Characterization of Balance Control After Moderate to Severe Traumatic Brain Injury: A Longitudinal Recovery Study

Olinda Habib Perez, Robin E. Green, George Mochizuki

O. Habib Perez, PhD, Rehabilitation Sciences Institute, University of Toronto, Toronto, Ontario, Canada; Sunnybrook Research Institute, Toronto, Ontario, Canada; and Toronto Rehabilitation Institute, Toronto, Ontario, Canada.

R.E. Green, PhD, Rehabilitation Sciences Institute, University of Toronto; Department of Psychiatry, University of Toronto; and Toronto Rehabilitation Institute.

G. Mochizuki, PhD, Rehabilitation Sciences Institute, University of Toronto; Department of Physical Therapy, University of Toronto; Toronto Rehabilitation Institute; and Sunnybrook Research Institute, 2075 Bayview Ave, Room M6-178, Toronto, Ontario, Canada M4N 3M5. Address all correspondence to Dr Mochizuki at: george.mochizuki@sunnybrook.ca.

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Background. Balance impairments after traumatic brain injury (TBI) are common and persist after injury. Postural asymmetries in balance have been reported, but not quantified, across recovery.

Objective. The objective of this study was to characterize balance recovery after moderate to severe TBI, with a focus on postural asymmetry.

Design. A secondary analysis of prospectively collected data was used in this study.

Methods. Data were from 45 participants with moderate to severe TBI. Participants' balance in 2 bipedal stances and 2 unipedal stances was assessed with force plates at approximately 2, 5, and 12 months after injury. Single-visit data from participants who were matched for age and served as healthy controls were collected for visual comparison using 95% confidence intervals. Spatial and temporal center-of-pressure (COP) measures were calculated from force plates in the anteroposterior (AP) and mediolateral (ML) directions.

Results. Despite improvements in net ML COP postural sway from 2 to 5 months after injury, there were no changes in AP postural sway across recovery. Postural sway in individuals with TBI was higher than normative values at all time points in both directions. Interlimb synchrony did not change across recovery in either direction. TBI weight-bearing asymmetry was lower than normative values at all time points and did not change across recovery. The characteristics of unipedal stance differed between limbs.

Limitations. Sample size was reduced as a result of the inclusion and exclusion criteria; future studies will benefit from a larger sample size.

Conclusions. The absence of recovery in ML COP postural sway, interlimb synchrony, and weight-bearing symmetry indicated that reduced ML control may contribute to balance impairments after TBI. These impairments may extend to dynamic balance tasks and may also place individuals with TBI at a higher risk for falls.

Traumatic brain injury (TBI) is among the leading causes of disability in North America.[1] Balance control—that is, maintaining one's center of mass within the base of support—is impaired after TBI.[2] These impairments persist years after injury, particularly in individuals with more severe TBI.[3] Previous studies of balance control after moderate to severe TBI characterize balance impairments at different stages of recovery or employ cross-sectional comparisons of balance measures to those of healthy controls or to normative values. These studies report impairments in balance at the acute and chronic stages after injury.[4–9]

Longitudinal examinations of balance impairment after injury are sparse. One study showed that postural sway improved across the first 3 months of injury.[9] One longitudinal study examining postural stability over a 2-year recovery window reported improvement in balance using the Romberg test;[2] however, no longitudinal studies employing posturographic outcomes to quantitatively measure balance have been conducted beyond the first months of injury.[9] Thus, it remains unclear whether continued balance recovery might be observed in the later stages of injury (ie, after 4 months) when more sensitive outcomes are employed.

Typically, posturographic analyses report net measures of control (contributions of both limbs) as their primary outcome.[4,9,10] Net measures of balance quantify postural sway in the anteroposterior (AP) and mediolateral (ML) directions, reflecting ankle and hip motion control, respectively.[11] Although net postural sway quantifies overall balance control, it lacks specificity with regard to the individual limb contributions to control.[12] This is important considering evidence that unilateral motor weakness and asymmetrical stance persist following TBI.[13–15] The extent of asymmetry in balance control has not yet been quantified. Because TBI may contribute to asymmetrical balance, which is linked to elevated fall risk in other neurologically injured populations,[16,17] it is important to characterize recovery trajectories in the context of asymmetry.

Between-limb center-of-pressure (COP) synchronization (the spatial and temporal relationships between the COP of both feet) is a sensitive measure of balance control during static standing in healthy adults[12,18] and adults after stroke.[17,19–21] In individuals with stroke, synchronization is reduced and temporally offset during standing balance tasks.[19] Single leg standing may also be an indicator of unilateral weakness or impairment. Because both bipedal and unipedal stances are used in functional balance assessments in other neurologic populations across recovery to identify underlying balance deficits,[22,23] they may also identify postural asymmetries after TBI.

The purpose of this study was to characterize the recovery trajectory of balance control across the first year of TBI with a focus on measures of postural asymmetry. Given the apparent association between brain injury and postural asymmetry, it was hypothesized that individuals with TBI would demonstrate postural asymmetry on measures of symmetry, including interlimb synchrony, stance load symmetry, and postural sway and time in unipedal stance. Because balance has demonstrated recovery over time using observational outcomes, it was also hypothesized that net balance measures would improve over the course of recovery and measures of postural asymmetry would improve across recovery.

