treadmill is meant to be used with VR, and to get a better insight into the impact of adding VR to treadmill walking, speed adaptations on the treadmill were tested both with and without VR.

Characterization of speed adaptation on an omnidirectional treadmill

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3.1 ABSTRACT

Background: Conventional treadmills are widely used for gait retraining in rehabilitation setting. Their usefulness for training more complex locomotor tasks, however, remains limited given that they do not allow changing the speed nor the direction of walking which are essential walking adaptations for efficient and safe community ambulation. These drawbacks can be addressed by using a self-pace omnidirectional treadmill, as those recently developed by the gaming industry, which allows speed changes and locomotor movements in any direction. The extent to which these treadmills yield a walking pattern that is similar to overground walking, however, is yet to be determined. **Methods:** The objective of this study was to compare spatiotemporal parameters, body kinematics and lower limb muscle activation of healthy young individuals walking at different speeds (slow, comfortable, fast) on a low-cost non-motorized omnidirectional treadmill with and without virtual reality (VR) vs. overground. **Results:** Results obtained from 12 young healthy individuals (18–29 years) showed that participants achieved slower speed on the treadmill compared to overground. On the treadmill, faster walking speeds were achieved by a mere increase in cadence, as opposed to a combined increase in cadence and step length when walking overground. At matched speed, enhanced stance phase knee flexion, reduced late stance ankle plantarflexion, as well as enhanced activation amplitudes of hip extensors in late stance and hip flexors in early swing were observed when walking on the treadmill. The addition of VR to treadmill walking had little or no effect on walking outcomes. Collectively, results show that the omnidirectional treadmill yields a different walking pattern and lead to different adaptations to speed compared to overground walking. We suggest that these alterations are mainly driven by the reduced shear forces between the weight bearing foot and supporting surface and a perceived threat to balance on the omnidirectional treadmill. **Conclusion:** Since such treadmills are likely to be used for prolonged periods of time by gamers or patients undergoing physical rehabilitation, further research should aim at determining the impact of repeated exposure on gait biomechanics and lower limb musculoskeletal integrity.

***Keywords* –** Gait, Locomotion, Kinematics, Electromyography, Virtual reality

3.2 BACKGROUND

Walking is essential to the completion of many activities of daily living (A. Patla & Shumway-Cook, 1999) and has been identified as an important determinant of participation (Danielsson et al., 2011), quality of life (Lord et al., 2004) and health (Fritz & Lusardi, 2009). For these reasons, there is abundant research that describes the characteristics of walking, primarily level walking along a straight line, in both healthy and pathological populations across different age groups.

One of the major requirements of community mobility is speed adaptation (A. Patla & Shumway-Cook, 1999). Gait speed, considered as a "sixth vital sign", directly correlates with functional ability (J. Perry et al., 1995) and balance confidence (Mangione et al., 2008). It has the potential to predict future health status (Studenski et al., 2003), functional decline and mortality (Hardy et al., 2007). Walking speed reflects both functional and physiological changes and is a discriminating factor in determining potential for rehabilitation (Goldie et al., 1996). It further aids in prediction of falls and fear of falling (Maki, 1997). Furthermore, progression of walking speed has been linked to clinical meaningful changes in quality of life as well as in home and community walking behavior (Schmid et al., 2007).

Besides the obvious constraints on walking speed imposed by traffic lights, there are other subtle pressures to adjust speed while walking in the community, such as slowing down or speeding up to avoid an approaching obstacle (Huber et al., 2014). Thus, one needs the ability to both increase and reduce walking speed to safely move around within the community. For these reasons, this study focused on the ability to walk at different speeds, including not only comfortable walking speed but also walking faster and slower walking speeds.

Unfortunately, gait-related mobility can be compromised by older age as well as by the presence of a neurological disorder such as stroke. A commonly used approach for gait rehabilitation is treadmill training, which allows the repeated practice of stereotyped, cyclical leg movements. This technology occupies a relatively small space and provides reliable speed control, sometimes with integrated body weight support system that facilitates stepping. Gait rehabilitation gains achieved through treadmill training, however, do not completely transfer to overground gait (Barbeau et al., 1998). Further, conventional treadmill training does not allow training important gait adaptations for community ambulation such as speed changes.

In the last decade, virtual reality (VR)-based training approaches for gait rehabilitation were proposed as a mean to allow patients training in meaningful and ecological environments that mimics the demands of everyday life, with the premise that such an approach would lead to better gait adaptation strategies and a better transfer of gains to everyday life (Darekar et al., 2015). Nowadays, VR systems for gait training usually consist of a visual display (e.g. rear-projection screen (Powell et al., 2009), helmet mounted display (A. Lamontagne et al., 2010) or 3D monitor/screen (Rizzo & Kim, 2005) coupled with a treadmill that allows the participant to train in real life scenarios. This technology remains limited, however, by the fact that it does not allow one to change direction while walking. For this reason, researchers as well as the gaming industry are currently working on the development of omnidirectional treadmills that allow changes in direction while accommodating gait speed changes. Coupled with the VR technology, omnidirectional treadmills provide visual motion information (optic flow) as experienced during overground locomotion, something that is not possible without VR given that the participant is stepping on the spot. This optic flow which provides information about the direction and speed generated by the relative motion between a participant’s eye and the immediate surroundings

(Pailhous et al., 1990) plays an important role in adjusting one's walking speed (A. Lamontagne et al., 2007; Prokop et al., 1997) and walking trajectory (Sarre et al., 2008; Warren et al., 2001). More research is needed, however, to determine the extent to which the gait pattern elicited on omnidirectional treadmills resembles that observed during overground locomotion. The latter consideration is important to ensure an optimal transfer of training gains to situations of everyday life, and to avoid unwanted gait movements that would ultimately lead to pain and injury.

To our knowledge, and given that omnidirectional treadmills are fairly recent, only one study carried out by Pavcic and Colleagues (2014) examined the influence of an omnidirectional treadmill on the walking pattern. The study, which used a motorized treadmill without VR, showed that torso and pelvis movements were similar on the treadmill vs. overground when turning while walking. However, the extent to which such findings can be extended to recent and low cost, non-motorized omnidirectional treadmills developed by the gaming industry remains unknown. Furthermore, how speed adaptations are achieved on omnidirectional treadmills and potential modulatory effects provided by optic flow through the virtual environment remain to be elucidated. In this research study, we specifically tested speed adaptations under three walking conditions, including walking on an omnidirectional treadmill with and without VR and walking overground. The two treadmill conditions were included to appraise the impact of the omnidirectional treadmill itself and the additional impact of VR which adds optic flow, the latter being shown to impact on temporal-distance factors and kinematics of gait (Sloot et al., 2014a).

Specifically, the objective of this study was to compare spatiotemporal parameters, body kinematics and lower limb muscle activation patterns while walking at different speeds on the omnidirectional treadmill with and without VR vs. overground. We hypothesized that as participants adapt their speed on the omnidirectional treadmill, they maintain a faster cadence and a shorter step length compared to when walking overground. It was further hypothesized that adding VR to omnidirectional treadmill would yield a walking pattern that more closely resembles that observed during overground gait compared to when walking on the omnidirectional treadmill without VR.

3.3 METHODS

3.3.1 PARTICIPANTS

A convenience sample of 12 healthy young adults between the ages of 18 and 29 years participated in the study (5 females and 7 males; participants' age = 24.4 ± 2.3 years (mean ± 1SD); comfortable walking speed = 1.42 ± 0.16 m/s as per the 10 m Walk Test (Bohannon, 1997). The demographic data of participants are reported in Table 1. All participants had normal or corrected-to-normal visual acuity, as measured by a score equal or above to 20/20 on the EDTRS visual acuity chart (Kaiser, 2009), and intact cognition, as per a score ≥ 26 out of 30 on the Montreal Cognitive Assessment (Nasreddine et al., 2005). Participants were excluded if they presented any condition interfering with locomotion (e.g., orthopedic, rheumatologic, or neurological), lower limb or back pain, as well as any visual condition interfering with 3D or color vision (e.g., strabismus, color blindness, etc.) The experiment was approved by the Research Ethics Board of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR) and all participants gave their written informed consent prior to entering the study.

3.3.2 INSTRUMENTAL SET UP AND PROCEDURES

The experiment took place at the Virtual Reality and Mobility Laboratory of the Jewish Rehabilitation Hospital-CISSS-Laval in one session lasting approximately 3 h, including preparation time and data collection. In addition to the assessment of characteristics listed in the participant section, anthropometric measurements (weight, height as well as segments length and width) were collected and participants were questioned as to whether they had any previous exposure to omnidirectional treadmill which lasted more-than one hour, as well as the frequency at which they play videogames per week and the time spent interacting with virtual environments (VEs) in the past three months. Participants were then requested to walk at different speeds under three *locomotor conditions*, in a random order: (1) walking overground without VR; (2) walking on the omnidirectional treadmill with VR and (3) walking on the omnidirectional treadmill without VR. *Speed conditions*, also presented in a random order, included walking at comfortable (measured a priori using the 10 m walk test overground), slow (66% of comfortable speed) and fast speed (133% of comfortable speed). Three blocks of 4 trials (4 trials X 3 speed conditions) yielding a total of 12 trials per locomotor condition were collected, for a grand total of 36 trials (12 X 3 walking conditions). Participants were allowed to rest between trials, as necessary.

