Changes in gait variability during different challenges to mobility in patients with traumatic brain injury

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Abstract

Postural stability may be compromised in patients who have sustained a traumatic brain injury (TBI). The purpose of the present study was to examine dynamic stability during gait by measuring spatial and temporal variability of foot placement, and to determine the effect of increased difficulty of the walking task on gait variability in patients with TBI. It was hypothesized that patients with TBI will show increased variability in step time, step length, and step width in comparison to healthy controls and that such differences would be accentuated by increased task difficulty. Participants (patients: \( n = 20 \), controls: \( n = 20 \)) were asked to walk across a pressure sensitive mat at their preferred pace (PW), as fast as possible (FW), and with their eyes closed (EC). In accordance with the hypotheses, patients had significantly greater variability in step time and step length in comparison to healthy controls, and when the complexity of the gait task increased (FW and EC tasks). Although step width variability showed no significant difference between the groups, both control and patient groups had increased step width variability in the EC task. It is proposed that such increases in variability reflect greater challenges to maintaining dynamic stability during gait among individuals with TBI and when performing more difficult tasks.

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Keywords: Traumatic brain injury; Gait; Variability; Dynamic stability

1. Introduction

The Brain Injury Association of America has estimated that in the United States alone, there are approximately 1.5 million people who sustain traumatic brain injury (TBI) every year, and 5.3 million Americans live with a disability due to brain injury. One of the frequently reported outcomes after TBI is increased postural instability [1,2], which is not surprising given that a diffuse brain injury can affect cognitive and sensorimotor processing which are both critical for the maintenance of stability.

Laboratory and clinical studies highlight the fact that dynamic stability during gait might be compromised in patients who are independent ambulators who have a high level of functional ability and walk at velocities exceeding 1.2 m/s. For example, Basford et al. [3] reported that patients with TBI who scored within a normal range on the Tinetti balance test, but who nonetheless complained of instability, showed significantly greater displacement and velocity of the center of mass (COM) in the medial-lateral direction during unobstructed gait. McFadyen et al. reported that patients exhibited a more cautious gait by slowing down and increasing their toe clearance when stepping over obstacles [4]. Dynamic instability in patients with TBI has been also linked to decreased community participation by Inness et al. [5]. The above studies suggest that dynamic instability might be a persistent deficit after TBI, and that gait velocity during unobstructed walking...
may underestimate the walking competency and should not be considered as the only index of recovery from TBI. It is imperative to develop and use measures that will reflect the level of impairment in dynamic stability when designing rehabilitation interventions and for discharge planning.

Studies have provided theoretical and empirical evidence suggesting that the control of balance during walking is mainly achieved by controlling the placement of the swing limb, and that the stance limb contributes little to alter the motion of the COM [6,7]. Thus, maintenance of dynamic balance requires and is reflected by precise spatial and temporal control of the foot placement. Consequently, examination of step pattern variability could provide insight into the control of dynamic stability.

Some variability is an inherent characteristic of motor behaviour [8]. However, there is not yet agreement whether increased variability is beneficial or detrimental to the motor performance. Increased variability may reflect a system capable of rapid reactions, highlighting the potential adaptability of the control system. In contrast, increased step-to-step variability may reflect a system in which the ability to maintain a relationship between COM and base of support (BOS) has been compromised. Studies focusing on healthy elderly persons and patients with neuropathologies suggest that increased variability in step width, stride length, and stride time reflects instability of the postural system during gait. Heitmann et al. [9] reported that variability in step width increased by nearly 10% in the elderly women who also reported falling compared to women who did not fall. A prospective study by Maki [10] reported that a relatively small increase (0.017 m for stride length and 0.016 m/s for velocity) in the stride-to-stride S.D. was associated with a doubled likelihood of experiencing a fall. In another prospective study, Hausdorff et al. [11] reported that step-to-step timing variability was twice as large in elderly persons who subsequently experienced falls compared to those who did not fall. Studies that have examined gait in patients who exhibit pathological gait (Parkinson’s, Alzheimer’s, and Huntington’s disease) also support the link between increased variability and dyscontrol of gait [12–14]. Overall, previous studies suggest that there is a positive relationship between increased step pattern variability and altered control of dynamic stability.

