TREADMILL AND OVERGROUND WALKING: THE EFFECTS OF SPEED ON GAIT OUTCOMES IN SUBJECTS WITH STROKE

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TABLE OF CONTENTS

PREFACE

Structure of Thesis

This is a manuscript-based thesis. A brief background and literature review is provided in the opening chapter pertaining mainly to (1) the gait deviations of the stroke subjects, and (2) the effects of treadmill ambulation in stroke and healthy individuals. Chapter 1 also includes the rationale for the study, with its specific objectives. Chapter 2 describes the methodology involved in this scientific inquiry, perhaps in greater detail than the following chapter. The sole manuscript is presented in Chapter 3, submitted to Archives of Physical Medicine and Rehabilitation. Finally, in Chapter 4, central findings of the study are interpreted, while concluding remarks and future directions are discussed.

Contribution of Authors

This study was conducted under the supervision of Dr. Lamontagne (primary supervisor) and Dr. Barbeau (co-supervisor), who contributed intellectually to the conception and design of the study, the analysis and interpretation of the results, and assisted endlessly in the revision of the manuscript. I, Roain Bayat, acted as the principal investigator, responsible for screening all patients at the JRH in order to determine their eligibility into the study, data collection and the subsequent analysis and written presentation of manuscript.

Acknowledgements

It is with great honor and pleasure that I put forth my associations and collaborations during this brief but remarkable academic voyage. First and foremost, I am forever grateful to my primary supervisor and mentor, Dr. Anouk Lamontagne. Her diligence in the process of scientific inquiry and brilliant nature served as a model to which I could measure my undertakings, and improve upon my shortcomings. Going beyond the call of duty, Dr. Lamontagne provided continual assistance in all matters pertaining to my research endeavors, including the revision of countless grant/scholarship applications. In addition, I would like to thank my secondary supervisor, Dr. Hugues Barbeau. His expertise and contribution to the project was greatly appreciated, and his caring nature as a leader was highly reassuring.

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Finally, the consistent encouragement and endless support received from my family, friends and colleagues instilled within me the desire and fervor needed in the completion of this journey. Many thanks to each and every one of you and God bless you all. But with the end of one journey begins the next, as I look forward to the new challenges life conceals, equipped with the newly acquired intellectual tools. If this holds true, then:

> "It is the mark of an educated mind to be able to entertain a thought without accepting it."
>
> Aristotle (384 BC - 322 BC)

Abstract

The gait pattern during treadmill walking is comparable with overground walking in healthy subjects, but the effects due to the mode of walking in stroke subjects have not been established. **Purpose:** (1) To compare the maximum gait speed of stroke subjects walking on treadmill vs. the ground. (2) To estimate the temporal-distance determinants of the maximal gait speed. (3) To compare temporal distance factors and body kinematics of stroke subjects walking at comfortable vs. maximum speeds during the two modes of locomotion. **Subjects:** Ten subjects (aged 63±19 years) with a hemiparesis due to a stroke (<3 months) were tested. **Methods:** Subjects walked at comfortable and maximal speeds on the treadmill and overground, and gait outcomes were thus compared. **Results:** Overground walking resulted in higher maximal speeds, greater stride lengths and a lower cadence, as compared to treadmill. The comfortable gait speed and the maximum stride length proved to be strong determinants for the maximal speed on both modes of locomotion, but the maximum cadence was correlated to maximum speed only overground. At matched speed, the hip and knee joint demonstrated greater excursion overground for both the paretic and nonparetic sides. **Conclusions:** Stroke subjects walked slower on the treadmill as compared to overground. Furthermore, a different strategy was implemented to increase gait speed on each surface. A guarded gait pattern was evident in the lower extremity kinematic patterns during treadmill ambulation, perhaps due to muscle weakness, reduced stability and fear of falling on the treadmill.

Abrégé

Le patron de marche sur le tapis roulant ressemble à celui observé au sol chez les sujets sains, mais les effets de ces modes de locomotion restent toujours inconnus chez les sujets ayant subi un accident vasculaire cérébral (AVC). **But:** (1) Comparer la vitesse de marche maximale sur tapis roulant et au sol chez des personnes qui ont subi un AVC. (2) Estimer les déterminants spatio-temporels de la vitesse de marche maximale. (3) Caractériser l'effet de la vitesse de marche (confortable vs rapide) et du mode locomoteur (au sol vs tapis roulant) sur la cinématique et les données spatio-temporelles des sujets ayant subi un AVC. **Sujets:** Dix sujets (âge : 63±19 ans) hémiparétiques ayant subi un AVC (< 3 mois). **Méthodologie:** Les données cinématiques et spatio-temporelles obtenues à différentes vitesses de marche ont été comparées sur le tapis roulant et au sol. **Résultats:** Comparativement au tapis roulant, la marche au sol a résulté en une vitesse de marche maximale plus rapide, de plus longs pas, de même qu'une cadence moins élevée. La vitesse comfortable et la grandeur de pas étaient toutes deux corrélées à la vitesse maximale sur les deux surfaces, alors que la cadence maximale l'était au sol seulement. À vitesse comparable, de plus grandes excursions de la hanche et du genou ont été observées au sol et ce, des côtés parétique et non-parétique. **Conclusions:** Les sujets hémiparétiques marchent plus lentement sur le tapis roulant. Ils utilisent des stratégies différentes sur les deux surfaces afin d'augmenter leurs vitesse de marche. La faiblesse musculaire, le manque d'équilibre et la peur peuvent expliquer les modifications observées sur le tapis roulant.

CHAPTER 1

BACKGROUND AND OBJECTIVES

Background

Overview of Stroke

Stroke refers to a disturbance in the blood flow of the brain resulting in a myriad of neurological sequelea. It is estimated that there are 4.5 million deaths a year from stroke in the world and over 9 million stroke survivors (Wolfe 2000). More striking, perhaps, are the estimates that by 2023 there will be an absolute increase in the number of patients experiencing a first stroke of about 30% compared to 1983 (Wolfe 2000). During acute hospitalization, 65% to 75% of stroke patients are incapable of walking independently (Wade, Wood et al. 1987; Jorgensen, Nakayama et al. 1995). While the most frequently stated functional goal of patients who have experienced a stroke is the restoration of the ability to walk (Waagfjord, Levangie et al. 1990), many stroke subjects are unable to assume their role as a community ambulator (Shumway-Cook and Woollacott 2001) due to chronic motor impairments (i.e. decrease muscle coordination, weakness, and spasticity).

Characteristics of Stroke Gait Pattern

First and foremost, walking after stroke is characterized by a decreased walking velocity, compared with age-matched controls (Titianova and Tarkka 1995; Turnbull, Charteris et al. 1995). The speeds vary from 0.23 m/s to 0.73 m/s (von Schroeder, Coutts et al. 1995), enormously deficient from the 1.33 m/s necessary for a "community ambulator" classification (Shumway-Cook and Woollacott 2001). Furthermore, due to comorbid cardiovascular disorders, the energy cost during locomotion in patients with hemipareis is higher than in able-bodied persons walking at the same velocity (Corcoran, Jebsen et al. 1970; Zamparo, Francescato et al. 1995). The endurance capabilities of stroke patients has been reported to be merely 49.8% of the healthy controls, as measured during a standard 6-minute walk test (Dean, Richards et al. 2001).

An asymmetry in terms of spatio-temporal parameters of the stride is prevalent, as demonstrated by a stance phase that is both longer and occupies a greater proportion of the gait cycle on the nonparetic side than the paretic side (Mischner-Ravensberb, Bergkamp et al. 1985; Nakamura, Handa et al. 1988). There is more variability as shown by a larger coefficient of variation for swing and stance time than healthy subjects. Stroke patients also walk with a shorter paretic stance and heel-strike duration, a longer swing duration (Lehmann, Condon et al. 1987). Finally, the movements of their lower body (Olney and Richards 1996) and upper body (Wagenaar and Beek 1992; Donker, Beek et al. 2001; Lamontagne, De Serres et al. 2003) are both disrupted during walking.

Determinants of Walking Speed

It has clearly been established in the literature that gait speed is a good indicator of the overall gait pattern and disability (Wade, Wood et al. 1987; Wagenaar and Beek 1992; Richards, Moulain et al. 1995; Hassid, Dorian et al. 1997; Roth, Merbitz et al. 1997). In order to distinguish fast-walking from the slow stroke subjects, Olney et al. (1994) have identified some important characteristics. Variables correlating significantly with self-selected speed included the maximum hip extension angle and the maximum hip flexion moment on the paretic side, and maximum ankle and hip powers on both the paretic and nonparetic sides. Nadeau et al. (1999) have also confirmed the hip flexor moment on the paretic side to be a significant variable determining comfortable gait speeds.

Investigating the relative contribution of the hip and ankle mechanical power during walking in healthy and acute stroke patients, Richards et al. (2001) have reported a negative net work by the ankle for the paretic and nonparetic side. The relative contributions of the hip were larger however. An increase in the hip pull-off in early swing compensates for the decrease in ankle push-off in late stance, during stroke ambulation.

Concerned with the maximum walking speed (MWS), Suzuki et al. (1999) have found that after four weeks of gait training of chronic stroke subjects, the biomechanical determinant of MWS had changed from the postural control of weight-shifting from left to right to the muscle strength during knee extension on the affected side. Similar to the comfortable speed, hip flexor and ankle plantarflexor moments were also found to be important factors for MWS in chronic stroke patients (Nadeau, Arsenault et al. 1999).

Adaptation to Speed

Investigating the effects of various speeds (slow, comfortable, fast) on gait parameters of normal subjects on the treadmill and overground (on the ground), Murray et al. (1984; 1985) have published rather interesting findings. Beginning with overground walking in normal individuals, speed related differences were found in the stride dimensions, temporal components and most of the simultaneous displacement patterns of body segments. As speed was increased from a slow to a faster speed overground, there was a significant increase in the vertical and lateral excursion of the head, the hip flexion-extension angle, ankle dorsiflexion angle, and the maximum heel elevation.

An earlier study reported that the forward speed of normal subjects increased by 45% when going from a “free” speed to a “fast” speed (Murray, Kory et al. 1966). A greater step length seen with faster walking was achieved by appropriate increases in the magnitude of certain excursions of the trunk and extremities, including: an increase of the hip flexion of the forward reaching extremity coupled with an increase of ankle extension of the rear extremity, an increase in forward inclination of the trunk, and marked increase in transverse rotation of the pelvis.

Although Bohannon (1992) has reported a gait speed increase of 48% as subjects switch from a comfortable to a maximum speed trial, there exists a lack of studies investigating the adaptation to speed in stroke subjects relating to temporal-distance parameters and kinematics,

Adaptation to Mode of Locomotion

According to Murray et al. (1984) across various speeds, normal subjects demonstrate shorter step lengths, faster cadence (steps/minute), shorter swing phase and longer double-support periods on the treadmill than on the floor. Stolze et al. (1997) have confirmed the above findings, and have reported an increase of

4% in the stride length and 6% increase in cadence when walking on the treadmill with the same walking speed as overground. Brandell and Williams (1974) on the other hand have found that although the stride length and velocity tended to be greater for a given cadence on the floor than on the treadmill, no statistically significant differences were found in normal individuals.

The adaptation to the treadmill in normal subjects has been assessed by comparing the gait parameters obtained after 5 and 10 minutes of treadmill walking. There were only minor adaptive changes of the step length between these two trials (Stolze, Kuhtz-Buschbeck et al. 1997). No published study has yet investigated the adaptation to the mode of locomotion in stroke subjects.

Gait Rehabilitation

Rehabilitation programs have endeavored to improve many of the gait deviations that predispose stroke patients to an increased risk of falls (Wolfson, Judge et al. 1995), poor endurance (Corcoran, Jebsen et al. 1970; Gersten and Orr 1971; Wolfson, Judge et al. 1995) and loss of functional independence. Physical therapists have rendered specialized training to develop functional walking speeds which could allow stroke patients to assume the role of household and community ambulators. Traditionally, principles of proprioceptive neuromuscular facilitation (PNF) and neurodevelopmental approaches have been utilized (Wang 1994; Lennon 2001) to achieve this desired goal. These treatments involve retraining gait, a dynamic locomotor task, under quasi-static conditions.

Emerging new neurorehabilitation concepts of motor learning, however, have supported the importance of the specificity of training, repetition, intensity and feedback to gait improvements (Carr and Sheppard 1987; Duncan and Badke 1987; Lister 1991; Richards, Malouin et al. 1993). While the use of a treadmill is standard in the rehabilitation of individuals with cardiac and pulmonary deficiencies (Nieuwland, Berkhuysen et al. 1998) to increase both strength and endurance, the potential benefits of treadmill gait training for the neurologically impaired has received growing attention in the past decade by investigators across continents.

Treadmill and overground ambulation do exhibit a notable biomechanical difference. Previous research has shown that the swing phase of gait (refer to Appendix I), in normal individuals walking on the ground, is reactive to the forward transfer of weight. On the treadmill however, this swing phase becomes an active lifting of the leg (Perry 1992).

In general, however, walking on the treadmill does not significantly alter the act of walking as it occurs overground. Several authors have reported that lower extremity electromyography activity (pattern of muscular contractions) (Murray, Spurr et al. 1985; Arsenault, Winter et al. 1986) and kinematics (joint positions and displacements) (Murray, Kory et al. 1966) did not markedly differ between treadmill and floor walking in normal subjects. The treadmill has thus been regarded as a valid instrument to study gait.

Treadmill Training

Offering a moving surface, the treadmill renders dynamic gait training for hemiparetic patients, with the added benefit of repetitive and rhythmic stepping. The effects ultimately lead to improvements of walking speeds on the ground, albeit with an incomplete transfer. In a study by Laufer et al. (2001), treadmill gait training for hemiparetic patients yielded a 135% increase in overground gait speed from an initial speed of 0.20 m/s to a final speed of 0.47 m/s. The control group, receiving overground ambulation training, improved 83% in their gait speed during the three weeks of training.

Although Laufer et al.(2001) have shown the feasibility of treadmill training without the use of a weight support apparatus, many researchers have focused on treadmill training with body weight support (BWS) in an effort to decrease weight bearing in hemiparetic subjects (Finch, Barbeau et al. 1991; Norman, Pepin et al. 1995; Hassid, Dorian et al. 1997; Hesse, Helm et al. 1997; Visintin, Barbeau et al. 1998; Hesse, Konrad et al. 1999; Danielson A 2000; Miyai, Fujimoto et al. 2000; Schindl, Forstner et al. 2000; Nilson, Carlsson et al. 2001). Incorporating an overhead harness, the BWS apparatus is designed to unload a percentage of the weight borne by the lower extremities during ambulation on a treadmill or on the ground (Fung, Barbeau et al. 1999; Miller, Quinn et al. 2002).

Recently, the effectiveness of treadmill training with and without BWS for improving walking speed has been proposed. A randomized clinical trial by Visintin et al.(1998) on the effects of BWS treadmill training vs. treadmill training full weight bearing (FWB) yielded a statistically significant increase in overground gait speed in the BWS group. Clinically however, the overground speed of 0.34 m/s at 6 weeks and 0.52 m/s at 3 months in the BWS group is quite distant from the functional speed of 1.33 m/s required to cross a street within the allotted time (Bohannon 1997). This evidence of a functionally low overground walking speed as been confirmed in another randomized trial (Nilson, Carlsson et al. 2001) in which stroke patients (3 weeks post affliction) received 10 weeks of gait training with treadmill BWS and demonstrated an overground speed of 0.80 m/s.