For all 3 locomotor conditions, full body kinematics was recorded using a 12-camera Vicon-512™ motion capture system (Vicon Motion Systems LTD, UK). Forty passive reflective markers were placed on specific body landmarks on the participant, as specified in the Plug-In-gait model from Vicon™ (Kadaba et al., 1989). The position of the markers was recorded at a sampling rate of 120 Hz and stored for offline analyses. Additionally, muscle activation was recorded using an 8-channel electromyography (EMG) system (Noraxon, USA) and by placing adhesive surface electrodes (silver-silver chloride, $1cm^2$ area, 1 cm inter-electrode spacing) bilaterally on four muscle groups of interest: rectus femoris (RF), semitendinosus (ST), tibialis anterior (TA) and medial gastrocnemius (MG). The skin was shaved, as needed, and cleaned with alcohol prior to apposing the surface electrodes. The pre-amplified EMG data was collected at 1080 Hz in Vicon™. The paragraphs below describe the specifics of each locomotor condition.

3.3.3 WALKING OVERGROUND WITHOUT VR

The physical environment (PE) consisted of a 28.68 m^2 area (7.8 m × 3.7 m) that was free of obstacles (Figure 3-1). Participants were first provided practice until they felt comfortable walking at each of the targeted speeds. During this practice, a Vive™ controller (HTC, Taiwan) tethered to the participant's pelvis was used to provide real-time feedback on the participant's instantaneous walking speed. Once habituation was completed, participants completed the experimental trials. At the beginning of each trial, they were positioned at one end of the walking area, facing a television (TV) screen located straight ahead (0°) in the far space (8.5 m from start position and at a height of 1 m). The TV display was used to inform participants about the speed condition to be performed (slow, comfortable, and fast) and to deliver the start and stop cues of the walking trials. The stop cue was provided after 6 m of forward displacement, based on the position of the VIVE ™ controller.

3.3.4 WALKING ON THE TREADMILL WITH VR

Participants were assessed while walking on the Virtualizer™ (Cyberith, Austria) omnidirectional treadmill and immersed in a VE that replicated the dimensions and features of the real-world laboratory and which also included the TV display. Participants wore special low friction slippers over the shoes and a harness with no body weight support. The Virtualizer contains six optical sensors located in the center of a 100 cm diameter walking surface, which determines the walking displacement of participants. Sensors on a ring which goes around the torso track the orientation of participants in space. This information is fed in real time to the Unreal ™ gaming engine to update the participant position and orientation within the VE. The VE was viewed using the HTC VIVE™ (HTC, Taiwan) head-mounted display (HMD). This HMD weights 470 g and has a field of view of 110° diagonal with resolution of 2160 × 1200 pixels and a refresh rate of 90 Hz. The position and orientation of the head tracked through the Vive's HMD was also fed to Unreal 4™ (Epic games, USA) for a real-time update of the participants' camera view within the VE. Together, the information provided by the treadmill and HMD allowed a decoupling of the participant's direction of walking and head orientation within the VE.

Prior to collecting experimental trials, participants were provided habituation by walking on the omnidirectional treadmill with and without VR until they felt comfortable walking without holding the ring surrounding the treadmill.

3.3.5 WALKING ON THE TREADMILL WITHOUT VR

Participants walked on the omnidirectional treadmill without the HMD, while receiving the instructions and cues on the TV display, as described for the overground walking condition. They were provided a priori habituation as for the treadmill walking condition with VR condition, but without the HMD.

3.3.6 DATA ANALYSIS

Kinematic data was first labeled using Vicon Nexus software. The Vicon Plug-in-Gait model was used to compute segment orientations, displacements, and center of mass (CoM) displacement. All data, including the Plug-in-Gait output and the original marker locations was imported in Matlab R2016b for further analyses. Kinematic data were filtered using a dual-pass, 2^{nd} order low-pass Butterworth filter with a cut off frequency of 10 Hz. The EMG data was band-pass filtered (10–400 Hz), rectified and smoothed at 20 Hz (A Lamontagne & Fung, 2004). Lower limb (hip, knee, and ankle) excursion of movement was calculated in all three planes. The orientation of lower limb joints were examined at specific times of the gait cycle, as illustrated in Figure 3-2. For the hip joint, we included peak hip flexion during early stance (HF1; [between 0 and 30% of gait cycle]), peak hip extension (HE; [40–70%]), peak hip flexion during swing (HF2; [70–100%]). Maximal knee flexion was measured during the stance [KF1; 0–40%] and swing phases [KF2; 60–100%] of gait. For the ankle, we examined peak dorsiflexion at heel strike (DF1; [0%]), peak dorsiflexion during mid stance (DF2; [20–60%]) and peak plantarflexion during late stance (PF; [60–80%]). To calculate walking speed across the different walking conditions and since the body is not progressing forward during treadmill walking, the displacement heel and toe markers along the anteroposterior and mediolateral axis were used (Krasovsky, Lamontagne, Feldman, & Levin, 2014). Step length was calculated as the displacement between successive contralateral heel contacts in the direction of progression. Cadence was obtained by computing the number of steps per minute. Swing time was calculated as the time interval between ipsilateral toe off and heel strike. Muscle activation amplitude was obtained using EMG integrals which were computed from linear envelopes for functionally-relevant time windows of the gait cycle, as described earlier (A Lamontagne & Fung, 2004): MG activation at push-off [30%:70%], TA activation at toe-off [60%:80%], ST activation in early stance [0%:30%], and RF hip flexion burst at toe-off [60%:80%]. Each outcome was measured for every gait cycle before being averaged across gait cycles and trials of the same locomotor and speed condition for each participant.

3.3.7 STATISTICAL ANALYSIS

Generalized estimating equation model (GEE) were used to analyze all outcomes. The model was comprised of 2 within-subject factors accounting for locomotor condition (overground with no VR, treadmill with VR, treadmill with no VR) and walking speed (slow vs. comfortable vs. fast). GEEs were followed by Tukey post-hoc tests with Bonferroni adjustments in the case of significant main or interaction effects. Statistical analyses were performed in SAS® 9.4 software and the level of significance was set at $\rho < 0.05$.

3.4 RESULTS

3.4.1 PARTICIPANTS

Most participants reported using videogames or simulators previously, that is either once a year ($n = 6$) or once a month ($n = 4$). Four had been previously exposed to virtual environments in the past three months but none had any previous exposure to walking on an omnidirectional treadmill.

3.4.2 SPEED ADAPTATION TASK

Figure 3-3 illustrates the average results for gait speed, step length and cadence. The GEE analysis revealed a significant main effect of locomotor condition for gait speed (X^2 (2107) = 11.41, $p = 0.0033$) and cadence (X^2 (2107) = 7.68, $p = 0.021$). Additionally, a significant main effect of walking speed condition was found on gait speed (X^2 (2107) = 11.75, $p = 0.0028$) and cadence (X^2 (2107), = 11.57, $p = 0.0031$). Post-hoc analyses showed that for a given speed condition, participants walked slower on the treadmill with or without VR compared to overground (range of difference = 0.64–0.69 m/s, $p < 0.0001$). A higher cadence was also observed on the treadmill with VR in comparison to overground ($p = 0.003$) and treadmill without VR ($p = 0.02$). Neither gait speed nor cadence showed interaction effects. For step length, an interaction effect of locomotor condition and walking speed (X^2 (4107), = 10.60, $p = 0.031$) was observed, with shorter step length on the treadmill with and without VR vs. overground ($p < 0.0001$). Note that no differences were observed for the treadmill conditions with vs. without VR in any of the outcomes mentioned above ($p = 0.07$ to 0.9).

Given the differences in walking speed across locomotor conditions and the well-recognized impact of walking speed on gait outcomes, all further comparisons reported below were completed at speed-matched conditions, that is while comparing outcomes measured during the 'overground slow' and 'treadmill fast' conditions which showed no significant differences ($p = 0.06$). This speed-matched analysis showed significantly higher cadence ($p < 0.0001$), shorter step length ($p < 0.0001$) as well as shorter swing time ($p < 0.0001$) but longer stance time ($p < 0.0001$) on the treadmill with and without VR ($p < 0.0001$) vs. overground. No differences were observed in the latter outcomes when comparing treadmill walking with vs. without VR ($p = 0.17$ to 0.68).

