AUTOMATED QUANTIFICATION AND COMPARISON OF SPATIO-TEMPORAL GAIT PARAMETERS DURING TREADMILL AND OVERGROUND WALKING

Aimee L. Betker[1], Graduate Member, IEEE, Pramila Maharjan[2], Chandrashekhar Yaduvanshi[2], Tony Szturm[2], and Zahra Moussavi[1], Senior Member, IEEE

[1]Department of Electrical & Computer Engineering, University of Manitoba, Manitoba, Canada
[2]School of Medical Rehabilitation, University of Manitoba, Manitoba, Canada

ABSTRACT

A critical part of rehabilitation is providing effective ways to document changes in balance and mobility restrictions/limitations. For overground walking, spatio-temporal gait parameters are widely collected using the GAITRite instrumented carpet. In addition to overground walking, treadmill walking has been shown to be an important tool in rehabilitation. An important advantage of treadmill walking is control over gait speed, which is essential when comparing most gait parameters over time and between participants, as speed can significantly influence the gait patterns. Thus, in this research, software was developed to analyze pressure data and calculate spatio-temporal gait parameters during treadmill walking. A flexible pressure mat was placed under the belt of any treadmill in order to record the foot pressures while the participant was walking. The calculated treadmill parameters were compared to the parameters obtained during overground walking on the GAITRite carpet at a similar speed and to treadmill walking at a fast speed, with and without hand support. Results showed that the spatio-temporal parameters which described the treadmill gait were similar to those describing overground gait. In addition, speed and hand support was shown to cause substantial changes in all parameters.

Index Terms— GAITRite, pressure mat, spatio-temporal, treadmill, walking.

1. INTRODUCTION

Human bipedal walking or gait is a complex motor behavior with many degrees of freedom; thus, there are redundant solutions for segment trajectories in reference to limb end points or behavior goals and under different environmental conditions. Many studies have used 3D motion analysis systems and biomechanical force plates in kinematic and kinetic analysis, in order to quantify and characterize walking metrics and performance [1]. More recently, a number of studies have focused on the spatio-temporal patterns of walking and its rhythm and variability

During gait, a step is generally broken down into three stages [2]: 1) the initial double support phase; the time prior to taking the step, where both feet are planted and adjustments are being made for preparation of swing limb unloading. During this time, the COP moves back towards the swing leg. This in turn causes the COM to accelerate towards the stance leg [3]; 2) the single support phase, the time from toe-off of the swing leg until the heel strike of the swing leg. The COP is now completely under the stance foot. The COM is moving forward along with the step, while shifting laterally towards the stance leg [3]; and 3) the final double support phase, where both feet are again planted after having taken a step. In [3], it is also concluded that the initial step accelerates the body to 90% of its steady-state velocity. Thus, temporal and spatial parameters regarding these stages can provide insight into the normality of a person's gait [4].

A critical part of rehabilitation is providing effective ways to document the changes in a person's balance and mobility limitations. Screening and early detection of system degradation and functional decline are very important when exploring and implementing preventive measures [5]. In addition, it is beneficial to identify the mechanisms underlying motor impairments and motor adaptation following neurological or musculoskeletal disorders.

In daily clinical practice, requirements on portability, cost, and noninvasiveness impose stringent demands on instrumentation and data collection techniques. Qualitative gait analysis is routinely performed in daily clinical practice, whereby gait deviations are identified in patients from visual observations [6]. A variety of objective methods have been used to assess human spatio-temporal gait parameters [4]. The GAITRite instrumented carpet (CIR Systems, Inc., Havertown, PA) for example, extracts these spatio-temporal parameters through the use of a pressure sensing carpet during over-ground walking. The average participant can pace approximately 5 to 6 steps on the carpet, at either a self-paced speed or paced to a metronome. These spatial and temporal parameters can help to identify a normative standard of acceptable 'healthy' values, as well as the progression of the values for a given individual. In addition, with age and/or pathology, these values will change and thus, diagnosis can be performed based on the objective measures the GAITRite system calculates/records [4]. The GAITRite system, test-retest reliability and the validity of the selected spatial and temporal parameters have been investigated by many researchers and all were found to be reliable [4,7].

