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Research Article

Comparison of the Muscle Pattern Variability During Treadmill Walking (Fixed and Self-Pace) and Over Ground Walking of Able-Bodied Adults

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Abstract

Study purpose: The purpose of the study was to understand whether treadmill walking (fixed and self-paced) exhibits sufficiently similar motor patterns to overground walking to justify its use as a rehabilitation modality in the recovery of normal walking function. The study compared the activity patterns of five lower-limb muscle groups (Hamstrings, Quadriceps, Tibialis Anterior, Gastrocnemius and Soleus) while walking on a Traditional Treadmill (FPT), a Self-Paced Treadmill (SPT) and during Overground Walking (OG). The Variance Ratio (VR), which quantifies cycle-to-cycle repeatability, was used as the primary comparator with a higher VR indicating greater variability across cycles. Eleven able-bodied adults participated (mean age 27.8 years, weight 72.3 kg, 5 female).

Major findings: The VR observed during FPT walking (0.22) was higher than both the SPT (0.18) and OG (0.20) walking but these differences were not statistically significant (F=1.23, P=0.3).

Interpretation: Counter intuitively, FPT walking created a more variable pattern of muscle activity than SPT, possibly by constraining the natural tendency to vary speed. The similarity between SPT and OG suggests this form of treadmill walking may have better training specificity than FPT walking for functional gait recovery. This possibility should be tested in future statistically powered trials including clinical populations.

Conclusion: Differences in muscle activity variability, while not statistically significant, suggests that SPT walking may offer a more specific training experience than fixed pace for gait rehabilitation.

Keywords

Fixed-Pace; Gait Rehabilitation; Self-Paced Treadmill; Variance Ratio; EMG

Abbreviations

EMG : Electromyogram
FPT : Fixed-Pace Treadmill
OG : Overground
SPT : Self-Paced Treadmill
VR : Variance Ratio

Introduction

Treadmill training is used for the gait rehabilitation of several neurological conditions such as uncomplete spinal cord injury [1-3], stroke [4-7] and cerebral palsy [8,9]. The kinematics of treadmill walking are considered similar enough to over ground walking [10-12] to recommend it as an appropriate tool for gait training. While reduced range of motion at the hip and knee have been reported during treadmill walking, compared with Overground (OG), [11], the magnitude of the differences (~2°) is small enough to consider treadmill walking kinematically equivalent to OG walking. During treadmill walking, the maximums of the ground reaction force were found significantly lower than during OG [11]. Riley et al., [11] also reported significant smaller moments at the hip knee joints as well as lower power maximums. In children with cerebral palsy, treadmill walking requires less ankle power but greater hip moments [13]. Watt et al., [14] observed the situation of healthy older adults during treadmill and OG walking. Treadmill walking induced lower power and lower moments compared with OG walking [14]. In terms of kinematics, the elderly participants presented shorter stride time, stride length and greater cadence [14].

The measurement of biomechanical variables has generated substantial insight into the mechanics of both normal [10,11,15] and impaired gait [7,8,16]. It can, however, only provide indirect evidence of the underlying control of the movement which is produced by the muscle activity. Rehabilitation, whether through manual techniques [17-19] or electrical stimulation [20,21] seeks to influence this muscle activity to attain better control of the movement. Understanding the effectiveness of these therapies can only be gained through direct measurement of muscle or motor cortex excitation, since the motor cortex is a principal actor in the changes in gait as its controls the muscle activity of the muscle groups at different stages of the gait cycle in order to achieve the target position [22,23]. The observation of muscle activity is therefore important information to observe when studying movement.

Martin and Li quantified muscle activity and measured the energy consumption during treadmill and OG walking [15]. Walking on a treadmill led to greater muscle activity defined by the root-mean-square and higher peak muscle activity [15], indicating higher energy expenditure. Lee and Hidler [10] also compared the muscle activity between treadmill and OG walking. They observed that, during treadmill walking the activity of the tibialis anterior and gastrocnemius was lower during the stance phase but higher during terminal swing compared to OG. The selected thigh muscles (adductor longus, vastus medialis, hamstrings) presented a higher activity OG from early to mid-swing and at the end of the swing phase and the muscle activity was lower than during treadmill walking [10].