The comparison of joint angles at specific points during gait cycle is illustrated in Figure 3-2. There were no statistically significant differences found for hip orientation or total hip excursion between locomotor conditions ($p = 0.26$ to 0.47). For the knee joint, a main effect of walking condition for KF1 (X^2 (2,36), = 11.59, $p = 0.003$) and for total knee excursion was observed (X^2 (2,36), = 9.01, $p = 0.011$). Post-hoc analyses showed that KF1 was larger for treadmill with and without VR compared to overground ($p < 0.0001$). Total knee excursion, however, was lower on the treadmill with ($p < 0.0001$) and without ($p = 0.003$) vs. overground. No significant difference was found for KF2 across locomotor conditions ($p = 0.47$). For the ankle joint, a main effect of locomotor condition was found for DF1 (X^2 (2,36), = 9.79, $p = 0.007$), DF2 (X^2 (2,36), = 11.06, $p = 0.004$) and PF (X^2 (2,36), = 9.47, $p = 0.008$), but not for total ankle excursion ($p = 0.07$). Post-hoc analyses revealed significantly larger dorsiflexion angles (DF1 and DF2) and smaller plantarflexion angle (PF) on the treadmill with and without VR compared to overground ($p < 0.0001$).

When comparing muscle activation amplitudes across locomotor conditions (Figure 3-4), a main effect of locomotor condition was found for hip muscles, that is ST (hip extensor) activation in early stance (X^2 (2,35), = 7.41, $p = 0.025$) and RF (hip flexor) activation at toe off (X^2 (2,36), = 8.74, $p = 0.01$), but not for other muscle groups such as MG activation at push off and TA activation at toe off ($p = 0.63$- 0.06). Post-hoc analyses revealed that ST activation was larger during treadmill walking with VR ($p = 0.001$) compared to overground walking, and larger during treadmill walking with vs. without VR ($p = 0.03$). RF activation was larger during treadmill walking with without VR compared to overground ($p < 0.0001$), with no differences between treadmill conditions ($p = 0.12$).

3.5 DISCUSSION

Low-cost omnidirectional treadmills with and without VR are becoming increasingly available and show promise for training clinical populations on complex locomotor tasks, as required for community ambulation such as modulating the speed or direction of walking in restricted space. Such combination of equipment allows for controlled, safe and repeated practice in ecological environments that are difficult to recreate in the laboratory or clinical setting. The omnidirectional feature of the treadmill also provides the option of changing the walking direction which is something that conventional treadmills do not allow and, if validated, could help train people with trajectory adaptation tasks.

Present findings show that 'low-cost' omnidirectional treadmills as the one tested in the present study impact on the biomechanics of gait, including temporal-distance parameters, lower limb kinematics and muscle activation. The addition of VR to treadmill walking induced limited differences, suggesting that the treadmill itself is the main contributing factor to alterations in gait biomechanics during VR-based omnidirectional treadmill walking.

Previous studies that investigated the effect of walking speed on the various temporal-distance factors of walking showed that faster walking speeds are achieved by decreasing the step duration (e.g., increasing cadence) and by increasing the step length. As speed increases, step length can only contribute up to a certain limit after which only cadence can be increased (Murray et al., 1966). As further detailed in Table 2, our results indicate that while participants increased both step length and cadence when progressing from slow to comfortable to fast speed during overground walking, they increased their speed during treadmill walking mainly by increasing cadence and showed little to no changes in terms of step length. Furthermore, participants generally achieved slower speeds on the treadmill compared to overground, due to shorter step length and despite of a higher cadence (for comfortable and fast speed). Interestingly, once controlling for speed, those alterations in step length and cadence between the two walking conditions persisted.

It should first be noted that the dimension of the treadmill, which was 100 cm in diameter, does not appear to explain the shorter step length during treadmill walking, given that the maximal step length that was observed during overground gait by the same participants was between 0.65 m and 0.8 m. Instead, we suggest that this shorter step length, as well as several other alterations in terms of temporal-distance factors, lower limb kinematics and muscle activation, are largely due to the low-friction walking surface of the treadmill and slippers which caused reduced shear forces between the weight bearing foot and supporting surface and lead to a perceived threat to balance. Indeed, the low friction between the foot and walking surface may have prevented participants from exerting a full ankle 'push off' in late stance, resulting in shorter step length. This reduction in step length was thus compensated, although not fully, by a faster cadence. In support of this hypothesis, participants in this study did show a significant reduction in late stance ankle plantarflexion on the treadmill vs. overground. Similar reductions in step and/or stride length (Cappellini, Ivanenko, Dominici, Poppele, & Lacquaniti, 2010; Fong, Hong, & Li, 2005; Tsai & Powers, 2009) and in gait speed (Tsai & Powers, 2009), as well as faster cadence (Cappellini et al., 2010), were also observed when walking on a slippery surface or while wearing footwear with lower friction insoles. People walking on slippery surfaces in simulated construction worksites, as participants of the present study walking on the omnidirectional treadmill, were also shown to adopt longer stance and shorter swing durations, as well as modified ankle joint kinematics, which altogether were suggested to represent gait adaptations that aim at preventing a slip (Fong et al., 2005).

Present findings also revealed that participants walking on the treadmill showed a more pronounced knee flexion in mid-stance, as well as both early- and mid-stance ankle dorsiflexion compared to overground gait. This kinematic pattern, which is typical of a crouched gait pattern (Steele, Seth, Hicks, Schwartz, & Delp, 2010), is consistent with the shorter step length displayed by the participants and may have served the purpose of maintaining the participants' CoM at a lower position and hence maximize balance, as observed earlier during conventional treadmill walking (Alton et al., 1998).

The present study also revealed significantly higher amplitudes in muscle activation in most muscle groups during treadmill vs. overground walking. Such observation is consistent with previous reports of higher muscle activation amplitudes in the lower limbs while walking on the treadmill compared to overground (Arsenault, Winter, & Marteniuk, 1986). The respectively larger activations in hip extensors (ST) and hip flexors (RF) in early stance and early swing may at first appear surprising, given the similar hip kinematic profiles observed between the locomotor conditions, as well as the smaller step length observed during the treadmill walking condition. Also, ankle plantarflexor activation at push-off (MG) did not differ between conditions but the corresponding peak plantarflexion amplitude was smaller during treadmill walking. These apparent discrepancies may be explained by a possible co-contraction between the flexor and extensor muscles around the hip and ankle joints. In the present case, and although habituation trials were provided prior to data collection, walking on an omnidirectional treadmill was new to all participants. Past studies have reported enhanced levels of muscle co-contraction when participants are learning new skills (Ford, Van den Bogert, Myer, Shapiro, & Hewett, 2008; Heald, Franklin, & Wolpert, 2018; Vereijken, Emmerik, Whiting, & Newell, 1992). Enhanced levels of muscle co-contraction during gait are typically observed under challenging balance conditions (Asaka, Wang, Fukushima, & Latash, 2008; Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2004; Shiratori & Latash, 2000) and in situations requiring enhanced joint stability (Boudarham et al., 2016). In the present context, it may have served as a strategy to enhance leg stiffness and maximize balance during the treadmill condition. Alternatively, and as reported by Cappellini and colleagues for locomotion on a slippery surface, different muscle synergies may have emerged, reflecting the adoption of a new 'gait mode' as opposed to a mere adaptation for uncertain surface conditions (Cappellini et al., 2010). Lastly, it should be noted that during treadmill walking, participants in the present study were constrained to the treadmill ring, to which they did not hold on, and wore the treadmill harness that did not provide any body weight support. Both the ring and harness, while inherent to the treadmill design, possibly provided haptic feedback to participants while walking. Such haptic feedback, in return, may have provided a stabilizing effect and reduced muscle activation amplitudes in the lower limbs (Oates, Hauck, Moraes, & Sibley, 2017). If such effects of haptic feedback were present, however, it appears that they were not large enough to alleviate the larger levels of muscle activation amplitude observed during treadmill walking in the present study.

Omnidirectional treadmills are very promising since they allow not only changes in walking speed but also changes in walking trajectory. Coupled with VR technology, they can be used to train clinical populations on complex locomotor tasks as required for community ambulation. However, as the results suggest, there exist differences in gait while walking on the treadmill and overground. Further research is thus needed to see the impact of longer exposure on gait especially since gamers spend extended hours on it. The latter consideration is also important for rehabilitation to ensure an optimal transfer of training gains to situations of everyday life, and to avoid unwanted gait movements that would ultimately lead to pain and injury. Secondly, higher level of muscle activation observed in this study during treadmill walking could also result in higher energy consumption, which is consistent with the recent study done on other non-motorized low-cost omnidirectional treadmills (Jochymczyk-Woźniak, Nowakowska, Polechoński, Sładczyk, & Michnik, 2019).

3.5.1 LIMITATIONS

A sample of convenience of young participants who have no sensorimotor impairments were included in the study. While this age range is not representative of the population at large, especially those typically seen in a rehabilitation setting, studying young participants gave benefit of understanding the influence of the omnidirectional treadmill on gait adaptations in the absence of other factors such as older age or a pathology affecting gait. This age group also represents the main users of omnidirectional treadmills which are primarily designed for entertainment purposes (video gaming). The performance of participants in the VE may also be shaped by the type of hardware and software used in this experiment (e.g., HMD, omnidirectional treadmill, etc.), and thus limit the generalization of the findings to another type of VR set up. Finally, while the present manuscript focused on speed adaptations, it is understood that one of the main advantages of the omnidirectional treadmill is the fact that it allows for direction changes. Participants of this study also took part in an experiment on locomotor steering and results will be presented in a different manuscript.