Through post-hoc analysis of the gait speed results of the Visintin et al. (1998) study, it has become apparent that there is an incomplete transfer of gait speed on the treadmill to overground speed following training on a treadmill FWB and with BWS (see fig. 1) (Barbeau and Visintin 2003). As depicted by the figures, a greater change in gait speed occurs on the treadmill compared to overground. The issue of an incomplete transfer of gait speed on the treadmill to overground speed following training on a treadmill full weight bearing, and with BWS has been briefly discussed by Barbeau et al. (2003). Contrary to these findings however, Hesse et al. (1999) have shown that treadmill testing with a lack of training period has rendered a slower gait speed on the treadmill, when compared to overground. It is thus unclear whether walking speeds will be faster or slower on the treadmill when compared to the overground condition.

In situations where higher walking speeds are demanded (e.g. at an intersection), stroke patients must fittingly adjust their speed. In keeping with the principles of task-specific training, Dobkin (1999) puts forth the argument that treadmill training should reproduce the velocities associated with successful home and community ambulation. A randomized clinical trial (Pohl, Mehrholz et al. 2002), recently conducted in Germany, has shown the benefits of treadmill training with aggressive stepwise increases in speed as compared to conventional gait training in stroke patients. Overground walking speed was significantly increased in the group trained at progressively faster speeds. The effect of fast walking on the gait pattern of the stroke subject, however, is unknown.

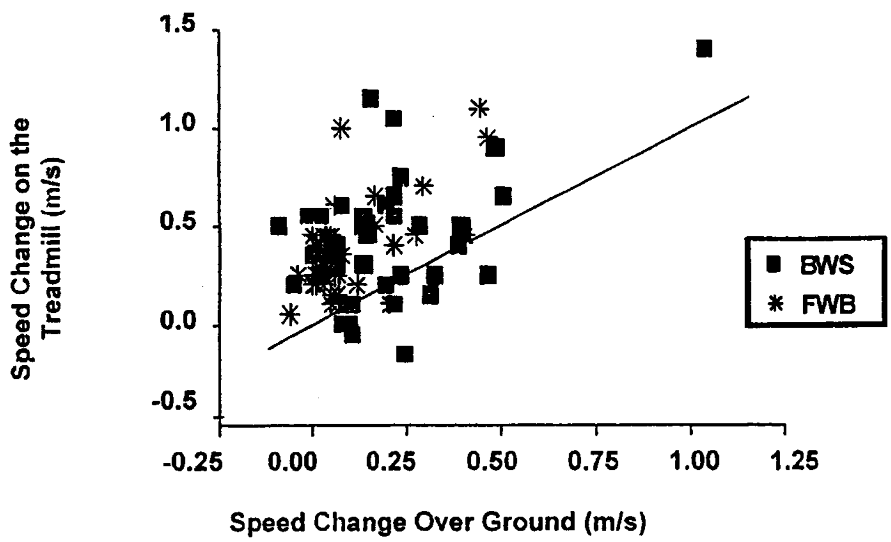

Figure 1: Scatterplots of the walking speed change on the treadmill in relation to the walking speed change overground, with locomotor training at full weight bearing (FWB) and body weight support (BWS). For each subject, a ■ and * has been plotted, depending on the weight support. When trained on the treadmill, stroke subjects demonstrate greater changes in speed on the treadmill than on the ground (Barbeau, Lamontagne et al. 2003).

Rationale for the Present Study

Post-hoc analysis of the gait speed results of the Visintin et al. (1998) study highlights the issue of an incomplete transfer of gait speed on the treadmill to overground speed following training on a treadmill FWB and with BWS. This failure of a complete carry-over effect of gait speed on the treadmill to overground is contradictory to another study (Hesse, Konrad et al. 1999) reporting higher gait velocities overground, with an absence of formal treadmill training. Further investigation of the gait performance under these two different conditions, beginning with the maximal speed attainable on each surface, is thus necessary. Furthermore, the temporal-distance determinants of maximal speed on the two modes (i.e. treadmill and overground), as well as the stepping strategies used to modify gait speed may also assist in efforts to comprehend the fundamental differences between overground and treadmill walking.

In stroke patients, several authors (Waagfjord, Levangie et al. 1990; Laufer, Dickstein et al. 2001) have reported favorable effects of treadmill training (without BWS) on temporal-distance factors (parameters of the gait cycle). Currently missing from the literature, nonetheless, is the manner in which the gait parameters and its kinematics are modified in stroke patients with a change in speed on the treadmill as compared to overground walking.

Evidence now exists for the improvement of overground walking speed with treadmill training conducted at progressively faster speeds (Pohl, Mehrholz et al. 2002; Sullivan, Knowlton et al. 2002). Nevertheless, most investigators have not trained patients at more functional speeds using treadmill training (with or without BWS), perhaps for the fear that "unphysiological" walking patterns might become established (Davies 1999). Such assertions may stem from studies that report exacerbation of unwanted or abnormal muscle activity (Dimitrijevic and Nathan 1967; Corcos, Gottlieb et al. 1986; Knutsson, Martensson et al. 1997) with increased speeds. In view of this uncertainty, it is essential to ascertain the effects of speed upon kinematics and temporal-distance features of gait on the treadmill as compared to overground.

OBJECTIVE

The primary objective of this study was to compare the maximum gait speed of stroke subjects walking on the treadmill and overground. In addition, secondary objectives were to estimate the temporal-distance determinants of the maximal gait speed, and compare the lower limb, pelvis and trunk kinematics and temporal distance factors of stroke subjects walking at comfortable vs. maximum speeds during the two modes of locomotion.

RESEARCH HYPOTHESES

The primary hypothesis is that the maximal walking speed of the stroke subjects will be significantly larger overground, as compared to treadmill. Utilizing the safety harness to minimize apprehension of the patients under both conditions will ensure that this difference is not due to issues surrounding self-perceived safety of subjects.

Furthermore, it must be noted that walking speed on the treadmill is externally driven by a mechanical motor. This characteristic of the treadmill will allow for a more typical stepping pattern by preventing the subject from using compensatory strategies to achieve higher speeds, a situation that may occur overground. It is however predicted that smaller step lengths will be observed on the treadmill. Therefore, the secondary hypothesis is that within the realm of fast walking, smaller angular displacement of hip excursion will result on the treadmill, as compared to overground trials.

CHAPTER 2

METHODS AND PROCEDURES

Subjects

Ten subjects (6F/4M; mean age 63 ± 19 y.o.) with hemiparesis (7 left and 3 right sided) due to a first stroke were recruited from the patients admitted to the Jewish Rehabilitation Hospital—Laval, Canada, for physical rehabilitation. The duration of hemiparesis was greater than 2 weeks and ranged from 3 to 18 weeks (see Chap. 3, Table 1). In order for stroke subjects to perform the testing, a cut-off gait speed between 0.15 m/s and 0.77 m/s was required for eligibility. The lower cut-off speed was found to be the level that best discriminated between those who required long-term care and those who were more mobile(Friedman, Richmond et al. 1988). Furthermore, it has been noted in the literature that stoke patients with severe gait dysfunctions (overground speed less than 0.15 m/s) are unable to ambulate on the treadmill full weight bearing at comfortable speeds, even with the assistance of two therapists(Visintin, Barbeau et al. 1998).

Considering the higher margin of cut-off, McGinley (1991) has reported a gait speed of 0.77 m/s to be sufficient for crossing a typical signaled intersection. In view of this finding, all patients walking at speeds above 0.77 were not included. Therefore, the study included stroke patients with mild to moderate gait impairments. Additionally, in order to be eligible to enter the study, patients had to be afflicted with hemiparesis caused by a first right of left cerebrovascular accident (middle cerebral artery). This duration of hemiparesis had to be greater than 2 weeks but less than 5 months, and subjects had to possess the ability to walk without personal assistance, in the presence or absence of a walking aid.

Finally, a Timed Up and Go score of greater than 20 seconds was required, signaling mobility difficulties by the subject (Podsiadlo and Richardson 1991).

Patients with the following criteria were excluded:

1. Unstable heart disease: This information was obtained from the patient's chart, and included such afflictions as a recent myocardial infarction or unstable angina. This precaution was taken in order to prevent risk of injury during maximal treadmill speeds.
2. Ankle instability: This information was obtained from the treating physiotherapist, in order to prevent risk of injury during maximal treadmill speeds.
3. Orthopaedic problems/Rheumatologic conditions: reports in the literature attest to a decrease in gait speed and abnormal gait patterns with arthroplasty of joints in the lower extremities (Hilding, Ryd et al. 1999; Lee, Tsuchida et al. 1999; Perron, Malouin et al. 2000).
4. Severe cognitive deficits (Mini-mental score less than 21/30) (Folstein, Folstein et al. 1975), for reasons of efficiency and feasibility.
5. Unable to comprehend English or French, for reason of feasibility to complete the study in a reasonable time.
6. A cerebrovascular accident with cerebellar or brainstem lesions.
7. Previous stroke or a history of other neurologic conditions.

Eligible subjects (see Appendix II) were approached by the primary investigator (Roain Bayat) and written consent obtained prior to participation (see

Appendix III). The protocol for this study was reviewed and approved by the Ethics Committee at the Jewish Rehabilitation Hospital in August 2003 (Appendix IV). In addition, five healthy age-matched controls (27 yrs to 83 yrs) were tested in order to establish comparative data pertaining to the gait speed transfer between the two modes of locomotion, as well as for some baseline kinematic variables (see Chap. 3, Table 1).

Sample Size

The primary outcome used for sample size calculation was the gait speed of the stroke patients, as measured during the two modes of locomotion (i.e. treadmill and overground). A difference of 0.15m/s may be viewed as clinically significant in this variable. The variability of overground gait speed was obtained from the study by Laufer et al.[37], rendering a standard deviation of 0.12m/s. The resulting sample size calculation, allowing for 95% power and an alpha = 0.05 yielded a final number of 10 subjects for the study.

Study Procedures

Upon arrival of the subject to the gait laboratory, one hour was needed for preparation, followed by one hour of testing. The hour of preparation consisted of two distinct components. Firstly, subjects walked on the Landice L8 Pro Trainer treadmill (Landice Inc, Randolph, NJ, U.S.A) at a "comfortable" pace to factor out the novelty of walking on a constantly moving surface. Gait parameters may be greatly affected when an individual is tested on the treadmill for the first time, thus measurements were taken when the subject had habituated. Although research by Wall et al.(1980) has shown 10 minutes of treadmill walking to be insufficient for habituation to occur in normal subjects, a maximum of 5 minutes was used for the stroke subjects to minimize fatigue. However, the stroke subjects were provided with a 10 minute bout of treadmill training, one day prior to testing. Rest periods were incorporated and allotted according to individual needs.

Next, markers were placed on the body of the subject which enabled acquisition of the data. Had the subjects completed the four walking tasks in a set order, fatigue may have settled, which may have been reflected in a poor walking quality in the trials closer to the end. In order to avoid this bias, the subjects were randomized to the walking trials (the treadmill or overground, as well as the speed with which they walk), thus ensuring that the order of exposure does not play a role in determining gait features.

The use of standardized instructions was employed to obtain both a comfortable and maximum walking speed from the subjects, in order to eliminate potential bias. During comfortable walking trials, subjects were instructed to "walk at the speed you feel most comfortable, as if you were out taking a stroll." Likewise, for the maximum walking trials, subjects were instructed to "walk at your fastest speed, as if you are in a hurry to get somewhere".

A safety harness was used to minimize risk of falls throughout the experiment. Inconsistent use of this apparatus (i.e. harness used solely on the treadmill) may lead to source of bias, since the subject's perceived safety may affect walking quality. Consequently, the safety harness was implemented under both walking surfaces: treadmill and overground, in an effort to eliminate this potential bias. On the ground, the safety harness was assembled in a trolley that slides at low friction, in both directions, on a metal channel bolted to the ceiling over the 7-m walkway (see Appendix V).

According to Wall et al (1980)., there is an initial accommodation to the treadmill which is characterized by a tripping/balance regaining gait. This accommodation takes place most rapidly in the first ten seconds of exposure to the new modality. Consequently, during treadmill walking, the subjects were required to take 10 consecutive steps, which attenuated the initial accommodation to treadmill.

Considering the nature of the walking surfaces to which subjects were exposed in this study (i.e. moving vs. stationary), a walking aid would have undoubtedly helped the patient differentially across these exposures. Gait outcomes would have been affected with the use of a walking aid, characterized by decrease in single support time and an increase in double support time (Chen, Chen et al. 2001). Therefore, subjects were prevented from using their walking aid during experimental testing. Furthermore, the use of the side-rails (parallel bars) for support was restricted on both the treadmill and during overground walking.

In order to find the "comfortable speed" of the subject on the treadmill, the belt speed was started with an initial speed of 0.15 m/s. Subsequent to giving the subjects the standardized instructions, a gradual increase by increments of 10% was executed in the speed until the subject stated: "ok, this is my most comfortable speed". At this point, the speed was increased by 5% and decreased by 5% and the subject was required to state the most "comfortable speed" (see Appendix VI). Once the speed was selected, a brief rest period was given, followed by the data collection trial.

The procedure for the "maximum speed" on the treadmill was conducted with great precautions. Firstly, the Borg Scale of the rating of perceived exertion (RPE) was introduced to the subjects (See Appendix VII). The measurement of RPE during short term exercise has been shown to be a reliable tool (Doherty, Smith et al. 2001). Since cardiac patients undergoing rehabilitation using treadmill are instructed to walk in the fairly light (numerical value of 11) and somewhat hard (numerical value of 15) (American College of Sports Medicine, 1991) all subjects participating in this experiment, who were free from heart disease (as per exclusion criteria) were instructed to walk within the "very hard" portion of the scale (numerical values of 17-18). Testing was stopped at the request of the subject or if the subject was deemed as being unable to maintain pace with the treadmill during the trial, such as the inability to recover from a missed step resulting in postural instability.

With regards to overground ambulation, subjects walked the 7-m walkway 3 times at the required speed, and the average was taken. As estimated from a published study (Nadeau, Arsenault et al. 1999), 4-6 complete gait cycles were captured.

Throughout the experiment, the heart rate of the stroke subjects was monitored. A sensor belt (Pulsar) was secured to the chest of the subject and the heart rate (bpm) was clear displayed. At all times during the experiment, the heart rate was maintained well below the 85% age adjusted maximal heart rate (i.e. 220-age) (American College of Sports Medicine, 1991).

Setting

The JRH is a 120 bed public rehabilitation hospital located in Laval, Quebec and affiliated with McGill University. More than 1100 patients are admitted and an equal number of patients receive outpatient services each year. On average, 254 patients are admitted each year for rehabilitation following a stroke. Testing took place in the Posture and Gait Laboratory of the JRH.

Data Acquisition

Kinematic data were acquired at 120 Hz using a Vicon-512™ motion analysis system with 6 high-resolution M-cameras. A 15-segment model was obtained from 37 reflective markers, based on the lower body marker set (PlugIn Gait) developed by Vicon. The lower body segments were defined by markers placed on the second metatarsal head of the toes, heels, lateral malleoli, mid-shanks, knee lateral condyles, mid-thighs, anterosuperior iliac spines, posterior superior iliac spines and sacrum. Markers placed on the acromio-humeral joints, sternal notch, xiophoid process and C7 vertebral process defined the thorax. The head comprised of 2 markers on the forehead, and 2 others on the occipital region. Finally, the arms consisted of markers placed on the mid-upper arm, lateral epicondyles, distal radius and ulna and the third metacarpal head (see Appendix VIII).

