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RESEARCH PAPER

Spectral analysis of centre of pressure identifies altered balance control in individuals with moderate-severe traumatic brain injury

Olinda Habib Perez[a,b,c], Robin E. Green[a,c,d] and George Mochizuki[a,b,c,e]*

[a]Rehabilitation Sciences Institute, University of Toronto, Toronto, Canada; [b]Sunnybrook Research Institute, Toronto, Canada; [c]Toronto Rehabilitation Institute, Toronto, Canada; [d]Department of Psychiatry, University of Toronto, Toronto, Canada; [e]Department of Physical Therapy, University of Toronto, Toronto, Canada

ABSTRACT

Purpose: To identify impairments and recovery of balance control after moderate-severe traumatic brain injury (TBI) through spectral analyses of static balance tasks and to characterise the contributions of each limb to balance control.
Methods: A retrospective analysis of longitudinal balance data from force platforms at 2, 5, and 12 months post-injury in 31 individuals with moderate to severe TBI was performed. Single-visit data from age-matched controls ($n = 22$) were collected for descriptive comparison. Net and individual limb centre of pressure measures and inter-limb centre of pressure coherence were calculated in low ($\leq$0.4 Hz) and high ($\geq$0.4 Hz) frequencies in the anteroposterior and mediolateral directions during standing with the eyes open and closed.
Results: Standing with the eyes closed increased net centre of pressure spectral power in low and high frequencies. Individuals with TBI demonstrated recovery in high frequencies in net centre of pressure in the mediolateral direction. Inter-limb coherence in the anteroposterior and mediolateral directions increased (recovered) over time in high frequencies. Weight-bearing asymmetry was visible in high frequencies in the anteroposterior and mediolateral directions.
Conclusions: Increased amplitude of low and high-frequency power suggests that individuals with TBI included in this study have impaired anticipatory and reactive balance mechanisms, which may be driven by weight-bearing asymmetries and which recover over time.

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KEYWORDS
Traumatic brain injuries; postural balance; inter-limb coordination; coherence; frequency analysis

➤ IMPLICATIONS FOR REHABILITATION

- Anticipatory and reactive balance impairments after traumatic brain injury may place individuals at increased risk for falls.
- Analyses from postural sway in static balance tasks infer changes in anticipatory or reactive balance control after traumatic brain injury.
- Addressing weight-bearing asymmetries in rehabilitation interventions post-traumatic brain injury may improve between-limb coordination for anticipatory and reactive balance control.

Introduction

Balance impairments after moderate-severe traumatic brain injury (TBI) are common [1]. In this population, balance impairments lead to increased instability, which elevates fall risk [2–4]. One method of measuring balance impairment is to assess the systems and mechanisms that affect balance control; however, only a few studies have assessed these mechanisms of balance after TBI using quantitative measures [5–10]. These studies have identified recovery of balance after injury, but have determined that simple balance tasks (i.e., standing quietly with eyes open) may not be sufficiently sensitive to reliably detect the full range of persisting balance impairments. Furthermore, while there is evidence indicating that dynamic balance control is impaired after injury [6, 11], evidence is sparse and limited to primarily reactive behaviours. Dynamic control includes elements of both anticipatory and reactive control, and as indicated by Arce et al. [12], both components are impacted by TBI. Because anticipatory and reactive mechanisms facilitate preparation and reaction to postural instability, respectively, it is important to advance understanding of changes that occur in these components of balance given that impairments to them increase risk of falls [2].

Most studies evaluating balance after TBI focus on clinical balance assessments and spatial measures of balance [1,5–13]. However, spectral analyses of balance measures have additional utility in understanding the underlying mechanisms of balance control and may help to better characterise and predict recovery in the TBI patients. Postural sway is generally characterised as consisting of low and high frequencies [14]. Low-frequency components ($\leq$0.4 Hz) are considered to be exploratory [14,15], slow migrations of the centre of pressure (COP) to a reference point by the central nervous system [16], or error corrections to equilibrium [17] useful for feedforward (in contrast to feedback) control [18]. Feedforward control of movement inherently reflects predictive models of behaviour [19,20] and plays a role in anticipatory control mechanisms. Higher frequency components ($\geq$0.4 Hz) are

CONTACT George Mochizuki george.mochizuki@sunnybrook.ca Sunnybrook Research Institute, 2075 Bayview Avenue, Rm M6-178, Toronto, ON M4N 3M5, Canada

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Table 1. Participant characteristics.

	TBI	HC
Sample size	31 (24 M/7 F)	22 (10 M/12 F)
Age	41.9 (16.9)	36.6 (13.8)
Mass (kg)		
T1	73.9 (10.7)	69.6 (12.8)
T2	79.18 (12.3)*	–
T3	81.9 (13.9)*	–
Injury severity (PTA)		–
Moderate	1	–
Severe	6	–
Very severe	16	–
Extremely severe	4	–
CB&M scale		–
T1	65.0 (18.1)	–
T2	78.0 (15.1)*	–
T3	78.7 (14.1)*	–
Years of education	14.60 (3.27)	17.0 (3.4)

Mean and standard deviation (SD) participant demographics of traumatic brain injury (TBI) and healthy control (HC) participants. TBI severity was characterised by the lowest post-traumatic amnesia (PTA) score.