In summary, patients with TBI exhibit deficits in the control of balance which may affect their mobility and consequently, independent living. Even patients who show a high level of recovery, as indicated by gait velocity approaching normal limits. Previous studies have not examined the extent to which dynamic stability might be affected after TBI. The present study was conducted to examine the dynamic characteristics of walking by examining the spatial and temporal variability of the locomotor pattern in individuals following TBI. We addressed the following questions: (1) do patients have greater spatial and temporal variability (i.e. reduced dynamic stability) during gait and (2) what is the effect of increasing the challenge during walking on gait variability? We hypothesized that patients would show increased variability in step time, step length, and step width, both, during walking at a self-selected walking speed with full vision, as well as when the task becomes more challenging (i.e. increased speed and absence of vision).

2. Subjects and methods

2.1. Subjects

Twenty patients who were receiving rehabilitation services (15 males and 5 females) who had a TBI were recruited from the Toronto Rehabilitation Institute within a 2-year period (age: 28.4 ± 11 years; height: 175.2 ± 8.2 cm; mass: 68 ± 12.7 kg). Detailed clinical and functional status of patients is presented in Table 1. Patients were recruited if they were able to walk independently and reported only minor locomotor deficits. Four patients were challenged when walking over different terrains, and two used a single point cane when ambulating outdoors (canes were not used during the experimental testing). Patients scored very high on the Balance Scale (Berg) (55.3 ± 1.2 out of 56). Furthermore, most patients were able to maintain balance for 15 s when standing on the left (n = 17) or the right leg (n = 16) (one patient was not tested on this task).

Twenty healthy participants (14 males, 6 females) with no neuromuscular or musculoskeletal deficits were recruited from the student population at University of Toronto to provide control data (age: 26.6 ± 5.6 years; height: 173.4 ± 9.8 cm; mass: 71.5 ± 11.5 kg). Ethical approval for the study was received from the Toronto Rehabilitation Institute, and all participants gave informed consent prior to participation.

2.2. Instrumentation

Spatial and temporal parameters of gait were recorded using a pressure sensitive mat (GAITRite®, CIR Systems Inc., Clifton, NJ, USA). The model used in the study was 4.60 m long by 0.90 m wide with an active area of 3.66 m × 0.61 m. The spatial resolution was 1.27 cm (13,824 pressure sensors arranged in a 48 × 48 matrix), and the temporal resolution was 100 Hz. Bilney et al. have recently shown that the GAITRite® system offers a reliable and valid method of measuring spatiotemporal gait parameters [15].

2.3. Study protocol

Participants were instructed to walk a distance of 8 m wearing their regular footwear. The pressure sensitive mat was placed in the middle of the walkway, which allowed approximately 2 m of acceleration and deceleration. Only data collected over the middle of the walkway was included
Table 1
Clinical and functional status of patients with TBI at the time of testing