Data Analysis

The primary outcome measure for the study was gait speed. Secondary outcomes included the temporal-distance factors (cadence, step length, stride length, double support phase and stance phase durations), angular displacements of the lower limbs in the sagittal plane, as well as the displacement of the thorax and pelvis in both the horizontal and sagittal planes. Foot strike and foot-off events were identified using toe and heel trajectories along the direction of progression, which allowed later calculations of temporal distance factors and normalization of kinematic profiles to 100% of the gait cycle duration.

Attributed to a lack of forward progression with respect to space on the treadmill (secondary to the subject stepping in place), a special algorithm had to be developed to calculate stride and step lengths, as well as gait speed. Using the trajectories of the foot markers, the distance from push-off to foot-contact (swing phase) was added to the distance of the subsequent foot-contact to push-off (stance phase). Gait speed was then calculated by dividing this stride length over the cycle duration.

Three-dimensional angles were reconstructed for thorax and pelvis using global coordinates. Local angles were calculated for the hip, knee, and angle joints. The sign conventions were as follows: positive for any flexion, dorsiflexion and anterior rotation motion. In addition, a positive angle was designated for all horizontal plane thorax and pelvic rotations towards the paretic side in the hemiparetic subjects and rotations to the right side in the healthy subjects. The angles at critical gait events for the lower extremity (i.e. hip angle at push-off, knee angle during swing phase and ankle angle at heel strike) were averaged across subjects. Peak to peak angles were also computed for the lower extremity during each gait cycle, and averaged for all subjects. Pelvis and trunk maximum and minimum angle in the two planes (i.e. sagittal and horizontal) and the average orientation was then averaged across subjects. Note that all calculations were performed for every gait cycle, and then averaged for every subject.

Statistical Analysis

Comparison of gait speed between the mode (treadmill vs. overground) and the speed (comfortable vs. maximum) was performed using a 2-way analysis of variance (ANOVA) for repeated measures with speed (comfortable vs. maximum) and mode (treadmill vs. overground) as the two factors. An independent t-test was used to compare the stroke and healthy groups pertaining to the modification of speed (i.e. the absolute change from comfortable to maximum speed) on each walking surface. Associations between the maximum gait speed and three important parameters (i.e. comfortable gait speed, maximum cadence and maximum stride length) were identified using Pearson correlation coefficients. Finally, temporal-distance factors (see Table 1) and the kinematics of gait were compared by means of a 2-way analysis of variance (ANOVA) for repeated measures with speed (comfortable vs. maximum) and mode (treadmill vs. overground) as the two factors (see Appendix IX). For all statistical tests, significance was set at $\alpha = 0.05$. All statistical analyses were performed using Statistica 6.0.

Table 1: Gait Temporal-Distance Factors (also refer to Appendix I, fig. 2)

Parameters	**Definitions**
Cycle duration	Time from IC of one foot to IC of the same foot
Double support phase 1	Time from IC of first foot to TO of second foot
Double support phase 2	Time from IC of second foot to TO of first foot
Double support duration	Sum of double support phases 1 and 2
Single support duration	Time from TO of one foot to IC of the same foot
Left to right stance duration ratio	Time in stance on the left to that of stance on the right
Stride length	Distance from IC of one foot to IC of same foot
Speed	Stride length/cycle duration (m/s)

IC: initial contact TO: toe-off

Confounding Variables

Owing to the design of the study (within-subject), many of typical confounding variables described by Charlson et al. (1987) for stroke patients did not bias the results of this study. These variables included: age, sex, side of lesion, time since stroke, previous strokes, visuospatial neglect, comprehension and cognitive impairments, depression and other comorbidities. For reasons of feasibility, however, some of the aforementioned characteristics were addressed through the exclusion criteria.

Speed effect due to mode of locomotion: Inherent to the task of treadmill walking, subjects walked at a slower speed, in comparison to overground (see hypothesis), under both comfortable and maximum conditions. As such, part of the differences in the temporal-distance factors and kinematics of gait obtained during treadmill, as compared to overground walking, may well have been due to differences in gait speed. This potential bias was addressed in the data analysis section by using matched speeds for treadmill and overground walking. Thus, the results pertaining to the temporal-distance factors and kinematics of gait were adjusted accordingly.

Study Design

Hypothesis	*Independent Variable(s)*	*Dependent Variable(s)*	*Confounding*
Primary	Treadmill vs. Overground	Gait Speed	N/A
Secondary	a) TM vs. OG b) Comf. vs Max.	Temporal-distance factors	Gait Speed
	a) TM vs. OG b) Comf. vs Max.	Kinematics	Gait Speed

TM: Treadmill OG: Overground Comf./Max.: Comfortable/Maximum Speed

Potential risks to subjects

Individuals partaking in the study wore the safety harness at all times when ambulating. In addition, a licenses therapist remained close to patients during all testing, thus minimizing risk of falls, especially at faster speeds. Furthermore, heart rate was monitored and rest periods given to accommodate the stroke subjects while ambulating at faster speeds on the treadmill. Utilization of the Borg Scale prevented subjects from over-exerting themselves during the experiment. There was no pain associated with the placement of markers or any other procedure in this experiment.

CHAPTER 3

TREADMILL AND OVERGROUND WALKING:

THE EFFECTS OF GAIT SPEED ON GAIT OUTCOMES IN SUBJECTS WITH STROKE

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TREADMILL AND OVERGROUND WALKING: THE EFFECTS OF GAIT SPEED ON GAIT OUTCOMES IN SUBJECTS WITH STROKE

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Abstract

Objective: To compare the maximum gait speed of stroke subjects during unsupported locomotion on the treadmill and overground. Secondary objectives were to estimate the temporal-distance determinants of the maximal gait speed, and to compare temporal distance factors and body kinematics between the two modes of locomotion.

Design: Block-randomized, repeated-measures study

Settings: Gait and Posture laboratory at a rehabilitation hospital.

Participants: Ten individuals with hemiparetic gait deficits whose walking speeds ranged between 0.24 m/s and 0.82 m/s. Five healthy age-matched controls were tested in order to establish comparative data pertaining to the gait speed transfer between the two modes of locomotion, as well as for some baseline kinematic variables.

Intervention: Following a brief habituation process to the treadmill, subjects walked at comfortable and maximal speeds on the treadmill and overground, in a random order.

Main Outcome Measure: Self-selected comfortable and maximum gait speed. Body kinematics and temporal distance factors were acquired using a 6-camera Vicon™ motion analysis system and compared between treadmill and overground walking at a similar speed.

Results: Overground walking resulted in higher maximal speeds ($p<0.001$), greater stride lengths ($p<0.001$) and a lower cadence ($p<0.02$), as compared to treadmill. The comfortable gait speed and the maximum stride length proved to be strong determinants for the maximal speed on both modes of locomotion ($p < 0.01$), but the maximum cadence was correlated to maximum speed only overground ($p< 0.05$). At matched speed, the hip and knee joint demonstrated greater excursion overground for both the paretic ($p < 0.01$) and nonparetic sides ($p < 0.05$). The trunk remained in a more flexed position during treadmill walking than overground ($p < 0.001$).

Conclusions: Stroke subjects walked slower on the treadmill as compared to overground. They also used a different strategy to increase gait speed, relying mostly on the stride length during treadmill ambulation. An alteration of the lower extremity kinematic patterns was also evident during treadmill ambulation, perhaps due to muscle weakness, intersensory conflict, reduced stability and fear of falling on the treadmill.

Key words: rehabilitation, hemiparesis, treadmill, locomotion

It is estimated that there are 4.5 million deaths a year from stroke in the world and over 9 million stroke survivors [1]. Although most stroke subjects walk with reduced walking speeds and an asymmetrical gait pattern [2, 3], the most frequently stated functional goal of patients who have experienced a stroke is the restoration of the ability to walk [4].

Walking after stroke is characterized by a slow gait speed [5, 6], poor endurance [7, 8], altered movement patterns [9, 10, 11], and compromised balance [12, 13]. Current concepts of motor learning highlight the importance of early, intense and task-specific interventions in neurorehabilitation [14, 15, 16, 17]. Treadmill training, recognized as a task-oriented approach for gait rehabilitation in the stroke population, has received widespread attention in recent years. Offering a moving surface, the treadmill renders dynamic gait training for hemiparetic patients, with the added benefit of repetitive and rhythmic stepping. Combined with body weight support, it provides an opportunity for the retraining of gait in even the severely impaired stroke subjects, allowing for early and prompt intervention [18, 19, 20, 21]. During treadmill locomotion, the training intensity can be monitored and manipulated with relative ease within a confined environment, thus enabling for improvements in the walking speed [18, 22] and endurance [23, 24].

As compared to conventional overground walking training, treadmill training was shown to produce larger increases overground walking speeds and functional walking ability in stroke subjects [15, 22, 25]. Upon completion of a treadmill training regimen however, gait speeds attained during treadmill ambulation exceed those measured overground [18, 21, 22, 25], which may perhaps be attributed to the task-specificity of the training on the two distinct surfaces. In contrast, as reported by Hess et al. [26], stroke subjects undergoing minimal treadmill training achieved faster overground walking speeds than on the treadmill.

The null net progression of the body in space during treadmill walking induces conflicting vestibular, visual and proprioceptive information with respect to displacement. The ensuing conflict in sensory information, seemingly resolved by the healthy subjects, requires intact sensorimotor integration and may cause treadmill walking to be more challenging to balance than overground walking for stroke subjects. Nonetheless, this uncertainty prompts further investigation of the gait performance under these two different conditions, beginning with the maximal speed attainable on each surface. Furthermore, the stepping strategies used to modify gait speed may also assist in efforts to comprehend the fundamental differences between overground and treadmill locomotion.

The quality of the walking pattern is another key element guiding our training paradigms, which may markedly be influenced by the moving surface of the treadmill. In healthy subjects, patterns of lower limb muscle activation and of vertical ground reaction forces resemble between treadmill and overground walking [27, 28, 29], suggesting that treadmill ambulation does not significantly alter the act of walking as it occurs overground. However, temporal distance factors differ between the two modes, healthy subjects demonstrating shorter step lengths, faster cadence (steps/min), shorter swing phase and longer double-support periods on the treadmill than on the floor [30]. To our knowledge, the only study comparing treadmill and overground walking in stroke subjects merely reported an unchanged cadence and an 11% improvement in the stance-time symmetry on the treadmill compared with overground at matched speeds. [31].

It must be noted that all studies pertaining to stroke treadmill ambulation test or train hemiparetic subjects with some postural support via partial body weight support, handrail support, therapist support, or a non-weight bearing safety harness. This usual practice is appropriate in cases where the interest merely lies in investigating clinical endpoints such as gait speed, endurance, and balance. If however, specific gait outcomes are sought and compared between the two modes of locomotion (i.e. overground vs. treadmill), a confounding variable emerges when subjects use external supports at their volition.

The primary objective of this study was to compare the maximum gait speed of stroke subjects walking on the treadmill and overground, during unsupported ambulation. A safety harness was used under both conditions in order to minimize perceived apprehension of the subjects. In addition, secondary objectives were to estimate the temporal-distance determinants of the maximal gait speed, and compare the lower limb, pelvis and trunk kinematics and temporal distance factors of stroke subjects walking at similar speeds.

The primary hypothesis contends the maximal walking speed of the stroke subjects to be significantly larger on the overground, as compared to treadmill. Moreover, within the realm of fast walking, it is projected that smaller angular displacements of hip excursion will result on the treadmill, mainly due to smaller step lengths, as compared to overground trials.

Methods

Subjects

Ten subjects (6F/4M; mean age 63 ± 19 y.o.) with hemiparesis (7 left and 3 right sided) due to a first stroke were recruited from the patients admitted to the Jewish Rehabilitation Hospital—Laval, Canada, for physical rehabilitation. The duration of hemiparesis was greater than 2 weeks and ranged from 3 to 18 weeks (Table 1). In order for stroke subjects to perform the testing, a cut-off gait speed between 0.15 m/s and 1.30 m/s was required for eligibility, as subjects above this range are deemed community ambulators [32]. Therefore, the study included stroke patients with mild to moderate gait impairments, and all subjects possessed the ability to walk without personal assistance, in the presence or absence of a walking aid. Finally, a Timed Up and Go score of greater than 20 seconds was required, signaling mobility difficulties by the subject [32].

Patients with the following criteria were excluded: unstable heart disease, ankle instability, orthopedic or rheumatologic conditions interfering with locomotion, severe cognitive deficits (Mini-mental score less than 21/30), a cerebrovascular accident with cerebellar or brainstem involvement, a previous stroke or a history of other neurologic conditions.

The protocol for this study was reviewed and approved by the Ethics Committee at the Jewish Rehabilitation Hospital. In addition, five healthy age-matched controls (27 yrs to 83 yrs) were tested in order to establish comparative data pertaining to the gait speed transfer between the two modes of locomotion, as well as for some baseline kinematic variables.

Experimental Procedures

Subjects were randomly assigned and instructed to walk at either a comfortable or maximal speeds on either the treadmill (Landice L8 Pro Trainer, Landice Inc, Randolph, NJ, U.S.A) or overground. No external aids such as walking aids or side-rails were used during the experimental session.

Before testing began, all subjects (i.e. stroke and healthy) received five minutes of habituation to the treadmill. In addition, they were provided with a 10-minute bout of treadmill training, one day prior to testing. Thus, a total of 15 minutes of habituation to the treadmill was provided, over a two-day period. Intervals of rest were incorporated and allotted according to individual needs. Acclimatization to the treadmill has shown to be an important prerequisite to any treadmill testing or training [33].

Throughout testing, heart rate of the subjects was monitored. A sensor belt (Pulsar) was secured to the chest of the subject and the heart rate (bpm) was clearly displayed. At all times during the experiment, the heart rate was maintained well below the 85% age adjusted maximal heart rate (i.e. 220-age)[34]. Furthermore, subjects also wore a safety harness during both modes of locomotion, and encouraged to test the limits of the harness prior to the start of the experiment. On the ground, the safety harness was assembled in a trolley that slid at low friction, in both directions, on a metal channel bolted to the ceiling over a 7-m walkway.

In order to determine the "comfortable speed" of the subject on the treadmill, the belt speed was initiated at a speed of 0.15 m/s. A gradual increase by increments of 10% was then executed in the new velocity until the subject stated: "ok, this is my most comfortable speed". At this point, the speed was increased by 5% and decreased by 5% and the subject was required to state the most "comfortable speed". Once the speed was selected, a brief rest period was given, followed by the data collection trial. Approximately twenty seconds of ambulation was required on the treadmill, rendering a minimum of 10 gait cycles for analysis. While the same procedure was followed for the healthy controls, the incremental speed increases occurred at a much faster rate until reaching their desired "comfortable speed".

The procedure for the "maximum speed" on the treadmill was conducted in a similar manner, in addition to the Borg Scale of the rating of perceived exertion (RPE) being implemented for safety purposes. Subjects were instructed to walk within the "very hard" portion of the scale (numerical values of 17-18). Testing was stopped at the request of the subject or if the subject was deemed as being unable to maintain pace with the treadmill during the trial, such as the inability to recover from a missed step resulting in postural instability. A licensed physiotherapist remained on guard in close proximity to all subjects while ambulating on the treadmill.