Clinical trials have found that treadmill training can improve endurance and functional mobility of stroke patients [4-6]. However, the level of mobility achieved is typically not sufficient to regain independent community ambulation [5,24]. Ada et al., [24] and Globas et al., [5] both reported that while most stroke patients (60-80%) were capable of walking independently at discharge, they were still limited in their walking abilities due to reduced walking speed [24] and the decrease of cardiovascular fitness linked to reduced mobility [5]. The predictable nature of standard treadmill walking, with unvarying speeds, can be useful for training symmetrical gait [7,16,25] but does not reflect community walking which is inherently variable and less predictable [26-28]. Rehabilitation outcomes are improved when the training modality matches the intended outcome [29], if independent community walking is the desired outcome, training should incorporate speed variation within a multi-sensorial experience that attempts to simulate the complexity and challenging nature of community walking, for example through the use of a virtual environment [30].

Self-Paced Treadmill (SPT) training differs from standard FPT training in that the treadmill can adapt its belt speed to the user's own speed, using position detection systems (e.g. motion analysis technology), making it possible to naturally vary walking speed. When combined with a virtual reality environment, this treadmill walking experience has been considered to be more similar to over ground walking than a traditional fixed pace treadmill [31,32].

The aim of this study was to test which type of treadmill walking (fixed or self-paced) was a better analogue for OG walking in terms of the muscle activity. This knowledge could help to optimise rehabilitation approaches for the recovery of functional walking, including community walking, by providing clear guidance on which type of treadmill training is most similar to everyday walking. To gain this understanding, the repeatability of the muscle pattern of five lower-limb muscle groups, selected for their primary role in walking, were compared between FPT, SPT and OG walking in healthy able-bodied participants.

The hypothesis tested in this study is that SPT walking will show more similarities with OG walking than FPT walking in terms of muscle pattern repeatability.

Materials and Methods

Study design: This was an observational study comparing the repeatability of lower-limb muscle activity patterns (measured with EMG) during three walking scenarios: FPT, SPT and indoor OG walking. For each participant, EMG recordings were made for each walking scenario, during which 20 to 30 steps were recorded. Each scenario was recorded at least three times.

Participants: Participants were unimpaired adults (6 male and 5 females) with a mean age of 27.8 years, (range 19 to 56), mean weight 72.3 kg (range 59.5 to 118 kg). Participants were recruited from the student body of a University using the following criteria; able to walk unassisted for a minimum of 500 m and communicate in English. Participants with a history of motion sickness, known to be pregnant or with a musculoskeletal injury that impaired their ability to walk were excluded. Wireless EMG electrodes (Delsys Trigno, Boston, USA) were then attached to the skin overlying five muscles of interest on both legs (hamstrings (biceps femoris), quadriceps (vastus lateralis), gastrocnemius, tibialis anterior and soleus) following the SENIAM recommendations [33]. All participants read an information sheet and signed a consent form that had been approved by the local ethics committee (reference KR/LG DEC.BioMed.2016.79).

Equipment: 3D kinematic data (joint angles and lower limb displacements) were collected using a 12-camera motion capture system (VICON, Oxford Metrics, Oxford, UK), at a sampling frequency of 100Hz. The cameras tracked reflective markers placed on body landmarks (Figure 1) according to the manufacturer's Plug-In-Gait model (VICON, Oxford Metrics, Oxford, UK). The kinematic data were only used as a means of identifying the different gait cycles. The treadmill data were recorded over 20 to 30 steps using a CAREN (Computer Assisted Rehabilitation Environment, Motek Medical, Amsterdam) N-mill treadmill system (Figure 2). Wireless EMG surface electrode (Delsys Trigno, Boston, USA) were used to record muscle activity (Figure 1), at a sampling frequency of 2kHz. The skin was prepared prior to EMG sensor attachment (including shaving if necessary and rubbing with alcohol) and the electrodes were attached to the skin using double sided sticking tape at anatomical locations.