*Denotes significant differences within participants with TBI at $p < 0.05$ from T1 value. Note that PTA severity was obtained from 27 of the 31 participants with TBI.

considered to reflect corrective responses to temporary instability [21], representing reactive control mechanisms [22]. Frequency decomposition of the COP has characterised balance in individuals post-stroke [21–24] and other neurologic populations [25] and may provide insight into the impairments in anticipatory and reactive control mechanisms that may place individuals with TBI at an increased risk of falls.

Typically, balance assessments involve quantifying the overall (net) contributions of both lower limbs to control. While appropriate in conditions where no asymmetries exist, individual foot contributions may provide additional information about the underlying control features in asymmetric conditions [26]. Importantly, previous studies identify persistent unilateral motor weakness and anecdotally report asymmetrical stance after TBI [11,27]. In addition, recent work from our laboratory demonstrates that balance asymmetry and mediolateral inter-limb synchrony in TBI closely resembles that of individuals with stroke [28–30], and may be one factor contributing to increased balance instability after TBI [13]. Balance asymmetry after TBI reflects underlying unilateral motor weakness, and may suggest that the limb with the higher weight-bearing is driving balance control mechanisms. In the spectral domain, balance asymmetry in individuals with neurological impairments has been identified by quantifying the extent of COP coherence, a measurement of correlation of frequency spectra between two time-varying signals, and is a representation of inter-limb coordination [31]. Examining the correlation of the COP frequencies of each limb can identify disorders of the postural system relating to anticipatory and reactive control mechanisms and may be useful in understanding inter-limb coordination in this population.

The purpose of this study was to investigate whether anticipatory and reactive balance impairments exist after TBI by carrying out spectral analyses (power spectral density and coherence) of static balance tasks. To our knowledge, no study has examined how individual foot contributions affect anticipatory and reactive control mechanisms in quiet standing across the recovery of TBI. The following hypotheses were made: First, we hypothesised that spectral measures of net COP would improve across time in individuals with TBI. A testing condition with the eyes closed was also included to increase postural challenge; thus, second, we hypothesised that performing tasks with the eyes closed would increase the amplitude of spectral measures of balance. Despite previous findings where inter-limb synchrony did not change across time [13], third, we hypothesised, that improvements across time in inter-limb coherence in individuals with TBI would be detectable because of increased sensitivity of spectral measures. Finally, we hypothesised that the individual limb applying the most vertical force (i.e., highest weight-bearing) would demonstrate increased COP power spectral density and decrease across recovery.

Methods

Participants

This study involved a secondary analysis of balance data from a larger study of individuals with clinically-confirmed moderate-severe TBI (from *The Toronto Rehab Traumatic Brain Injury Recovery Study*) who were assessed at multiple time points, including the three-time points of this study. Details of the larger study and its inclusion and exclusion criteria have been reported previously [13]. All of the participants were recruited from a large, central, in-patient acquired brain injury programme in Toronto, Canada. At the time of the first of the three time-points of this study, all participants were in-patients in the programme. At the time of the second two time points, all participants had been discharged. This original sample of individuals with moderate-severe TBI was characterised as having more males than females and with injuries resulting predominantly from car accidents and falls, followed by sporting injuries. Additional eligibility criteria for this study were completion of instrumented balance assessments on dual force plates at three-time points, and the absence of lower extremity orthopaedic injuries in either or both extremities, as confirmed by review of acute care and in-patient rehabilitation records by a senior OT and a senior PT with extensive experience in TBI.

Seventy-three participants with TBI completed instrumented balance assessments on dual force plates. Of the 73 participants with TBI, 37 participants were ineligible because of missing balance data at one time-point, and five were ineligible due to lower extremity orthopaedic injuries. Therefore, 31 participants with TBI were included in the analysis. While in-patients during the first time-point of the study, all participants were receiving the normal standard of care for the programme, which typically included 2–3 h of therapy per day comprising physical therapy, occupational therapy, and/or speech therapy as deemed clinically appropriate. Upon discharge, the majority of patients continued to receive out-patient therapy for several months. Patients covered by medical insurance (about 50%) received continued out-patient therapy, typically through the duration of the study and beyond.

A group of age-matched healthy control participants was recruited from the community for descriptive comparison and assessed on one occasion. Healthy control data were used to allow for verification of impaired balance performance of the TBI group at Time 1 of the study. Demographic and injury characteristics of the sample are reported in Table 1. All participants (or a substitute decision maker) provided informed consent. This study was approved by the Research Ethics Board at the Toronto Rehabilitation Institute.