With regards to overground ambulation, subjects walked the 7-m walkway 3 times at the required speed, while 4-6 complete gait cycles were captured per trial. One healthy control subject was asked to walk at "one-third" his/her comfortable speed on both modes of locomotion, in order to match more closely the speed of the stroke group.

Data Acquisition

Kinematic data were acquired at 120 Hz using a Vicon-512™ motion analysis system with 6 high-resolution M-camera sampling. A 15 -segment model was obtained from 37 reflective markers, based on the lower body marker set (PlugIn Gait) developed by Vicon. The lower body segments were defined by markers placed on the second metatarsal head of the toes, heels, lateral malleoli, mid-shanks, knee lateral condyles, mid-thighs, anterosuperior iliac spines, posterior superior iliac spines and sacrum. Markers placed on the acromio-humeral joints, sternal notch, xiophoid process and C7 vertebral process defined the thorax. The head comprised of 2 markers on the forehead, and 2 others on the occipital region. Finally, the arms consisted of markers placed on the mid-upper arm, lateral epicondyles, distal radius and ulna and the third metacarpal head.

Joint centers were calculated by the PlugIn Gait software provided by Vicon™ using anthropometric data and a "modeling stage", which took the real marker trajectories, and generated 'virtual' marker trajectories that represented kinematic joint angles for the trunk, pelvis, and bilateral hip, knee and ankle. A quintic spline filter was applied to the real marker trajectory data before the modeling stage. Data were then filtered with a low-pass Butterworth filter with a cut-off frequency of 10 Hz.

Data Analysis

The primary outcome measure for the study was gait speed. Secondary outcomes included the temporal-distance factors (cadence, step length, stride length, double support phase and stance phase durations and symmetry variables), angular displacement of the lower limbs in the sagittal plane, as well as the displacement of the thorax and pelvis in both the horizontal and sagittal planes. Foot strike and foot-off events were identified using toe and heel trajectories along the direction of progression, which allowed later calculations of temporal distance factors and normalization of kinematic profiles to 100% of the gait cycle duration.

Attributed to a lack of forward progression with respect to space on the treadmill (secondary to the subject stepping in place), a special algorithm had to be developed to calculate stride and step lengths, as well as gait speed. Using the trajectories of the foot markers, the distance from push-off to foot-contact (swing phase) was obtained. This distance was then added to the distance the foot markers covered during the subsequent foot-contact to push-off (stance phase) of the same leg, to account for the backward translation of the treadmill belt. Gait speed was then calculated by dividing this stride length over the cycle duration. Overall, there was an 84% agreement in the speed calculated speed using the algorithm, to that displayed on the treadmill control unit.

Three-dimensional angles were reconstructed for thorax and pelvis using global coordinates. Local angles were calculated for the hip, knee, and angle joints. Given that the primary outcome (i.e. gait speed) and the secondary outcomes (temporal distance factors) would be most affected by the sagittal motions of the hip, knee and ankle joints, kinematic analyses of the aforementioned joints were restricted to the sagittal plane, . The sign conventions were as follows: positive for any flexion, dorsiflexion and anterior rotation motion. In addition, a positive angle was designated for all horizontal plane thorax and pelvic rotations towards the paretic side in the hemiparetic subjects and rotations to the right side in the healthy subjects. The angles at critical gait events for the lower extremity (i.e. hip angle at push-off, knee angle during swing phase and ankle angle at heel strike) were averaged across subjects. Peak to peak angles were also computed for the lower extremity during each gait cycle, and averaged for all subjects. Pelvis and trunk maximum and minimum angle in the two planes (i.e. sagittal and horizontal) and the average orientation was then averaged across subjects. Note that all calculations were performed for every gait cycle, and then averaged for every subject.

Statistical Analysis

Comparison of gait speed between the mode (treadmill vs. overground) and the speed (comfortable vs. maximum) was performed using a 2-way analysis of variance (ANOVA) for repeated measures with speed (comfortable vs. maximum) and mode (treadmill vs. overground) as the two factors. . An independent t-test was used to compare the stroke and healthy groups pertaining to the modification of speed (i.e. the absolute change from comfortable to maximum speed) on each walking surface. Associations between the maximum gait speed and three important parameters (i.e. comfortable gait speed, maximum cadence and maximum stride length) were identified using Pearson correlation coefficients. Finally, temporal-distance factors and the kinematics of gait were also compared by means of a 2-way analysis of variance (ANOVA) for repeated measures with speed (comfortable vs. maximum) and mode (treadmill vs. overground) as the two factors. For all statistical tests, significance was set at $\alpha = 0.05$. All statistical analyses were performed using Statistica 6.0.

Results

Gait Speed and Temporal-Distance Factors on the treadmill vs. overground

As demonstrated in Fig. 1A, stroke subjects were capable of increasing gait speed beyond their comfortable level ($p < 0.001$). The absolute increases in speed were larger ($p<0.01$) overground ($\delta=0.31$ m/s) than on the treadmill ($\delta=0.16$ m/s). However, the percent changes from comfortable to maximum pace were similar between the two modes of locomotion (62% overground vs. 55% treadmill, $p > 0.05$). Note also that gait speed was always faster on the ground than on the treadmill ($p < 0.001$), both at comfortable ($\delta=0.55$ m/s) and maximal speed ($\delta=0.86$ m/s).

Healthy controls walked faster than stroke subjects under both overground and treadmill conditions ($p < 0.01$) (Fig. 1B). In addition, the healthy controls walked at the same speed on the treadmill and overground ($p > 0.05$), either at comfortable or maximum speed, a trend not mirrored by the stroke subjects. Lastly, compared to stroke subjects, healthy controls also showed significantly larger increases in gait speed from comfortable to maximal pace, on the treadmill (δ=0.71 m/s or 61%, $p < 0.001$), but not overground (δ=0.68 m/s or 49%, $p > 0.05$).

Temporal-distance factors and some key symmetry variables of gait are listed in Table 2. Comparisons between the two modes of locomotion, for the paretic limb, revealed a larger stride length ($p < 0.001$), and longer single stance and cycle duration ($p < 0.01$) overground, whereas a higher cadence ($p < 0.05$) and a longer double support phase ($p < 0.01$) duration was observed on the treadmill. When considering both the treadmill and overground conditions together, fast walking induced shorter cycle duration, shorter time spent in stance and double support phases, as well as higher cadence and larger stride length ($p < 0.01$ to $p < 0.001$) as compared to walking at comfortable speed.

The stroke subjects demonstrated more symmetric stride lengths on the ground ($p < 0.05$), as reflected by a ratio of the paretic to nonparetic side being closer to one. Other notable symmetry variables such as the stance ratio and cycle duration ratio proved to be unaffected by the mode of locomotion ($p > 0.05$). Furthermore, the speed of walking did not have an effect on symmetry of walking ($p > 0.05$).

Determinants of the Maximal Gait Speed

As shown in Fig. 2A, the initial comfortable speed correlated strongly with the maximum attainable gait speed, both on the treadmill and overground ($r = 0.81$; $r = 0.79$, $p < 0.01$). Maximum stride length also correlated with maximal speed for the two modes of locomotion ($r = 0.75$; $r = 0.81$, $p < 0.01$). While the cadence (Fig. 2B) was significantly associated with the maximal speed for overground walking ($r = 0.71$, $p < 0.05$), it failed to show the same trend on the treadmill ($r = 0.16$, $p > 0.05$).

Comparison of Treadmill vs. Overground Walking at Matched Speed

In order to control for the faster speed during overground, as compared to treadmill locomotion, key temporal distance factors such as the cadence and stride lengths in Table 2 have been plotted separately for each speed condition in Fig. 3A & B. A distinct margin of overlap in the walking speeds on the ground and treadmill, as depicted by the vertical dashed lines S and S', allows for comparisons to be made across walking modes, at matched speeds. These graphs show that when controlling for gait speed, cadence is still higher on the treadmill, and stroke subjects walked with smaller stride lengths compared to overground. This trend is similar for both sides, although only the paretic side has been illustrated in Figure 3.

The increase in walking speed overground (Fig. 3C) was achieved by an increase in both cadence and stride length ($r = 0.84$ and $r = 0.85$ respectively, $p < 0.01$). Speed increase during treadmill walking, however, was limited due to a fixed cadence which was always higher than that overground. Thus, the treadmill mainly induced increases in stride lengths ($r = 0.93$, $p < 0.01$) to achieve greater speeds.

Comparisons of the kinematic patterns between treadmill and overground walking were also carried out at matched gait speeds (Figures 4 and 5). To do so, kinematic variables were compared between the treadmill maximum (TMM) speed (0.47 ± 0.18 m/s) and the overground comfortable (OGC) speed (0.55 ± 0.17 m/s) conditions in the stroke subjects. These two conditions displayed similar speed outputs ($p > 0.05$, from a paired t-test with repeated measures), also evident from Fig 1A.

Figure 4 depicts the total angular excursions of the lower extremity joints during treadmill and overground locomotion. At matched speed, the hip joint demonstrated greater extension excursion overground for both the paretic ($p < 0.01$) and nonparetic sides ($p < 0.05$), as compared to the treadmill. A similar pattern emerged for the knee joint, as greater excursions were experienced on the ground, for both paretic and nonparetic sides ($p < 0.001$). Ankle joint excursion on the nonparetic side, but not on the paretic side, was greater overground than on the treadmill ($p < 0.001$).

The angles at critical gait events for the hip, knee and ankle are shown in Fig. 5, once again matched for the walking speed. Hip extension at push-off (A) was greater overground than on treadmill ($p< 0.001$) for both paretic and nonparetic sides. Knee flexion in early swing (B) was larger on the ground ($p < 0.05$) on the paretic side only, as compared to the treadmill. Finally, ankle dorsiflexion at heel strike (C) on the nonparetic side was higher on the treadmill than overground ($p < 0.05$).

Empirical observations of the kinematic analysis of the lower extremity were also conducted. In the sagittal plane revealed similar profiles for hip, knee, and ankle on the treadmill and overground, for the matched speed conditions speed (Fig. 6). One noticeable difference emerged in the ankle joint (Fig 6C), which displayed a lack of plantarflexion (i.e. eccentric control from the ankle dorsiflexors) shortly after paretic heel strike in the maximum treadmill speed condition. The overground pattern, characterized by a clear ankle plantarflexion following heel contact, resembled the healthy pattern, as previously documented [27].

Trunk kinematic comparisons revealed significantly greater maximum and mean thorax flexion angle ($p < 0.001$) on the treadmill, as compared to overground (Fig. 7A).

Comparisons of pelvis and thorax angular excursions of the stroke subjects in the horizontal plane (Fig. 7B) failed to yield any significant differences between the modes of locomotion ($p > 0.05$).

Trunk and pelvis, however, displayed a rotation bias towards the paretic side, both during treadmill and overground walking, in the horizontal plane (Fig. 7B). During the stance phase of the right (or paretic) limb, the pelvis and thorax thus rotated to the left, while they rotated toward the right during the swing phase. Although the pattern of movement of the pelvis in the stroke subjects closely resembled that of the healthy subjects, the thorax displayed an overall shift of approximately 10° rotation towards the paretic side in the stroke population.

Discussion

Faster speeds overground as compared to treadmill

This study has shown that, consistent with our hypothesis, stroke subjects walked faster overground than on the treadmill and increased their speed to a higher extent during overground walking. Our results support those reported by Hesse et al. [26], who have shown slower speeds on the treadmill than during ground-level walking with or without weight support.

Interestingly, a group of age-matched healthy subjects, who were also naïve to the treadmill, achieved comparable speeds on the two modes. Moreover, when compared to stroke subjects, these healthy subjects demonstrated superior speed modification capacity on the treadmill than they were capable overground, as reflected in a larger absolute difference between maximum and comfortable speeds.

An unlikely explanation that would account for the stroke group difference in gait speed between treadmill and overground is the limitation to step lengths due to the physical dimensions of the treadmill. Given that the healthy subjects demonstrated equivalent speeds on the two modes, in addition to larger speed increments from comfortable to fast speeds on the treadmill, this factor may be ruled out with much certainty. Numerous other factors may however account for this disparity, including muscle weakness, altered sensorimotor integration, fear of falling and habituation to treadmill walking.

Generally, overground ambulation allows subjects the luxury of controlling the speed at which the limbs are brought into an extension position. This strategy permits an opportunity for the nonparetic side to compensate, during its swing phase, for any shortcomings of the paretic side in order to maintain a constant gait speed. Results from Table 2 confirm higher paretic single stance percent overground, as compared to treadmill at both comfortable and maximum speeds (27 and 30 respectively for overground, 23 and 25 respectively for treadmill). By virtue of stepping in place, the constant speed of the belt dictates the rate at which hip extension occurs on the treadmill. Consequently, adequate muscle strength and power is required in both lower extremities to swing the limb forward, matching the speed of the belt. As reported by several studies [35, 36, 37], hip pull-off and ankle power bursts on the affected side are strong determinants of gait speed in subjects with hemiparesis. Unfortunately, weakness of these muscle groups in the paretic limb may have influenced gait speed to a greater extent on the treadmill, as compared to the overground condition, for the reasons previously stated.

Treadmill walking may also produce an added challenge to balance, as compared to overground walking, in two ways. Firstly, when walking on the treadmill, proprioceptive inputs arise from the locomotor movements of lower limbs, while the opposite motion of the belt matches this rate of movement. Contrary to overground walking however, the limb is being pulled back by the treadmill during stance, serving as a source of postural challenge. In addition to the proprioceptive differences, the visual and vestibular systems detect an overall net absence of forward progression. This apparent "sensory conflict" is likely responsible for the transient loss of stability, or "after effect" observed in healthy individuals after treadmill walking [38]. An intact CNS appropriately downchannels and upchannels the relevant sensory information, in order to maintain stability in a variety of environments [39]. The stroke subjects, however, presenting with defective sensorimotor integration [40], were unable to cope with the apparently contradictory sensory information provided by the treadmill.

Secondly, surface texture may have been another factor perturbing motor control during the two modes of locomotion. Overground walking occurred on a smooth surface comprised of linoleum tiles. Conversely, the treadmill required subjects to ambulate on a corrugated belt with relatively greater elastic bounce of the treadmill frame.

Although subjects wore a protective overhead harness during both modes of locomotion, fear of falling, which reduces anticipatory postural adjustments and subsequent voluntary movement amplitudes [41, 42], may have also played a small role in the slower gait speed of the stroke subjects on the treadmill. Finally, although an initial period of practice of 15 minutes on the treadmill was given to both groups, it cannot be totally ruled out that the habituation may not have been sufficient for the patients to adapt to this new task.

Dissimilar strategy to increase walking speed on the treadmill vs. ground

Our results showed that the maximum walking speed of the stroke subjects on both surfaces was highly [43] correlated to their comfortable speed (r = 0.79 to 0.81). Whereas this confirms that preferred speed is a strong predictor of maximal speed during overground walking [44], it shows that the same scenario is also true for treadmill ambulation. In the present study, maximal speed during both modes of locomotion were also found to correlated to maximal stride length, but cadence surprisingly failed to predict maximal walking speed, exclusively on the treadmill (r = 0.16, see Fig. 2). This low correlation coefficient is quite distant from the relatively high value (r = 0.76) obtained by Hesse et al. [45]. In that study however, it is not clear whether subjects were using handrail support during treadmill ambulation. Furthermore, the cadence has been correlated with "gait speed", and little detail is provided surrounding its true value (i.e. comfortable speed, maximum speed or the mean gait speed). Our findings clearly illustrate that stroke subjects walk with a higher cadence during treadmill walking, which likely limits its margin for manipulation when attempting to execute faster speeds. This higher cadence predicts the maximum gait speed overground, but not on the treadmill, thus revealing a partly dissimilar walking strategy to increase walking speed on the two modes of locomotion.

