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Abstract

Gait initiation is a useful surrogate measure of supraspinal motor control mechanisms but has never been evaluated in a cohort following concussion. The aim of this study was to quantify the preparatory postural adjustments (PPAs) of gait initiation (GI) in fifteen concussion patients (4 females, 11 males) in comparison to a group of fifteen age- and sex-matched controls. All participants completed variants of the GI task where their dominant and non-dominant limbs as the 'stepping' and 'support' limbs. Task performance was quantified using the centre of pressure (COP) trajectory of each foot (computed from a force plate) and the centre of mass (COM) trajectory (estimated from an inertial measurement unit placed on the sacrum). Concussed patients exhibited decreased COP excursion on their dominant foot, both when it was the stepping limb (sagittal plane: 9.71mm [95% CI: 8.14 to 11.27mm] vs 14.9mm [95%CI: 12.31 to 17.49mm]; frontal plane: 36.95mm [95% CI: 30.87 to 43.03mm] vs 54.24mm [95%CI: 46.99 to 61.50mm]) and when it was the support limb (sagittal plane: 10.43mm [95% CI: 8.73 to 12.13mm] vs 18.13mm [95%CI: 14.92 to 21.35mm]; frontal plane: 66.51mm [95% CI: 60.45 to 72.57mm] vs 88.43mm [95%CI: 78.53 to 98.32mm]). This was reflected in the trajectory of the COM, wherein concussion patients exhibited lower posterior displacement (19.67mm [95%CI: 19.65mm to 19.7mm]) compared with controls (23.62mm [95%CI: 23.6 to 23.64]). On this basis, we conclude that individuals with concussion display deficits during a GI task which are potentially indicative of supraspinal impairments in motor control.

Keywords	brain concussion [MeSH]; gait [MeSH]; biomechanics [MeSH]; kinetics [MeSH]; postural balance [MeSH].

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Original article

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ABSTRACT

Gait initiation is a useful surrogate measure of supraspinal motor control mechanisms but has never been evaluated in a cohort following concussion. The aim of this study was to quantify the preparatory postural adjustments (PPAs) of gait initiation (GI) in fifteen concussion patients (4 females, 11 males) in comparison to a group of fifteen age- and sex- matched controls. All participants completed variants of the GI task where their dominant and non-dominant limbs as the 'stepping' and 'support' limbs. Task performance was quantified using the centre of pressure (COP) trajectory of each foot (computed from a force plate) and the centre of mass (COM) trajectory (estimated from an inertial measurement unit placed on the sacrum).

Concussed patients exhibited decreased COP excursion on their dominant foot, both when it was the stepping limb (sagittal plane: 9.71mm [95% CI: 8.14 to 11.27mm] vs 14.9mm [95%CI: 12.31 to 17.49mm]; frontal plane: 36.95mm [95% CI: 30.87 to 43.03mm] vs 54.24mm [95%CI: 46.99 to 61.50mm]) and when it was the support limb (sagittal plane: 10.43mm [95% CI: 8.73 to 12.13mm] vs 18.13mm [95%CI: 14.92 to 21.35mm]; frontal plane: 66.51mm [95% CI: 60.45 to 72.57mm] vs 88.43mm [95%CI: 78.53 to 98.32mm]). This was reflected in the trajectory of the COM, wherein concussion patients exhibited lower posterior displacement (19.67mm [95%CI: 19.65mm to 19.7mm]) compared with controls (23.62mm [95%CI: 23.6 to 23.64]). On this basis, we conclude that individuals with concussion display deficits during a GI task which are potentially indicative of supraspinal impairments in motor control.

Key words: brain concussion [MeSH]; gait [MeSH]; biomechanics [MeSH]; kinetics [MeSH]; postural balance [MeSH].

1. Introduction

Concussion assessment has undergone an evolution in recent years (Doherty et al., 2017; Johnston, Doherty, Buttner, & Caulfield, 2017). The traditional clinical assessment of concussion was initially based on a grading scale of injury severity, and this has evolved to become a multifaceted assessment of patients' function in an individualised manner (McCrory et al., 2013). Indeed contemporary assessment of concussion now includes a multimodal evaluation of symptoms, cognition and motor function (Register-Mihalik, Littleton, & Guskiewicz, 2013).

The evaluation of motor function following concussion has been limited to static postural control (Powers, Kalmar, & Cinelli, 2014) and continuous gait (Parker, Osternig, P, & Chou, 2006) tasks. However, it remains unclear how concussion may affect motor tasks of dynamic balance such as gait initiation.