Methods

Participants with TBI

Data were obtained from the database of a larger, ongoing prospective longitudinal study of cognitive and motor recovery in people with moderate to severe TBI, for which motor (posturographic) assessments were undertaken at approximately 2, 5, and 12 months after injury, in the Toronto Rehab Traumatic Brain Injury Recovery Study.[24,25] Participants for the larger study were recruited from an urban acquired brain injury program. Inclusion criteria were as follows: diagnosis of moderate to severe TBI on the basis of the lowest Glasgow Coma Scale score of 12 or less (determined at the scene of the accident or in the emergency department on the day of injury), posttraumatic amnesia of 1 day or more, or both conditions; recovered from posttraumatic amnesia by 6 weeks after injury; between 18 and 80 years old; able to use at least 1 upper extremity; and able to follow commands in English. Exclusion criteria were as follows: history of TBI or other neurological disorder and history of psychotic disorder. For the present study, an additional inclusion criterion was the completion of all 3 motor assessments (ie, at 2, 5, and 12 months after injury). Throughout the larger study, different technologies were used to assess balance. Initially, assessments were conducted on a single force plate. Later, assessments were conducted on dual force plates in order to obtain data from each individual limb. Consequently, an exclusion criterion for the present study was the use of mixed force plate techniques (ie, single *and* dual force plates) across different time points for an individual participant. For example, a person assessed with 1 force plate at 2 months and 2 force plates at 5 months, 12 months, or both would be excluded. Another exclusion criterion was the presence of lower extremity orthopedic injury, as determined by a physical therapist and an occupational therapist.

Instrumented balance assessments were completed in 97 of 139 participants with clinically confirmed TBI in the larger study. Fifty-one of these individuals completed all 3 balance assessments using *either* a single force plate *or* dual force plates. Of these, 6 were excluded for lower extremity orthopedic injuries. Therefore, 45 individuals with TBI were included in the analysis, with 14 and 31 participants completing balance assessments exclusively with a single force plate and dual force plates, respectively. Individuals recruited to the study received the normal standard of care. For inpatients, this care included a combination of physical therapy, occupational therapy, speech therapy, or a combination of these. Following discharge from the inpatient program, many patients continued to receive clinical services, as per clinical need and

Table 1.
Demographics of Participants With Traumatic Brain Injury (TBI) and Participants Who Served as Healthy Controls (HC)[a]

Demographic	Participants With TBI	Participants Who Served as HC
Sample size (men/women)	45 (36/9)	22 (10/12)
Age, y	43.2 (17.3)	36.6 (13.8)
Years of education	14.5 (3.2)[b]	17 (3.4)
Mass, kg		
T1	74.1 (13.5)	69.6 (12.8)
T2	78.7 (14.3)[c]	
T3	82.0 (15.9)[c,d]	
FIM score at discharge,[e] median (range)	119 (91–126)	
Severity of TBI[f]		
Moderate	1	
Severe	9	
Very severe	23	
Extremely severe	7	
CB&M Scale score,[g] out of 96, median (range)		
T1	65 (15–95)	
T2	74 (29–95)[c]	
T3	78 (27–95)[c]	

[a]Data are reported as group means (standard deviations) unless otherwise indicated. CB&M = Community Balance and Mobility; FIM = Functional Independence Measure; T1 = 2 months after injury; T2 = 5 months after injury; T3 = 12 months after injury.
[b]Significant difference between HC and TBI groups at $P < .05$.
[c]Significant differences from T1 value within individuals with TBI at $P < .05$.
[d]Significant differences from T2 value within individuals with TBI at $P < .05$.
[e]Data were obtained from 39 of the 45 participants with TBI.
[f]TBI severity was characterized on the basis of posttraumatic amnesia in 40 of the 45 participants with TBI.
[g]Data were obtained from 44 of the 45 participants with TBI.

availability. An age-matched group of 22 individuals were recruited from the university and local community to serve as healthy controls (HC) and were assessed on 1 occasion. All participants (or their substitute decision makers) provided informed consent for the original study. The present study was approved by the Research Ethics Board at the Toronto Rehabilitation Institute. Demographic and injury characteristics are presented in Table 1.

Study Design

A secondary analysis of prospectively collected data was used in this study. Within-subjects analysis was used to characterize recovery over time. The primary balance-related outcome measures included root-mean-square (RMS) of the net (both feet combined) COP in the AP and ML directions, cross-correlation of the COP in the AP and ML directions (all in bipedal stance), unipedal stance time, and RMS in unipedal stance.

Data Collection and Procedures

Posturographic (force plate) and clinical measures of balance (Community Balance and Mobility [CB&M] Scale)[26] were assessed at approximately 2 months (T1), 5 months (T2), and 12 months (T3) after injury. The CB&M Scale is a 13-item tool (scored out of a total of 96) that was specifically developed to evaluate balance and mobility in individuals with TBI.[26] A higher score on the CB&M Scale indicates better balance. Data were collected using either a single-force-plate (AccuSway) or a dual-force-plate (both from Advanced Mechanical Technology, Inc, Watertown, Massachusetts) arrangement.