Treadmill induces a "mincing" gait pattern in the stroke subjects

When walking on the treadmill, stroke subjects demonstrated shorter stride lengths than when walking on the floor. Although this anomaly may be attributed to their slower gait speed on the treadmill, the difference still remained when comparing treadmill and overground walking at matched speed. Furthermore, the stroke subjects also displayed faster cadence and shorter cycle duration during treadmill walking than overground, in the presence or absence of matching for the walking speed. Altogether, these observations suggest an effect of the walking surface, or mode of locomotion, on temporal-distance factors.

As expressed by Wall et al. [46], a “mincing” gait pattern occurred on the treadmill. This pattern of quicker and shorter strides also describes the cautious gait of elderly people with balance problems, as noticed during overground ambulation [47]. The characteristics of treadmill ambulation presented in this paper are thus testimony to reduced stability during this mode of locomotion for the stroke subjects. Murray et al. [27] have also confirmed these temporal distance findings (i.e. decreased stride lengths, increased cadence and shorter cycle duration) in healthy subjects ambulating on the treadmill, but testing took place in the absence of any form of acclimatization to the treadmill. A recent study by Harris-Love et al. [31] has shown an unchanged cadence and the contrary with respect to the temporal components of treadmill gait (i.e. a longer % single stance and stance periods). However, subjects in that study were permitted the use of handrails on the treadmill ad libitum, which may have influenced their gait outcomes.

The kinematic profiles presented attest to a resemblance of the overall gait pattern of the lower extremity during the two modes of locomotion. Moreover, a lack of deterioration in the kinematic profiles with greater walking speeds was shown by our results. Despite controlling for the slower walking speed on the treadmill however, stroke subjects demonstrated an overall reduction in the excursions of the lower extremity joints. This diminution of overall movement at the hip and knee joints, more specifically, translated into a reduction of the step length, as evident from our analysis of joint angles at critical gait events (Fig. 5).

Our results also show more flexion of the thorax during treadmill walking which may indicate an attempt by the stroke subjects to lower their center of mass, thereby enhancing stability. Trunk and pelvic motions were also displaying a constant rotation of both segments towards the paretic side. This peculiar pattern diverged from that of the healthy pattern, wherein a bilateral oscillation crossing the midline occurred. Such bias in trunk and pelvis orientation toward the paretic side is likely due to weakness in the body core musculature, leading to asymmetry.

Conclusion

The present study compared the maximum gait speed of stroke subjects on two common walking surfaces: treadmill and overground. It shows that stroke subjects, in contrast to healthy controls, walk faster overground than on the treadmill and can increase their speed better during overground walking. Probable reasons for this disparity were attributed to muscle weakness, altered sensorimotor integration, fear of falling and habituation to treadmill walking.

We also showed that stroke subjects used different strategies to increase walking speeds on the two modes, with respect to the cadence and stride lengths. Despite evidence of some alterations of body kinematic patterns on the treadmill, no major gait deviations arose with treadmill ambulation. Moreover, higher speeds of ambulation failed to infuse unwarranted kinematic patterns on either mode of locomotion. These findings may indeed have implications for the restoration of gait in the rehabilitation setting, as the walking surface may be chosen to train a particular aspect of the locomotor pattern. Since the treadmill condition was inherently less stable to the stroke patients, it can perhaps be utilized to challenge stability for greater long term effects on the overground gait speed. Handrail support and a secure weight support treadmill suspension systems may be added for patient safety during treadmill walking.

In the final analysis, further investigation is needed into the neuromuscular impairment affecting ambulation on the treadmill, including weakness, abnormalities of muscle tone, and the task-specific control problems. Undoubtedly, electromyographic (EMG) and kinetic data will assist in providing valuable insight in this domain. Furthermore, with the advent of more complex and innovative instrumentation, a virtual environment may be created during treadmill ambulating, thus reinstating the optic flow normally encountered during overground walking. This technological breakthrough is an exciting and promising new avenue in the investigation of perception, postural control, and motor learning.

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Figure Caption

Fig 1. Mean and 95 % confidence interval (C.I.) of the comfortable and maximum gait speed achieved by the ten stroke (A) and the five healthy subjects (B) walking on overground and on the treadmill. While speed is that of the paretic limb for the stroke subjects, the speed of both limbs has been averaged in the healthy group. *** $p < 0.001$

Fig 2. Relationship between maximum gait speed achieved on each mode of locomotion (i.e. treadmill and overground) and the average comfortable speed (A), the maximum cadence (B) and the maximum stride length (C). The r values indicate the association between variables.

Fig 3. Strategies used by stroke subjects to increase gait speed on the two modes of locomotion at a comfortable speed (A), maximum speed (B) and for a percent change in speed (C). The cadence appears on the left column, while the stride length appears on the right column. The vertical dashed lines demarcated by S and S' indicate a margin of matched gait speed for the two modes, with an r value showing the association.

Fig 4. Mean and 2 standard error of mean (S.E.M.) of the total (peak to peak) excursions of the hip (A), knee (B), and ankle (C) overground and on the treadmill at matched speeds, for the paretic and nonparetic sides. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Fig 5. Mean and 2 standard error of mean (S.E.M.) of the angular excursions at critical gait events for hip (A), knee (B) and ankle (C) overground and on the treadmill at matched speeds, for the paretic and nonparetic sides. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Fig 6. Mean sagittal plane angular displacements of all stroke subjects for the hip (A), knee (B) and ankle for the paretic and nonparetic sides, during treadmill (TM) and overground (OG) walking at similar speeds. All cycles have been normalized to one gait cycle, from heel strike (0%) to heel strike of the same limb (100%). Small arrows denote the average point of toe-off under the various conditions, as per the legend.

Fig 7. Angular displacements of thorax and pelvis in a healthy and all stroke subjects for the sagittal (A) and horizontal (B) planes, on the treadmill (TM) and overground (OG) walking at similar speeds. Kinematic data have been normalized to a gait cycle of the right limb for the healthy, and the paretic limb for the stroke subjects. Rotations in the horizontal plane (B) are denoted as positive towards the right side (R) and negative towards the left (L) in the healthy subjects, while positive indicates a rotation towards the paretic (P) side, and negative towards the nonparetic (NP) in the stroke subjects. Small arrows denote the average point of toe-off under the various conditions, as per the legend.

*** $p < 0.001$.

Table 1: Characteristics of Stroke and Healthy Subjects

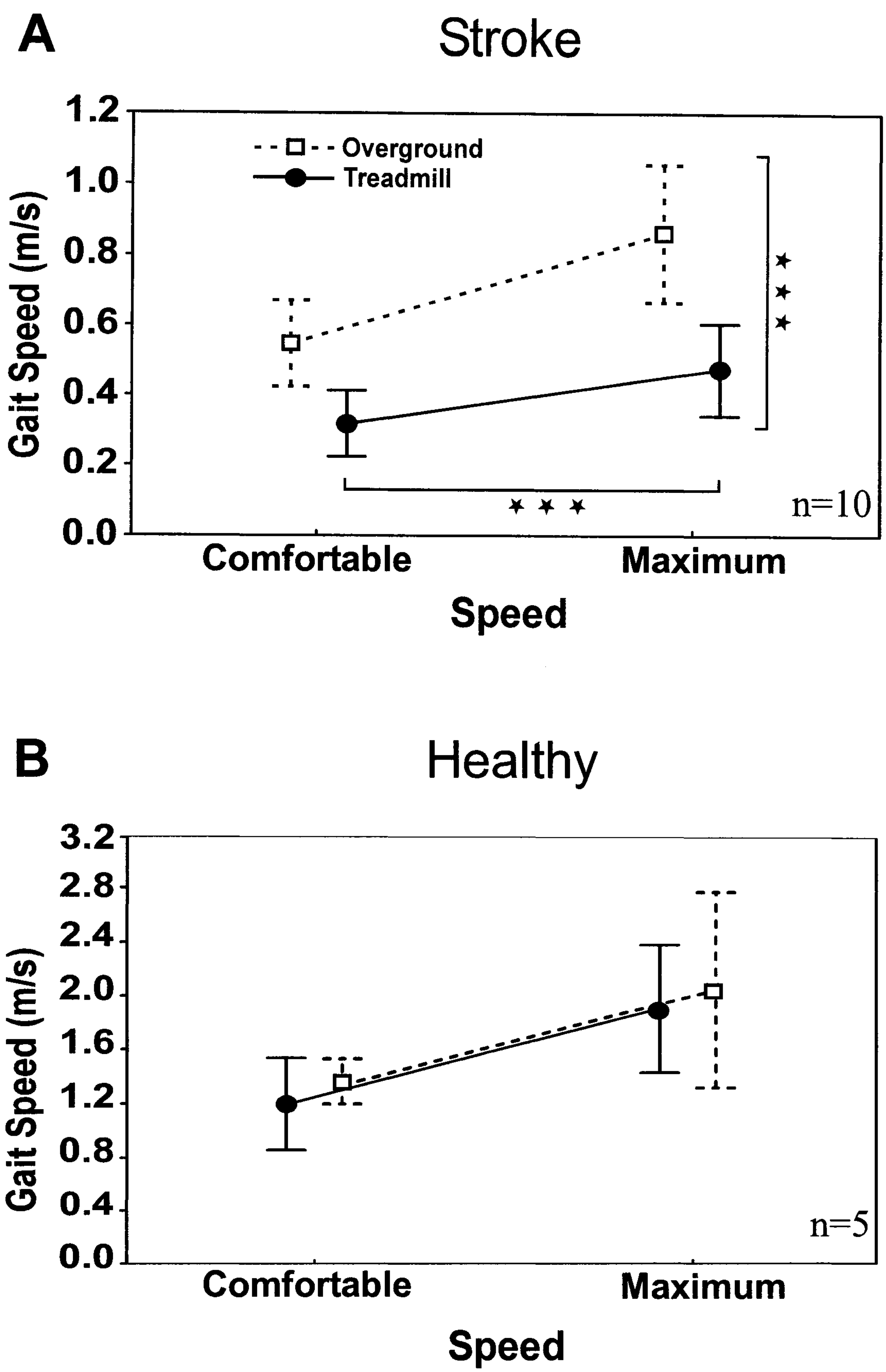
Subject	Gender (M/F)	Age (Years)	Paretic Side (L/R)	Assistive Device (not used for testing)	Time Since Stroke (days)	Gait Speed (m/s)
STROKE						
1	M	83	L	cane	47	0.56
2	F	79	L	walker	58	0.53
3	M	36	R	quad. cane	96	0.47
4	F	68	L	quad. cane	19	0.36
5	M	29	L	cane	64	0.51
6	M	78	L	quad cane	46	0.55
7	M	49	R	cane	127	0.24
8	F	64	L	cane	19	0.82
9	M	67	R	walker	69	0.67
10	F	74	L	walker	97	0.76
Mean	6M/4F	63	3R/7L	N/A	64	0.55
SD		19			35	0.17
HEALTHY						
Mean	3M/2F	59	N/A	N/A	N/A	1.54
SD		21				0.36

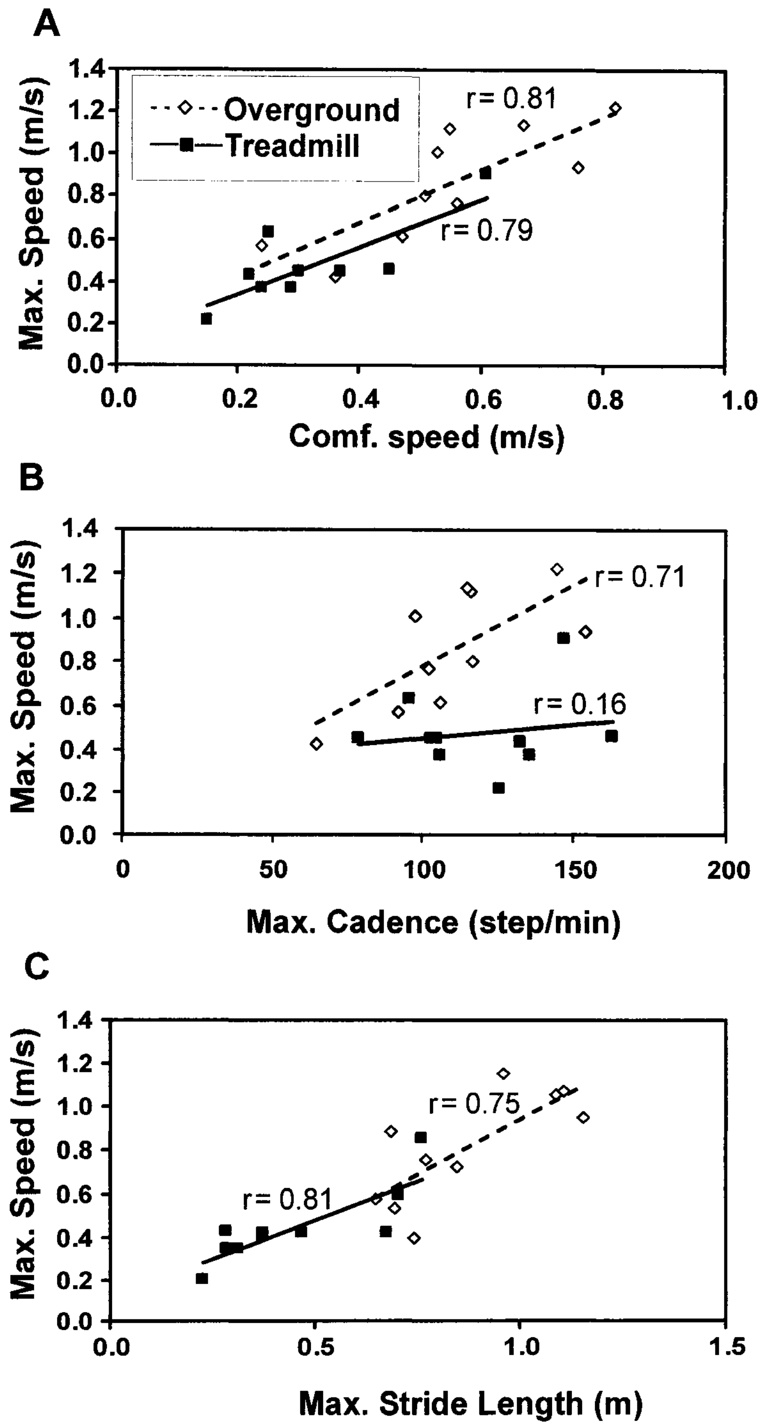
Table 2: Temporal-distance factors and Symmetry Variables