In addition to over-ground walking, treadmills are important tools in rehabilitation. Gait rehabilitation using a treadmill and body weight support system is a safe and promising rehabilitation program for both restoration of walking function and fitness. One important advantage of treadmill walking is control over gait speed; this is essential for comparison of most gait parameters over

CCECE/CCGEI May 5-7 2008 Niagara Falls. Canada
978-1-4244-1643-1/08/$25.00

time and between participants, as speed can significantly influence the gait patterns [8].

Although the GAITRite carpet is portable and suitable for over-ground walking, it cannot be used in conjunction with a treadmill. In [9], a treadmill was instrumented with two AMTI force plates to provide plantar pressure information. However, this system is relatively expensive and therefore not suitable for everyday clinical use. In addition, it required a restructuring of the treadmill. Conversely, the flexible force sensitive application (FSA) treadmill pressure mat may be placed under the belt of any treadmill in order to record foot pressures while the participant is walking. The FSA mat is available at a reduced cost in comparison with the AMTI force plates and can still easily be used in other applications. Thus, the goal of this study is to obtain the same spatial and temporal parameters that the GAITRite system provides for over-ground walking from the FSA data for treadmill walking.

2. MEHTODOLOGY

Six community dwelling people (1 female), who have suffered from a central nervous system disorder (Table I), volunteered to participate in this study and gave informed consent. Ethics approval was granted prior to recruiting participants by The University of Manitoba, Faculty of Medicine, Research Ethics Board.

2.1. Experimental Setup

The GAITRite instrumented carpet (CIR Systems, Inc., Havertown, PA) was used to record the foot pressures and spatio-temporal parameters during over-ground walking.

The Biodex Rehabilitation Treadmill 3 (Biodex Medical Systems, Inc., Shirley, NY, USA) was used for the treadmill walking. The pressures were recorded during treadmill walking using a flexible pressure mat (Verg Inc., Winnipeg, MB, Canada). The pressure mat was of dimension 53 cm x 106 cm x 0.036 cm and contained a 16 x 32 grid of piezo resistive sensors spaced 2.8575 cm apart. The pressure mat was secured to the metal base of the treadmill, placed underneath the belt of the treadmill, using Velcro.

TABLE I
Participant diagnosis and characteristics.

Participant Number	Age	Diagnosis	Date of Incidence	Walking Aid
1	57	LCVA with apahsia	2006	No
2	50	PD	2005	No
3	81	LCVA, two time	1999,2005	Cane
4	67	SCI, partial T5-T9	2003	No
5	49	ABI	1971	No
6	20	ABI	2003	no

LCVA, left cerebro-vascular accident; PD, Parkinson's disease; SCI, spinal cord injury; ABI, acquired brain injury.

2.2. Protocol

Participants first performed the over-ground walking on the GAITRite instrumented carpet. Spatio-temporal parameters were recorded for 4 sequential walks over the carpet, resulting in 14-16 steps per participant. For each participant, the average gait speed was determined from the GAITRite system. Pressure data was then collected at 13 Hz for treadmill walking at two different speeds. A *slow* speed was set to the GAITRite average speed; a *fast* speed was set to a 30% increase of the GAITRite average speed. Participants were first given a 2 minute period to accommodate to treadmill walking at the given pace prior to testing. Three 2-4 minute walking trials were then performed on the treadmill, with a 2-5 minute rest period between each trial. The length of the trial was such that 50 steps were taken with each foot at the given treadmill speed. In the first trial, participants walked without any hand support with the treadmill set to the slow speed. In the second trial, the participants walked without hand support with the treadmill set to the fast speed. This trial was used to examine the effect of gait speed on the spatio-temporal parameters and variability. In the third trial, participants walked at the fast speed, however, they were permitted to hold on to side rails of the treadmill with one hand in order to emulate use of a walking aid.