Data collection and procedure

Clinical measures of balance (Community Balance and Mobility (CB&M) scale)[32] and force plate balance tasks were undertaken with participants with TBI at approximately 2-months (T1),

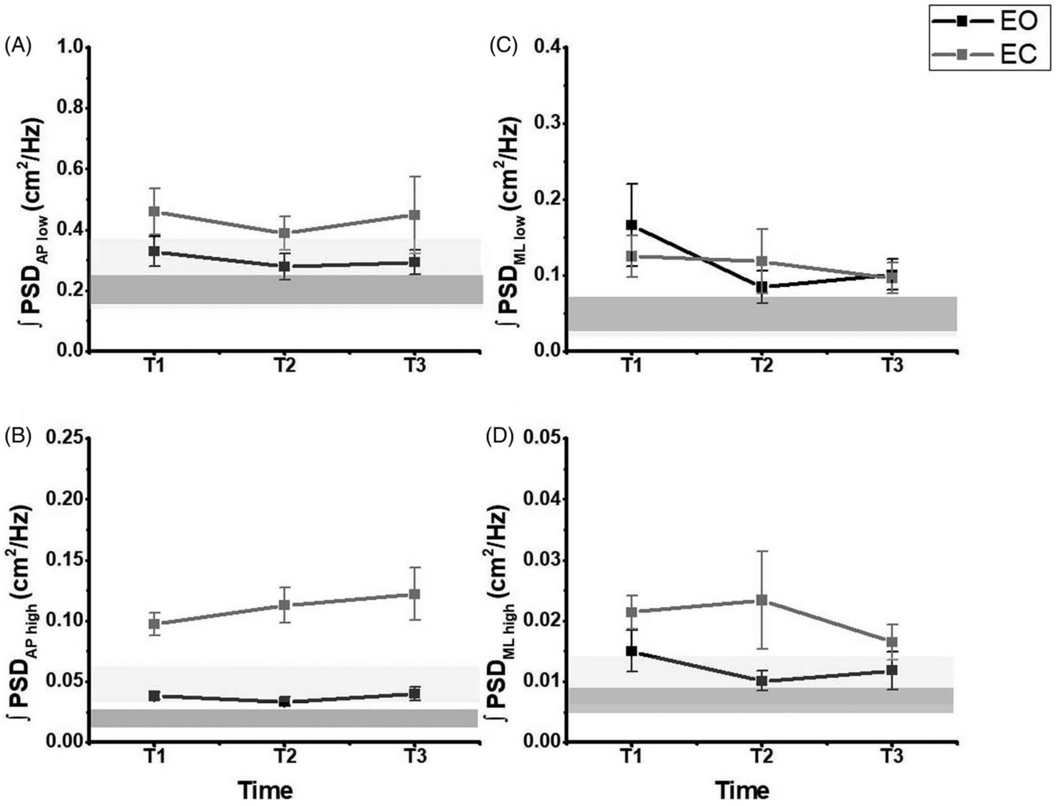

Figure 1. Net center of pressure (COP) mean integral of the power spectral density (PSD) in low (A) and high (B) frequencies in the anteroposterior (AP) direction, and the low (C) and high (D) frequencies in the mediolateral (ML) direction. Group means and standard error for participants with TBI across recovery are displayed for eyes open (EO; black) and eyes closed (EC; grey). The light grey shading and darker grey shading represent the 95% confidence intervals for the net COP mean integral of the PSD in healthy controls for the EC and EO tasks, respectively. Dark grey shading represents the overlap in these intervals.

5-months (T2), and 12-months (T3) post-injury. Data were collected using dual force plates (AMTI, Watertown, MA), positioned with the y-axes in parallel, and separated with by minimal distance (approximately 1 mm). Participants stood with each foot on a separate force plate in two stance conditions: eyes open (EO) and eyes closed (EC). Foot position was standardised with heel centres 0.17 m apart and foot angled at 14° [33]. Participants were instructed to stand quietly for 50 s looking straight ahead. Ground-reaction forces and moments from each plate were sampled at 50 Hz for all participants with TBI. Data from the healthy control participants were collected after the completion of the initial *Recovery Study*.

Data analysis

Ground-reaction forces and moments were low-pass filtered using a fourth ordered dual-pass Butterworth filter with a 10 Hz cut off frequency prior to processing. The net anteroposterior (AP) and mediolateral (ML) COP and the respective time series were calculated for all participants. For the spectral analysis, individual limb and net displacements of the COP were processed by fast Fourier transform. The power spectrum density (PSD) estimation was obtained in Matlab using Welch method with non-overlapping Hanning windows of 5-s data segments. The power spectrum was divided into two frequency bands: low frequency (0–0.4 Hz) and high frequency (0.4–3 Hz). The integral for the low and high-frequency bands was computed using the trapezoidal method. Individual limb COP PSD was calculated and grouped based on the leg with the lowest weight-bearing and highest weight-bearing limb for comparison in the AP and ML direction. Net AP and ML COP PSD were also calculated. Inter-limb coherence estimates were obtained from non-overlapping Hanning windows of 5-s data segments, with a frequency resolution of 0.04 Hz, Coherence analysis included frequencies in the 0–5 Hz range, with frequencies below 0.4 Hz and above 0.4 Hz representing low and high-frequency bands, respectively. In the AP and ML direction, the coherence for each frequency bin in the low and high-frequency bands were averaged accordingly if they exceeded the statistical confidence limit (see below). Inter-limb coherence is expressed as a number between 0 and 1, with 1 indicating a perfect correlation and 0 indicating an absence of a correlation. For each participant, the average coherence in low and high frequencies were transformed using Fisher transformation [34].