Initiation of gait requires preparatory postural adjustments (PPAs) to stabilise the postural perturbation induced by a forthcoming voluntary movement (Bouisset & Do, 2008). As such, evaluation of gait initiation (GI) may be useful for understanding whether concussion impairs the PPAs needed to execute the transition from standing posture to cyclic gait (Halliday, Winter, Frank, Patla, & Prince, 1998). To date however, no data are available on motor performance during GI in a population with a history of concussion.

GI is achieved by PPAs that first shift the centre of pressure (COP) posteriorly and laterally. This process enables the centre of mass (COM) of the body to accelerate anteriorly and contra-laterally to the stepping limb (Ledebt, Bril, & Breniere, 1998). These events occur before any observable movement of the feet (Ledebt et al., 1998). The COP then moves

medially from its posterior and lateral position toward the stepping foot, during which there is corresponding movement of the vertical projection of the COM. Finally, the COP transitions to the support foot as the individual takes their first step. This corresponds with the initial double support phase of the first step, and ends with toe-off of the support foot.

Optimal performance during GI is represented by an efficient transition from static stance to cyclic gait with minimisation of the risk associated with this volitional perturbation on controlled stability; it is underpinned by both the movement of the COP during GI and the corresponding movement of the COM of the body.

Quantification of PPAs is typically achieved using force plates and camera-based systems in gait analysis laboratories. Recently however, inertial measurement units (IMUs) which contain accelerometers and/or gyroscopes have provided an interesting alternative to obtrusive and expensive laboratories for gait and balance assessment (Horak & Mancini, 2013; Mancini, Zampieri, Carlson-Kuhta, Chiari, & Horak, 2009) including the analysis of GI (Mancini et al., 2009; Martinez-Mendez, Sekine, & Tamura, 2011).

Recently published research has demonstrated impaired PPAs during GI in patients with impairment of the central nervous system as evidenced by decreased velocity and magnitude of COP displacement (C. J. Hass, Waddell, Fleming, Juncos, & Gregor, 2005; C. J. Hass, Waddell, Wolf, Juncos, & Gregor, 2008). However, little is known about the effect of concussion on GI.

Therefore, the purpose of this investigation was to investigate whether patients who were symptomatic following concussion exhibit altered PPAs during a GI task, as determined with IMU and COP outcomes. We hypothesised that concussion patients would exhibit impaired PPAs during GI (decreased magnitude of COP displacement [measured with a force plate], and COM displacement [measured with an IMU]).

2. Methods

2.1 Participants

The recruitment site used for the present investigation was a university affiliated hospital emergency department 'concussion-clinic'. This clinic manages a caseload patients across the full spectrum of concussion severity: those with acute concussion in whom symptoms resolve within what is considered an 'acceptable' timeframe of 7-10 days (McCrory et al., 2005), and those with persistent symptoms that extend beyond this.

Fifteen patients were recruited at convenience from the clinic, within 1-month of sustaining a concussion. The diagnosis of concussion was made by a hospital physician and was consistent with that of the latest international expert consensus definition (McCrory et al., 2013) as an injury caused by a direct blow to the head, face, neck, or elsewhere in the body resulting in impaired neurological function and clinical symptoms.

After evaluation at the ED, prospective subjects were informed about the study and provided written permission (parent/guardian permission if a subject was younger than 18 years) for study investigators to relay detailed study information via telephone contact. If participants were interested, they provided informed consent.

A convenience sample of fifteen age- and sex- matched 'healthy' participants were also recruited and tested. These controls (parent/guardian if a participant was younger than 18 years) were informed about the study via posters and flyers placed in the catchment area of the hospital, wherein they were provided with details to contact investigators if they chose. All prospective participants were interviewed; provided they met the study inclusion and exclusion criteria, they were considered eligible for enrollment. The following exclusion criteria were adopted for all participants: 1) any lower extremity injury that may affect gait; 2) history of cognitive deficiencies; 3) history of ≥3 previous concussions (to ensure

exclusion of those with chronic mild traumatic brain injury (Howell, Osternig, & Chou, 2013); 3) loss of consciousness following the concussion for >1 minute (McCrory et al., 2013); a previously documented concussion in the previous year. Participant demographics for each group are provided in Table 1. The institutional review board of the university and that of the hospital approved the study protocol. All subjects and parents/guardians (if a subject was younger than 18 years) provided written consent to participate in the study.

2.2 Questionnaires

The extent of self-reported impairment was quantified using the graded symptom scale checklist component of the SCAT3 (McCrory et al., 2013). The Short-Form-36 (SF-36) was utilized to assess perceived general health status (Ware & Sherbourne, 1992).