2.3. Treadmill Spatio-Temporal Analysis Software

The software for analyzing the spatio-temporal gait parameters during treadmill walking was created using custom scripts in Matlab. The analysis program first reads in the pressure file recorded during treadmill walking. For each recorded data frame, the connected pressure zones are segmented, in order to determine individual footprints. Based on the differential position of each segment's center of pressure (COP), the footprints are then joined together to create individual steps. The steps are then labeled as being taken with either the left or right foot, based on the horizontal position of the step's COP. The path will then be displayed, N steps at a time (where N is configured by the user), with the step number and foot indicated; left footprints are labeled in green and right footprints are labeled in blue (Fig.1). If required, the user then corrects any mislabeled steps, after which the path is

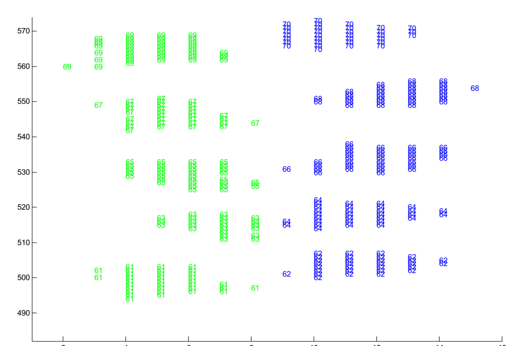

Fig. 1. Path display for the treadmill analysis software; foot number is indicated by a digit; left footprints are green and right footprints are blue.

updated.

For each step, the following spatial parameters were calculated: 1) the toe angle: the angle the foot (heel through big toe) makes with the forward progression line of the foot; 2) the step width: the distance between the forward progression lines of each foot; and 3) the horizontal reference: distance between horizontal zero of the walkway and the progression line of the foot. It should be noted that the anterior-posterior spatial parameters could not be calculated, as the vertical position of the feet is not held constant.

The following temporal parameters were calculated for each step: 1) on time: time when the foot first contacts mat; 2) off time: time of last foot contact with the mat; 3) the step time: time between the on time of one foot and the on time of the other foot; 4) the gait cycle time: the time between two consecutive on times for the same foot; 5) the single support time: the time where only one foot is contacting the surface; 6) the swing time: the time between time off and time on for a given foot; 7) the double support time: the time where both feet are contacting the surface; and 8) the stance time: the time between time on and time off of a given foot.

There are three output files, in comma delineated ASCII format, containing temporal and spatial statistics for each step, the average of the parameters, and the standard deviation of the parameters for: 1) all steps; 2) right steps; and 3) left steps.

2.4. Outcome Measures

For this study, the following spatio-temporal parameters were calculated for the data collected during the treadmill trials: 1) the stance time; 2) the swing time; 3) the step time; 5) the double support time; 6) the step width; and 7) the horizontal reference (H-Ref). These spatio-temporal parameters will be compared between the GAITRite walks and treadmill walking at the slow speed (i.e., the average GAITRite speed). Additionally, a comparison of the spatio-temporal parameters will be made between the three different treadmill trials. Note that the parameter H-Ref is not available through the GAITRite system and thus, will only be compared between the treadmill trials. The mean and standard deviation (SD) and coefficient of variation (CV) of the spatio-temporal parameters were calculated over all participants, based on the foot, for the GAITRite walks and treadmill trials.

3. RESULTS

The mean and SD for each of the spatial-temporal parameters for each trial are presented in Table II. The CVs for each of the spatial-temporal parameters for each trial are presented in Table III.

4. DISCUSSION

A simple and quick method is needed to obtain spatio-temporal parameters for a large number of continuous steps during steady state walking [10]. It is desirable to calculate these parameters for a variety of different analysis procedures and outcome measures, in order to explore the relationship between gait variability and stability in patient populations (with neurological or musculoskeletal disorders/conditions) and in aging [4,7]. Models using spatio-temporal gait parameters have generated both short-term and long-range correlations; these correlations have indicated central nervous system deficits. For example, increased stride-to-stride variability has been related to increased fall risk and general mobility limitations [11].

In this study, we developed software to analyze pressure data during treadmill walking, in order to obtain spatio-temporal gait parameters. The spatio-temporal outcome measures were compared between overground walking on the GAITRite carpet and treadmill walking at a speed set to the average of the GAITRite walk. Results showed that there was a 100 ms decrease in stance time on the treadmill when compared to overground walking at a similar speed. Conversely, there was a 300 ms increase in the swing time for the treadmill when compared to the

TABLE II
Mean and SD for each of the spatio-temporal outcome measures, on a per foot basis.