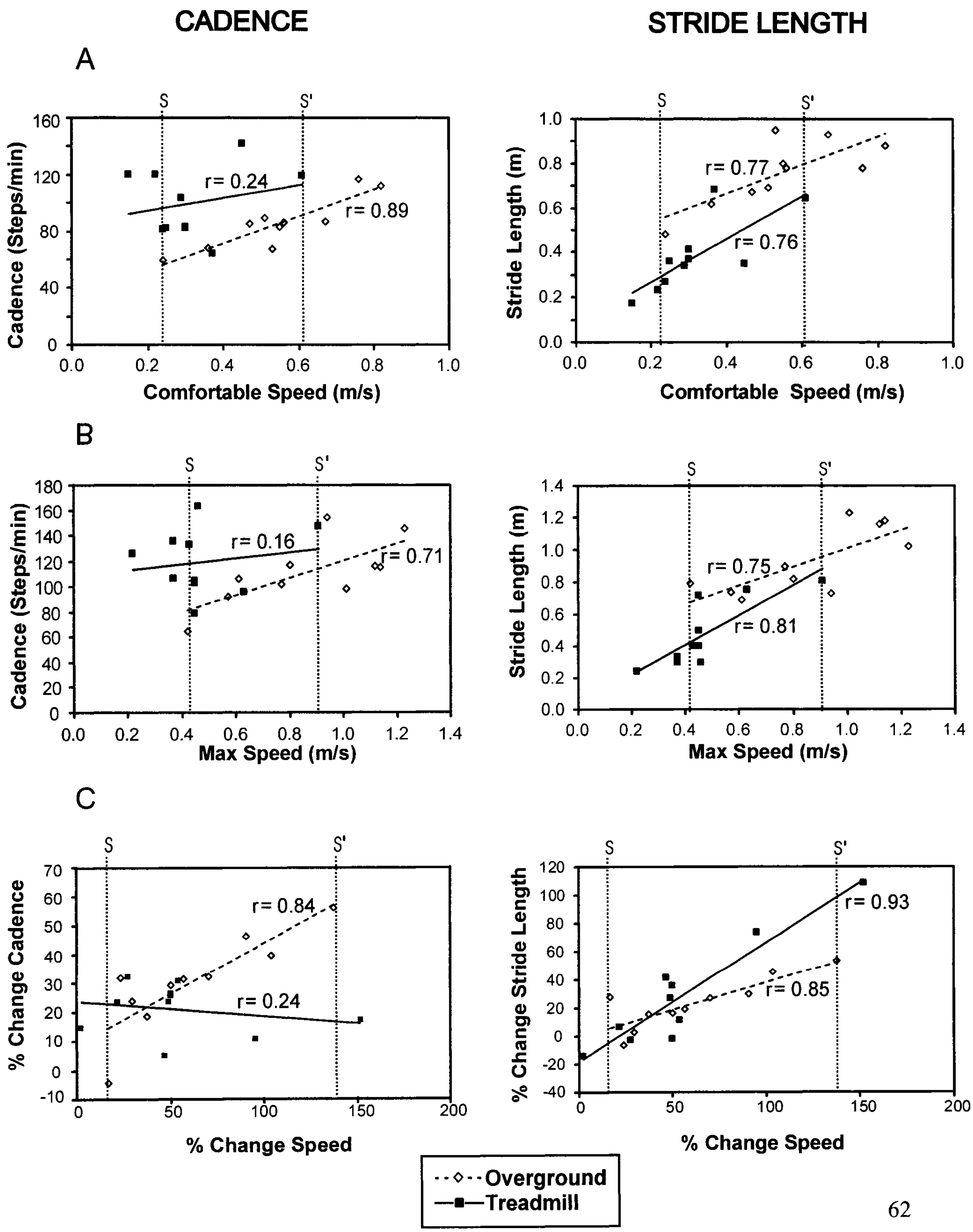
Temporal Distance Variable	Mean ± S.E				Significant Effect	p value
	OVERGROUND		TREADMILL			
	Comf.	Max.	Comf.	Max.		
Cadence* (steps / min)	85 ± 5.8	111 ± 8.1	100 ± 7.8	122 ± 9.2	Mode Speed	0.017 <0.001
Stride Length* (m)	0.76 ± 0.05	0.93 ± 0.06	0.38 ± 0.05	0.48 ± 0.07	Mode Speed	<0.001 0.003
%Single Stance*	27 ± 2.0	30 ± 2.0	23 ± 1.5	25 ± 2.0	Mode	0.010
%Double Support	41 ± 1.8	32 ± 2.0	48 ± 2.2	40 ± 2.2	Mode Speed	0.010 <0.001
% Stance*	68 ± 2.7	62 ± 1.9	71 ± 1.5	66 ± 1.3	Speed	0.004
Cycle Duration (s)	1.5 ± 0.10	1.1 ± 0.10	1.3 ± 0.10	1.1 ± 0.08	Mode Speed	0.011 <0.001
Stride Length Ratio†	1.0 ± 0.02	1.0 ± 0.02	0.89 ± 0.06	0.88 ± 0.03	Mode	0.024
Stance Ratio†	0.93 ± 0.06	0.88 ± 0.04	0.93 ± 0.04	0.89 ± 0.03		
Cycle Duration Ratio†	1.1 ± 0.10	1.1 ± 0.12	1.2 ± 0.12	1.1 ± 0.11		

* Paretic side
† Ratio is Paretic to Nonparetic
Comf. = Comfortable Speed
Max. = Maximum Speed
S.E. = standard error
n.s. = nonsignificant at $p < 0.05$

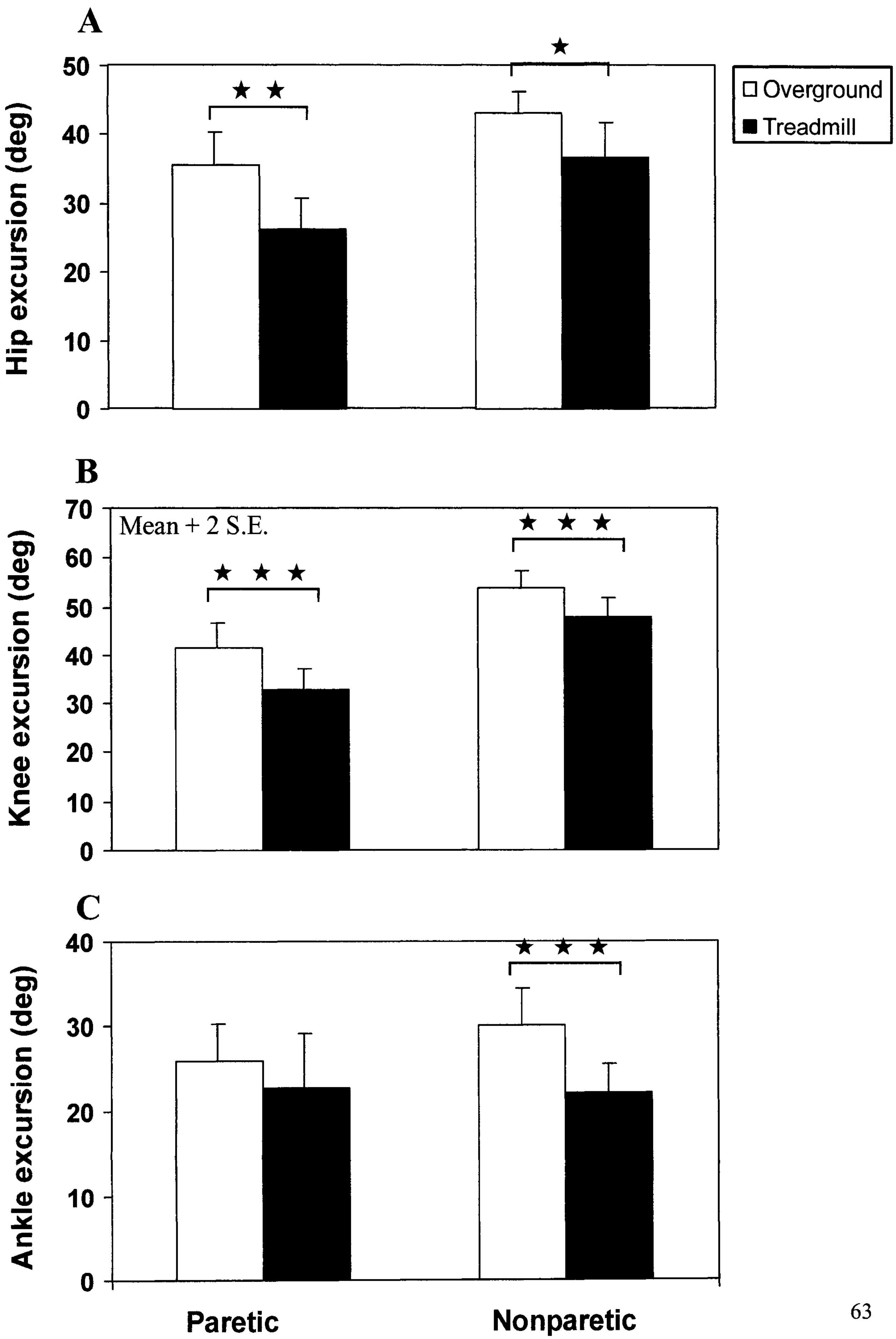
FIGURES

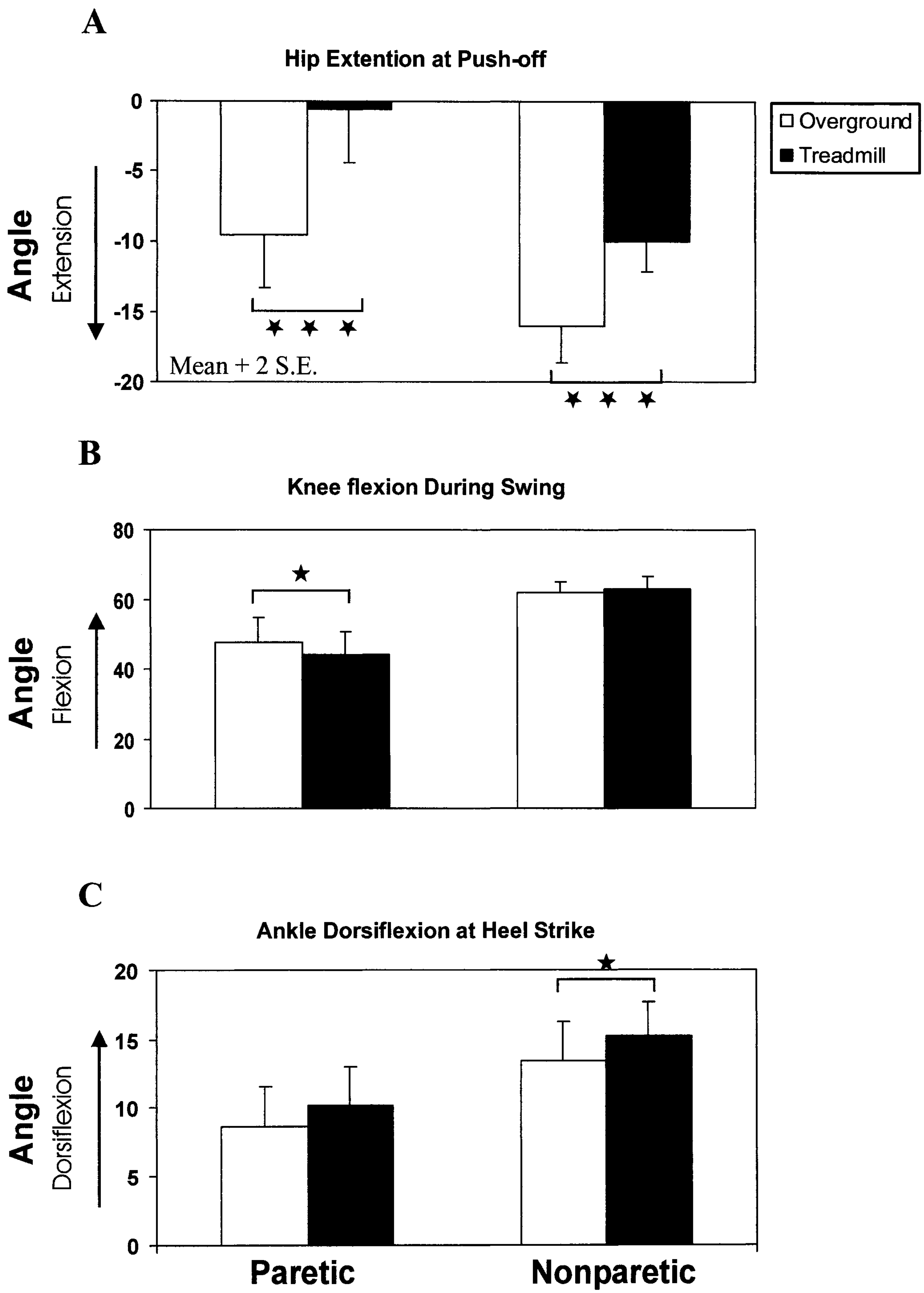

A
Stroke
Overground
Treadmill
Gait Speed (m/s)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Comfortable
Maximum
Speed
n=10
B
Healthy
Gait Speed (m/s)
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
Comfortable
Maximum
Speed
n=5

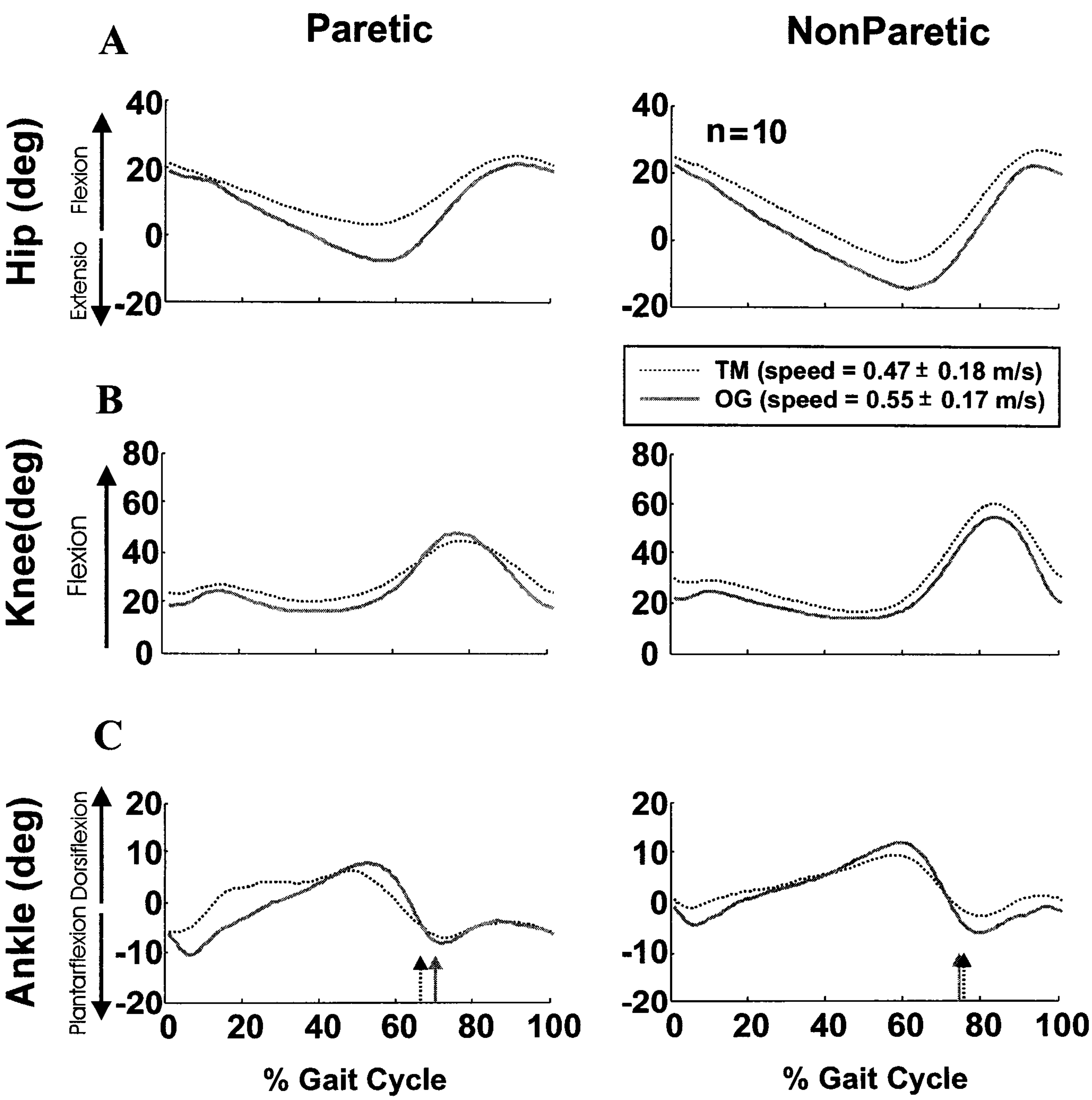

A
Overground
Treadmill
r= 0.81
r= 0.79
Max. Speed (m/s)
Comf. speed (m/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
B
r= 0.71
r= 0.16
Max. Speed (m/s)
Max. Cadence (step/min)
0
50
100
150
200
C
r= 0.75
r= 0.81
Max. Speed (m/s)
Max. Stride Length (m)
0.0
0.5
1.0
1.5

