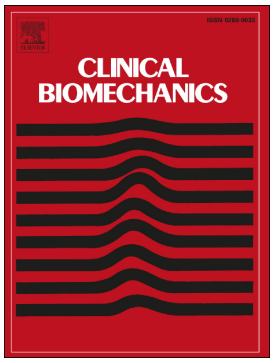

Quantification of postural control deficits in patients with recent concussion: An inertial-sensor based approach

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Abstract

Background: The aim of this study was to quantify postural control ability in a group with concussion compared with a healthy control group.

Method: Fifteen concussion patients (4 females, 11 males) and a group of fifteen age- and sex- matched controls were recruited. Participants were tested during the performance of the three stance variants (bilateral, tandem and unilateral stance) of the balance error scoring system standing on a force place, whilst wearing an inertial measurement unit placed at the posterior aspect of the sacrum.

Findings: The area of postural sway was computed using the force-plate and the '95% ellipsoid volume of sway' was computed from the accelerometer data. Concussed patients exhibited increased sway area (1513mm^2 [95% CI: 935 to 2091mm^2] vs 646mm^2 [95%CI: 519 to 772mm^2] p = 0.02) and sway volume (9.46m^{3}s^{-6} [95%CI: 8.02 to 19.94m^{3}s^{-6}] vs 2.68m^{3}s^{-6} [95%CI: 1.81 to 3.55m^{3}s^{-6}]) in the bilateral stance position of the balance error scoring system. The sway volume metric also had excellent accuracy in identifying task 'errors' (tandem stance: 95%CI: 85-96%, p < 0.001; unilateral stance: 95%CI: 86-96%, p < 0.001).

Interpretation: Individuals with concussion display increased postural sway during bilateral stance. The sway volume that was calculated from the accelerometer data not only differentiated a group with concussion from a healthy control group, but successfully identified when task errors had occurred. This may be of value in the development of a pitch-side assessment system for concussion.

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

1. Introduction

A recent report indicated that >200,000 patients with sports-related concussion are managed in US emergency departments every year (1). The true incidence of concussion is likely to be underestimated however due to the high variability of symptom severity (2).

Presently the assessment of athletes' readiness for return-to-play following a sports-related concussion is centered upon a clinical examination called the Sport Concussion Assessment Tool 3 (otherwise known as the 'SCAT3')(2). Symptom reporting, neuropsychological testing are considered to be the "cornerstones" of correct post-concussion management (3). Furthermore, the National Athletic Trainers' Association (NATA) have recommended that objective assessment of postural control be a fundamental component in the assessment of concussion-induced deficits (7). The theoretical rationale of this recommendation is that postural stability assessment may elucidate concussion-associated motor control deficits (7). The most frequently utilized clinical tool for post-concussion postural control assessment and the instrument included in the SCAT3 is the Balance Error Scoring System (BESS). The SCAT3 version of the BESS requires the clinician to sum the number of errors a patient accrues in the maintenance of three stance positions with their eyes closed: feet together, single-leg (on the non-dominant limb), and tandem stance whilst standing on a firm surface (8). In this manner, postural control performance is subjectively defined by the frequency of any discreet losses of balance, or the frequency that balance strategies are used in the maintenance of postural stability over the course of the 20-s trial.

While the BESS is accessible and quick to administer, it suffers from practice (9), learning (10, 11) and fatigue (12) effects. The most significant limitation with the BESS from a clinical perspective is that if a patient completes its stance variants without losing their

balance or needing to perform any gross movements in the maintenance of balance, then no performance metric is available for the minutiae of postural adjustments completed during the task. To overcome this , Brown et al (13) and Alberts et al(14) in separate studies utilized varying arrangements of inertial measurement units (IMUs) to gather kinematic data during the BESS. Although traditional laboratory-based biomechanical analysis methods (such as center of pressure acquisition [COP] with a force plate) of measuring postural control are accurate and objective, the implementation of these methods in a clinical context is hindered by their lack of portability, the high cost of the necessary equipment and the time required to test and analyze the acquired data. In contrast to expensive laboratory outcomes, IMU technologies offer an accurate, cheap and portable means to objectively quantify the quality of postural control. Online cloud storage and computing facilitates their potential for integration in a clinical environment.

Brown et al (13) used the linear acceleration data from an IMU fixed to the forehead of healthy participants performing the BESS to develop an algorithm that scored the number of task failures that were accrued during a given trial, thus quantifying the traditional outcome of the test (i.e the number of task failures) that a clinician is otherwise required to document. Importantly, the algorithm that was utilized did not provide a true measure of postural control, but rather a subjective metric (the reliability and validity of which has been questioned) (15).