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age (years)</th>
<th>Duration since injury (weeks)</th>
<th>Cognitive symptoms</th>
<th>Weakness during isolated movements</th>
<th>One-legged stance (s)</th>
<th>Velocity (m/s) for a self-paced task</th>
<th>Endurance (maximum walking distance 1000 m)</th>
<th>Walking aids</th>
<th>Terrain characteristics which required supervision</th>
</tr>
</thead>
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<tr>
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<td>19</td>
<td>7</td>
<td>Y</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Y</td>
<td>N</td>
<td>N</td>
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<tr>
<td>M</td>
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<td>3</td>
<td>N</td>
<td>N/A</td>
<td>2.6</td>
<td>0</td>
<td>0.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>N</td>
<td>Cane Y</td>
</tr>
<tr>
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<td>12</td>
<td>Y</td>
<td>Y</td>
<td>15 15</td>
<td>0.99&lt;sup&gt;a&lt;/sup&gt;</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
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<td>N</td>
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<td>15 15</td>
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<td>Y</td>
<td>N</td>
<td>Y</td>
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<tr>
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<tr>
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<td>Y</td>
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<td>4.6 1</td>
<td>1.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>F</td>
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<tr>
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<tr>
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<td>Y</td>
<td>N</td>
<td>Cane N</td>
</tr>
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<td>N</td>
<td>Y</td>
<td>15 15</td>
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<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>M</td>
<td>24</td>
<td>17</td>
<td>Y</td>
<td>N</td>
<td>15 15</td>
<td>1.30</td>
<td>Y</td>
<td>N</td>
<td>N</td>
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<tr>
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<td>Y</td>
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<td>15 15</td>
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<td>Y</td>
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<tr>
<td>F</td>
<td>59</td>
<td>40</td>
<td>N</td>
<td>N</td>
<td>15 15</td>
<td>1.11&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

M, male; F, female; N, no; Y, yes.

<sup>a</sup> Subgroup of patients who walked at a self-paced velocity of <1.2 m/s.
in the analysis, which was 3.66 m (the active area of GAITRite® system). There were three walking tasks:

1. walk at a preferred pace (PW);
2. walk as fast as possible (FW);
3. walk with eyes closed at a preferred pace (EC) (participants were asked to keep their eyes closed as they walked across the mat).

Each participant completed three walks in each of the tasks.

2.4. Data analyses

Preliminary analyses using Student’s t-tests were conducted to determine whether the groups were comparable with respect to age, height, and weight. Spatial and temporal gait variables: velocity, step time, step length, and step width, were extracted using the GAITRite® software. In addition, the x–y coordinates for heel placement for each step were also extracted. Step time and step length were defined as the time elapsed and distance traversed, respectively, between the heel strike of the left and right feet. Step width was defined as the perpendicular distance between the anterior/posterior axes of the two feet aligned at the heels.

Analysis was conducted to examine whether the gait pattern was symmetric between the left and right steps. The mean number of steps recorded over the active area of the pressure mat was calculated for both groups and all tasks. Subsequently, means and S.D. were calculated for the following variables: velocity, step time, step length, step width. The mean variables were submitted to a repeated measures analysis of variance (ANOVA) with group (patients, controls) and task (PW, FW, EC) as the independent variables.

Variability of the gait pattern (step time, step length, and step width) was examined using the coefficient of variation (CV, where \( CV = \frac{S.D.}{\text{mean}} \times 100 \)). CV, a measure of relative variability [16], was calculated for each participant, trial, and task using all the steps that were collected over the active area of the GaitRite® mat. Therefore, we obtained three CV scores for each task and participant based on the mean and S.D. obtained on individual trials. Since it is possible that the number of steps included in the analysis could affect the overall means or the variability measures, we analyzed the data in two ways. First, analyses were conducted on data which included all the steps. A secondary analysis was performed on a reduced dataset which included only the three middle steps of each trial (the minimum number of steps recorded over the active area in any trial). In other words, if four or five steps were recorded on the GAITRite® mat, we excluded the first or the first and last steps, respectively. All data were tested for normality and log transformation was performed when data significantly departed from normality, which resulted in lognormal distribution [16]. The CV data were analyzed using a repeated two-way ANOVA with group (patients, controls) as the between factor and task (PW, FW, EC) as the within factor. Post-hoc analysis was performed using Tukey’s HSD test and effects were considered significant at \( p < 0.05 \).

3. Results

There were no significant differences in the age, height, and weight between healthy controls and patients. Means and S.D.s for velocity, step time, step length, and step width were presented to describe the sample population. Student’s t-tests performed on step length and step time variables showed no significant differences between left and right steps for both patients and controls. Thus, subsequent analyses were conducted on the data which combined the left and right steps.