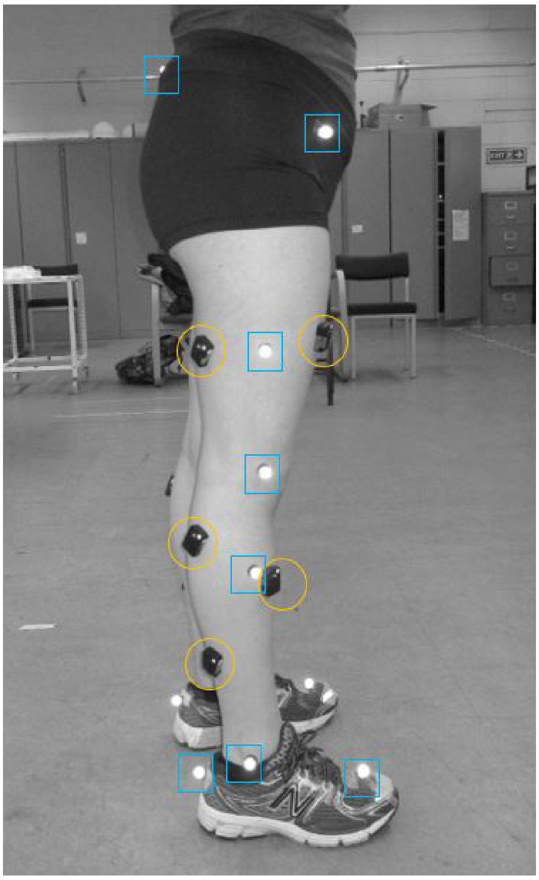


Figure 1: Wireless EMG electrodes (in circles) and reflective markers (in rectangles) placement.

Figure 2: Participant walking on the Motek CAREN treadmill platform facing a 180° virtual environment screen.

Movement tasks: Participants were first asked to walk in a straight line in a flat, well-lit gait lab. This OG walk was repeated four times at three speeds (comfortable, slow and fast). The recordings at the three different speeds allowed referring to them as everyday life walking situations such as fast walk as when running late to catch a bus, slow walk as during a stroll in the park on a warm sunny day. Also, the analysis of the data at different speeds and how they influence the EMG data outcome might be the object of further investigations. The participant then walked on the treadmill at a fixed pace. The data were collected during continuous walking, after a period of adaptation to the treadmill of around three to five minutes. The FPT walk was performed at three self-selected walk paces (comfortable, slow and fast). To determine the participant's preferred self-selected speed, the treadmill speed was initially set at a speed of 0.8 m/s. Then the speed was increased or decreased according to the request of the user until the comfortable speed was reached.

Only the comfortable self-selected speed's results will be presented here. The same procedure was repeated for the collection of self-paced walking data. Participants wore comfortable shoes (trainers) throughout.

Variance Ratio (VR) calculations: The variability of the EMG signal was calculated for each muscle during each of the three walking conditions (SPT, FPT, OG) at the self-selected comfortable walking speed of each participant, using a mathematical parameter known as the Variance Ratio (VR). The VR was used to compare the envelopes of the EMG signals. The EMG signal was first normalised to the maximal amplitude of the muscle signal. The signal was then centred around 0 by subtracting its median value to the signal, leaving as many values over zero than below zero. The signal was then rectified. The envelope was designed as the Root Mean Square (RMS) of the signal which also leads to a smoother signal.

The VR is defined as the sum of the square of the deviation from the mean envelope of the EMG, over one gait cycle divided by the sum of the square of the deviation from the mean EMG envelope of all recorded cycles. When the consecutive cycles have very different shapes the VR value is close to 1, whereas, when the shapes are similar the VR is closer to 0. The VR was calculated over six consecutive gait cycles for each condition.

$$VR = \frac{\sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij}-\bar{X}_i)^2/k(n-1)}{\sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij}-\bar{X})^2/(kn-1)} \quad (1)$$

Where X_{ij} is the value of the j^th^ EMG envelope element at time i, $\bar{X}$ is the mean of the average EMG envelope signal, $\bar{X}_i$ is the average of the EMG envelope values over j cycles at time i, k is the number of points in a cycle and n is the number of cycles.

To analyse the variability of the muscle activity, the VR was used [34,35]. For each participant, the VR data of muscles from both sides were averaged to produce one value per muscle.