Outcome Measure	Step	GAITRite	Treadmill		
		Walk	Slow	Fast	Fast, Supported
Stance Time [s]	Left	0.87 ± 0.07	0.74 ± 0.06	0.70 ± 0.08	0.62 ± 0.06
	Right	0.82 ± 0.08	0.62 ± 0.06	0.54 ± 0.07	0.59 ± 0.07
Swing Time [s]	Left	0.44 ± 0.08	0.76 ± 0.11	0.94 ± 0.08	0.93 ± 0.12
	Right	0.49 ± 0.09	0.82 ± 0.07	0.84 ± 0.09	0.99 ± 0.12
Step Time [s]	Left	1.40 ± 0.10	1.50 ± 0.10	1.60 ± 0.07	1.60 ± 0.12
	Right	1.45 ± 0.08	1.51 ± 0.09	1.30 ± 0.07	1.60 ± 0.12
Double Support Time [s]	Left	0.39 ± 0.05	0.31 ± 0.06	0.27 ± 0.07	0.28 ± 0.08
	Right	0.39 ± 0.06	0.33 ± 0.04	0.29 ± 0.05	0.29 ± 0.09
Step Width [cm]	Left	12.50 ± 1.80	16.70 ± 1.77	16.60 ± 2.27	14.90 ± 1.85
	Right	12.40 ± 1.50	17.00 ± 1.66	17.00 ± 2.17	15.00 ± 1.92
H-Ref [cm]	Left	N/A	33.20 ± 1.35	26.60 ± 1.27	32.30 ± 2.00
	Right	N/A	16.50 ± 1.70	17.40 ± 1.63	17.40 ± 1.45

TABLE III
Coefficient of variation [%] for each of the spatio-temporal outcome measures, on a per foot basis.

Outcome Measure	Step	GAITRite	Treadmill		
		Walk	Slow	Fast	Fast, Supported
Stance	Left	7.17	8.72	11.29	9.89
Time	Right	7.17	9.66	9.60	11.24
Swing	Left	8.00	8.30	8.67	13.39
Time	Right	9.00	8.41	10.50	12.54
Step	Left	6.80	6.57	4.19	7.24
Time	Right	7.10	5.87	5.52	7.59
Double	Left	12.00	18.00	25.93	28.57
Support	Right	11.00	17.00	17.24	31.03
Step	Left	29.00	10.60	13.65	12.41
Width	Right	30.00	9.80	13.00	13.00
H-Ref	Left	N/A	4.05	4.76	4.60
	Right	N/A	10.30	9.34	8.34

overground walking. The CV values for the temporal parameters were similar for the treadmill and overground walking. There was a 3-4 cm increase in the step width on the treadmill when compared to the overground walking; however, the CV was substantially lower on the treadmill trial. Our results demonstrate that the spatio-temporal parameters which described the treadmill gait were similar to those describing overground gait. Our findings are mainly consistent with other studies, which used a 3D motion analysis system and treadmill embedded force plate to record kinematic and kinetic parameters [1,12]. However, our study reports that on the treadmill, participants spent more time in the swing phase than the stance phase, an interesting result that has not been previously reported.

The spatio-temporal parameters were also compared during treadmill walking for two different speeds. Speed is an important independent variable to control and normalize when comparing spatio-temporal gait parameters, both within and between participants and over time [13]. This is difficult to do during overground walking and is typically achieved by using a treadmill to set and control speed. Our results showed substantial changes in all temporal parameters with an increase in treadmill speed, both with and without hand support. Note that stance duration decreased and the step width decreased with use of one hand support (cane simulation).

Another important issue when testing people with balance and mobility limitations is safety. A treadmill with hand rails and the use of overhead body support systems is an effective way to prevent falls and injuries. Treadmills can also be used in conjunction with virtual reality/environment hardware/software, an emerging and effective rehabilitation tool [14]. A simple method to quantify balance and mobility while performing tasks in the virtual environment would be of great value.