The number of steps recorded over the active area was different between the two groups and the three tasks. The mean number of steps taken by controls and patients was 3.7 ± 0.7 versus 4.4 ± 0.9 in the PW task; 3 ± 0.1 versus 3.7 ± 0.6 in the FW task; 4.4 ± 1.2 versus 7.1 ± 2.2 in the EC task, respectively. Patients demonstrated a greater number of steps during all three tasks. Analysis of variance performed on the full and reduced datasets provided very similar results. In particular, the mean gait variables were not significantly different when all steps were included compared to the analysis on the reduced dataset. Most differences were less than the resolution of the system (spatial <1.27 cm, temporal <10 ms), except for mean step time for the patient group in the EC task which was 20 ms greater in the reduced dataset compared to the full dataset (representing approximately one fifth of the S.D.).

The magnitude of variability in step time, step length, and step width was slightly reduced in the PW and FW tasks, but all the effects remained statistically significant in both analyses. The variability of step length decreased substantially in the EC task when the reduced data set was used; however, patients still exhibited 50% more variability in step length in the EC task compared to controls. Since both analyses provided similar results, results for the full dataset are described next.

The means of the gait variables for both groups and all tasks are shown in Table 2. Patients’ velocities were significantly slower compared to controls in all tasks \( (F(1, 38) = 23.59, p < 0.0001) \), but patients were able to modify their speed according to task. For instance, controls and patients increased their speed on average by 61% and 64% respectively, in the FW task with respect to the PW task. Similarly, both groups slowed their gait when challenged without vision. Of note, the decrease in velocity in the EC task (compared to the PW task) doubled in the patient group compared to the control group (37% versus 17%). The result was a much slower absolute average velocity in the EC task for patients versus controls (0.76 m/s versus 1.22 m/s).
Table 2  
Means of the gait variables for all three tasks for patient and control groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Task</th>
<th>Patients with TBI</th>
<th>Healthy controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>PW*</td>
<td>1.21 ± 0.24</td>
<td>1.47 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>FW*</td>
<td>1.99 ± 0.44</td>
<td>2.35 ± 0.24</td>
</tr>
<tr>
<td></td>
<td>EC*</td>
<td>0.76 ± 0.28</td>
<td>1.22 ± 0.30</td>
</tr>
<tr>
<td>Step time (s)</td>
<td>PW</td>
<td>0.572 ± 0.05</td>
<td>0.541 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>FW</td>
<td>0.427 ± 0.06</td>
<td>0.406 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>EC*</td>
<td>0.671 ± 0.1</td>
<td>0.592 ± 0.11</td>
</tr>
<tr>
<td>Step length (normalized to height)</td>
<td>PW*</td>
<td>0.39 ± 0.05</td>
<td>0.45 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>FW*</td>
<td>0.47 ± 0.05</td>
<td>0.55 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>EC*</td>
<td>0.27 ± 0.08</td>
<td>0.40 ± 0.06</td>
</tr>
<tr>
<td>Step width (cm)*</td>
<td>PW</td>
<td>9.90 ± 2.57</td>
<td>9.91 ± 2.69</td>
</tr>
<tr>
<td></td>
<td>FW</td>
<td>10.38 ± 3.43</td>
<td>10.11 ± 2.65</td>
</tr>
<tr>
<td></td>
<td>EC*</td>
<td>12.05 ± 3.94</td>
<td>9.85 ± 3.99</td>
</tr>
</tbody>
</table>

a It is possible that we failed to find statistical differences between the groups for the PW and FW tasks for step width because the resolution of the system was only 1.27 cm.

* Tasks in which differences between groups were significant (p < 0.05).

The variability analyses focused on step time, step length, and step width. In partial support of the hypothesis, a significant interaction effect between group and task was found for step time: \( F(2, 75) = 6.55, p = 0.0024 \) and step length: \( F(2, 75) = 4.71, p = 0.0119 \), but not for step width: \( F(2, 75) = 2.59, p = 0.0828 \). Patients exhibited significantly greater variability in step time and step length in the EC task in comparison to all other tasks, which is evident in Fig. 1a and b. Interestingly, step time variability in the controls remained at a constant level across all the tasks; however, step time variability increased for the patients when the task required increased velocity or when visual input was removed. Step length variability was consistently higher in patients compared to healthy controls in all the tasks.