2.3 Protocol

Data acquisition was completed in the University Biomechanics Laboratory. Participants were tested in the barefoot condition and were instructed as to the correct protocol for GI task completion; they were allowed a number of practice trials for familiarization. Participants began all trials of GI standing in a relaxed position on two adjacent walkway-embedded force plates [AMTI (Watertown, MA)] with their feet "hip width" apart and their hands by their sides. Participants then began walking in response to an auditory cue and continued along the 10-m walkway at their normal, comfortable pace. The auditory cue triggered an event marker which signaled the beginning of the trial for further analysis. Three trials of GI were completed for both the dominant and non-dominant limbs. For this investigation, the dominant limb was defined as that which the individual would use to "kick a ball as far as possible". The order in which participants completed the task (i.e. stepping first with their dominant or non-dominant limbs) was randomized.

2.4 Data acquisition

Prior to completion of the GI task, all participants were instrumented with three 3D inertial sensors (Shimmer 3, Dublin, Ireland) containing accelerometers (±8g) and gyroscopes (±1000°/s) along the three orthogonal axes in frontal, sagittal and transverse planes of motion. The sensors were placed at the posterior aspect of the sacrum at the level of the posterior superior iliac spines and the anterior portion of each leg-shank 5cm above the lateral malleoli by the same investigator for every participant.

Based on the 3D linear accelerations, angular rates and angular positions were extracted at a sampling frequency of 102.4Hz from the sensors and sent wirelessly via a Bluetooth link to an Android Tablet (AndroidOS:4.3(Jelly Bean)) using a Multi Shimmer Sync For Android® v2.5 appliance. Custom scripts in Matlab (Mathworks, Natick, MA) were then used to first filter the sensor position and angular data with a fourth-order, low-pass Butterworth filter with cutoff frequency of 4 Hz, and then the second order derivative of the positional and angular data with respect to time to yield linear (ML and AP) and angular acceleration of the sensor.

Vertical forces under each force plate were used to calculate the position of the COP. Kinetic data were sampled at 100 Hz using the force-plate. The kinetic data time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency.

The filter cut-offs were chosen on the basis of preliminary analyses of the signal spectrum from a pilot dataset, which revealed predominance in the lower frequencies and the noise in the higher frequencies. On this basis, custom scripts in R programming language were used to filter the COP, sensor position and angular data with a fourth-order, zero phase, low-pass

Butterworth filter with a cut-off frequency of 5 and 4 Hz respectively.

2.5 Data analysis

The COP on the force plates was defined by the arithmetic means of the antero-posterior and medio-lateral time-series relative to the origin of the force platform. This normalised COP trace was divided into 3 periods for the both the stepping and support limbs (C. J. Hass et al., 2005).

Period 1 commenced with the auditory cue and ended with the COP located in its most medial position toward opposing foot (event 1); period 2 represents the movement of the COP from this medial position to its most posterior and lateral position (event 2); period 3 extends from event 2 until toe-off as the COP translates forward.

An R algorithm was developed to characterize PPAs during GI from 3D accelerometer and gyroscope signals of the IMUs worn on the legs and trunk. First the two gyroscope (ML) signals of the leg sensors and the two linear acceleration signals (ML and AP) that captured by the trunk sensor were filtered with a fourth-order, zero phase, low-pass Butterworth filter with cutoff frequency of 4 Hz. Following this pre-processing step, the algorithm was designed to identify a series of PPA measures following calculation of the trunk accelerations and the computed centre of mass (COM) (Pai & Patton, 1997) : 1) peak resultant accelerations (AP and ML); 2) peak displacement (AP and ML) of the COM.

A representative trajectory of the COM and COP trajectories during the GI task are presented in figure 1.

2.6 Statistical analysis

Total score on the SF36, in addition to scores on its sub-sections were compared between the concussion and control groups using multivariate analysis of variance. The p-value for this analysis was set a-priori at $p<0.05$.

Separate two-way between-groups multivariate analyses of variance was performed to investigate differences between concussion and control participants during the GI task for the COP- and COM-based outcomes. The dependent variables related to the COP trajectory were peak excursions in the anteroposterior (AP) and mediolateral (ML) directions and the peak resultant COP (AP and ML) excursions. The dependent variables related to the IMU placed on the sacrum were its resultant accelerations (AP and ML) and the magnitude of the displacement of the COM in the AP and ML directions. Group (concussion vs control), task (stepping first with the dominant limb or non-dominant limb) and limb (dominant vs non-dominant) were included as independent variables in the COP analysis. Only group and task were included as independent variables in the COM analysis.

3. Results

All participants in the concussion group were symptomatic at the time of testing (on the basis of the graded symptom scale checklist of the SCAT3). The average number of days since the concussive injury was nine and the range was between 3-27days.