For single-force-plate assessments, participants placed both feet on 1 force plate. For dual-force-plate assessments, the plates were positioned with the y-axes in parallel and separated by 1 mm. Participants placed 1 foot on each force plate. For both the single- and dual-force-plate arrangements, participants stood in 2 bipedal and 2 unipedal conditions: standardized position (heel centers 0.17 m apart and long axis of the foot angled at 14°)[27] with eyes open (EO) and eyes closed (EC), and unipedal stance with the right leg and the left leg. For all bipedal conditions, participants were instructed to stand quietly for 45 seconds looking straight ahead (with no visual cues). A 45 second period was used to ensure sample duration reliability[28,29] while reducing the risk of muscle fatigue and falling. For unipedal stances, participants were instructed to maintain their balance without touching the ground as best as possible for 30 seconds. Rest breaks were provided between each condition or when needed. All conditions were assessed in a single session. Ground-reaction forces and moments from each plate were sampled at 50 Hz. The sampling rate for all assessments was kept consistent regardless of whether the single- or dual-force-plate arrangement was used. HC data were collected at 1 time point for all balance tasks for visual comparison. The order of test conditions was the same for all participants (bipedal EO, EC; unipedal right, left).

Data Processing and Analysis

Ground-reaction forces and moments were filtered with a low-pass filter (10 Hz) using a fourth-order dual-pass Butterworth filter prior to processing. In bipedal stance, the net COP was calculated and the RMS of the AP and ML COP time series was quantified. Interlimb synchrony was measured by calculating the cross-correlation function between the left and right mean-removed AP and ML COP waveforms. Interlimb synchrony was defined by the cross-correlation coefficients at zero phase-lag [$R_{xy}(0)$], calculated at incremental phase-shifts defined by the sampling rate by iteratively shifting the right limb COP forward and backward in time over the entire length of the record.[20] The magnitude of the coefficient (range: − 1.0 to 1.0) illustrates the strength of correlation of the COP time series.

Weight-bearing symmetry was calculated using 2 measures. Stance load symmetry was defined as a ratio of the vertical force applied onto 1 force plate, relative to the sum of the vertical forces applied onto both force plates. This was determined for both the left and right side. Absolute stance load symmetry was defined as the stance load symmetry ratio of the less-loaded limb (regardless of whether it was the left or right side).[19]

Unipedal stance time and RMS were used to characterize asymmetry in weakness and postural instability, respectively. Time in unipedal stance was calculated as the time from foot lift off to the first drop down contact if the participant could not sustain the full 30 seconds. RMS during unipedal stance was only calculated for the duration over which participants maintained a unipedal standing position. All balance data were processed using MATLAB R2014a (MathWorks, Natick, Massachusetts).

Data Analyses

Statistical analyses were performed using SPSS v23.0 (IBM SPSS Statistics, Armonk, New York). To test the hypothesis that net measures of balance (net AP and ML COP RMS) would improve across the 3 time points, a series of 3 × 2 two-way analyses of variance (ANOVAs) were conducted to assess the main effects of time (T1, T2, T3) and condition (EO, EC). A 1-way ANOVA was used to probe the effect of time on the CB&M Scale. To test the hypothesis that postural symmetry would improve across time points, a series of 3 × 2 two-way ANOVAs was conducted to analyze the effects of time and condition on features of the $R_{xy}(0)$ in the AP and ML directions. Because the $R_{xy}(0)$ values are bounded by values of − 1 and 1, a Fisher transform was applied. Hypothesis testing for improvement in postural symmetry over time also included paired *t* tests to determine whether stance load symmetry was different between the left foot and the right foot at each time point, and a 3 × 2 two-way ANOVA was conducted to analyze the effects of time and condition on absolute stance load symmetry. The final probe of the hypothesis of improved symmetry over time, as measured by unipedal standing duration and AP and ML RMS, was a series of 3 × 2 within-subjects ANOVAs with time and leg as factors.

Data were log-transformed if the values were not normally distributed. In cases where the assumption of sphericity was not met, Greenhouse-Geisser values were reported. Statistical significance was set at $P < .05$ with a Bonferroni adjustment in multiple comparisons.

Secondary Analyses

To understand the relationships between interlimb synchrony and postural sway and between interlimb synchrony and absolute stance load symmetry in individuals with TBI, Spearman correlations between $R_{xy}(0)$ and COP RMS and between $R_{xy}(0)$ and absolute stance load symmetry were determined.[19]

Role of the Funding Source

Equipment and space were funded with grants from the Canada Foundation for Innovation, Ontario Innovation Trust, and Ministry of Research and Innovation. O. Habib Perez was supported by ONF-REPAR and Ontario Student Opportunity Trust Funds. The Toronto Rehab Traumatic Brain Injury Recovery Study was supported by CIHR (MOP-86704), PSI (12-43), and NSERC (458054). R.E. Green holds a Tier 2 Canada Research Chair in Traumatic Brain Injury and Cognitive Rehabilitation Neuroscience. The funders played no role in the design, conduct, or reporting of this study.