Step width variability was not significantly different between patients and controls, but there was a main effect of task, \( F(2, 38) = 18.49, p < 0.0001 \). This difference was associated with significantly greater variability in the EC task compared to the PW task seen in both groups (Fig. 1c).

Although participants were asked to walk at their preferred pace in the PW and EC tasks, and as fast as possible in the FW task, it is possible that variability was at least partly due to different gait speeds during the three different walks.\(^1\) This hypothesis was examined by calculating the variability of velocity for the three trials for both groups. Results showed that the variability (i.e. S.D.) of velocity was greater in the patient group when compared to the control group (PW task: 0.063 m/s versus 0.054 m/s; FW task: 0.113 m/s versus 0.093 m/s; EC task: 0.0806 m/s versus 0.0549 m/s, respectively). Therefore, variability in velocity could have contributed to the increased variability in the step patterns.

\(^1\) We would like to thank anonymous reviewer for this suggestion.

Overall, the results from the present study showed that independent ambulators following TBI had increased variability of step patterns compared to age-matched healthy controls, particularly in the FW and EC tasks. Given the diffuse nature of brain trauma in TBI affecting different cerebral structures, and the heterogeneity of the sequelae, we conducted additional analyses to examine whether patients who walked at slower velocities were more likely to exhibit greater variability. Patients were divided into two groups based on their walking velocity using the criterion of 1.2 m/s, which is considered to be a minimum average speed to ambulate safely and independently in the community [17]. Patients who were walking at a speed slower than 1.2 m/s (group 1: \( n = 10 \)) had an average velocity of 1.02 m/s. In contrast, patients in the faster-walking group (group 2: \( n = 10 \)) walked at an average velocity of 1.41 m/s, which was slightly lower than the average velocity for the control group (1.47 m/s). The variability of gait pattern was calculated for the two groups and the results of the analyses are presented in Fig. 2. A repeated measures ANOVA with patient group (1 and 2) and task (PW, FW, EC) as the
independent variables was conducted to determine if any of the differences were statistically significant. Results showed no significant interaction effects. The variability in step length was significantly different between the slow and fast walking groups, $F(1, 18) = 4.76$, $p = 0.0427$. Patients who walked slower had greater variability in step length in the PW and EC tasks, but not in the FW task. No significant differences were found between the two groups of patients in step time or step width variability. More importantly, as shown in Fig. 2, both groups had increased variability in step time and step length in the FW and EC tasks compared to the control group.

4. Discussion

Results provide support for the hypothesis that dynamic stability during walking is impaired in patients who had sustained a brain injury but were independent ambulators. It has been previously suggested that adapting slower gait speed and a wider base of support serve to increase stability during walking, whereas, increased variability of the gait patterns has been linked to increased dynamic instability [10]. In the present study patients demonstrated altered gait patterns, significantly decreased velocity in all tasks, and increased BOS during the most challenging task (EC). These alterations might reflect adaptations required to increase stability during walking. In contrast, the increase in step pattern variability in patients, particularly when the walking tasks were more challenging, more likely reflects impaired dynamic stability. An important finding is that patients who walked at a self-paced speed comparable to that of the controls exhibited increased variability of step patterns only in the more challenging tasks. This might support the proposition that increased variability is a consequence of impaired dynamic stability and only becomes apparent with challenging tasks. In contrast, patients who were walking at a slower self-paced velocity showed increased spatiotemporal variability across all of the tasks. These results suggest that the requirements of dynamic stability are task specific.