5. CONCLUSION

In this research, software was developed to analyze pressure data and calculate spatio-temporal gait parameters during treadmill walking. The calculated treadmill parameters were compared to the parameters obtained during overground walking on the GAITRite carpet at a similar speed and to treadmill walking at a fast speed, with and without hand support. Results showed that the spatio-temporal parameters which described the treadmill gait were similar to those describing overground gait. In addition, speed and hand support caused substantial changes in all parameters.

ACKNOWLEDGEMENT

This work was supported by the Natural Sciences and Engineering Research Council (NSERC).

REFERENCES

[1] M.L. Harris-Love, R.F. Macko, J. Whitall, and L.W. Forrester, “Improved hemiparetic muscle activation in treadmill versus over ground walking,” *Neurorehabil Neural Repair*, vol.18, no. 3, pp. 154-60, Sep. 2004.

[2] M. Henriksson, and H. Hirschfeld, “Physically active older adults display alterations in gait initiation,” *Gait and Posture*, vol. 21, no. 3, pp. 289-96, Apr. 2005.

[3] Y. Jian, D. A. Winter, M.G. Ishac, and L. Gilchrist, “Trajectory of the body COG and COP during initiation and termination of gait”, *Gait and Posture*, vol. 1, pp. 9-22, 1993.

[4] E.B. Titanova, P.S. Mateev, and I.M. Tarkka, “Footprint analysis of gait using a pressure sensor system,” *J Electromyogr Kinesiol*, vol. 14, no. 2, pp. 275–281, Apr. 2004.

[5] R. Leinonen, E. Heikkinen, and M. Jylha, “Predictors of decline in self-assessments of health among older people-a 5-year longitudinal study,” *Social Science & Medicine*, vol. 52, no. 9, pp. 1329-1341, May 2001.

[6] J.L. McGinley, P.A. Goldie, K.M. Greenwood, and S.J. Olney, “Accuracy and reliability of observational gait analysis data: judgments of push-off in gait after stroke,” *Phys Ther*, vol. 83, no. 2, pp. 146 –160, Feb. 2003.

[7] B. Bilney, M. Morris, and K. Webster, “Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait,” *Gait Posture*, vol. 17, no. 1, pp. 68-74, Feb. 2003.

[8] A.J. Taylor, H.B. Menz, and A.M. Keenan, “The influence of walking speed on plantar pressure measurements using the two-step gait initiation protocol,” *Foot*, vol. 14, no. 1, pp. 49-55, Mar. 2004.

[9] J.B. Dingwell, and B.L. Davis, “A rehabilitation treadmill with software for providing real-time gait analysis and visual feedback,” *J Biomech Eng*, vol. 118, no. 2, pp. 253–5, May 1996.

[10] L. Li, J.M. Haddad, and J. Hamill, “Stability and variability may respond differently to changes in walking speed,” *Hum Mov Sci*, vol. 24, no. 2, pp.257-67, Apr. 2005.

[11] D.H. Gates and J.B. Dingwell, “Peripheral neuropathy does not alter the fractal dynamics of stride intervals of gait,” *J Appl Physiol*, vol. 102, no. 3, pp. 965–971, Mar. 2007.

[12] R. Bayat, H. Barbeau, and A. Lamontagne, “Speed and temporal-distance adaptations during treadmill and overground walking following stroke,” *Neurorehabil Neural Repair*, vol. 19, no. 2, pp. 115-124, Jun. 2005.

[13] G. Mockel, C. Perka, K. Labs, and G. Duda, “The influence of walking speed on kinetic and Kinematic parameters in patients with osteoarthritis of the hip using force-instrumented treadmill and standardized gait speeds,” *Arch Orthop Trauma Surg*, vol. 123, no. 6, pp. 278–282, Jul. 2003.

[14] S.H. You, S.H. Jang, Y-H. Kim, M. Hallett, S.H. Ahn, Y-H. Kwon, J. H. Kim, and M.Y. Lee, “Virtual Reality–Induced Cortical Reorganization and Associated Locomotor Recovery in Chronic Stroke: An Experimenter-Blind Randomized Study,” *Stroke*, vol. 36, no. 6, pp. 1166-1171, Jun. 2005.