Statistical analysis

Statistical analyses were performed using IBM SPSS version 23.0 (Armonk, NY). To test the hypotheses that spectral measures would improve across recovery for participants with TBI and that vision affects balance stability 2 × 3 analysis of variance **(**ANOVA**)**, with Condition (EO, EC) and Time (T1, T2, and T3) as factors, were conducted for AP and ML PSD and inter-limb coherence. Coherence estimates for the low and high frequencies bands were considered statistically significant when they exceeded the confidence limit of 0.283 (derived from 10 non-overlapping windows of 5-s segments) at $\alpha = 0.05$ [35]. To test the hypothesis that the higher weight-bearing limb would demonstrate increased COP power and decrease across recovery, a 2 × 2 ×3 ANOVA was conducted with Foot (lowest weight-bearing and highest weight-bearing), Condition and Time as factors. PSD measures were log transformed to meet assumptions of normality and inter-limb coherence was Fisher transformed. In cases where sphericity was

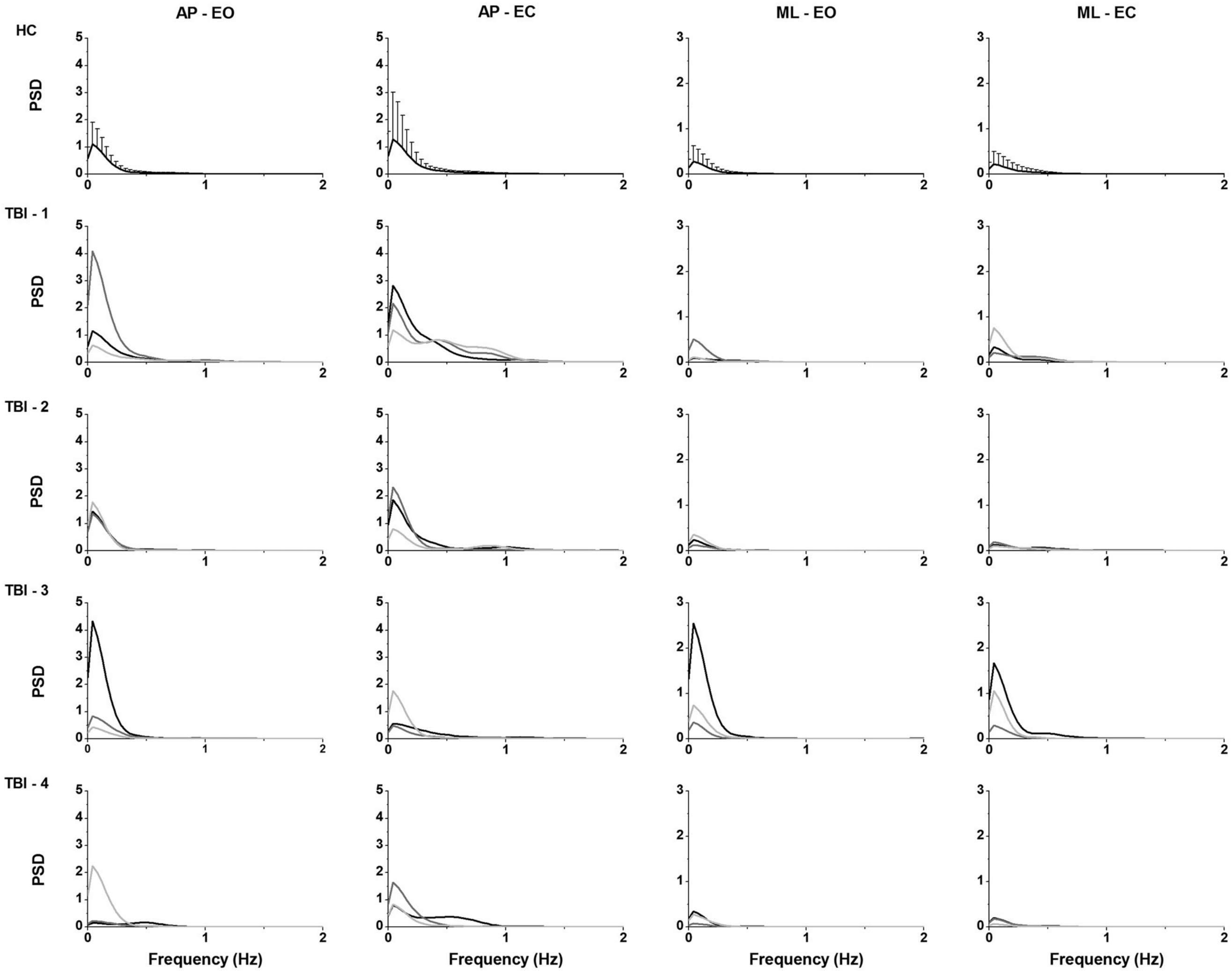

Figure 2. Mean and standard deviation for the net centre of pressure (COP) power spectral density (PSD) for healthy controls in the anteroposterior (AP) and mediolateral (ML) direction for eyes open (EO) and eyes closed (EC) conditions (top row). Individual data net COP PSD from a sample of four participants with TBI across recovery [T1 (black), T2 (grey), and T3 (light grey)] in the AP and ML direction in both EO and EC conditions (row 2–5).

not met, Greenhouse–Geisser values were reported. Statistical significance was set at $p < 0.05$.