3.6 CONCLUSION

The present study examined spatiotemporal parameters, body kinematics and lower limb muscle activation patterns while walking at different speeds on a non-motorized omnidirectional treadmill with and without VR vs. overground. Results show that participants achieved slower speeds and displayed differences in their walking pattern when ambulating on the omnidirectional treadmill compared to overground. Omnidirectional treadmill walking also yielded different walking adaptations in response to speed changes compared to overground walking. Alterations of the walking pattern observed on the omnidirectional treadmill are reminiscent of those observed when walking on surfaces providing reduced shear forces and conditions that impose a threat to postural stability. Furthermore, the addition of VR to treadmill walking induced limited differences, suggesting that the treadmill itself is the main contributing factor to those alterations.

Non-motorized omnidirectional treadmills, as the one examined in this study, were primarily designed for entertainment purposes. Nevertheless, such treadmills show promise for rehabilitation and research inquiries given that they allow changing the speed and direction of walking in a safe and controlled environment and within a confined space. Given the walking alterations revealed in the present study, however, further research is needed to determine the impact of a prolonged use of the treadmill on gait in order to ensure an optimal transfer of training gains to situations of everyday life, and to avoid unwanted gait patterns that could ultimately lead to pain and injury.

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Conflict of interest statement

All authors declare that they have no conflicts of interest.

Table 3-1. Participant characteristics

Participant number	Gender	Age (years)	Height (cm)	Weight (kg)	Hand dominance
1	Male	18	178	95	Right
2	Female	23	160	56	Right
3	Male	28	174	70	Right
4	Female	24	163	77	Right
5	Male	26	175	70	Right
6	Female	22	153	59	Right
7	Female	25	170	51	Right
8	Male	26	170	72	Right
9	Female	28	168	70	Right
10	Male	27	178	72	Right
11	Male	29	165	79	Right
12	Male	29	178	69	Right
Mean (± 1SD)		25.4 (3.3)	169.3 (8.0)	70 (11.5)	-

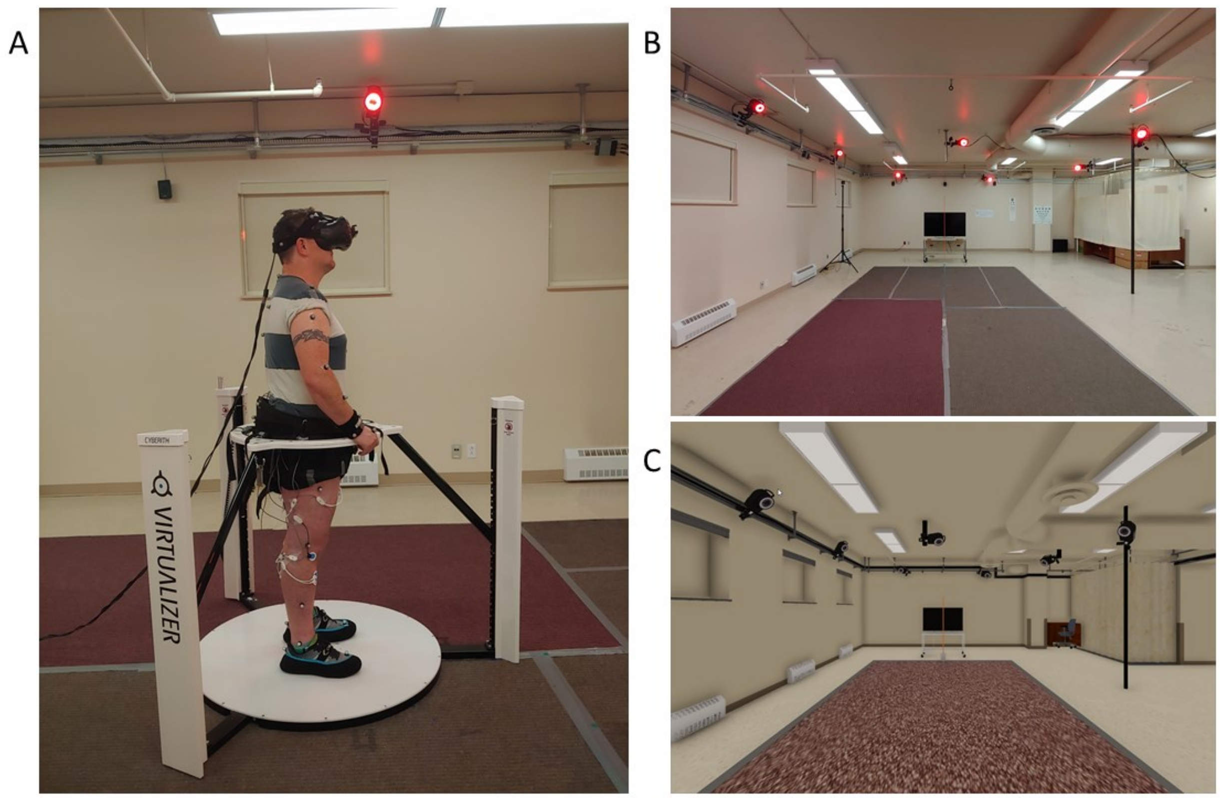

Figure 3-1. Omnidirectional treadmill with HTC Vive™ **(a)**. Environment as viewed from the start position of the participant overground **(b)**. Virtual environment as viewed in the HTC Vive™ **(c)**

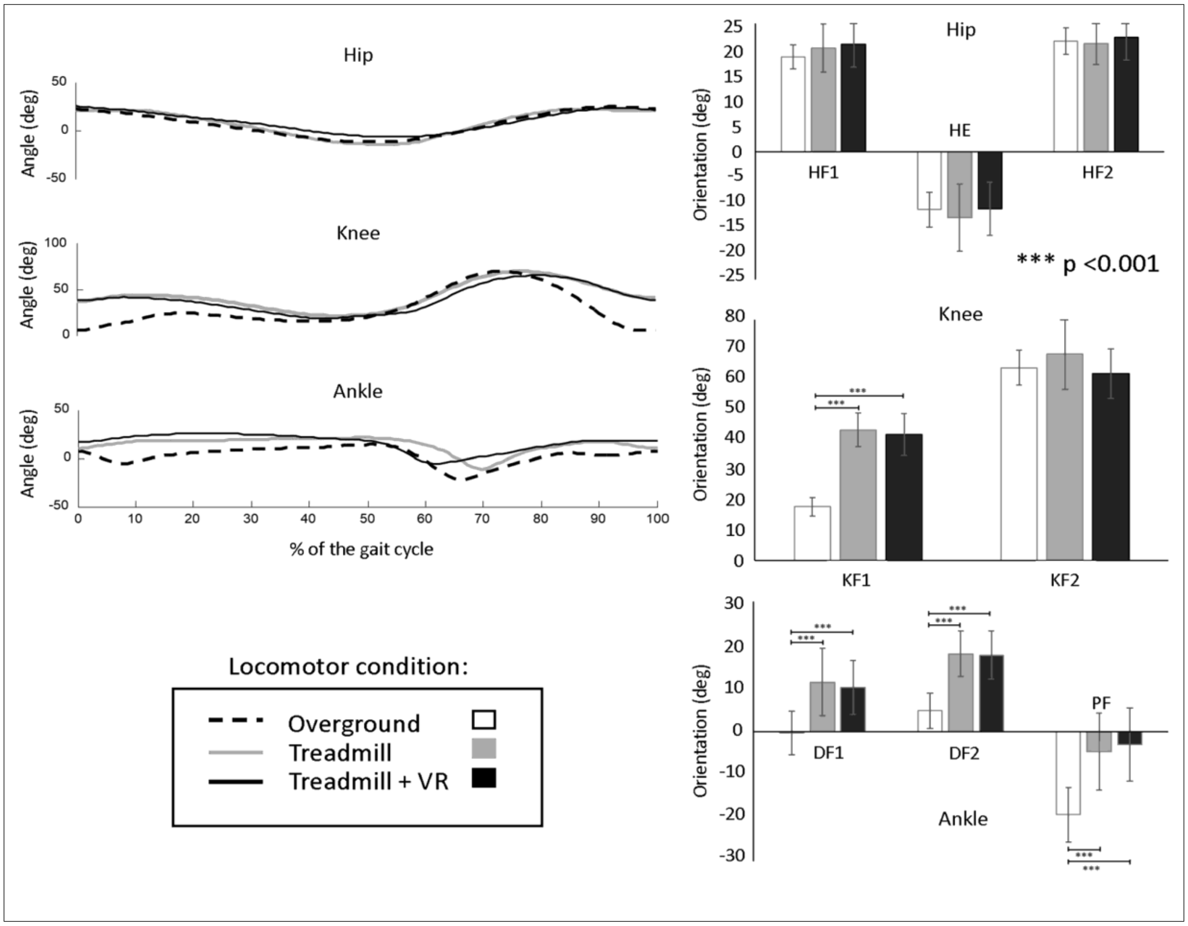

Figure 3-2. On the left: Hip, knee, and ankle joint orientation in the sagittal plane as a function of gait cycle in one representative participant. Note the similarities in the hip profile, whereas the knee and ankle joint presented differences which are further depicted in the bar graphs on the right. On the right: Mean values (± 1SD) for the sagittal orientation of hip, knee and ankle at specific times of the gait cycle. Values for the hip are peak hip flexion in early stance (HF1; [between 0 and 30% of gait cycle]), peak hip extension (HE; [40–70%]) and peak hip flexion during swing (HF2; [70–100%]). For the knee, maximal knee flexion during the stance phase [KF1; 0–40%] and the swing phase [KF2; 60–100%] are illustrated. For the ankle, values are peak dorsiflexion at heel strike (DF1; [0%]), peak dorsiflexion during mid stance (DF2; [20–60%]) and peak plantarflexion during late stance (PF; [60–80%]). Statistically significant main effects are indicated, as applicable. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.0001$