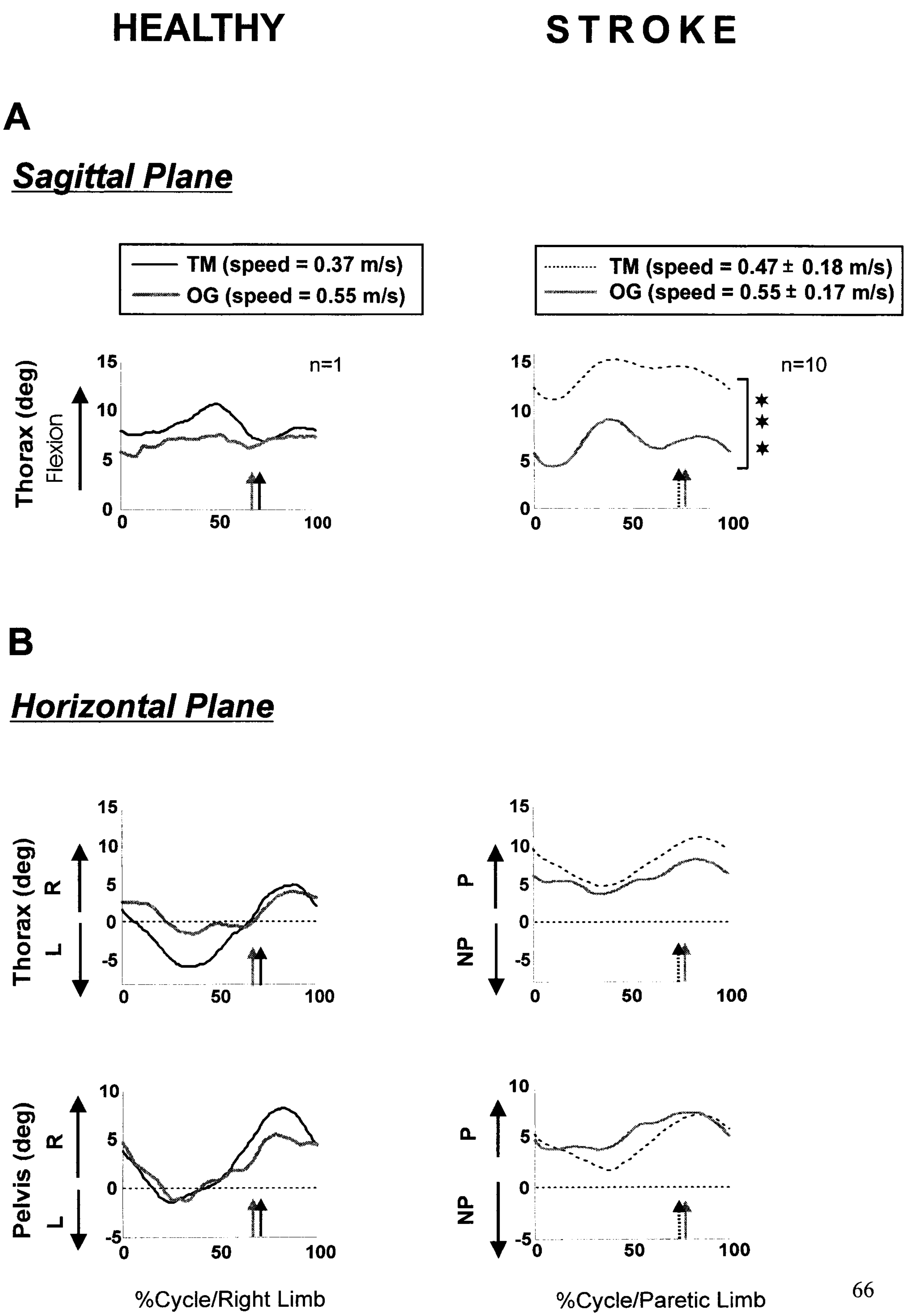


CADENCE
STRIDE LENGTH
A
S
S'
r= 0.24
r= 0.89
Cadence (Steps/min)
Comfortable Speed (m/s)
r= 0.77
r= 0.76
Stride Length (m)
Comfortable Speed (m/s)
B
r= 0.16
r= 0.71
Cadence (Steps/min)
Max Speed (m/s)
r= 0.75
r= 0.81
Stride Length (m)
Max Speed (m/s)
C
r= 0.84
r= 0.24
% Change Cadence
% Change Speed
r= 0.93
r= 0.85
% Change Stride Length
% Change Speed
Overground
Treadmill


A
B
C
Hip excursion (deg)
Knee excursion (deg)
Ankle excursion (deg)
Overground
Treadmill
Mean + 2 S.E.
Paretic
Nonparetic
0
10
20
30
40
50
60
70


A
Hip Extention at Push-off
Angle
Extension
0
-5
-10
-15
-20
Mean + 2 S.E.
Overground
Treadmill
B
Knee flexion During Swing
Angle
Flexion
80
60
40
20
0
C
Ankle Dorsiflexion at Heel Strike
Angle
Dorsiflexion
20
15
10
5
0
Paretic
Nonparetic


A
B
C
Paretic
NonParetic
n=10
Hip (deg)
Flexion
Extensio
Knee(deg)
Flexion
Ankle (deg)
Plantarflexion Dorsiflexion
TM (speed = 0.47 ± 0.18 m/s)
OG (speed = 0.55 ± 0.17 m/s)
% Gait Cycle
% Gait Cycle



HEALTHY
STROKE
A
Sagittal Plane
TM (speed = 0.37 m/s)
OG (speed = 0.55 m/s)
TM (speed = 0.47 ± 0.18 m/s)
OG (speed = 0.55 ± 0.17 m/s)
n=1
n=10
Thorax (deg)
Flexion
B
Horizontal Plane
Thorax (deg)
R
L
P
NP
Pelvis (deg)
%Cycle/Right Limb
%Cycle/Paretic Limb

CHAPTER 4

CONCLUSION

Stroke is a seriously disabling neurological condition impacting significantly on a person's ability to walk. It has been reported that in 50 percent of stroke patients, walking impairments are still observed 3 months after the insult (Wade, Wood et al. 1987). In the Framingham Study, at six months after onset of stroke, 22 percent of stroke survivors were still dependent in ambulating 150 feet (Gresham, Phillips et al. 1979). Thus, the restoration and improvement of walking ability in these subjects constitutes a major treatment goal of physical therapy.

The present study showed that stroke subjects, in contrast to healthy age-matched controls, walk faster overground than on the treadmill and can adjust their speed better during overground walking. With further analysis, it was shown that stroke subjects used different strategies to increase walking speeds on the two modes, with respect to the cadence and stride lengths. Since the treadmill condition was inherently less stable to the stroke patients, it can perhaps be utilized to challenge stability for greater long term effects on the overground gait speed. Handrail support and a secure weight support treadmill suspension systems may be added for patient safety during treadmill walking.

Although treadmill ambulation resembled the overground condition, they differed in the following: slower speed of walking, decreased stride lengths and in increase cadence on the treadmill. The trunk also displayed more forward bending on the treadmill than overground, even when controlling for speed. The practical applications of these findings are geared towards physiotherapist who may wish to reinforce the aforementioned features of gait with treadmill training.

The effects of gait speed were also established with this study, as higher speeds of ambulation evoked more favorable temporal-distance features, mainly: greater stride lengths, decreased double support and stance times on the paretic limb. Furthermore, higher speeds of ambulation failed to infuse unwarranted kinematic patterns on either mode of locomotion, as evidenced by the similarity in the joint profiles. Considering the hip joint overall excursion, it was interesting to note that faster speeds did lead to significantly greater movements on both the paretic and nonparetic sides of the body (unreported data).

Although task-specificity may be in question during the two modes of locomotion, our findings from the healthy subjects have shown that the intact human nervous system allows for a great degree of adaptation and reorganization of sensory processing during the novel task of treadmill walking. Moreover, this process was achieved in a relatively short period of time (i.e. 15 minutes of total practice).

This study however was limited in the small amount of habituation period allotted to the stroke subjects. It is thus conceivable to assume stroke group to have demonstrated higher gait speeds, with associated improved movement patterns, had a longer period of variable practice been implemented in the experimental protocol. Incidentally, training studies on the treadmill validate this assumption, as stroke subjects have been shown to ultimately ambulate with superior gait speeds on the treadmill, as compared to overground (Visintin, Barbeau et al. 1998).

Future Directions

The application of electromyographic (EMG) data can be used to better understand the different strategies used to increase walking speeds on the treadmill, as compared to overground. As previously alluded to, the hip flexors and ankle plantar flexors constitute important muscles of the lower extremity, deserving of EMG analysis. The EMG signal will determine the activation timing of such muscles to verify the presence of unwanted activation patterns, such as excessive cocontrations or spasticity (Knutsson and Richards 1979). In addition, the amplitude of contraction obtained with EMG can identify weaknesses that may have a more pronounced effect on gait, depending on the mode of ambulation.

Furthermore, with the advent of more complex and innovative instrumentation, a virtual environment may be created during treadmill ambulating, assisting to restore the visual perception of walking. The optic flow stimuli may consist of a computer-generated image projected into a rear-projection screen or a head-mounted display and carefully matched to the gait speed of the moving subject. Integrating a psychophysical aspect for the cognitive processing during human locomotion in such scientific inquiries is an exciting and promising new avenue in the investigation of perception, postural control, and motor learning.

A better understanding of the muscular activity, coupled with the provision of the necessary visual cues during treadmill ambulation can have positive implications for the training paradigms of stroke patients.

APPENDICES

APPENDIX I

HUMAN GAIT CYCLE

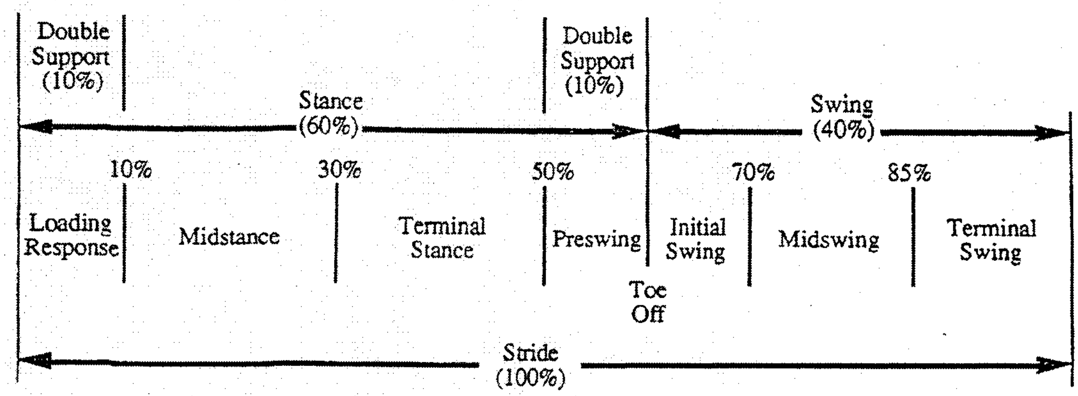


Figure 1: Graphic depicting the phases of the gait cycle and their proportions as percentage of the gait cycle

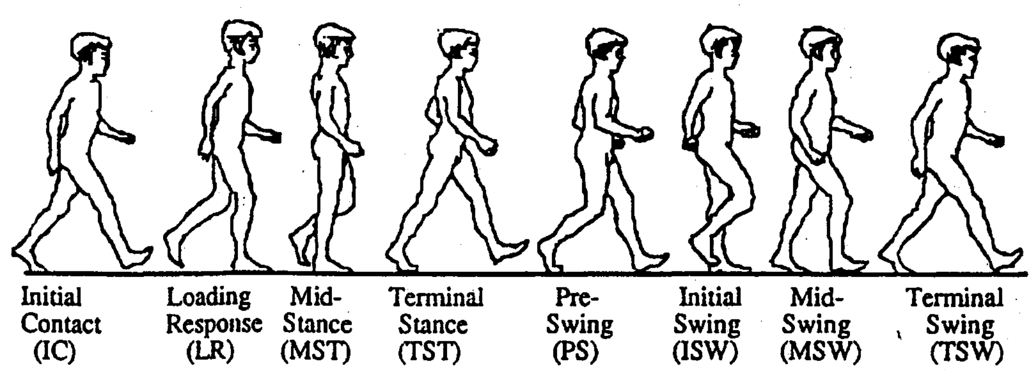


Figure 2: The phases of the gait cycle shown with the corresponding body position for sagittal plane motion

APPENDIX II

Inclusion Criteria

1. Gait speed between 0.15 – 0.77 m/s ___
2. Hemiparesis 2° first CVA (MCA) ___
3. Duration of hemiparesis > 4 wks ___
4. Walk w/o assitance ___
5. TUG > 20 seconds ___

Exclusion Criteria

1. Known heart disease ___
2. Ankle instability ___
3. Orthopaedic problems/Rheumatologic conditions ___
4. Severe cognitive deficits ___
5. Unable to comprehend English/French ___
6. Cerebellar or brainstem lesions ___
7. Previous stroke & Hx of other neuro. conditions ___

APPENDIX III

Treadmill and overground walking: the effects of speed on the gait quality in stroke patients

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Consent Form

Objective: The main purpose of this study is to evaluate how a person who had a stroke walks on the treadmill and on the ground under different speeds. This information will be used in the future to determine the best way to retrain walking for stroke rehabilitation.

Description of the experiment: The experiment session will take place at the Posture and Gait Research Laboratory of the Jewish Rehabilitation Hospital. You will be asked to come to one experimental session that will last approximately two hours (1 hour for preparation and 1hour for testing).