Statistical analysis

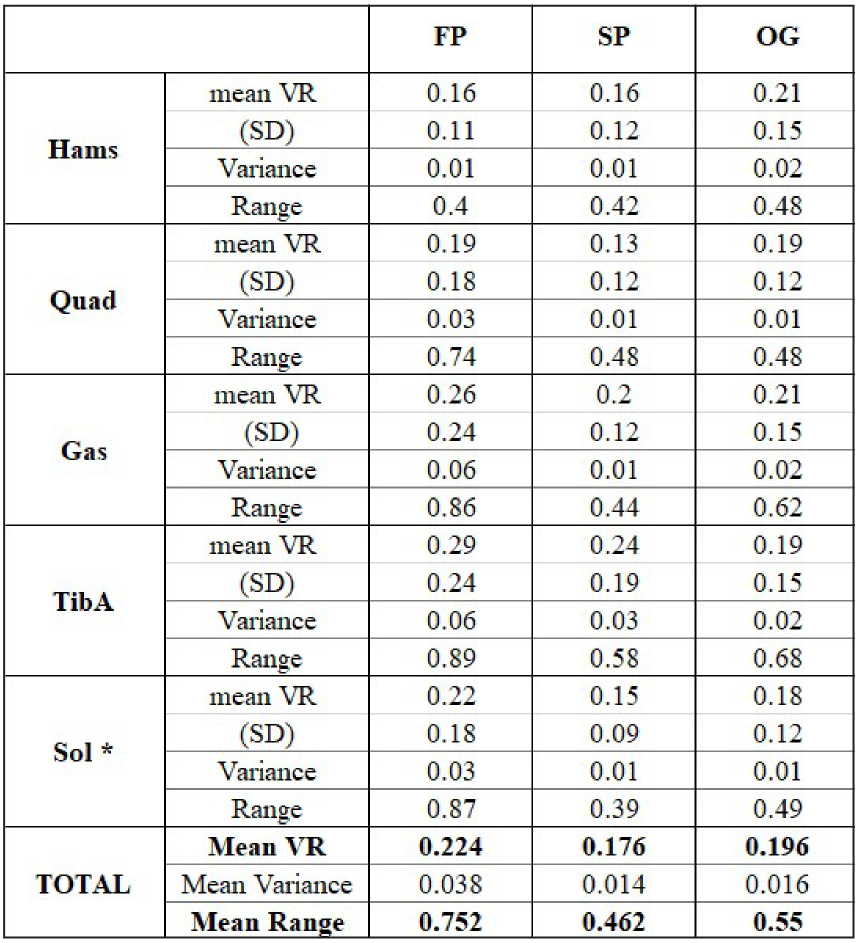
The VR were compared statistically across the three walking conditions at the comfortable walking speed using a repeated ANOVA. A level of statistical significance was set at $p<0.05$. The participant's speed and step length were also statistically compared using a one way ANOVA, with a level of statistical significance set at $p<0.05$.

Results

Variance Ratio: The results of the inter-individual analyses are shown in table 1. When all muscles were combined the FPT walking had the largest mean VR value and wider range of VR values (Mean VR = 0.22, mean Range = 0.75) compared to SPT (Mean VR = 0.18, mean Range = 0.46) and OG walking (Mean VR = 0.20, mean Range = 0.55).

The repeated ANOVA analysis did not reveal any significant differences between the three walking scenarios, apart for the soleus muscle (p=0.019) which presented higher VR values during FPT walking. There was, however, a trend for the VR values, to be lower for SPT and OG walking for all muscle groups, except for the hamstrings which had its highest VR during OG walking (Figure 3).

The following table shows the superimposition of the muscle signals (envelope and rectified signal) over six gait cycles. The duration of each gait cycle was normalised in order to observe the variability of the signal. The upper leg muscles (hamstrings and quadriceps) appear to present more repeatability across the different walking scenarios in comparison to the Tibialis anterior and the soleus. In this case the Hamstrings show more variability during OG than in the other cases. While the soleus appeared to act during the swing phase only during SPT, it appears to be activated also during stance during SPT and OG.