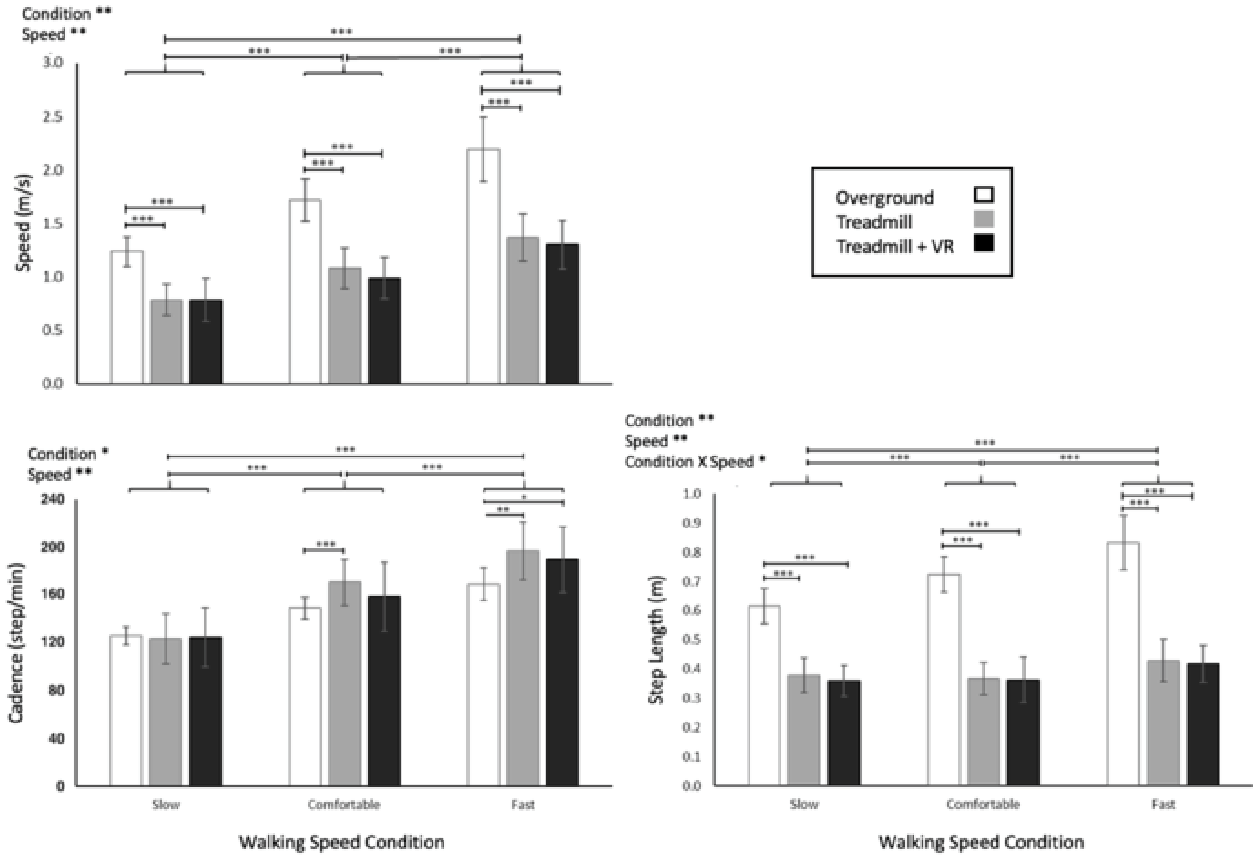

Figure 3-3. Average values (± 1SD) for gait speed, step length and cadence. Statistically significant main and interaction effects are indicated, as applicable. Likewise, post-hoc comparisons that were statistically significant are also illustrated.

*p < 0.05; **p < 0.01; ***p < 0.0001

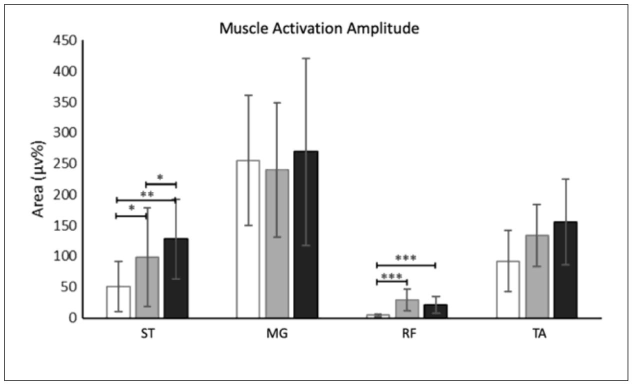

Figure 3-4. Average (± 1SD) muscle activation amplitudes recorded across locomotor conditions as participants are walking at matched speed. Activation amplitudes were calculated for the semitendinosus (ST) in early stance [0–30%], medial gastrocnemius (MG) at push-off [30–70%], rectus femoris (RF) at hip flexion burst at toe off [60–80%], tibialis anterior (TA) at toe-off [60%—80%]. Statistically significant differences are indicated, as applicable.

*p < 0.05; **p < 0.01; ***p < 0.0001

Table 3-2. Temporal distance factors while walking overground vs. on the treadmill with and without VR

Outcome measure	Overground	Treadmill	Treadmill + VR
Speed (m/s)	1.24 ± 0.14	1.37 ± 0.22	1.30 ± 0.23
Cadence (steps/min)	63.16 ± 3.86	98.49 ± 12.02***	95.04 ± 13.74***
Step length (m)	0.62 ± 0.006	0.43 ± 0.07***	0.42 ± 0.06***
Stance time (%)	51.56 ± 6.38	65.72 ± 2.42***	66.00 ± 2.47***
Swing time (%)	49.78 ± 8.02	34.67 ± 2.54***	34.48 ± 2.75***

***Level of significance $p<0.001$

CHAPTER 4: GENERAL DISCUSSION

4.1 DISCUSSION OF FINDINGS

Locomotion on foot is a fundamental aspect of our daily lives that can be compromised following a neurological insult or with older age. Conventional treadmills have been used for gait rehabilitation for decades and even though all the gains from treadmill training cannot be transferred to overground walking, numerous studies showed gait improvements following treadmill training. For instance, a systematic review done by Polese and colleagues (2013) concluded that treadmill training in individuals with stroke resulted in faster walking speeds and greater walking distances immediately after treadmill intervention compared to control group who did not train on the treadmill. Treadmill training with addition to VR also provides a safe environment to train individuals on more complex environmental tasks such as crossing the street.

“Low cost” omnidirectional treadmills, which are more commonly available now, show potential for training clinical populations on complex locomotor tasks required for community ambulation and which necessitate changes of speed and/or direction. The combination of an omnidirectional treadmill and VR allows for controlled, safe and repeated practice in virtual, ecological environments that are difficult to recreate in the laboratory or clinical settings. Whether such treadmills, with or without VR, yield walking patterns that resemble those observed in everyday life in the physical world, however, was unclear.

The overall purpose of this MSc thesis was to examine the disparities in walking patterns as individuals walk at different speeds on an omnidirectional treadmill with and without the immersive virtual reality experience (VR) vs. overground. By analyzing spatiotemporal factors of gait, lower limb kinematics and lower limb muscle activations, we aimed to gain an understanding of gait characteristics when walking on the omnidirectional treadmill, which is an essential step prior to using such technology as an assessment or training tool in rehabilitation. The study presented in this thesis focused on speed adaptations as a first step, with the longer-term objective of examining, in the future, adaptations to changes in walking trajectory (e.g., turning while walking).

Results of the study revealed that participants primarily increased their speed on the treadmill by increasing cadence with little to no changes in step length. This contrasts with overground walking, where both step length and cadence were increased when progressing from slow to comfortable to fast speed, aligning with previous studies. Additionally, due to shorter step length and despite of a higher cadence, participants achieved slower speeds on the treadmill compared to overground. Importantly, even once controlling for speed, those alterations in step length and cadence between treadmill vs overground walking persisted. This difference in walking strategy is a crucial consideration in the context of rehabilitation, where retraining gait patterns that match typical overground walking would be the ultimate objective.