Results

Demographic Characteristics

Demographic information for individuals with TBI and HC are presented in Table 1. Individuals with TBI were assessed, on average, at 64.7 (SD = 28.1) days (T1), 156.2 (SD = 36.5) days (T2), and 401.5 (SD = 60.6) days (T3) after injury. There was no significant difference between individuals with TBI and HC in age ($t_{51.0} = 1.7$; $P > .05$; $d = 0.42$) or mass ($t_{65} = 1.3$; $P > .05$; $d = 0.34$) at T1. A significant increase in mass within individuals with TBI across time ($F = 42.6$; $df = 1.3,61.5$; $P < .001$; partial $\eta^2 = 0.49$) from T1 to T2 ($P < .001$) and from T2 to T3 ($P < .001$) was observed. The HC group completed more years of education than did individuals with TBI ($t_{64} = -3.0$; $P = .004$; $d = 0.77$).

Clinical Measures of Balance

Analysis of the CB&M Scale identified a significant effect of time ($F = 31.8$; $df = 1.6,62.0$; $P < .05$; partial $\eta^2 = 0.46$). Bonferroni post hoc tests identified that the improvements in clinical balance measures were statistically significant only between T1 and T2 ($P < .001$) and between T1 and T3 ($P < .001$). There was no statistically significant difference between T2 and T3 ($P > .05$).

Net Measures of Balance (Bipedal COP RMS)

The 3 × 2 ANOVA demonstrated that there were no changes across recovery in AP RMS; however, ML RMS decreased across time. There was a significant within-subjects reduction in the measure of ML RMS across time ($F = 4.32$; $df = 1.6,66.7$; $P = .024$; partial $\eta^2 = 0.10$) for individuals with TBI. Bonferroni adjusted post hoc analysis

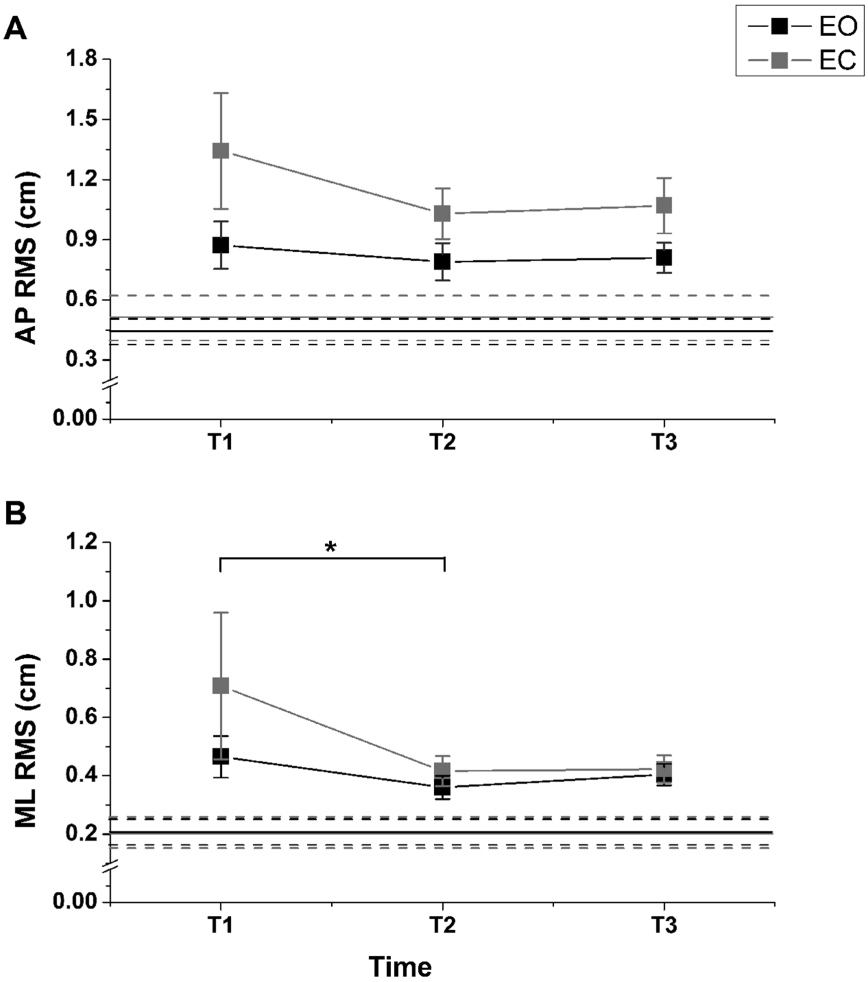

Figure 1.
Anteroposterior (AP) (A) and mediolateral (ML) (B) root-mean-square (RMS) group means and standard errors for individuals with traumatic brain injury (TBI) across recovery in eyes-open (EO) (black squares) and eyes-closed (EC) (dark gray squares) conditions. Solid and dashed lines represent means and 95% confidence intervals for center-of-pressure RMS in healthy controls in each condition, respectively. The asterisk denotes a significant difference across time (2 months after injury [T1] and 5 months after injury [T2]) for individuals with TBI at $P < .05$. T3 = 12 months after injury.

identified a significant reduction for the ML RMS from T1 to T2 ($P = .015$). There was a significant condition effect in AP RMS, with individuals with TBI producing greater RMS with EC than with EO ($F = 55.0$; $df = 1{,}42$; $P < .001$; partial $\eta^2 = 0.57$). Figure 1 demonstrates the results for individuals with TBI and normative ranges for HC. AP and ML RMS for individuals with TBI fell outside the HC ranges at all time points.