		FP	SP	OG
Hams	mean VR	0.16	0.16	0.21
	(SD)	0.11	0.12	0.15
	Variance	0.01	0.01	0.02
	Range	0.4	0.42	0.48
Quad	mean VR	0.19	0.13	0.19
	(SD)	0.18	0.12	0.12
	Variance	0.03	0.01	0.01
	Range	0.74	0.48	0.48
Gas	mean VR	0.26	0.2	0.21
	(SD)	0.24	0.12	0.15
	Variance	0.06	0.01	0.02
	Range	0.86	0.44	0.62
TibA	mean VR	0.29	0.24	0.19
	(SD)	0.24	0.19	0.15
	Variance	0.06	0.03	0.02
	Range	0.89	0.58	0.68
Sol *	mean VR	0.22	0.15	0.18
	(SD)	0.18	0.09	0.12
	Variance	0.03	0.01	0.01
	Range	0.87	0.39	0.49
TOTAL	**Mean VR**	**0.224**	**0.176**	**0.196**
	Mean Variance	0.038	0.014	0.016
	Mean Range	**0.752**	**0.462**	**0.55**

Table 1: Descriptive statistics of the VR for each muscle group Hamstrings (Hams) Quadriceps (Quad), Gastrocnemius (Gas), Tibialis Anterior (TibA) and Soleus (Sol) in Fixed Pace (FP), Self-Pace (SP) and Overground (OG) walking, at a comfortable (Comf) self-selected walking speed; *p<0.05.

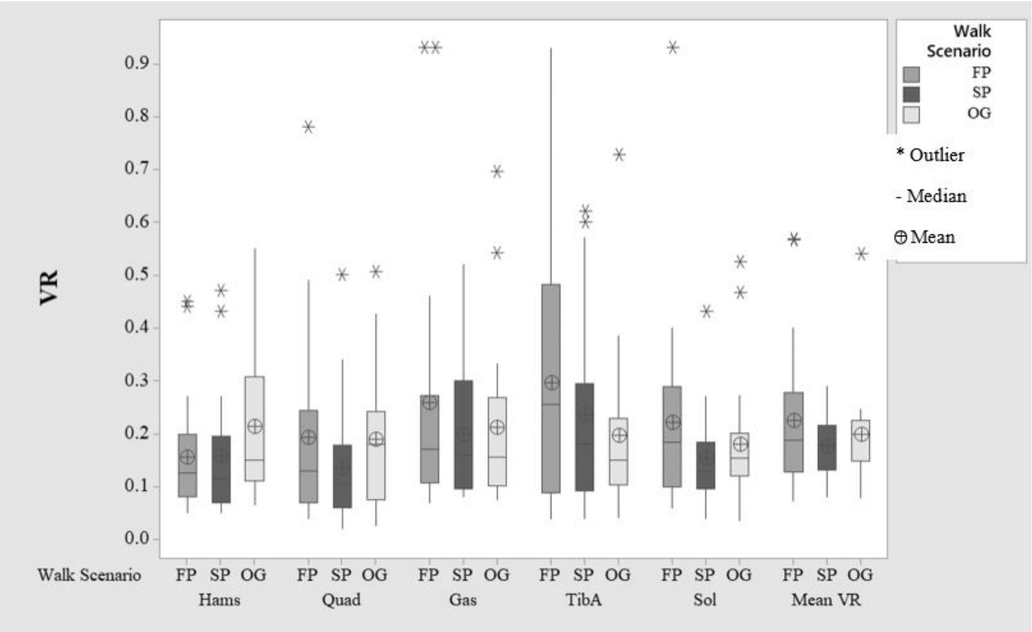


Figure 3: Mean VR value for each muscle group at the self-selected comfortable speed for the three walking scenarios.