Factors that could explain this slower walking speed include the unfamiliarity of participants with the treadmill, altered sensory feedback, and the design of the treadmill itself that comprises of a low friction walking surface. While individuals tested in the study were given a period of habituation to the treadmill, and although the study did not explicitly examine whether a longer habituation period would lead to walking speeds more comparable to overground walking, it is reasonable to hypothesize that extended exposure and practice could narrow this speed discrepancy, as individuals become more accustomed to the treadmill.

A significant reduction in late stance ankle plantarflexion on the treadmill vs. overground was also observed, along with a more pronounced knee flexion in mid-stance and ankle dorsiflexion in early and mid-stance, which is a typical crouched gait pattern (Steele et al., 2010). The shorter step length could be the result of a low friction between the foot and walking surface, which prevented participants from exerting a full ankle 'push off' in late stance, resulting in shorter step length. Previous studies examining locomotion on slippery or low friction surfaces observed similar reductions in step and/or stride length (Cappellini et al., 2010; Fong et al., 2005; Tsai & Powers, 2009) and gait speed (Tsai & Powers, 2009), as well as faster cadence (Cappellini et al., 2010). Similar modifications in joint kinematics were also reported, which altogether suggest that the observed gait adaptations to treadmill walking in the present thesis work aimed at preventing a slip (Fong et al., 2005). Accordingly, the crouched gait pattern that was observed may have served the purpose of lowering the height of the participants' CoM to counteract a perceived threat to balance (Alton et al., 1998).

Significantly higher amplitudes in muscle activation were also observed during treadmill vs. overground waking in most lower limb muscle groups examined in this study , which aligns with previous reports examining conventional treadmill walking (Arsenault et al., 1986). Results also revealed, however, that this enhanced muscle activation during treadmill walking was not necessarily associated with larger amplitudes of movement (e.g., hip flexion and extension, as well as ankle plantarflexion), and was further accompanied by smaller step lengths, which may at first appear surprising. The possibility of muscle co-contraction between the flexor and extensor muscles around the hip and ankle joints may explain these apparent discrepancies. Indeed, enhanced levels of muscle co-contraction were reported by others when performing an unfamiliar task (Ford et al., 2008; Heald et al., 2018; Vereijken et al., 1992), when walking under challenging balance conditions (Asaka et al., 2008; Krishnamoorthy et al., 2004; Shiratori & Latash, 2000) or when enhanced joint stability is required (Boudarham et al., 2016). In the present thesis work, the unfamiliarity with the treadmill walking task and the low friction walking surface would be factors that may have triggered muscle co-contraction.

The addition of VR technology to the omnidirectional treadmill provides visual motion information (optic flow) that we experience during overground walking. This otherwise would not be possible without VR as users are stepping on the spot on the treadmill. This optic flow, generated by the relative motion between participant's eye and the immediate surroundings (Pailhous et al., 1990), plays an important role in adjusting one's walking speed (A. Lamontagne et al., 2007; Prokop et al., 1997) and direction (Warren et al. 2001). However, it was found that adding VR to the treadmill did not significantly change the gait patterns. This suggests VR had a little impact on walking adaptation and treadmill itself was the primary factor affecting the changes that were observed in this thesis work.

4.2 SIGNIFICANCE AND FUTURE DIRECTIONS

Omnidirectional treadmills offer new possibilities for both gait retraining and entertainment. However, their impact on walking biomechanics requires careful consideration, especially if used for rehabilitation and/or prolonged periods. A first implication is that improvements in biomechanical adaptations observed on the omnidirectional treadmill, for instance in the context of gait retraining in a clinical population, may not directly translate to improvements in overground walking skills. Furthermore, the higher levels of muscle activation observed during treadmill walking may negatively impact user fatigue and energy consumption, particularly in populations with limited endurance. Given the observed changes in biomechanics and muscle activations when walking on the treadmill, one cannot rule out a potential risk of musculoskeletal injury with prolonged use in the context of rehabilitation or entertainment (e.g., gamers). This aspect warrants further investigation to ensure the safe and effective use of omnidirectional treadmills in rehabilitation.

This present research advanced our understanding of a ‘typical’ low-cost omnidirectional treadmill developed by the games industry on gait biomechanics. Findings also have practical implications in designing improved treadmill technologies for rehabilitation and entertainment purposes. Since the research study included in this thesis was published, the Virtualizer™ treadmill developed by Cyberith was modified and now includes a motion platform which actively tilts, creating an incline in the walking surface (i.e., backward tilt for forward walking and the opposite for walking backward), which according to the developers makes it easy walk and reduce physical effort when walking on the treadmill. While such claims would need to be confirmed, frequent modifications to the design of VR technologies in general are the norm rather than the exception. On the one hand, the resulting improvements enhance possibilities for researchers and other users, but the modifying a technology also poses the challenge of re-validating it before using it for research or clinical purposes.

This thesis work has a few limitations. Beyond the fact that the technology is constantly evolving, investigating how different age groups, fitness levels, and those with gait impairments adapt to the treadmill would extend the generalizing these findings to a larger population and would add further support the use of such tool in the clinical setting. Future studies could also examine whether a longer habituation period with the treadmill minimizes gait differences between treadmill and overground walking, as well as the impact of prolonged treadmill use on gait biomechanics, in order to optimize the transfer of training gains to situations of everyday life, and to avoid unwanted gait patterns that could ultimately lead to pain and injury.

4.3 CONCLUSIONS

To summarize, even though omnidirectional treadmill used in this research led to different gait biomechanics compared to overground walking, it sets the stage for future research to explore the full potential and limitations of these devices in various applications, ranging from clinical rehabilitation to entertainment and fitness. Omnidirectional treadmills, especially when integrated with VR, could be valuable tools for gait analysis and rehabilitation, providing users the options of changing the speed and direction of walking in safe and controlled environments that can mimic everyday life locomotor challenges. Present insights pave the way for future research and for the use of VR-based omnidirectional treadmills in gait rehabilitation.

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CONSENT FORM PARTICIPATING IN A RESEARCH PROJECT

1. Title of the Project

Characterization of walking adaptations on an omnidirectional treadmill

2. Investigators

Smit H. Soni (MSc candidate)
Rehabilitation Sciences
School of Physical and Occupational Therapy
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3. Introduction

We are asking you to participate in a research project involving the comparison of gait parameters of young healthy subjects walking overground and on an omnidirectional treadmill with and without virtual reality. Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks, and inconvenience as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you to ask any question that you deem useful to the researcher and the other members of the staff assigned to the research project and ask them to explain any word or information which is not clear to you.

4. DESCRIPTION OF THE STUDY AND ITS PURPOSE

Treadmills are widely used for gait retraining in rehabilitation setting. Their usefulness for training more complex locomotor tasks, however, remains limited given that they do not allow changing the speed nor the direction of walking. The latter walking adaptations are essential for efficient and safe community ambulation. These drawbacks can be addressed by using a self-pace omnidirectional treadmill, which allows both speed changes and direction change over 360^{O} while walking. This type of treadmill, however, is new and the extent to which it causes a walking pattern that is similar to overground walking remains to be determined.

This study will help appraise the impact of omnidirectional treadmills on locomotor movements and muscle activation patterns, which is an essential step before they can be used as an assessment or training tool in rehabilitation.

Objectives:

1. To estimate the extent to which the coordination of head, thorax, pelvis, and feet movements differ while walking and turning on the omnidirectional treadmill vs. overground
2. To compare spatiotemporal parameters, body kinematics and lower limb muscle activation while walking at different speeds on the omnidirectional treadmill vs. overground

5. NATURE OF YOUR PARTICIPATION

Your participation will consist of one evaluation session lasting for 3 hours. The session will comprise of a clinical evaluation to assess your eligibility for the study and your walking speed. This will be followed by the evaluation of your gait on the treadmill and overground. All the evaluation will take place at the Jewish Rehabilitation Hospital in Laval.

5.1 Clinical evaluation (20 minutes):

You will first be evaluated on your visual acuity (visual chart) and cognitive function (Montreal Cognitive Assessment) so that we can confirm your eligibility for this study. If you are eligible, we will then proceed with the evaluation of your walking speed (5m walk test). The results of the visual acuity test and cognitive test will be also communicated to you.

5.2 Walking evaluation (1h40 minutes):

Preparation (40 minutes):

Your height, weight and segment length and width will be measured. Small reflective markers (40) will be placed on different parts of your body (head, torso, arms, and legs) using hypoallergenic self-adhesive tape. Your movements based on these markers will be recorded by cameras as you walk. To record the activation of your muscles, the skin over 8 muscles of the legs (4 per leg) will be cleaned with alcohol and 2 self-adhesive electrodes will be attached over each site. In order to facilitate access to the leg muscles for the placement of the electrodes, we will ask you to wear shorts. Note that the small areas where the electrodes will be attached will also be shaved with a disposable razor if they are covered with hair. You will not experience any sensation during the recording of the EMG.