Alberts et al (14) subsequently developed an objective and quantitative scoring system for the BESS on the basis of an IMU placed on the posterior aspect of the sacrum in a group of healthy participants; data from the accelerometer and gyroscope were used to calculate a 3D 95% ellipsoid volume of sway during task completion. This ‘sway-volume’ metric was deemed more sensitive of BESS performance than errors alone, but could not be used to determine how many errors occurred, thus limiting any ability to make inferences of the

relationship between the traditional quantitative score (number of task failures) and objective performance quality (based on biomechanical outcomes). Importantly, neither Brown et al nor Alberts et al evaluated their technology in a cohort of concussion patients (13, 14). Therefore, the purpose of this investigation was to utilize IMU data to develop an adaptive algorithm with an output that combines the clinical metric of task failures (if and when they occur, as per Brown et al (13)), with a quantitative scoring system of BESS performance (as per Alberts et al (14)) and test it on a cohort of individuals with a recent sports-related concussion.

Our aims were as follows: (1) to quantify postural control ability using the 95% ellipsoid volume of sway in the context of a 'gold-standard' of assessment (COP analysis with a force plate) and compare it between participants with recent concussion and a 'healthy' control group; (2) to evaluate the accuracy of the algorithm for identifying task 'errors' that occur in a given trial (as determined by examiner observation, if they occur).

Our hypothesis is that individuals with concussion will exhibit increased sway area on the basis of the COP force plate analysis, and increased sway volume on the basis of the IMU analysis.

2. METHODS

2.1 Participants

Fifteen patients were recruited at convenience from a university affiliated hospital emergency department (ED), 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 (2). After evaluation at the ED, prospective subjects were informed about the study and provided written permission for study investigators to relay detailed study information via telephone contact.

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 recent lower extremity musculoskeletal injury within the past 12-months (16); 2) history of cognitive deficiencies; 3) history of ≥3 previous concussions (to ensure exclusion of those with chronic mild traumatic brain injury (17); 3) loss of consciousness following the concussion for >1 minute (2); 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 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 (2).

2.3 Testing procedure.

Participants completed the BESS as it is described in the SCAT3 (2); following familiarization and they completed the test in three stance positions (bilateral, non-dominant limb unilateral and tandem stance). Participants were instructed to stand as still as possible for each 20s trial with their eyes closed and hands resting on their iliac crests (19). Standardized instructions for completing the BESS were read aloud to each participant, and the administrator demonstrated each task before testing (19). The same test administrator

completed the protocol for all participants and had experience administering the BESS, being a chartered physiotherapist with >5years experience. A second administrator assessed each BESS trial to verify the scoring. The standardized balance errors were documented and cross-referenced by these examiners for each trial and consisted of: moving the hands off the hips; opening the eyes; step, stumble, or fall; abduction or flexion of the hip beyond 30 degrees; lifting the forefoot or heel off the testing surface; remaining out of the proper testing position for greater than 5s. The maximum number of errors per condition was limited to 10, and the total BESS score was the sum of errors committed during all three stance positions. Participants performed three 20-s trials for each test condition barefoot on a force plate.

2.4 Data collection

Prior to completion of the BESS, all participants were instrumented with one 3D inertial sensor (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 sensor was placed at the posterior aspect of the sacrum at the level of the posterior superior iliac spines by the same investigator for every participant. Figure 1 illustrates the experimental setup.

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 a Android Tablet (AndroidOS:4.3(Jelly Bean)) using a Multi Shimmer Sync For Android® v2.5 appliance. Preliminary analysis of the signal spectrum from a pilot dataset revealed predominance in the lower frequencies and the noise in the higher frequencies; thus, custom scripts in R programming language were used to filter the sensor position and angular data with a fourth-order, zero phase, low-pass Butterworth filter with a cutoff frequency of 4 Hz. Following this, the first order derivative of the gyroscope data (V) (angular accelerometer,

was extracted. Finally combining the two linear accelerations (ML and AP) and one angular acceleration (V), the 3D volume of sway was established as described by Alberts et al (14). These data were used to construct an ellipsoid volume that, with 95% probability, contained the centre of the 3D acceleration data. Kinetic data were acquired at 100 Hz using an AMTI (Watertown, MA) walkway embedded force-plate. The inertial sensor unit was time synchronized with the force-plates.

The kinetic data of interest was the center of pressure (COP) (the location of the vertical reaction vector on the surface of a force-plate) for each trial. COP data acquired from trials of the unilateral stance were used to compute the sway area (in millimeters [mm]) of the combined AP and ML COP path using an algorithm previously published and described in the seminal paper by Prieto et al (20). COP sway area was calculated based on the 20 second interval for each stance trial, and averaged across the three trials for each participant on each limb. The AP and ML time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency (21).

2.5 Statistical analysis

2.5.1 Self-report outcomes

Total score on the graded symptom scale of the SCAT3 were compared between the concussion and control groups using multivariate analysis of variance. The p-value for this analysis was set a-priori at $p<0.05$.

2.5.2 Concussion vs control: Sway volume & Sway area

To fulfil our first experimental aim, and test the hypothesis that the concussion group would exhibit increased 95% ellipsoid volume of sway on the basis of the IMU data, and sway area on the basis of the COP data, a series of independent samples t-tests were undertaken for each

task variant. The significance level for these analyses was adjusted for the number of test variables using a Bonferonni adjusted alpha of $p < 0.025$. Effect sizes were calculated using eta-squared.