Results

Thirty-one participants with TBI completed balance assessments across three-time points post-injury and data from 22 healthy control participants were collected at a single time-point. Neuroimaging identified the injury characteristics of the individuals with TBI as: contusion ($n = 13$), intracerebral haemorrhage ($n = 11$), hematoma ($n = 10$), brain atrophy/encephalomalacia ($n = 8$), skull fracture ($n = 5$), diffuse axonal injury ($n = 5$), oedema ($n = 3$), midline shift ($n = 2$), and intraventricular haemorrhage ($n = 1$). Participants with TBI were assessed on average at 59.8 (SD $= 29.0$), 150 (SD $= 28.9$), and 412 (SD $= 69.3$) days post-injury at T1, T2, and T3, respectively. There were no significant differences in age between groups ($t_{49.8} = 1.3$, $p = 0.22$, $d = 0.42$; Table 1) and no significant differences in mass between the healthy control group and the TBI group at T1 ($t_{49} = 1.3$, $p = 0.204$, $d = 0.36$). There was a significant mass increase of approximately 8 kg in the participants with TBI across the three time points ($F_{1.4,38.9} = 24.1$, $p < 0.001$, partial $\eta^2 = 0.46$), with Bonferroni *post-hoc* tests identifying significant differences between T1 to T2 ($p < 0.001$) and T1 to T3 ($p < 0.001$). The healthy control group completed more years of education in comparison to participants with TBI ($t_{50} = -2.6$, $p = 0.01$, $d = 0.72$).

With regard to clinical recovery, the clinical balance measures (CB&M) showed significant improvements over time ($F_{1.4,38.6} = 26.4$, $p < 0.001$, partial $\eta^2 = 0.49$), specifically between T1 and T2 ($p < 0.001$) and T1 and T3 ($p < 0.001$). There were no significant changes from T2 to T3 (Table 1).

Net COP power spectral density

Net COP PSD in the AP direction at low frequencies and in the AP and ML direction at high frequencies was increased in the eyes closed condition. Additionally, changes across recovery were found for high frequencies in the ML direction. The 2 × 3 ANOVA demonstrated significant effects of Condition for low frequencies in the AP ($F_{1,27} = 20.3$, $p < 0.001$, partial $\eta^2 = 0.429$) direction (Figure 1(A)). Significant effects of Condition were also identified for high frequencies in the AP ($F_{1,27} = 88.9$, $p < 0.001$, partial $\eta^2 = 0.77$) and ML ($F_{1,27} = 31.5$, $p < 0.001$, partial $\eta^2 = 0.54$) direction, with greater net COP power in EC than EO. A significant effect of Time was observed for ML net COP PSD in high frequencies ($F_{2,54} = 7.1$, $p = 0.002$, partial $\eta^2 = 0.21$). Bonferroni-adjusted *post-hoc* tests showed ML net COP PSD in high frequencies was significantly greater in T1 when compared to T2 ($p = 0.03$) and T3