Evaluation (1 hour):

Three walking conditions will be assessed, in a random order: (1) walking on the treadmill with virtual reality (VR), (2) walking on the treadmill without VR and (3) walking overground without VR. As you will walk overground or on the treadmill, you will be instructed to change your direction of walking (left, right, straight ahead). Additionally, you will be asked to walk straight at different walking speeds (comfortable, fast, slow). The virtual environment, when present, will be displayed through a helmet mounted display placed on your head. The maximal distance of walking for each trial is 8m. Each walking condition will be repeated 4 times, for a total of 72 walking trials. In order to walk on the treadmill, we will provide you with slippers to put on your shoes.

You will be provided with the practice trials until you feel comfortable with the task. A member of the research team will stay next to you throughout the evaluation. You will also be provided rest periods as often as needed. You will be asked to fill up a presence questionnaire to provide your experience in VR after the end of the experiment.

Representation of a participant walking on the omnidirectional treadmill with the helmet mounted display for virtual reality

6. Benefits from your participation

This study does not provide you any direct benefit. However, the results from this study will provide information that will help identify the impact of omnidirectional treadmills on the locomotor pattern, which is an essential step before they can be used as an assessment or training tool in rehabilitation.

7. Risks and inconveniences associated with your participation

Risks:

Wearing the helmet mounted display while walking on the treadmill might cause disorientation and a loss of balance. The treadmill, however, is equipped with a harness and a safety system that will prevent any fall.

Inconveniences:

The travel time from your home to the research center and the 3-hour participation time may represent an inconvenience for some participants.

The walking activity during the evaluation may cause fatigue. Furthermore, the viewing of virtual reality images may cause dizziness. In such case, the fatigue and dizziness will disappear with rest periods.

The adhesive material of surface electrodes and reflective markers used in this study are hypoallergenic. The strictest hygiene (single-use electrode collars and razor, hypoallergenic tape, cleaning the skin with alcohol) will be implemented. However, despite the application of these sanitary measures, it could be that the skin where the markers / electrodes are placed gets irritated. In such cases, a soothing lotion will be applied on the skin.

8. Confidentiality

All personal information gathered about you during the study will be coded in order to ensure your confidentiality. Only the members of the research team will have access to this information. However, in order for monitoring purposes, your research records may be consulted by a person mandated by the Research Ethics Committee of CRIR or by an Ethics Unit of the Minister of Health and Social Services of Quebec, who adhere to a policy of strict confidentiality. This data (paper and electronic files) will be kept under lock and key at the Jewish Rehabilitation Hospital by the person in charge of this study for a period of five years following the end of the study, after which it will be destroyed. In the event that the results of this study are presented or published, no information that can identify me will be included.

9. Access to results of the study

At the end of the study, you may have access to the results of the study if desired. If you want us to send them to you, please indicate your email address.

EMAIL: ____

10. Voluntary participation and withdrawal

You are free to accept or refuse to participate in this research project. You can withdraw from the study at any time without giving any reason or being subjected to prejudice of any kind. You simply have to notify the contact person of the research team. In case of withdrawal from the study, all documents concerning your participation will be destroyed if that is your decision.

11. Future research study

It may be that the results obtained following this study result in another research study. In this case, do you accept to be contacted to participate in other scientific studies done in a similar area of research?

☐ No

☐ Yes, for one year *

☐ Yes, for two years*

☐ Yes, for three years*

* Note that if you select one of these three cases, your personal details will be kept by the principal investigator for the period to which you consent.

12. Financial compensation

Transportation and parking costs incurred through your participation in this project will be reimbursed, up to a maximum of $30 per total participation, upon presentation of receipts.

13. Responsibility clause

By agreeing to participate in this study, you do not give up any of your legal rights nor release the researchers or institutions involved of their legal and professional obligations.

14. Contact persons

If you have questions about the research project, if you wish to withdraw from the study or if you want to speak with the research team, please contact Anouk Lamontagne by telephone (450-688-9550 extension 531) or by email (Anouk.lamontagne@mcgill.ca).

If you have questions about your rights and recourse or your participation in this research project, you can contact Me Anik Nolet, coordinator of the Research Ethics Committee of CRIR establishments (Tel: (514) 527-9565 ext. 3597; email: anolet.crir@ssss.gouv.qc.ca). You can also contact Hélène Bousquet, local complaints commissioner of CISSS-Laval at 450-668-1010 ext. 23628 or by e-mail at: plaintes.csssl@ssss.gouv.qc.ca.

15. Consent

I state that I have read and understood this project, the nature and extent of my participation, as well as the benefits and risks/inconveniences to which I will be exposed as presented in this form. I have been given the opportunity to ask questions concerning any aspects of the study and have received answers to my satisfaction. A signed copy of this consent form will be given to me.

I, the undersigned, voluntarily agree to take part in this study. I can withdraw from the study at any time without prejudice of any kind. I certify that I have had sufficient time to consider my decision.

NAME OF PARTICIPANT SIGNATURE

______________________________ ______________________________

Signed at ________________, the ___________, 20_____

16. Commitment of researcher or representative

I, the undersigned ___________________________________, certify that I have

a) explained the terms of this form to the participant.
b) answered the questions regarding this research study.

c) explained clearly that he/she remains, at all times free to end his/her participation in the research project described above.

____

Signature of the Principal Investigator or representative

THE RESEARCHER PROVIDES A COPY OF THE SIGNED CONSENT FORM TO THE PARTCIPANT AND KEEPS ONE IN THE RESEARCH CHART.

FORMULAIRE DE CONSENTEMENT POUR LA PARTICIPATION À UN PROJET DE RECHERCHE

1. TITRE DU PROJET

Caractérisation des adaptations de la marche sur un tapis roulant omnidirectionnel

2. CHERCHEURS

Smit H. Soni (Candidat à la maîtrise)
Sciences de la Réadaptation
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Anouk Lamontagne, PhD, PT (Chercheuse)
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École de Physiothérapie et d'Ergothérapie
Université McGill
Hôpital Juif de Réadaptation (HJR) site du CRIR

3. INTRODUCTION

Nous vous demandons de participer à un projet de recherche visant la comparaison de paramètres de marche chez de jeunes participants en bonne santé, durant la marche au sol et sur un tapis roulant omnidirectionnel, avec et sans la réalité virtuelle. Avant de donner votre accord à participer à ce projet, veuillez prendre le temps de lire et de considérer attentivement les renseignements qui suivent.

Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et inconvénients, de même que les personnes à contacter en cas de besoin.

Ce formulaire de consentement pourrait contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et autres membres de l'équipe assignés au projet de recherche, et de leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair.

4. DESCRIPTION DE L'ÉTUDE ET DE SON OBJECTIF

Les tapis roulants sont largement utilisés en réadaptation pour l'entraînement à la marche. Cependant leur utilité pour l'entrainement à des tâches de marche plus complexes est limitée, compte tenu du fait qu'ils ne permettent pas de modifier la vitesse ou la direction de marche. Or, ces derniers paramètres d'adaptation sont essentiels pour un déplacement efficace et sécuritaire au sein de la communauté. Ces inconvénients peuvent être évités en utilisant un tapis roulant auto-rythmé et omnidirectionnel qui permet à la fois des changements de vitesse et de direction de plus de 360^{O} pendant la marche. Il est possible de remédier à ces inconvénients en utilisant un tapis roulant auto-rythmé et omnidirectionnel, qui permet à la fois des changements de vitesse et de direction de plus de 360^{O} pendant la marche. Toutefois, ce type de tapis roulant est nouveau et il reste à déterminer dans quelle mesure le patron de marche qu'il crée est similaire à celui de la marche au sol.

Cette étude aidera à évaluer l'impact de l'utilisation de tapis roulants omnidirectionnels sur les mouvements de marche et les patrons d'activation musculaire, ce qui est une étape essentielle avant qu'ils puissent être utilisés comme outils d'évaluation ou d'entrainement en réadaptation.

Objectifs :

1. Estimer dans quelle mesure la coordination des mouvements de la tête, du thorax, du bassin et des pieds diffère lors de la marche sur tapis roulant omnidirectionnel vs.la marche au sol;
2. Comparer les paramètres spatio-temporels, la cinématique du mouvement et l'activation des muscles des jambes lors de la marche à différentes vitesses sur un tapis roulant omnidirectionnel vs. la marche au sol.

5. NATURE DE VOTRE PARTICIPATION

Votre participation consistera en une session d'évaluation de 3 heures. Cette session comprendra une évaluation clinique pour déterminer votre éligibilité à l'étude et votre vitesse de marche. Elle sera suivie par une évaluation de votre patron de marche sur le tapis roulant et au sol. Toute l'évaluation aura lieu à l'Hôpital juif de réadaptation à Laval.

5.1 Évaluation clinique (20 minutes) :

Un membre de l'équipe de recherche évaluera d'abord votre acuité visuelle (échelle d'acuité visuelle) et vos fonctions cognitives (Évaluation cognitive de Montréal) afin de confirmer votre éligibilité pour cette étude. Si vous êtes éligible, nous procéderons alors à l'évaluation de votre vitesse de marche (test de 5 mètres de marche). Les résultats des tests d'acuité visuelle et des fonctions cognitives vous seront également communiqués.