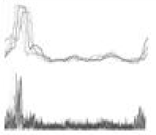
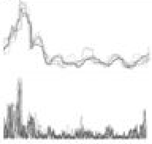
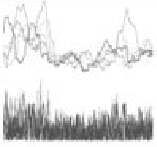
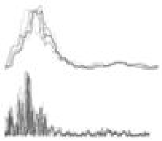
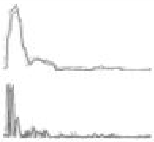
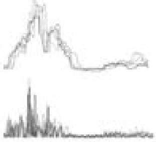
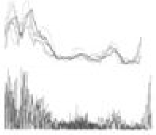
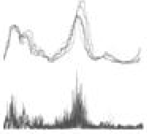
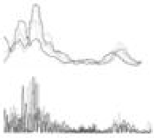
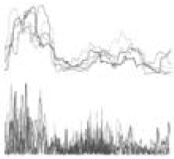
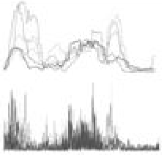
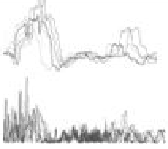
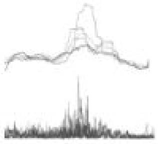
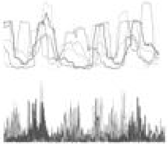
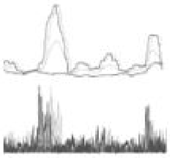
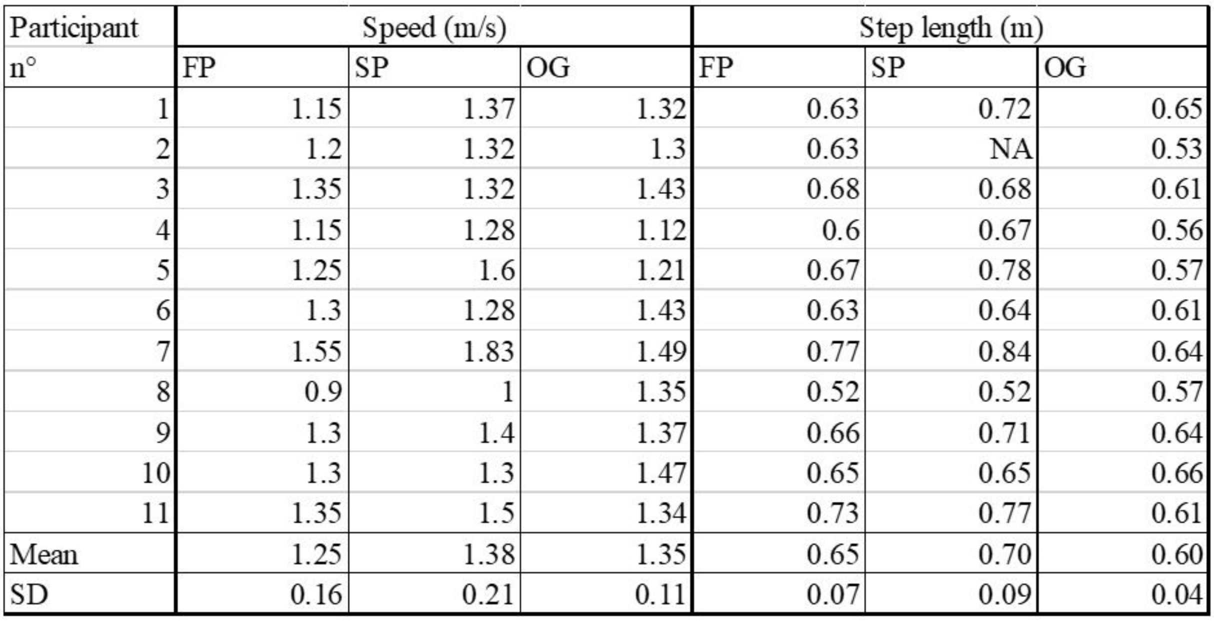
Muscle	FP	SP	OG
Hams			
Quad			
Gas			
TibA			
Soleus			

Table 2: Superimposed muscle Activity pattern over six gait cycles for one participant. For each muscle, on top the EMG envelopes, at the bottom the rectified EMG signals.

Walking speed and step length: The average walking speed across the participants was slower during FPT walking (1.25±0.16 m/s) in comparison with SPT and OG walking. The slower walk during FPT at a self-selected speed in comparison to OG as been previously reported in the literature previously [36,37]. The speed was the fastest during SPT walking s presented in table 3. The step length was the shortest during OG walking (0.60±0.04 m) and longest during SPT walking (0.70±0.09 m).

The results of the ANOVA analysis showed no significant differences between the speeds of the different walking situations (p=0.194). The outcome of the ANOVA analysis of the step length show significant differences between the walking situations (p=0.013), in this case, the step length during SPT were found significantly different from OG's step length.