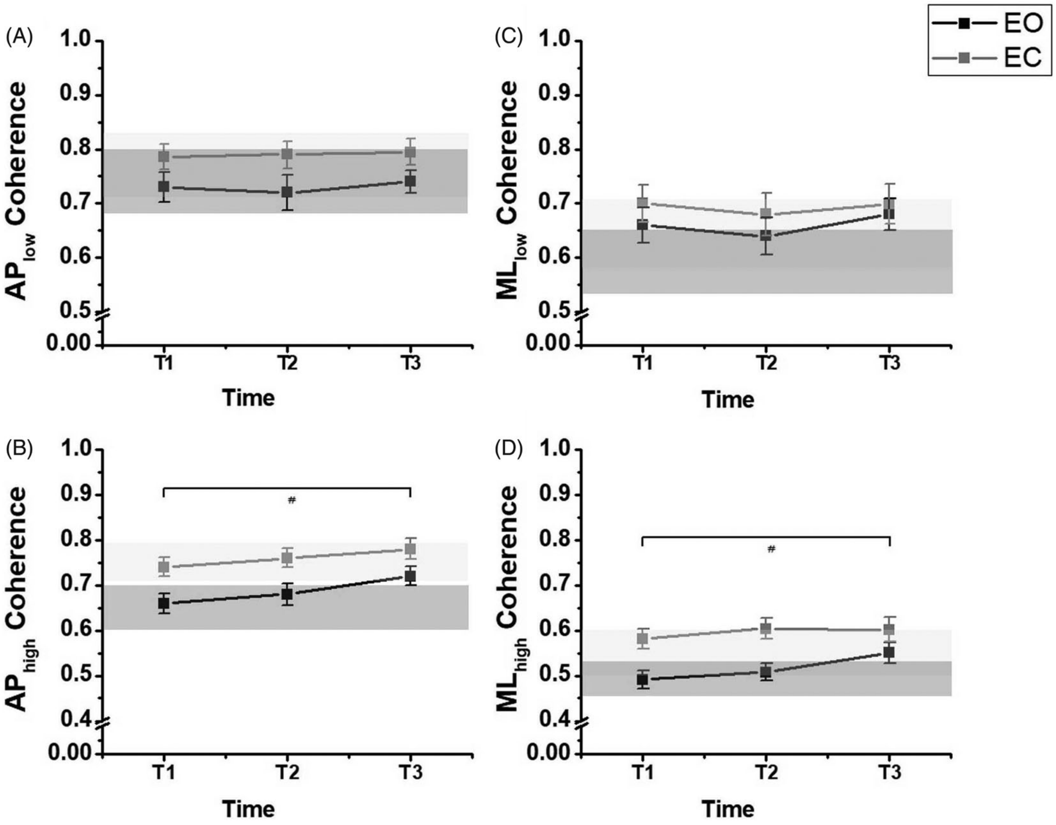

Figure 3. Mean and standard error (SE) anteroposterior (AP) (A) and mediolateral ML (B) inter-limb coherence in low frequencies and AP (C) and ML (D) inter-limb coherence in for high frequencies. Group means and standard error (SE) for participants with TBI are displayed for eyes open (EO; black) and eyes closed (EC; grey) conditions across recovery. The light grey shading and darker grey shading represent the 95% confidence intervals for the mean inter-limb coherence in healthy controls for the EC and EO tasks, respectively. Dark grey shading represents the overlap in these intervals.

($p = 0.01$; Figure 1(D)). No other significant effects of Time were found. In low frequencies, the mean net COP PSD of participants with TBI fell outside the top 95% confidence interval (CI) of healthy controls. In high frequencies, this only occurred in EC. Figure 2 demonstrates the mean PSD for the net COP for healthy controls and a sample of four participants with TBI across recovery.

Inter-limb coordination

Inter-limb coherence

Standing with the eyes closed increased inter-limb coherence in low and high frequencies in the AP direction and in high frequencies in the ML direction. Additionally, inter-limb coherence increased across recovery in high frequencies in both the AP and ML direction (see Figure 3). A main effect of Condition was found in the 2×3 ANOVA for AP coherence for the low ($F_{1,27} = 9.0$, $p = 0.006$, partial $\eta^2 = 0.25$) and high ($F_{1,27} = 31.2$, $p < 0.001$, partial $\eta^2 = 0.54$) frequencies, and for high frequencies in the ML direction ($F_{1,25} = 31.9$, $p < 0.001$, partial $\eta^2 = 0.56$). In addition, high frequencies demonstrated significant effects of Time for AP coherence ($F_{2,54} = 5.8$, $p = 0.005$, partial $\eta^2 = 0.17$) and ML coherence ($F_{2,50} = 3.6$, $p = 0.035$, partial $\eta^2 = 0.13$). Bonferroni-adjusted *post-hoc* tests identified that inter-limb coherence in high frequencies increased between T1 and T3 in the AP ($p = 0.009$) and ML ($p = 0.03$) direction. In the descriptive comparison of AP and ML inter-limb coherence to healthy controls, participants with TBI fell within the 95% CI of the healthy control data.

Individual limb COP

Amplitude of the PSD in the individual limb increased in low and high frequencies in the eyes closed condition in the AP and ML direction (see Figure 4). The high-frequency range in the ML direction demonstrated a trend towards increased PSD amplitude for the foot with higher weight-bearing. Specifically, the $2 \times 2 \times 3$ ANOVA demonstrated a significant main effect of condition with EC producing greater power in low frequencies in the AP direction ($F_{1,27} = 21.0$, $p < 0.001$, partial $\eta^2 = 0.44$), and greater power in high frequencies in the AP ($F_{1,27} = 87.9$, $p < 0.001$, partial $\eta^2 = 0.77$) and ML ($F_{1,7} = 66.1$, $p < 0.001$, partial $\eta^2 = 0.71$) direction. There was no significant Condition effect in the low-frequency PSD in the ML direction ($p = 0.08$). There was no significant effect of foot (i.e., between the lowest weight-bearing and highest weight-bearing) in low or high frequencies ($p \geq 0.075$ for both conditions). With the exception of a few incidences, PSD in low and high frequencies in both the AP and ML direction in participants with TBI primarily fell outside the 95% CI of healthy controls.

Discussion

This study examined whether anticipatory and reactive control mechanisms are impaired after TBI and characterised contributions of each limb to these control mechanisms. Spectral analyses of the COP during quiet standing with eyes open and closed measured changes in balance at three-time points during recovery of TBI. Consistent with the hypotheses, standing with the eyes closed increased net COP measures of balance, inter-limb coherence, and individual foot COP spectral measures. Recovery

