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

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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
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

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.

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

the 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

TABLE I

Participant diagnosis and characteristics.

<table>
<thead>
<tr>
<th>Participant Number</th>
<th>Age</th>
<th>Diagnosis</th>
<th>Date of Incidence</th>
<th>Walking Aid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57</td>
<td>LCVA with aphasia</td>
<td>2006</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>PD</td>
<td>2005</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>LCVA, two time</td>
<td>1999, 2005</td>
<td>Cane</td>
</tr>
<tr>
<td>4</td>
<td>67</td>
<td>SCI, partial T5-T9</td>
<td>2003</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>49</td>
<td>ABI</td>
<td>1971</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>ABI</td>
<td>2003</td>
<td>No</td>
</tr>
</tbody>
</table>

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

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.
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; 4) the double support time; 5) the single support time: the time where only one foot is contacting the surface; 6) the step width: the time between time off and time on for a given foot; 7) the horizontal reference: 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.

3. RESULTS

The mean and SD for each of the spatio-temporal parameters for each trial are presented in Table II. The CVs for each of the spatio-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- 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 overground walking at a similar speed.

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

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>GAITRite Walk</th>
<th>GAITRite Slow</th>
<th>Treadmill Fast</th>
<th>Treadmill Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance [s]</td>
<td>0.59 ± 0.07</td>
<td>0.60 ± 0.07</td>
<td>0.57 ± 0.09</td>
<td>0.61 ± 0.08</td>
</tr>
<tr>
<td>Time [s]</td>
<td>0.62 ± 0.08</td>
<td>0.63 ± 0.08</td>
<td>0.65 ± 0.09</td>
<td>0.67 ± 0.10</td>
</tr>
<tr>
<td>Swing [s]</td>
<td>0.29 ± 0.09</td>
<td>0.30 ± 0.09</td>
<td>0.31 ± 0.09</td>
<td>0.32 ± 0.09</td>
</tr>
<tr>
<td>Time [s]</td>
<td>0.31 ± 0.07</td>
<td>0.32 ± 0.07</td>
<td>0.33 ± 0.08</td>
<td>0.34 ± 0.09</td>
</tr>
<tr>
<td>Step [s]</td>
<td>0.84 ± 0.09</td>
<td>0.85 ± 0.09</td>
<td>0.86 ± 0.10</td>
<td>0.87 ± 0.11</td>
</tr>
<tr>
<td>Time [s]</td>
<td>0.93 ± 0.12</td>
<td>0.94 ± 0.12</td>
<td>0.95 ± 0.13</td>
<td>0.96 ± 0.14</td>
</tr>
<tr>
<td>Double Support [s]</td>
<td>0.99 ± 0.12</td>
<td>1.00 ± 0.12</td>
<td>1.01 ± 0.13</td>
<td>1.02 ± 0.14</td>
</tr>
<tr>
<td>Support Time [s]</td>
<td>0.91 ± 0.12</td>
<td>0.92 ± 0.12</td>
<td>0.93 ± 0.13</td>
<td>0.94 ± 0.14</td>
</tr>
<tr>
<td>Step Width [cm]</td>
<td>32.30 ± 2.00</td>
<td>32.40 ± 2.01</td>
<td>32.50 ± 2.02</td>
<td>32.60 ± 2.03</td>
</tr>
<tr>
<td>Time Right [s]</td>
<td>25.93 ± 2.03</td>
<td>26.00 ± 2.04</td>
<td>26.07 ± 2.05</td>
<td>26.14 ± 2.06</td>
</tr>
<tr>
<td>H-Ref [cm]</td>
<td>28.57 ± 2.06</td>
<td>28.60 ± 2.07</td>
<td>28.63 ± 2.08</td>
<td>28.67 ± 2.09</td>
</tr>
</tbody>
</table>
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 step width decreased with use of one hand support (cane simulation).

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 belt 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.

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REFERENCES