3.1 Self-reported outcomes

Regarding the questionnaire results (SF36 and graded symptom scale of the SCAT3), there was a statistically significant main effect for the combined dependent variables, $F(10,20) = 3.8$, $p < 0.01$, Wilks' Lambda = 0.33, $\eta p^2 = 0.67$.

The concussion group reported significantly lower scores (indicating poorer perceived general health) in total SF36 score and a number of its sub-sections. The concussion group also reported a greater number of more severe symptoms on the graded symptom scale

checklist of the SCAT3. The results of this analysis (with means and standard deviations) are presented in Table 2.

3.2 COP outcomes

There was a statistically significant effect for group ($p = 0.001$) and limb ($p < 0.001$). A statistically significant interaction was also observed task*limb ($p < 0.001$). Based on our primary objective, we focused on the results of the dependent variables for group main effect; the only variable to reach statistical significance, using a Bonferonni adjusted alpha level of .01, was the peak magnitude of the COP excursion in the posterior direction ($p = .001$; $\eta_p^2 = 0.1$), and the total ML excursion of the COP ($p < .001$; $\eta_p^2 = 0.16$). Due to the task*limb interaction, we evaluated the mean scores for the peak magnitude of the COP excursion in the posterior direction and the total ML excursion of the COP separately for the variants of the task (whether they were stepping first with their dominant or non-dominant limbs) and the limb involved (dominant or non-dominant limb). This was achieved via a series of t-tests comparing concussion vs control. Due to our previous statistical correction to control for type 1 error, the p-value for these analyses was not adjusted for multiple comparisons and was set at $p < 0.05$.

This post hoc analysis revealed that concussion patients exhibited decreased peak magnitude of the COP excursion in the posterior direction on their dominant foot, both when the dominant foot was the stepping limb and when it was the support limb. They also displayed a reduction in the total magnitude of the ML excursion of the COP. Again, this finding was specific to the dominant foot, both when it (the dominant foot) was the stepping limb and when it was the support limb. The mean values (with 95% confidence intervals) for the dependent variables delineated by group, task and limb are presented in Table 3. A representative schematic of these results is displayed in Figure 2.

3.3 COM outcomes

There was a statistically significant effect for group only ($p < 0.001$;). Two variables reached statistical significance, using a Bonferonni adjusted alpha level of .01: the resultant acceleration of the IMU in the AP plane ($p = .001$; $\eta_p^2 = 0.05$) and the magnitude of the COM excursion in the AP plane ($p < .001$; $\eta_p^2 = 0.07$).

Inspection of the mean scores with associated 95% confidence intervals delineated by task revealed that the concussion group exhibited decreased resultant acceleration in the AP plane, both when the dominant foot was the stepping foot, and when it was the support limb. Concussed patients also displayed a reduction in the magnitude of the COM displacement in the AP plane. Again, this finding was specific to the dominant foot, both when it (the dominant foot) was the stepping limb and when it was the support limb. The mean values (with 95% confidence intervals) for the COM dependent variables delineated by group, task and limb are presented in Table 4.

4. Discussion

The principle finding of the current investigation is that patients with a recent concussion demonstrate impaired PPAs during a GI task. This was determined via two data acquisition techniques, one of which is considered a 'gold standard' method of postural control assessment (the COP from a force plate), and the other which is an emerging technology in this field (trunk acceleration and COM displacement via an IMU) (Wu et al., 2002). More specifically, it was identified that concussed patients exhibit a reduction in the normalised magnitude of the posterior displacement of the COP on their dominant limb, both when it was the stepping limb and when it was the support limb. This coincided with a smaller total ML excursion in both instances. These findings were reflected by the IMU placed at the trunk, which elucidated a reduction in the resultant acceleration in the AP plane for the concussion group, with a coinciding reduction in the COM displacement. There was also a trend of a

decrease in the magnitude of the COM and COP displacements in the ML plane for concussion patients, although these did not reach significance based on the a priori alpha in our multivariate statistical model.

The value of using two technologies to measure what is essentially the same construct (PPA for GI) is that one (the force plate) qualifies the other (the IMU) as a potentially valid mechanism by which motor control deficits may be assessed (Mayagoitia, Lotters, Veltink, & Hermens, 2002). This is important due to the high cost and extensive resources necessary to acquire and process the force plate data. In contrast, IMU technologies are clinically accessible, with the potential to bring the objective assessment of motor control deficits following concussion 'to the masses' (Horak & Mancini, 2013).