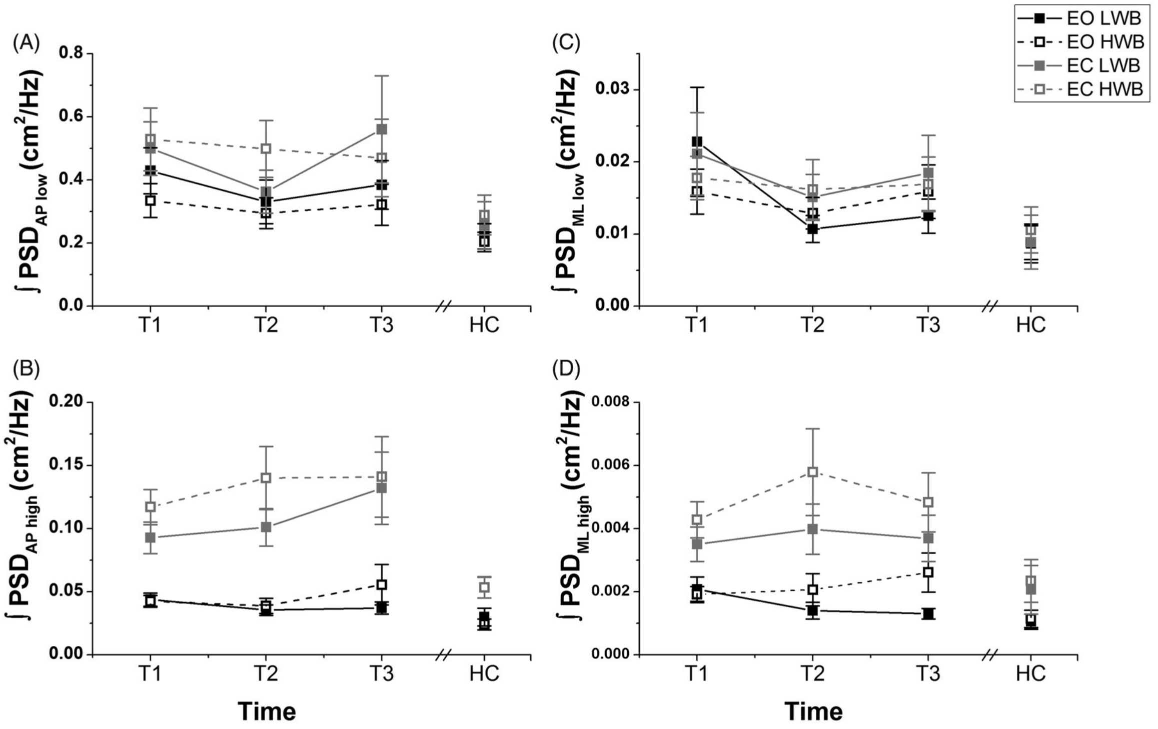

Figure 4. Individual limb center of pressure (COP) mean integral of the power spectral density (PSD) in low (A) and high (B) frequencies in the anteroposterior (AP) direction, and the low (C) and high (D) frequencies in the mediolateral (ML) direction. Group means and standard error for participants with TBI across recovery are displayed across time. Lower weight-bearing (LWB; solid) and higher weight-bearing (HWB; open) limb are represented in eyes open (EO; black) and eyes closed (EC; grey). Group means and 95% confidence intervals (depicted with error bars) are displayed for healthy control data.

changes after TBI were identified in high frequencies in the ML direction. The PSD between the limb that produces the higher and lower weight-bearing were visible in high frequencies in the ML direction. Additionally, inter-limb coherence in the high-frequency range increased in both the AP and ML direction over the course of recovery; but mean values for these data fell within the range of normative data.

Anticipatory and reactive balance control mechanisms are impaired after TBI

This study identified greater low-frequency power of net COP in the AP direction and greater high-frequency power in both the AP and ML direction for participants with TBI. The only improvements observed over the course of recovery were in the high frequencies of the net ML COP. This measure of recovery was primarily driven by performance in the EO condition, as participants with TBI produced greater power in the EC condition at all three-time points compared to 95% CI of healthy controls. This suggests that overall control of anticipatory and reactive balance mechanisms may be impaired after TBI and do not improve unless visual information is present.

The effects of removing vision on balance control have been previously studied [36,37]. This manipulation increases sway, especially in the AP direction because of the direction in which visual or optic flow information is processed [38–40]. Distinct frequency intervals have been linked to sensory systems used by postural control systems, suggesting that the visual, vestibular, and somatosensory/proprioceptive system are associated with low ($<$0.3 Hz), middle (0.3–1 Hz) and high ($>$1 Hz) frequencies of sway, respectively [25,41–43]. Identifying anticipatory and reactive balance control mechanisms using low and high frequencies in this study does not completely align to previous reports. Balance control, both anticipatory and reactive, requires the use of the multiple sensory systems [44–46] and it may be inaccurate to suggest that individual frequency intervals are solely used by the associated sensory system [47]. Some studies suggest that an impaired vestibular system contributes to balance deficits post-TBI [1,5]; however, disruption of vestibular system function has been shown to affect postural sway frequencies that span the 0.25–5 Hz range [48,49]. Given that the majority of observed differences between healthy controls and participants with TBI were found in the eyes closed condition, it is possible that both the somatosensory and vestibular system were impaired in our sample and individuals post-injury were thus further reliant on visual information in both low and high frequencies. If verified, such over-reliance on visual processing could provide an explanation for some of the increased mental fatigue experienced by patients with moderate-severe TBI. It is also possible that brain regions that integrate multiple sensory modalities [50,51] were injured, thus impacting the ability to accurately process incoming multi-modal sensory information.