Preparation: In order for you to get used to the treadmill, a five minute practice session will be given before testing. Then, small spherical reflective markers will be placed over many parts of your body (head, trunk, pelvis, middle of each thigh, knees, middle of each lower leg, ankles and foot). This procedure will allow for the recording of your movements as you walk, either on the treadmill or overground. In addition, adhesive electrodes will be placed on your skin over specific muscles in your legs in order to record their muscle activity. A small area of your skin will be shaved and cleaned with alcohol prior to their placement.

Evaluation: You will be asked to walk on the ground several times at your usual speed and at your fastest speed. Then, this procedure will be repeated, only this time you'll be walking on the treadmill. Ample rest periods will be given to you, thus preventing fatigue. When on the treadmill, a walk less than 20 seconds will simply be asked of you at each speed, repeated two times.

At all times during this experiment, a harness attached to the ceiling will protect you. This apparatus will fit around your waist and prevent you from falling either on the ground or on the treadmill. For additional safety, a licensed physical therapist will also be near you during testing.

Risks related to the experiment: Due to the fact that you will be performing small bouts of fast walking, your heart rate and blood pressure will rise. As a precautionary measure, you will wear a device around your chest that will display your heart rate. Rest periods will be allotted to you in order to maintain a safe range. In addition, you will be instructed to exert yourself according to a valid scale, thus minimizing risk of over-exertion. During ambulation, a harness will prevent you from falling and a therapist always be on guard to lend a hand. There exists a very slight possibility of skin reaction to the electrode gel, in which case your attending nurse will be informed.

Advantages: Although this study may not be of direct benefit to you, the results will help our understanding for the most optimal walking training strategy for stroke subjects like yourself.

Confidentiality: Personal information will remain confidential, and your name will not, under any circumstances, appear in the presentation and/or publication of the data. Should video presentation of the results be used, signed consent will be provided by you prior to your face appearing on screen.

Consent: Please be advised that your participation in this research undertaking is strictly on voluntary basis, and you may withdraw at any time. Refusing to participate will not affect the treatment you receive while at the Jewish Rehabilitation Hospital.

For more information regarding this project, please contact Roain Bayat at (450) 688-9550 ext. 643 or Dr. Hugues Barbeau at (514) 398-4519 or Dr. Anouk Lamontagne at (450) 688-9550 ext. 623. Should you wish to discuss the study with an individual outside the research milieu, please contact the hospital representative, Michelle Nadon, at (450) 688-9550 ext. 232.

Signing below indicates that you are aware of the conditions for this project and have given consent for your participation. A copy of this form will be provided to you for your records.

Subjet : ______________________ Date : ____________________
(Signature)

______________________ Tel : ____________________
(Nom)

Witness: ______________________ Date : ____________________
(Signature)

______________________ Tel : ____________________
(Name)

La marche sur le tapis roulant et sur le plancher: Les effets de la vitesse sur la qualité de la marche auprès de patients ayant eu un accident cérébrovasculaire

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FORMULAIRE DE CONSENTEMENT

But: Cette étude a pour but d'évaluer la façon dont une personne, qui a subi un accident cérébrovasculaire, marche sur un tapis roulant et sur le plancher et ce, à des vitesses différentes; soit la vitesse comfortable et à la vitesse maximale. Les données aideront à déterminer la meilleure stratégie pour entraîner une personne à la marche suite à un accident cérébrovasculaire.

Description de l'évaluation : L'évaluation aura lieu à l'hôpital juif de réadaptation, au Laboratoire de Recherche de la Marche et de la Posture. On vous demandera d'être présent pour une session expérimentale qui durera approximativement deux heures, soit 1 heure pour la préparation et 1 heure pour l'évaluation.

Préparation : Afin de s'habituer au tapis roulant, une période de 5 minutes de pratique vous sera accordée avant l'évaluation. Ensuite, des marqueurs réfléchissants seront collés à différents endroits sur votre corps (tête, épaules, bassin, milieu de chaque cuisse, genoux, bas des mollets, chevilles et pieds). L'enregistrement de l'activité des muscles de vos jambes sera effectuée à l'aide d'électrodes jetables et auto-adhésives qui seront placées directement sur votre peau. Avant la pose des électrodes, une petite région de votre peau sera rasée et nettoyée avec de l'alcohol.

Évaluation : On vous demandera de marcher plusieurs fois sur le plancher à une vitesse confortable et ensuite à votre vitesse maximale. Par la suite, cette séquence sera répétée

sur le tapis roulant. On vous demandera de marcher moins que 40 secondes seulement sur le tapis roulant, soit 20 secondes pour chaque vitesse. Des périodes de repos vous
seront accordées afin de diminuer la fatigue. De plus, vous serez toujours sécurisé par un harnais qui sera attaché au plafond pour éviter une chute possible. Ce dernier sera porté lorsque vous êtes sur le plancher et sur le tapis roulant. De plus, un(e) physiothérapeute certifié(e) marchera derrière vous pour assurer votre sécurité.

Risques reliés à l'expérience : Puisque vous allez marcher rapidement pendant de courtes periodes, votre rythme cardiaque et pression sanguine augmenteront. Pour votre sécurité, vous porterez un petit appareil sur votre poitrine qui mesurera votre pouls. Des périodes de repos vous seront accordées afin de garder votre pouls à l'intérieure une limite sécuritaire. En plus, lors de marches à des vitesses maximales, vous suivrez une échelle standard en ce qui concerne votre effort, pour assurer que vous n'excédez pas un niveau trop élevé. Comme mentionné, le harnais vous empêchera de chuter et un thérapeute formé sera toujours présent pour vous aider. Il existe la possibilité de rougeurs de la peau à l'endroit où les électrodes sont appliquées; en ce temps votre infirmière sera avisée.

Avantages : Malgré le fait que cette étude ne vous apporte aucun bénéfice direct, les résultats nous aideront à déterminer la meilleure stratégie pour entraîner à la marche des individus qui ont subi un accident cérébrovasculaire.

Confidentialité : Toute information personnelle sera gardée confidentielle et votre nom n'apparaîtra en aucun cas lors de la présentation des données. De plus, si des enregistrements vidéos sont utilisés pour des besoins éducationnelles, votre visage n'apparaîtra pas à l'écran à moins qu'un formulaire d'autorisation soit signé.

Consentement : Votre participation à ce projet scientifique est entièrement volontaire et vous pouvez vous retirer à tout moment. Votre refus de participer à cette expérience n'affectera en aucun cas les traitements que vous recevez dans cet hôpital.

Pour plus de renseignements, veuillez contacter Roain Bayat au (450) 688-9550 poste 643 ou Dr. Hugues Barbeau au (514) 398-4519 ou Dr. Anouk Lamontagne au (450) 688-9550 ext. 623. Si vous souhaitez parler à quelqu'un qui n'est pas impliqué dans le projet de recherche, vous pouvez contacter Mme. Michelle Nadon, représentante de l'hôpital, au (450) 688-9550 poste 232.

Votre signature indique que vous êtes au courant des conditions reliées à ce projet et que vous donnez votre consentement pour y participer. Une copie de ce formulaire vous sera remise pour vos dossiers.

Sujet : ______________________ Date : ______________________
(Signature)

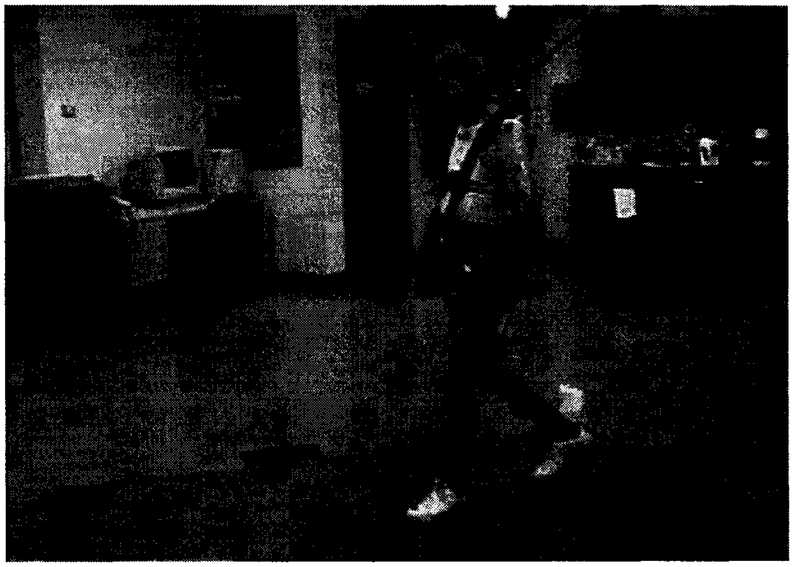
______________________ Tél : ______________________
(Nom)

Témoin : ______________________ Date : ______________________
(Signature)

______________________ Tél : ______________________
(Nom)

APPENDIX V

OVERGROUND AND TREADMILL SAFETY HARNESS



OVERGROUND SET-UP

TREADMILL SET-UP

APPENDIX VI

INCREMENTAL TREADMILL SPEED CHANGE DURING EXPERIMENTATION

INITIAL 10% INCREASE m/s (mph)	**SUBSEQUENT 5% INCREASE** m/s (mph)	**SUBSEQUENT 5% DECREASE** m/s (mph)
0.15 (0.34)	0.16 (0.35)	N/A
0.17 (0.37)	0.17 (0.38)	0.16 (0.35)
0.18 (0.41)	0.19 (0.43)	0.17 0.39)
0.20 (0.45)	0.21 (0.47)	0.19 (0.42)
0.22 (0.49)	0.23 (0.52)	0.21 (0.47)
0.24 (0.54)	0.25 (0.57)	0.23 (0.51)
0.27 (0.59)	0.28 (0.62)	0.25 (0.56)
0.29 (0.65)	0.31 (0.69)	0.28 (0.62)
0.32 (0.72)	0.34 (0.76)	0.31 (0.68)
0.35 (0.79)	0.37 (0.83)	0.34 (0.75)
0.39 (0.87)	0.41 (0.91)	0.37 (0.83)
0.43 (0.96)	0.45 (1.01)	0.41 (0.91)
0.47 (1.05)	0.49 (1.11)	0.45 (1.00)
0.52 (1.16)	0.54 (1.22)	0.49 (1.10)
0.57 (1.27)	0.60 (1.34)	0.54 (1.21)
0.63 (1.40)	0.66 (1.47)	0.60 (1.33)
0.69 (1.54)	0.72 (1.62)	0.65 (1.46)
0.76 (1.70)	0.80 (1.78)	0.72 (1.61)
0.83 (1.87)	0.88 (1.96)	0.79 (1.77)
0.92 (2.05)	0.96 (2.15)	0.87 (1.95)
1.01 (2.26)	1.06 (2.37)	0.96 (2.14)
1.11 (2.48)	1.17 (2.61)	1.05 (2.36)
1.22 (2.73)	1.28 (2.87)	1.16 (2.59)
1.34 (3.00)	1.41 (3.15)	1.28 (2.85)

APPENDIX VII

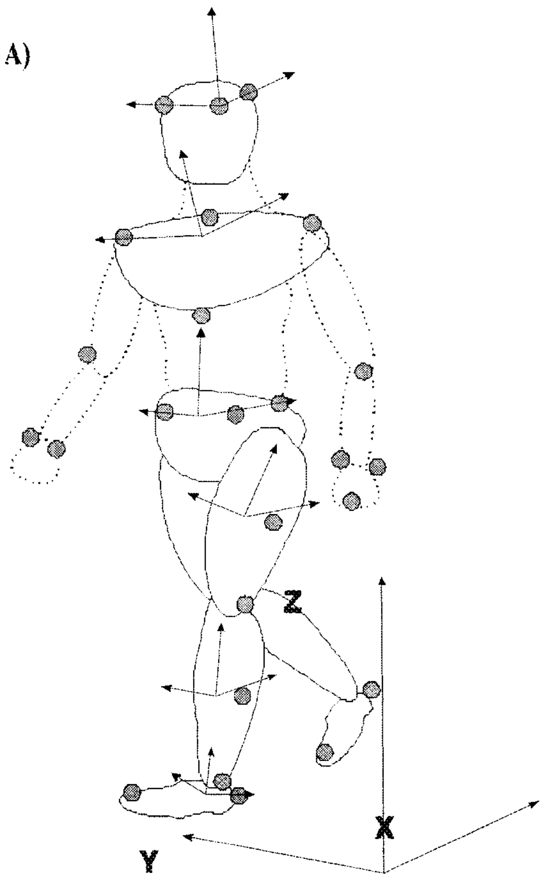
Borg 6 – 20 Scale
(Borg, 1986)

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

APPENDIX VIII

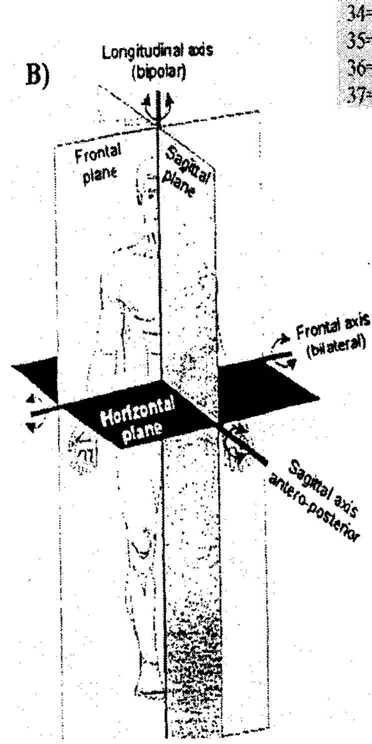
KINEMATIC MODEL

A)



1= Left front head
2= Right front head
3= Left back head
4= Right back head
5= C7
6= T10
7= Clavicle
8= Sternum
9= Left shoulder
10= Left upper arm
11= Left elbow
12= Left lateral write
13= Left medial wrist
14= Left middle finger
15= Right shoulder
16= Right upper arm
17= Right elbow
18= Right lateral write
19= Right medial wrist
20= Right middle finger
21= Sacrum
22= Left ASIS
23= Right ASIS
24= Left PSIS
25= Right PSIS
26= Left thigh
27= Left knee
28=Left Tibia
29= Left Ankle
30= Left Heel
31= Left Toe
32= Right Thigh
33= Right Knee
34= Right Tibia
35= Right Ankle
36= Right Heel
37= Right Toe

B)



APPENDIX IX

ANALYSIS PLAN

EXPOSURE Treadmill walking: comfortable and fast speed (10 consecutive steps at each speed) Overground walking: comfortable and fast speed (3 trials at each speed)			
PARAMETERS	**DATA COLLECTION**	**OUTCOMES**	**STATISTICS**
Performance (Within stroke group)	Vicon system 6 high resolution cameras (120Hz)	Gait speed (m/s)	2-way ANOVA, w/ repeated measures
Performance (Between stroke and healthy groups)	Vicon system	Gait speed (m/s)	Independent t-test
Performance	Vicon system	Determinants of gait speed	Pearson correlation coefficients
Kinematics	Vicon system	*<u>Sagittal Plane</u>:* Bilateral hip, knee & ankle Pelvis and Trunk *<u>Horizontal Plane</u>:* Pelvis rotation Trunk rotation **Angular displacements*	2-way ANOVA, w/ repeated measures (× 10)
Temporal-distance factors	Vicon system	<u>*Bilateral Data*</u>: Cycle duration (s) Total double support (s) Single limb support (s) Lt. to Rt. Stance ratio Stride length (m) Speed (m/s)	2-way ANOVA, w/ repeated measures (× 10)

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