GI is fundamentally a voluntary transition between two 'automated' modes of movement: static posture and cyclic gait. As such, GI necessitates feedforward control of a series of PPAs in the modulation of this transition. These PPAs are typically deconstructed into a series of three periods on the basis of a battery of COP 'events' (C. J. Hass et al., 2005). The COM that was calculated from the IMU data followed a similar trajectory, albeit with the observation that the discreet events that were so clear in the COP trajectory were not so for the COM; this is likely a product of a series of kinematic determinants which produce a smooth, undulating pathway of translation of the COM as part of the commencement of human locomotion (Saunders, Inman, & Eberhart, 1953).

The instant prior to the first contact of the stepping foot is recognized as the most challenging event for stability control during gait initiation (Chang & Krebs, 1999), and is predicated by the above described events/periods. While the GI process is only completed when the body reaches a constant walking speed (Gormley, Barr, Bell, Ravey, & Mollan, 1993), we limited our analysis to the start of GI. The initial posterior shift of the COP during GI is necessary to

generate forward motion by propelling the COM away from the support limb to the stepping limb (C. Hass, Bishop, Doidge, & Wikstrom, 2010). The magnitude of this posterior displacement has been shown to decline naturally with age (Polcyn, Lipsitz, Kerrigan, & Collins, 1998), but is also associated with disability (C. J. Hass et al., 2005; C. J. Hass et al., 2008). The principle finding of the current investigation that the group with concussion exhibited reduced displacement of both the COP and COM therefore demonstrate that this injury is associated with negative alterations in supraspinal aspects of motor control. The aberrancies were present for both variants of the GI task (whether it was the dominant or the non-dominant limb taking the first step) for the COM. In contrast, only the dominant limb displayed the aforementioned aberrancies on the basis of the COP trace. We postulate two potential reasons for this. First, it is possible that we did not have the statistical power to accommodate the greater variability that seemed to coincide with the metrics that were extracted for the non-dominant limb (greater variability was evident for the outcomes on the non-dominant limb compared with the dominant limb). Alternatively, the dominant limb may be the primary 'anchor' in the completion of GI and as such, the deficits that exist may be unique to it. Fundamentally however it is unclear as to why the COP deficits were dominant-limb specific, based on the available data.

To our knowledge, this the first investigation to quantify GI in a cohort of concussion patients, and should encourage further research into the possibility of utilising GI as a means to quantify motor control deficits in this population and their recovery. Indeed, the novelty of the study provokes a series of questions that cannot be answered. First, is it possible that increasing 'cognitive load' through a dual task protocol would further alter the PPAs of GI in symptomatic concussion patients in comparison to controls? This can only be answered with further research into GI in concussed populations. Second, do COP and COM trajectories during GI coincide with the extent of the concussion associated impairment? Importantly,

there was substantial heterogeneity in the concussion cohort regarding the timeframe since injury, the average number of days being 9 (since the concussive event occurred) but the range was 3-27days. Therefore, while it is plausible to deduce on the basis of the current findings [and other recently published material (D. Howell, L. Osternig, & L. S. Chou, 2015; D. R. Howell, L. R. Osternig, & L. S. Chou, 2015)] that complete recovery may not occur within the generally accepted timeframe of 7-10 days (McCrory et al., 2005), it remains unclear exactly how the impairments in GI materialize following concussion. As such, the clinical applicability of these findings is limited, due to the design of the study (cross-sectional) and the heterogenous nature of the concussion sample of participants with regards to their 'time-since-injury'. However, it is worth considering that it may be more relevant to base the evaluation of individuals with a history of concussion on the presence/absence of symptoms, rather than their 'time-since-injury'. In this regard, the concussion cohort evaluated in the present study is representative of the wide spectrum of concussion severity as it included those in whom symptoms were persistent and resolved within 7-10 days. Still, a longitudinal analysis is necessary to ascertain whether GI performance is associated with the resolution of symptoms, and whether the identified deficits are clinically meaningful.

In conclusion, this study has elucidated that individuals with concussion display deficits during a GI task comparable to those which have previously been established in populations with impairment (C. J. Hass et al., 2005; Okada, Fukumoto, Takatori, Nagino, & Hiraoka, 2011), musculoskeletal injury (C. Hass et al., 2010) and an increased risk of falling (Khanmohammadi, Talebian, Hadian, Olyaei, & Bagheri, 2015). It is therefore plausible that concussion is associated with PPAs during GI which may be representative of negative alterations in supraspinal aspects of motor control, as demonstrated by the decreased magnitude of both the COP and the COM in the transition from static standing posture to cyclic gait in the concussion group.