Measures of Asymmetry

Interlimb COP temporal synchrony. Interlimb synchrony did not change across recovery in either the AP or ML direction; there were no significant effects of time for AP $R_{xy}(0)$ and ML $R_{xy}(0)$ (Fig. 2A and B) ($P > .05$). A significant condition effect was found in AP $R_{xy}(0)$ ($F = 14.9$; $df = 1{,}27$; $P = .001$; partial $\eta^2 = 0.36$), and approaching significance for ML $R_{xy}(0)$ ($P = .058$). AP $R_{xy}(0)$ with EC was significantly higher than that with EO. AP interlimb synchrony in individuals with TBI was within the normal range for HC; however, mean ML interlimb synchrony in individuals with TBI was outside the range for HC with EO.

Weight-bearing symmetry. Paired *t* tests within the TBI cohort demonstrated that there were no stance load asymmetries between the left and right limbs ($P > .05$) at each time point. Absolute stance load symmetry did not significantly change across recovery for individuals with TBI ($P > .05$), and there were no significant differences between EO and EC ($P > .05$). However, individuals with TBI at all time points fell outside the HC ranges in both EO and EC across their recovery (Fig. 3).

Unipedal stance. Of the 31 participants whose data were collected on dual force plates, 2 participants were unable to complete unipedal stance at T1 and were excluded from the within-subjects ANOVAs. Unipedal stance duration demonstrated asymmetries in individuals with TBI (Fig. 4A). A significant main effect of time ($F = 10.1$; $df = 2{,}56$; $P < .001$; partial $\eta^2 = 0.27$) and leg ($F = 6.3$; $df = 1{,}28$; $P = .018$; partial $\eta^2 = 0.18$) was observed. The left leg maintained a significantly longer duration in unipedal stance in comparison to the right leg ($P = .018$). Bonferroni adjusted post hoc analysis demonstrated that individuals with TBI significantly improved unipedal stance duration between the first 2 time points ($P < .001$); however, time in unipedal stance showed a trend toward deteriorating at T3 ($P = .067$). Unipedal stance duration in individuals with TBI fell outside the HC range throughout their recovery. Asymmetries in individuals with TBI were not identified in unipedal stance RMS. The 3×2 within-subjects ANOVA revealed no significant main effects of time or between leg in AP and ML RMS in individuals with TBI ($P > .05$) (Fig. 4B and C).

Secondary Analyses

Secondary analyses revealed moderate correlations between AP $R_{xy}(0)$ and ML COP RMS and between ML $R_{xy}(0)$ and ML COP RMS. Reduced AP $R_{xy}(0)$ was significantly associated with greater ML RMS across all 3 time points, with the strongest relationship at T1 ($r = -0.55$; $P = .002$) (Tab. 2). Increased ML $R_{xy}(0)$ was significantly correlated with lower ML RMS at T1 and T2. There were no