These findings advance understanding of the characteristics of anticipatory and reactive balance control after TBI. A previous study demonstrated age-appropriate sway amplitudes and slightly higher latencies in unpredictable feet-in-place reactions after TBI [11], while poor postural gain control has been found in self-initiated bimanual load-lifting post-TBI [12]. It has been postulated that impaired anticipatory neural circuits lead to delayed reaction times and increased variability in movement control [52–54]. Preparation for balance instability and the latencies and amplitude of postural reactions are imperative for dynamic balance control [55–58]. This results corroborate findings of previous studies and suggest that anticipatory and reactive balance mechanisms were impaired. This may contribute to the increased risk of falls that is observed in people with TBI [3]. Further studies are needed to understand the components of dynamic balance control to address balance specific impairments post-TBI.

Inter-limb coordination after TBI

Inter-limb coordination was analysed using coherence analysis to identify frequencies of the COP under each foot that were correlated [31]. Although inter-limb coherence improved across time points, group means fell within the 95% CI of healthy controls. Inter-limb coherence in the AP and ML direction increased at high frequencies, suggesting that the relationship between limbs in frequencies that correspond to reactive balance control increases out to one year after injury. Previous work from our laboratory in healthy controls has demonstrated that inter-limb coordination requires decoupling in preparation for unpredictable perturbations [59]. Although inter-limb coherence in participants with TBI did not differ from healthy controls in either low or high frequencies, the increased coherence at high frequencies suggests an inappropriately high level of coupling between limbs, with respect to reactive balance control mechanisms. Poor inter-limb vertical force amplitude coupling during bimanual load lifting has been found after TBI [12]. Moreover, poor inter-limb synchrony in the ML direction has been found post-TBI, resembling the levels of synchrony observed in stroke patients [13]. Inter-limb coherence is a relatively novel analysis for postural asymmetry and has shown sensitivity in other neurologically-impaired populations. Individuals with Huntington's disease produced reduced inter-limb coherence compared to healthy young and older adults [31]. The absence of descriptive differences found in this study between TBI and healthy controls may be attributable to differences in the way in which "significant" coherence was identified. This study applied a statistical confidence limit to quantify coherence, similar to what has been used in other physiological studies [35], while Myklebust et al. [31] did not. The use of confidence limits removed low coherence values from the analysis in the individuals with TBI.

Inter-limb coordination in this study was also analysed using weight-bearing asymmetry categorisation. Although asymmetry in high frequencies did not reach statistical significance in the ML direction, previously reported weight-bearing asymmetry after TBI [13] may contribute to the descriptive differences observed between the TBI group and healthy controls, affecting reactive balance mechanisms. Weight-bearing asymmetry reduces postural stability for dynamic balance control [60]. Interestingly, the limb with the higher weight-bearing in this study displayed means much greater than the 95% CI of healthy controls in both the eyes open and eyes closed conditions at high frequencies. Individuals post-stroke that demonstrated a reduced ability to recover from balance also displayed greater COP amplitude of high frequencies in standing balance [22]. This finding suggests that the imbalance in weight-bearing symmetry may be driving the amplitude of power of the higher weight-bearing limb in frequencies that are important for reactive balance control. The findings suggest that TBI patients are less likely to recover from balance perturbations. Thus, these findings may further explain the specific mechanisms of increased risk of falls in TBI.

The role of the postural challenge

This study used an eyes closed condition to increase the postural challenge. In line with our hypothesis, spectral measures demonstrated significant main effects of condition with higher COP power in eyes closed within the TBI group. Other studies have demonstrated that performing concurrent cognitive-balance tasks reveal balance impairments after TBI [61]. This suggests that a postural challenge may be more sensitive at detecting balance impairments in individuals with TBI. As an example, adding a mental arithmetic task increases overall frequency of the COP in the AP direction [62]. The findings of this study revealed that spectral measures demonstrated that participants with TBI fall outside the 95% CI of healthy controls more frequently. Thus, increasing postural challenge through eyes closed conditions or *via* a secondary cognitive task may help to provide greater insights into the balance impairments after TBI, especially in the more chronic stages of injury when balance impairments are more subtle.

Taken together, these findings offer novel ideas regarding the putative underlying mechanisms of balance control problems in TBI patients in the sub-acute and chronic stages of injury that warrant further research. As both anticipatory and reactive balance control may be compromised in moderate-severe TBI, research and ultimately clinical interventions will need to focus on restorative and compensatory approaches for both types of control difficulty. The findings suggest that balance difficulties are more readily revealed when patients are not able to use their vision to compensate, suggesting an important assessment modality (i.e., "eyes-closed" balance conditions) for clinicians. Moreover, the findings suggest that in those with balance impairments, deficits may manifest more prominently in those with compromised vision or in conditions where vision is compromised (i.e., low-light conditions or at bed-time when supports for correcting vision [i.e., glasses, contact lenses] may have been removed). If verified, patient management could include education in this regard.

Conclusions

In this sample of patients with moderate-to-severe TBI, net COP power was elevated in comparison to that observed in healthy controls at both low and high frequencies. This is interpreted as indicating alterations in anticipatory (low frequency) and reactive (high frequency) control after TBI. Additionally, high-frequency measures, which represent reactive control mechanisms, were largely affected in inter-limb coordination measures. High-frequency measures also demonstrated recovery over time. These findings may demonstrate an improvement in reactive balance control over time in individuals with TBI. Further research is needed into anticipatory and reactive balance control in this population to confirm or disconfirm these findings.

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Disclosure statement

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