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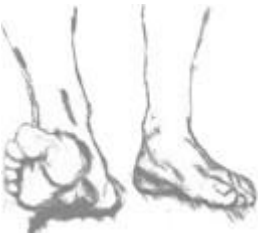
Figure 1. Explanatory figure depicting the trajectory of the COP (centre of pressure) and the COM (centre of mass) during gait initiation where the right is the stepping limb and the left is the support limb. Note that the COM trajectory has been enlarged relative to the base of support. For the COP, grey lines depict the stepping limb; black lines depict the support limb. Note that the COP trajectories are not in synchrony-the stepping limb completes its path prior to the support limb. The two traces are representative of the mean of the entire cohort in the current study.

Figure 2. Pictorial representation of the post-hoc analysis. Data relates to the dominant limb only. Grey lines depict the centre of pressure (COP) trajectory of the stepping limb. Black lines depict the COP trajectory of the support limb. Continuous lines depict the control group. Dotted lines depict the concussion group. Note that the COP trajectories are not in synchrony-the stepping limb completes its path prior to the support limb.

COM

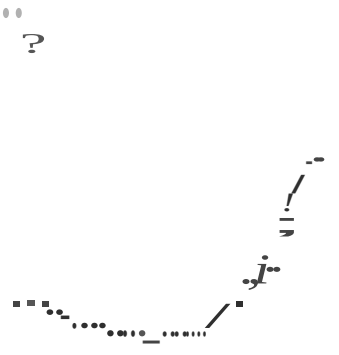


Toe-off

Stepping limb • Support limb

Toe-off

Event 1



Event 2

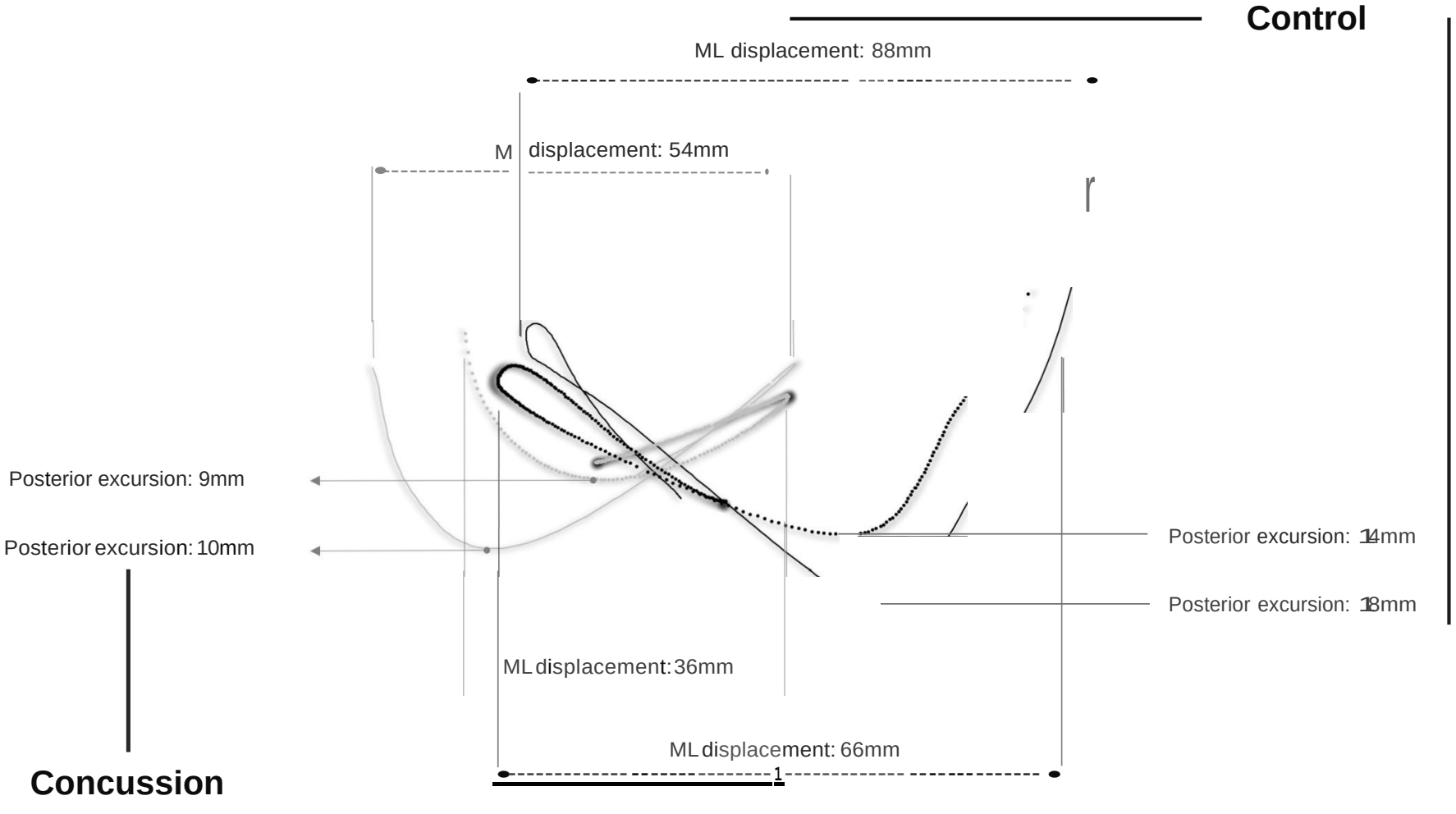

Control
ML displacement: 88mm
M displacement: 54mm
Posterior excursion: 9mm
Posterior excursion: 10mm
Posterior excursion: 14mm
Posterior excursion: 18mm
ML displacement: 36mm