5.2 Évaluation de la marche (1h40 minutes) :

Préparation (40 minutes):

Votre taille, votre poids et la longueur et largeur de certaines parties du corps seront mesurés. De petits marqueurs réfléchissants (40) seront placés à différents endroits de votre corps (tête, torse, bras et jambes) en utilisant du ruban auto-adhésif hypoallergénique. Vos mouvements, basés sur ces marqueurs, seront enregistrés par des caméras pendant que vous marcherez. Afin d'enregistrer l'activité de vos muscles, la peau au niveau de 8 muscles des jambes (4 muscles par jambe) sera nettoyée avec de l'alcool et 2 électrodes auto-adhésives seront placées sur chaque muscle. Afin de faciliter l'accès aux muscles des jambes pour la pose des électrodes nous vous demanderons de vous vêtir d'un short. Veuillez noter que la petite surface de peau sur laquelle les électrodes seront placées sera rasée avec un rasoir à usage unique si elle est recouverte par des poils. Vous ne ressentirez aucune sensation désagréable durant l'enregistrement de l'activité de vos muscles.

Évaluation (1 heure):

Trois conditions de marche seront évaluées, dans un ordre aléatoire : (1) marcher sur le tapis roulant avec la réalité virtuelle (RV), (2) marcher sur le tapis roulant sans la RV et (3) marcher au sol sans la RV. Pendant que vous marcherez au sol ou sur le tapis roulant, nous vous demanderons de changer votre direction de marche (gauche, droite, tout droit). Nous vous demanderons aussi de marcher en ligne droite à différentes vitesses (vitesse confortable, rapide, lente). L'environnement virtuel, lorsque présent, sera visualisé grâce à un casque de réalité virtuelle placé sur votre tête. La distance de marche maximale pour chaque essai sera de 8 mètres. Chaque condition de marche sera répétée 4 fois, pour un total de 72 essais de marche. Lors de la marche sur le tapis roulant, nous vous fourniront des pantoufles que vous aurez à enfiler par-dessus vos chaussures.

Vous aurez des essais de pratique jusqu'à ce que vous vous sentiez confortable avec la tâche. Un membre de l'équipe de recherche sera à côté de vous tout au long de l'évaluation. Vous pourrez également prendre des pauses aussi souvent que nécessaire.

Représentation d’un participant lors de la marche sur le tapis roulant omnidirectionnel avec le casque de réalité virtuelle

6. Bénéfices liés à votre participation

Vous ne retirerez personnellement aucun avantage à participer à cette étude. Cependant, les résultats de cette étude fourniront des informations qui pourront aider à identifier l’impact d’un tapis roulant omnidirectionnel sur le patron de marche. Ceci est une étape essentielle avant que ce type de tapis roulant puissent être utilisés comme outils d’évaluation et d’entrainement en réadaptation.

7. Risques et inconvénients associés à votre participation

Risques :

Le port du casque de réalité virtuelle sur le tapis roulant pourrait entrainer une désorientation et une perte d’équilibre. Cependant, le tapis roulant est équipé d’un harnais et d’un système de sécurité qui préviendront tout risque de chute.

Inconvénients :

Le temps de transport entre votre domicile et le centre de recherche ainsi que le temps de participation de 3 heures peuvent représenter des inconvénients pour certains participants.

L'activité de marche pendant l'évaluation peut causer une fatigue. De plus, le visionnement des images de réalité virtuelle peut causer des nausées. Si tel est le cas, cette fatigue et ces nausées se résorberont avec des périodes de repos.

Le matériel adhésif des électrodes et des marqueurs réfléchissants utilisés dans cette étude sont hypoallergéniques. L'hygiène la plus stricte (électrode et rasoir à usage unique, ruban hypoallergénique, nettoyage de la peau à l'alcool) sera appliquée. Cependant, malgré l'application de ces mesures d'hygiène, il est possible que la peau soit irritée à l'endroit où les marqueurs auront été placés. Dans de tels cas, une lotion calmante sera appliquée sur la peau.

8. CONFIDENTIALITÉ

Toutes les informations personnelles recueillies sur vous durant l'étude seront codées afin de garantir votre confidentialité. Seuls les membres de l'équipe de recherche auront accès à ces informations. Cependant, à des fins de surveillance, votre dossier de recherche pourra être consulté par une personne mandatée par le Comité d'Éthique de la Recherche du CRIR ou par une Unité d'Éthique du Ministère de la Santé et des Services Sociaux du Québec, qui adhère à une politique de stricte confidentialité. Ces données (fichiers papier et électronique) seront conservées sous clé à l'Hôpital juif de réadaptation par la personne en charge de l'étude pendant une durée de 5 ans suivant la fin de l'étude et seront détruites après cette période. Dans l'éventualité où les résultats de cette étude sont présentés ou publiés, aucune information ne permettant de vous identifier ne sera inclue.

9. ACCÈS AUX RÉSULTATS DE L'ÉTUDE

À la fin de l'étude, vous pourrez avoir accès aux résultats de l'étude. Si vous souhaitez les recevoir, merci de nous indiquer l'adresse courriel à laquelle nous pourrons vous les transmettre.

ADRESSE COURRIEL

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10. PARTICIPATION VOLONTAIRE ET DROIT DE RETRAIT

Vous êtes libre d'accepter ou de refuser de participer à ce projet de recherche. Vous pouvez vous retirer de l'étude à tout moment, sans avoir à donner de raisons et sans que cela n'entraine aucun préjudice à votre égard. Vous avez simplement à informer la personne contact au sein de l'équipe de recherche. En cas de retrait de l'étude, tous les documents concernant votre participation seront détruits si vous le décidez.

11. FUTURE ÉTUDE DE RECHERCHE

Il est possible que les résultats obtenus à la suite de cette étude donnent lieu à un autre projet de recherche. Dans ce cas, acceptez-vous d'être contacté pour participer à d'autres études scientifiques dans le même domaine de recherche?

☐ Non

☐ Oui, pour un an *

☐ Oui, pour deux ans*

☐ Oui, pour trois ans*

* Veuillez noter que si vous sélectionnez une de ces trois cases, vos coordonnées personnelles seront conservés par le chercheur principal durant la période pour laquelle vous aurez consenti.

12. COMPENSATION FINANCIÈRE

Les frais de transports et de stationnement occasionnés par votre participation à cette étude seront remboursés, jusqu'à un montant maximal de 30$ par participation et sur présentation des reçus.

13. CLAUSE DE RESPONSABILITÉ

En acceptant de participer à cette étude, vous ne renoncez à aucun de vos droits ni ne libérez les chercheurs, ou les établissements impliqués de leurs obligations juridiques et professionnelles.

14. PERSONNES À CONTACTER

Pour toutes questions à propos du projet de recherche, si vous souhaitez vous retirer de l'étude ou si vous désirez parler à un membre de l'équipe de recherche, merci de bien vouloir contacter Anouk Lamontagne par téléphone (450-688-9550 poste 531) ou par courriel (anouk.lamontagne@mcgill.ca).

Si vous avez des questions concernant vos droits et recours, ou votre participation à ce projet de recherche, vous pouvez contacter Me Anik Nolet, coordonnatrice du comité d'Éthique de la recherche des établissements du CRIR (Tel: (514) 527-9565 poste 3795; courriel: anolet.crir@ssss.gouv.qc.ca). Vous pouvez aussi contacter Hélène Bousquet, commissaire aux plaintes locales du CISSS de Laval au 450-668-1010 poste 23628 ou par courriel à : mailto: plaintes.csssl@ssss.gouv.qc.ca.

15. CONSENTEMENT

Je déclare avoir lu et compris ce projet, la nature et l'étendue de ma participation, de même que les bénéfices et risques/inconvénients auxquels je serai exposé, comme présenté dans ce formulaire. J'ai eu l'opportunité de poser des questions relatives à tous les aspects du projet et j'ai reçu des réponses satisfaisantes. Une copie signée de ce formulaire de consentement me sera remise.

Je, soussigné(e), accepte volontairement de participer à cette étude. Je peux retirer ma participation à n'importe quel moment sans préjudice d'aucune sorte. Je certifie avoir eu suffisamment de temps pour considérer ma décision.

NOM DU PARTICIPANT	SIGNATURE
______________________________	______________________________

Signé à ________________, le ___________, 20_____

16. ENGAGEMENT DU CHERCHEUR PRINCIPAL OU DE SON REPRÉSENTANT

Je, soussigné(e) ___________________________________, certifie que j'ai

d) expliqué les termes de ce formulaire au participant
e) répondu aux questions en lien avec ce projet de recherche
f) expliqué clairement qu'il/elle demeure libre en tout temps de mettre fin à son/sa participation au projet de recherche décrit ci-dessus

____
Signature du chercheur principal ou de son représentant

LE CHERCHEUR FOUNIT UNE COPIE DU FORMULAIRE DE CONSENTEMENT SIGNÉ AU PARTICIPANT ET CONSERVE UNE COPIE DANS LE CLASSEUR DE RECHERCHE.