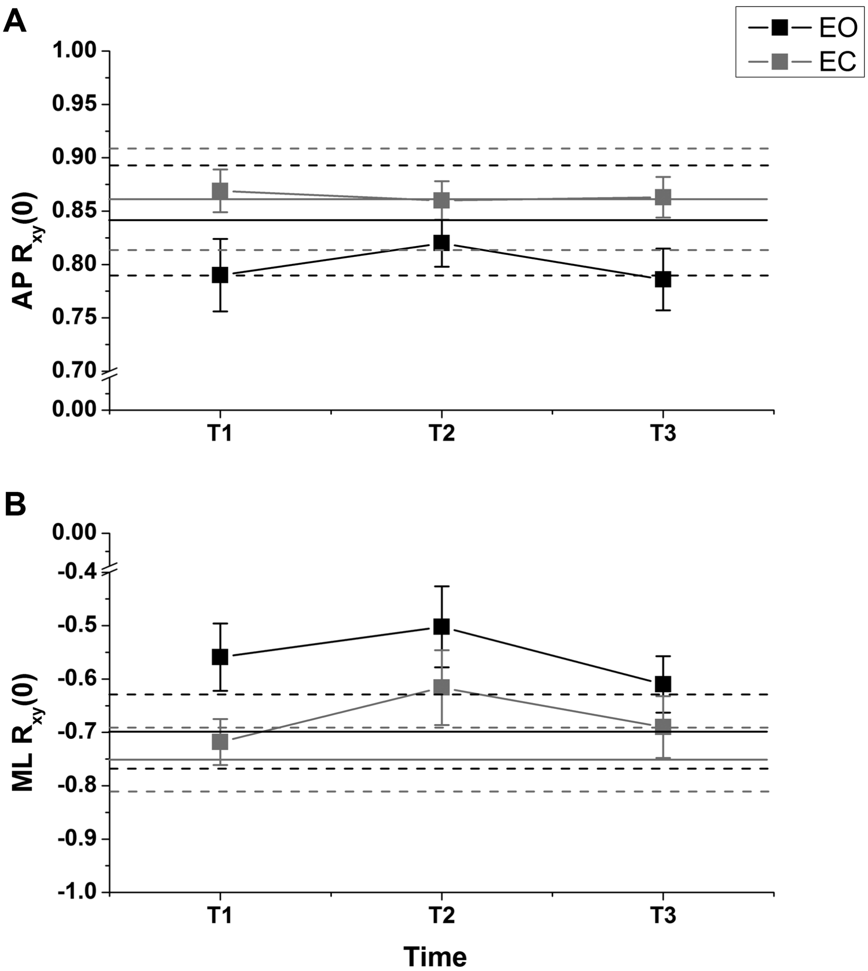

Figure 2.
Anteroposterior (AP) (A) and mediolateral (ML) (B) interlimb synchronization [$R_{xy}(0)$] group means and standard errors for individuals with traumatic brain injury across recovery in eyes-open (EO) (black squares) and eyes-closed (EC) (dark gray squares) conditions. Solid and dashed lines represent means and 95% confidence intervals for $R_{xy}(0)$ in healthy controls in each condition, respectively. T1 = 2 months after injury; T2 = 5 months after injury; T3 = 12 months after injury.

statistically significant relationships between AP RMS and either AP or ML $R_{xy}(0)$. Absolute stance load symmetry did not demonstrate any statically significant relationships with AP or ML $R_{xy}(0)$.

Discussion

This study characterized balance control across recovery after TBI with a focus on quantifying postural asymmetry. In partial support of the hypothesis, improvements were observed from 2 to 5 months of injury in the ML direction. However, net measures of balance in the AP direction did not improve across recovery in individuals with TBI. Absolute stance load asymmetry, ML interlimb synchrony and unipedal stance time were outside of normative data ranges. In contrast to the study hypothesis, postural asymmetry measures did not improve across recovery. Overall, the findings indicate that some balance impairments do improve from 2 to 5 months following moderate to severe TBI, though not between 5 and 12 months after injury.

Balance Improvement Within the First 5 Months After TBI

Overall ML balance control (measured by ML RMS) improved from T1 to T2 after injury. Additionally, functional balance and mobility (on the CB&M Scale) improved from T1 to T2 but plateaued from T2 to T3. Consistent with previous studies,[2,9] the greatest improvements occurred within the first 5 months after TBI. Net ML postural sway is controlled by hip abductors/adductors, and reflects the ability to load and unload vertical force from 1 limb to another.[12] Thus, the central nervous system may prioritize the reduction ML RMS to increase stability and reduce fall risk.[30] Tightened AP sway resulting from increased ML sway has been reported after the onset of Parkinson disease.[31] Increased ML sway is also associated with reduced occipital and cerebellar brain volume in individuals with right cerebral artery infarctions.[32]

These findings differ from studies comparing individuals with concussion to healthy controls, which report increased COP in the AP direction, the ML direction, or both.[33–35] These differences could be accounted for by differences in the foot position used across studies. The present study employed a standardized foot position based on the average position for preferred stance in 262 adults.[27] In contrast, other studies have the feet closer together, in parallel, or both.[33–35] Both conditions reduce the size of the base of support and increase postural challenge, resulting in increased COP. These differences may also reflect variability based on the severity or mechanisms of injury. Indeed, the present study found greater AP and ML RMS values than Geurts et al,[4] but similar values to that of Brauer et al,[10] in which there was greater similarity in TBI severity.

Unipedal stance time improved in individuals after TBI, increasing by approximately 10 seconds from T1 to T2. This suggests improvements in strength and postural steadiness in both limbs.[36] Unipedal stance is commonly included in clinical balance assessments and is associated with increased fall risk.[37,38] Previous studies examining unipedal stance duration after moderate to severe TBI report reduced duration in patients with chronic TBI[39] and unipedal stance time similar to that of T2 in the present