Previous studies have reported that the variability of step timing was the most sensitive predictor distinguishing older adults with an increased risk of falls, suggesting that increased temporal variability might be the best marker of dynamic instability [10,11]. In our sample of patients, step time variability increased significantly when patients walked at higher speeds and quadrupled when visual input was not available. In contrast, the variability in step time of controls remained at a constant level (between 3 and 4%) across the tasks tested. To our knowledge, the incidence of falls in patients with TBI has not been examined. Given the fact that patients with TBI are younger on average than the populations previously studied who are at risk of falls, it is not possible to make conclusions regarding the functional impact of the increased temporal variability during walking following TBI.

Healthy young participants exhibit relatively small variations in step length. For example, Danion et al. [18] reported stride length variability ranging between 1.5% and 3% (CV), and higher variability was found when participants were asked to walk with a shorter than preferred step length and pre-determined cadence. In the present study, patients exhibited significantly greater variability in step length at self-paced velocities (ranging up to 7.8%), and their variability increased on average by 1.5% in the FW. However, when patients were divided into two groups (based on their velocity during the self-paced walk) only patients who were slower walkers showed increased step length variability in the PW. On the other hand, step length variability increased disproportionately in both groups when patients could not rely on visual input to guide foot placement suggesting that vision is critical for dynamic stability.

In contrast to our hypothesis, variability in step width was not significantly different between the two groups across the
tasks. Both patients and controls had increased variability in the EC task. Previous studies have suggested that step width variability might be an indicator of dynamic instability on the basis of the prognostic value of such measures as a predictor of fall risk [9,10]. The lack of a significant difference in step width variability between the groups could be due to the limited spatial resolution of the GAITRite® system. The differences in mean step length between patients and controls were, on average, at least 10 cm, which is much larger than the resolution of the system by approximately a nine-fold. Therefore, we think that the findings can be unambiguously interpreted. In contrast, the actual differences in step width were much smaller. It is possible that we did not find statistical differences between the groups or the tasks due to the resolution of the system.

An important result from the current work is that increased step-to-step variability is associated with increasing challenge during walking. Walking faster is more challenging for the postural system because double support is greatly reduced and the COM is outside the BOS for a longer duration [19]. Precise spatial and temporal control of the foot placement of the swing limb is critical during fast gait, and yet, when patients increased their speed step time variability increased significantly.

As expected, the most significant increases in variability were when visual input was withdrawn. Vision provides critical exteroceptive and exproprioceptive information during locomotion, including environmental context, as well as the relative position of the limbs with respect to potential obstacles [20]. Although in the present study the task did not involve any obstructions, participants in both groups showed increased spatiotemporal variability of step patterns in the EC task. In fact, patients’ step time variability almost tripled. These results emphasize the importance of visual input for maintaining dynamic stability.

The study is limited by the lack of information about the type and severity of the brain injury. Patients were admitted into the study on average 23 weeks post injury, and the functional status at the time of testing was assessed to characterize their ambulatory status. A previous study of gait has reported that the Glasgow Coma Scale is a poor predictor of future locomotor ability [4], but they did not examine variability of step patterns. Future studies should examine the relationship between the type and severity of the initial injury and the degree of recovery by examining the spatiotemporal variability of gait longitudinally.

Our participants were asked to walk a standardized distance with the consequence that the number of steps in each task varied between groups and tasks. Analyses performed on the full dataset (with varied number of steps) and the reduced dataset, which contained equal number of steps showed comparable results, with the exception of step length variability in the EC task. Although the magnitude of step length variability was significantly smaller in the reduced dataset, it was still 50% greater in the patient group compared to the control group. The results of the two analyses indicate that step pattern variability is a robust measure and should be considered in gait analyses.

In conclusion, temporal and spatial variability of foot placement is significantly larger in a population of independent ambulators following TBI, particularly when the task becomes more challenging by removing visual input. The increased variability is most likely a reflection of dynamic instability. Importantly, the Berg test did not reveal the deficits suggesting that the Berg test is not a sensitive measure to predict dynamic stability in gait. These findings support that a more dynamic postural assessment, spanning a range of environmental situations and under altered sensory conditions is required in the TBI population to accurately evaluate postural control within functional mobility and to establish the potential impact on activities of daily living.

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References