ML displacement: 66mm
Concussion

Table 1. Demographics (mean[SD]) for the concussion and control groups

	Age (years)	Height (m)	Body mass (kg)	Physical activity levels	Days since most recent concussion
Concussion (Males = 11; Females = 4)	21.83 [3.5]	1.77 [0.1]	77.61 [13]	6.61 [2.3]	9 [7]
Control (Males = 11; Females = 4)	22.46 [3.7]	1.76 [0.1]	72.20 [10]	5.57 [3.5]	NA

*Physical activity levels were self-reported as the number of hours of designated physical activity or training per week.

Table 2. Results (mean and standard deviation [SD]) of the self-report outcome analysis.

	SF36																SCAT3			
	relative general health		limitations of activities		physical health		emotional health		social activities		pain		energy and emotions		perceived general health		total		Symptom severity (/132)		Symptom number (/22)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Concussion	6.13	0.96	16.29	3.58	1.43	1.87	2.07	1.21	5.71	2.02	5.00	2.08	26.86	7.25	13.86	2.68	76.50	17.89	26.86	21.57	10.86	5.20
Control	5.29	1.73	19.63	0.81	3.25	1.48	2.56	0.96	7.44	1.03	7.25	1.29	35.38	4.01	13.69	1.66	95.31	6.65	6.19	7.95	4.00	4.75
P-value	0.105		0.001*		0.006*		0.226		0.006*		0.001*		<0.001*		0.834		0.001*		0.001*		0.001*	

*indicates a statistically significant difference

SCAT3 = Sport Concussion Assessment Tool 3; SF36 = Short Form-36

Table 3. Mean values (with 95% CI) for the dependent variables related to the COP during the GI task.