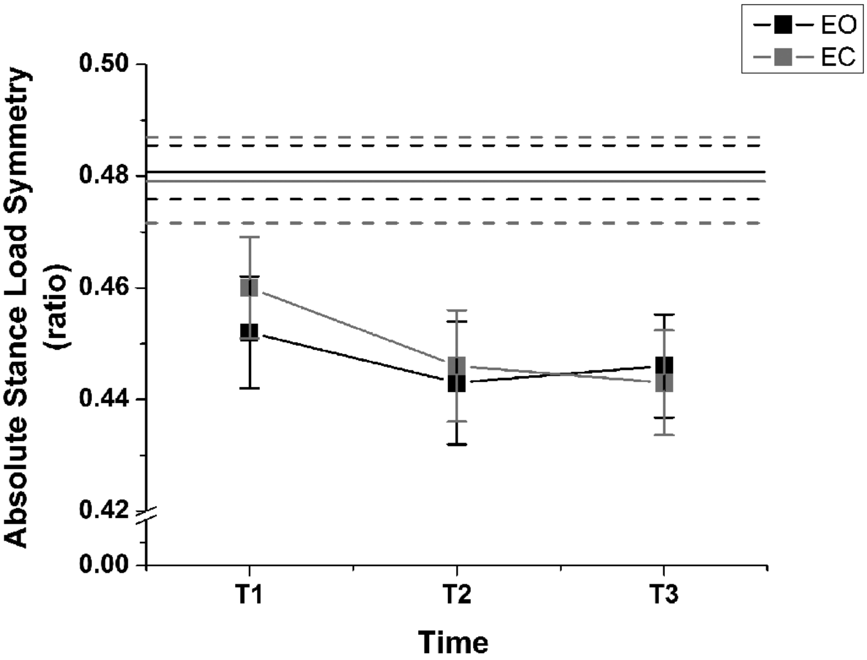

Figure 3.
Absolute stance load symmetry (ratio for the less loaded limb), depicted as group means and standard errors for individuals with traumatic brain injury across recovery in eyes-open (EO) (black squares) and eyes-closed (EC) (dark gray) conditions. Solid and dashed lines represent means and 95% confidence intervals for the absolute stance load symmetry ratio in healthy controls in each condition, respectively. T1 = 2 months after injury; T2 = 5 months after injury; T3 = 12 months after injury.

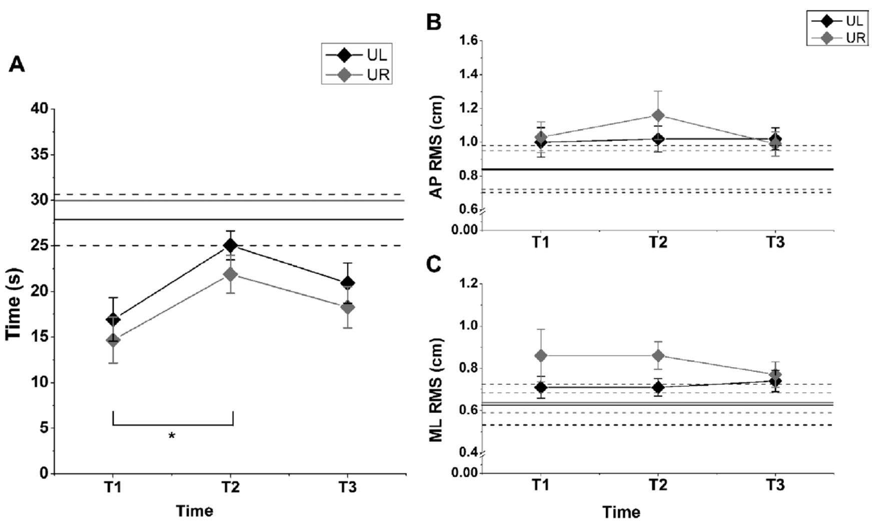

Figure 4.
(A) Time in unipedal stance in left leg (UL) (black diamonds) and right leg (UR) (dark gray diamonds), depicted as group means and standard errors for individuals with traumatic brain injury (TBI) across recovery. (B and C) Anteroposterior (AP) (B) and mediolateral (ML) (C) root-mean-square (RMS) group means and standard errors for individuals with TBI across recovery in left leg (UL) (black diamonds) and right leg (UR) (dark gray diamonds). The asterisk denotes significant differences between T1 (2 months after injury) and T2 (5 months after injury) in individuals with TBI. Solid and dashed lines represent means and 95% confidence intervals in healthy controls in each condition, respectively. T3 = 12 months after injury.

study.[40] Unipedal stance time is associated with mobility,[39] and thus may be an important assessment during the course of recovery.

In contrast to our hypotheses, measures of balance control focusing on postural asymmetry in bipedal stance did not change across recovery. Though interlimb synchrony in the AP and ML direction did not improve after injury, the secondary analyses revealed that AP and ML interlimb synchrony was linked to ML postural sway. Similar findings have been noted in individuals after stroke.[19] In TBI, the relationship between interlimb synchrony and postural sway suggests that temporal decoupling of the plantar flexors of the left and right legs is linked to poor ML balance control. Additionally, lower interlimb synchronization may be related to greater corrective motions of proximal joints rather than distal joints.[19]

Absolute stance load symmetry did not improve. Unlike the previous study,[19] the present study did not identify a relationship between interlimb synchrony and weight-bearing asymmetry. These variables are sensitive to postural asymmetry in neurological populations with hemiparesis[17] and spasticity;[20] however, others also report initial improvements in the first 6 months, followed by plateau at 12 months and a subsequent decline by 24 months after stroke.[41] The commonalities between the present and previous studies suggest that improvements within the first 5 months of recovery in overall balance and unipedal stance time corresponds and may be primarily attributed to features of inpatient and outpatient rehabilitation,[9] spontaneous recovery, or both.[42]

Asymmetry After TBI

This study found that weight-bearing asymmetry exists after TBI, with the least vertically loaded foot bearing 44% of total body weight. In comparison to HC (48%), absolute stance load symmetry was lower in individuals with TBI at all time points, indicating a subtle but substantial postural asymmetry. Importantly, absolute stance load symmetry is lower in individuals after stroke ranging from 40% to 45%.[17,19,20,41]

Table 2.
Relationship Between Interlimb Synchronization [$R_{xy}(0)$] and Standing Balance Measures[a] for Eyes-Open Condition[b]