Participant	Speed (m/s)			Step length (m)		
n°	FP	SP	OG	FP	SP	OG
1	1.15	1.37	1.32	0.63	0.72	0.65
2	1.2	1.32	1.3	0.63	NA	0.53
3	1.35	1.32	1.43	0.68	0.68	0.61
4	1.15	1.28	1.12	0.6	0.67	0.56
5	1.25	1.6	1.21	0.67	0.78	0.57
6	1.3	1.28	1.43	0.63	0.64	0.61
7	1.55	1.83	1.49	0.77	0.84	0.64
8	0.9	1	1.35	0.52	0.52	0.57
9	1.3	1.4	1.37	0.66	0.71	0.64
10	1.3	1.3	1.47	0.65	0.65	0.66
11	1.35	1.5	1.34	0.73	0.77	0.61
Mean	1.25	1.38	1.35	0.65	0.70	0.60
SD	0.16	0.21	0.11	0.07	0.09	0.04

Table 3: Walking speed and step length per participants.

Discussion

The hypothesis tested in this study was that SPT walking would show more similarities with OG walking than FPT walking. While the individual VR values support this hypothesis with a small sample, no statistical significances were observed.

Observation of muscle variability

Range of the VR: The larger range of VR during FPT walking suggests that the muscle activity is more variable cycle to cycle during this type of walking compared to SPT and OG. In their study on monkeys, Goodkin and Thach [38] found that more muscles than necessary were activated when the primate was performing a constrained task. In contrast, when the task was performed freely the muscle activity was consistent with the minimum required to perform the movement. Similarly, the result of our study could be explained by the restrictive nature of FPT walking which may not replicate normal OG walking. Indeed, FPT walking may impose a non-natural recruitment pattern that activates more muscle groups than necessary for normal gait.

It appears, therefore that the use of SPT should be integrated to the treadmill training instead of FPT as it may better prepare the patient for natural overground walking.

Interpretation of the higher variability: FPT walking has been described as an unnatural walk that is simplified due to the reduction of the normal comfortable speed and stepping variations, leading to a predictable and repetitive pattern of walk [12,39]. Treadmill walking is described by Hollman et al., [40] as the imposition of mechanical constraints that affect the gait dynamic. The higher variability (high VR values) of the FP agrees with Berstein's statement regarding the motor control associated with the repetition of precise tasks. To perform successfully a task that require precision several times, it is necessary to possess a large range of motor control variability [41].

Limitations of this Study

Number of participants and its influence on statistical significance: This study only included 11 unimpaired participants and so lack of statistical significance when comparing VRs between the different walking situations could be due partly to the small sample size. Despite this, there was a trend for the VR to be smaller during SPT walking than in the other two types of walking (OG and FPT). EMG is a notoriously a noisy signal so a larger sample might clarify the differences.

Familiarity with treadmill walking: Another factor that might have affected the results was each participant's level of familiarity with treadmill walking. The recruitment criteria did not define or restrict prior experience of walking on a treadmill. This potential risk was moderated by the fact that participants were given time for familiarisation with the treadmill before data recording was initiated. However, this familiarisation time was not fixed, and may have been insufficient for some individuals, introducing an unquantified influence. Papegaaiji and Steenbrink [12] recommended a treadmill familiarisation of at least six minutes. This could be used to improve the data collection for future work on treadmill data collection.

Clinical implication: Taking into account the ultimate goal of recovery and the afore mentioned utility to make the training match the end goal [29], the practice of speed variation is necessary in order to perform efficiently everyday walking. While the amount of training and the administration of the training have still to be measured and adjusted, the integration of SPT walking in the gait rehabilitation could provide further insurance of the walking independence of the rehabilitation patients.

It appears that FPT training is preferable when the end goal of the rehabilitation training is to improve fitness as it has been proven effective and important. SPT might be preferable when the end goal is to prepare to everyday indoor and outdoor community walking. The combination of SPT with a virtual environment can make SPT treadmill walking a tool of choice to practice overground walking, speed changes and/or practice obstacle avoidance or negotiation.

Conclusion

While no statistically significant difference was observed between FPT, SPT and indoor OG walking, the VR values during SPT and OG walking were the closest compared to FPT which had the highest VR values. These observations suggest that SPT might be a more relevant training practice than fixed pace for gait rehabilitation.

Conflict of Interests

All authors declare no conflicts of interest in this article.

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