Task	Limb	Period of PPA		Concussion	Control	P-value
Stepping limb: dominant foot Support limb: non-dominant foot	Dominant limb	Period 1	(η^2) Peak ML COP excursion	43.53mm [95%CI: 39.37 to 47.68]	42.03mm [95%CI: 40.31 to 43.74]	
			Peak AP COP excursion	12.46mm [95%CI: 9.64 to 15.28]	12.67mm [95%CI: 11.08 to 14.26]	
		Period 2	Peak ML COP excursion	83mm [95%CI: 72.72 to 93.27]	98.52mm [95%CI: 92.08 to 104.96]	
			Peak AP COP excursion*	9.71mm [95%CI: 8.14 to 11.27]	14.9mm [95%CI: 12.31 to 17.49]	0.032 (0.15)
		Period 1-3	Total ML COP excursion*	36.95mm [95%CI: 30.87 to 43.03]	54.24mm [95%CI: 46.99 to 61.5]	0.024 (0.17)
			Total AP COP excursion	22.17mm [95%CI: 19.18 to 25.16]	27.57mm [95%CI: 24.55 to 30.59]	
	Non-dominant limb	Period 1	Peak ML COP excursion	64.62mm [95%CI: 61.08 to 68.16]	66.76mm [95%CI: 62.69 to 70.83]	
			Peak AP COP excursion	33.58mm [95%CI: 26.78 to 40.39]	35.59mm [95%CI: 30.67 to 40.51]	
		Period 2	Peak ML COP excursion	143.87mm [95%CI: 132.38 to 155.36]	146.87mm [95%CI: 138.3 to 155.45]	
			Peak AP COP excursion	12.61mm [95%CI: 10.19 to 15.03]	15.85mm [95%CI: 13.73 to 17.97]	
		Period 1-3	Total ML COP excursion	75.72mm [95%CI: 67.82 to 83.62]	94.49mm [95%CI: 88.19 to 100.8]	
			Total AP COP excursion	46.2mm [95%CI: 40.14 to 52.26]	51.44mm [95%CI: 47.13 to 55.74]	
Stepping limb: non-dominant foot Support limb: dominant foot	Dominant limb	Period 1	Peak ML COP excursion	60.85mm [95%CI: 58.82 to 62.87]	57.14mm [95%CI: 53.54 to 60.74]	
			Peak AP COP excursion	28.16mm [95%CI: 24.84 to 31.47]	22.6mm [95%CI: 20.81 to 24.38]	
		Period 2	Peak ML COP excursion	129.69mm [95%CI: 122.92 to 136.46]	137.4mm [95%CI: 125.74 to 149.07]	
			Peak AP COP excursion*	10.43mm [95%CI: 8.73 to 12.13]	18.13mm [95%CI: 14.92 to 21.35]	0.009 (0.21)
		Period 1-3	Total ML COP excursion*	66.51mm [95%CI: 60.45 to 72.57]	88.43mm [95%CI: 78.53 to 98.32]	0.019 (0.18)
			Total AP COP excursion	38.59mm [95%CI: 35.71 to 41.46]	40.73mm [95%CI: 37.49 to 43.97]	
	Non-dominant limb	Period 1	Peak ML COP excursion	46.53mm [95%CI: 40.85 to 52.2]	45.19mm [95%CI: 40.88 to 49.49]	
			Peak AP COP excursion	27.34mm [95%CI: 21.3 to 33.38]	30.48mm [95%CI: 24.63 to 36.34]	
		Period 2	Peak ML COP excursion	115.34mm [95%CI: 104.12 to 126.55]	120.69mm [95%CI: 114.05 to 127.34]	
			Peak AP COP excursion	9.88mm [95%CI: 7.32 to 12.44]	10.48mm [95%CI: 8.69 to 12.27]	
		Period 1-3	Total ML COP excursion	51.05mm [95%CI: 44.67 to 57.43]	58.9mm [95%CI: 52.49 to 65.31]	
			Total AP COP excursion	37.22mm [95%CI: 31.66 to 42.78]	40.96mm [95%CI: 35.55 to 46.38]	

*indicates statistically significant difference between concussion and control groups. AP = antero-posterior; CI = confidence interval; COP = centre of pressure; ML = medio-lateral; PPA = preparatory postural adjustment;. Period 1 commenced with the auditory cue and ended with the COP located in its most medial position toward opposing foot; period 2 represents the movement of the COP from this medial position to its most posterior and lateral position (event 2); period 3 extends from event 2 until toe-off as the COP translates forward (Figure 1).

Table 4. Mean values (with 95% CI) for the dependent variables related to the COM during the GI task.

Task		Concussion	Control	P-
Stepping limb: dominant foot Support limb: non-dominant foot	value Acceleration (ML)	2.47mm/s^2 [95%CI: 2.17 to 2.76]	2.43mm/s^2 [95%CI: 2.2 to 2.65]	
	Acceleration (AP)*	3.52mm/s^2 [95%CI: 3.16 to 3.88]	4.05mm/s^2 [95%CI: 3.69 to 4.4]	0.002
	COM displacement (ML)	10.88mm [95%CI: 10.86 to 10.89]	10.42mm [95%CI: 10.41 to 10.44]	
	COM displacement (AP)*	19.67mm [95%CI: 19.65 to 19.7]	23.62mm [95%CI: 23.6 to 23.64]	0.001
Stepping limb: non-dominant foot Support limb: dominant foot	Acceleration (ML)	2.73mm/s^2 [95%CI: 2.45 to 3]	2.42mm/s^2 [95%CI: 2.21 to 2.62]	
	Acceleration (AP)*	3.51mm/s^2 [95%CI: 3.18 to 3.83]	3.9mm/s^2 [95%CI: 3.6 to 4.2]	0.006
	COM displacement (ML)	11.42mm [95%CI: 11.41 to 11.43]	9.6mm [95%CI: 9.59 to 9.61]	
	COM displacement (AP)*	19.91mm [95%CI: 19.88 to 19.93]	22.82mm [95%CI: 22.8 to 22.84]	0.004

*indicates statistically significant difference between concussion and control groups, based on the 95% CIs. AP = antero-posterior; CI = confidence interval; COM = centre of mass; ML = medio-lateral.

Highlights

- Gait initiation (GI) performance is evaluated in a cohort with recent concussion.
- Concussed patients exhibit altered postural adjustments during gait initiation.
- These alterations are reflective of impaired sensorimotor control.