Parameter	AP $R_{xy}(0)$	ML $R_{xy}(0)$
AP COP RMS		
T1	0.082 (.67)	−0.053 (.79)
T2	0.27 (.14)	−0.17 (.36)
T3	0.14 (.46)	−0.19 (.31)
ML COP RMS		
T1	−0.55 (**.002**)	0.49 (**.007**)
T2	−0.40 (**.027**)	0.49 (**.005**)
T3	−0.40 (**.026**)	0.28 (.13)
Absolute stance load symmetry		
T1	0.20 (.30)	−0.22 (.25)
T2	0.10 (.58)	−0.22 (.25)
T3	0.28 (.13)	−0.009 (.96)

[a]Standing balance measures were center-of-pressure (COP), root-mean-square (RMS), and absolute stance load symmetry.
[b]Data are reported as Spearman correlation coefficients (associated *P* values). Statistically significant *P* values are shown in bold type. AP = anteroposterior; ML = mediolateral; T1 = 2 months after injury; T2 = 5 months after injury; T3 = 12 months after injury.

Weight-bearing asymmetry may reduce postural stability for dynamic balance control.[43] Though postural asymmetry has been observed after TBI prior to postural perturbations,[14] in static balance through a greater lateral COP position,[7] and during bimanual lifting,[44] the extent of asymmetry after TBI has not been quantified. Postural asymmetry after TBI underscores the balance deficits that exist in this population.

Cross-correlation analysis [$R_{xy}(0)$] revealed poor to good interlimb synchrony. ML interlimb synchrony in individuals with TBI fell outside the HC range, similar to observations in individuals after stroke.[17,19,20] Arce et al[44] found poor interlimb vertical force amplitude coupling in the heels and fore-feet during bimanual load lifting after TBI. The authors suggested that because of an absence of simultaneous weight shifting from the heel to forefoot and back in both limbs in individuals with TBI, postural gain control in vertical force is impaired after TBI.[44] The observed stance load asymmetry and poor interlimb synchrony in the present study supports the notion that postural gain control may be impaired after TBI. Although the mean AP interlimb synchrony fell outside the HC 95% confidence interval, the range of AP interlimb synchrony (−0.024 to 0.99) from individuals with TBI was greater, demonstrating that some participants with TBI fall outside the normal range for HC (0.54 to 0.98). Poor interlimb synchrony may be related to motor impairment and increased falls, as shown in adults after stroke.[17]

The majority of the analyses characterizing asymmetry in bipedal conditions did not reveal unilateral weaknesses or impairments. In contrast, unipedal stance time identified a weaker or impaired right limb in comparison to the left limb. Additionally, increased unipedal stance RMS in the right leg suggests that the weaker and impaired right limb in individuals with TBI produces greater postural sway. Premorbid leg dominance may have influenced these findings; however, without determining leg dominance for stability tasks,[45] it is unclear whether TBI preferentially affected the dominant limb. Initial dynamic force control within the first 5 seconds of unipedal stance increases force variability[36] and may have contributed to the reduction in unipedal stance time in participants with TBI. We suggest that future studies analyze the dynamic control from bipedal to unipedal stance to understand postural steadiness after TBI.

Study Limitations

Although this study identified postural asymmetry and an absence of improvements across recovery after TBI, there are limitations. Sample size was significantly reduced as a result of the inclusion/exclusion criteria and future studies will benefit from a greater sample size. Changes in body weight may have influenced the quantitative balance measures.[46] However, since premorbid weight was unknown, it is unclear whether weight gain was a return to premorbid weight or related to inactivity after injury.

Clinical Relevance

These findings indicate that postural asymmetry is evident in individuals with moderate to severe TBI. Balance improves over time, but the majority of improvements occur within 5 months after injury. Postural asymmetry may be a mechanism that contributes to asymmetrical weight-bearing and a manifestation of unilateral motor weakness, which has previously been reported in individuals with TBI.[13–15] Thus, examining asymmetry may be a useful tool for assessing balance ability. In the absence of force plates, unipedal stance time may be a simple way of measuring asymmetry. Because increased interlimb synchrony is an indicator of reduced fall risk in the community in other neurological populations,[47] individuals with moderate to severe TBI may benefit from interventions that target asymmetry in balance control to improve the ability to defend against falling. Future studies should specifically probe relationships between asymmetry and fall risk in individuals with TBI.

Conclusion

This study used posturographic measures to examine balance control and postural asymmetry longitudinally out to 1 year after TBI. In spite of initial improvements out to 5 months after injury, poorer performance on a number of outcomes over time indicates that postural asymmetry may contribute to ongoing balance impairments.

Author Contributions and Acknowledgments

Concept/idea/research design: O. Habib Perez, R.E. Green, G. Mochizuki
Writing: O. Habib Perez, R.E. Green, G. Mochizuki
Data collection: O. Habib Perez, R.E. Green
Data analysis: O. Habib Perez
Project management: O. Habib Perez, G. Mochizuki
Providing participants: R.E. Green
Consultation (including review of manuscript before submitting): R.E. Green

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Ethics Approval

The present study was approved by the Research Ethics Board at the Toronto Rehabilitation Institute. All participants (or their substitute decision makers) provided informed consent for the original study.

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Disclosure

The authors completed the ICJME Form for Disclosure of Potential Conflicts of Interest. The authors declared no conflict of interest.

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