2.5.3 Using sway volume to identify task failure/success

To fulfil our second experimental aim, we firstly stratified successful and failed trial IMU data (95% ellipsoid volume of sway) for all participants. These data were analyzed using receiver operating characteristic (ROC) curves to determine a task-specific ellipsoid volume threshold needed for task completion. Specifically, an ROC curve was plotted for all trials delineated by stance position. The ROC analysis graphed the sensitivity (true positive) and one minus specificity (false positive) of the failure threshold (of sway volume) for each stance variant of the BESS task on the *Y* and *X*-axis, respectively, while systematically moving the test's cut-off score (for task failure/success) across its full range of values. The overall accuracy of the threshold for classifying a task as 'successful' or 'failed' was determined by the area under the curve (AUC). This is the primary advantage of an ROC analysis:that its accuracy can be quantified by calculating the AUC (22). Perfect diagnostic accuracy (for task failure/success) corresponds to an AUC of 1.00. An AUC of .556 represents low diagnostic accuracy, .639 indicates medium accuracy, and .714 and above denote high accuracy (23). The asymptotic statistical significance level was set for each task at $P < 0.05$.

Preliminary assumption testing was conducted to check for normality, linearity and univariate/multivariate outliers, with no serious violations noted.

All data were analyzed using Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL, USA).

3. Results

3.1 Self-reported outcomes

Regarding the SCAT3, there was a statistically significant main effect for the combined dependent variables ($p < 0.01$).

The concussion group reported a greater number of more severe symptoms on the grade symptom scale checklist of the SCAT3. The results of this analysis (with means and standard deviations) are presented in Table 2.

3.2 Biomechanical outcomes

All participants successfully completed at least one trial of the bilateral and tandem stance conditions. Ten of the fifteen concussion patients could complete the unilateral stance position after three attempts, with eleven of the fifteen controls completing at least one trial. Based on the analysis of successfully completed trials, the concussion group exhibited significantly greater sway as determined by both the COP (sway area) and IMU (sway volume) analyses in the bilateral stance condition only. The results of the analysis comparing sway are presented in Table 3. An illustrative diagram depicting these results is presented in Figure 3.

A post-hoc exploratory t-test analysis was completed to compare the number of failures accrued by the concussion and control groups during their three trials of each of the stance conditions of the BESS. The average number of failures of three trials was utilized for the analysis. The p-value for this post-hoc analysis was set at $p < 0.05$.

There were no differences between the concussion and control groups on the basis of the number of failures accrued during the three trials of each stance position of the BESS. Results of this analysis are presented in Table 4.

3.3 Fails detection

No participants failed during the bilateral stance task. Therefore, two outcomes (task completion during the tandem and unilateral variants of the BESS) were submitted to an ROC curve analysis. Sway volume during the tandem and unilateral stance variants reached the asymptotic significance level ($p< 0.001$ in both instances).

The ROC curves for task failure during the tandem and unilateral stance variants of the BESS are presented in Figure 2.

4. Discussion

The current investigation details a three-tiered assessment of impairment in patients with concussion: the self-report outcome (the graded symptom scale of the SCAT3) quantified the perceived general health status of the cohort, while the clinical test (the BESS), in combination with the laboratory setup, evaluated the performance and technique of postural control, respectively. We combined a traditional laboratory-based 'gold-standard' quantitative measure of motor function (the force plate) with an emerging technology (the IMU) to contextualise the results of the latter (24).

Our results demonstrate that concussion is associated with poorer self-perceived general health and increased postural sway during the BESS task as determined by the COP and IMU analyses. Specifically, on the graded symptom scale of the SCAT3, the concussion group reported having a greater number of symptoms and greater symptom severity compared with controls. Importantly, the concussion cohort in this study were quite heterogeneous; the time of testing post-concussion ranged from 5-27 days. That deficits in self-perceived general health are still evident in this post-injury period is in agreement with recent research supporting the potential for concussion to have long term effects (25).

The findings in the self-report outcomes coincided with increased sway area of the COP and volume of sway of the IMU placed on the sacrum during the bilateral stance position of the BESS. Instrumentation of the BESS with the force plate and IMU setup in this manner facilitated its objectification, and subsequent identification of motor control deficits in the concussion group relative to the non-injured control group. These deficits in postural control would otherwise not have been evident on the basis of the traditional BESS outcome, wherein there were no differences between the concussion and control groups following our post-hoc analysis of the number of errors accrued for each stance position (8).

The objective identification of a between-groups difference in what is considered to be the 'easiest' of the stance variants of the BESS is an interesting finding, with potential value in a clinical context. A limitation of the clinical scoring system of the BESS it it's potential for floor and ceiling effects. For instance, participants will rarely incur any errors in the bilateral stance position. As such, the diagnostic accuracy of this component for concussion using the traditional clinical outcome is belied by a floor-effect (14). Despite this, a minutiae of postural corrections are necessary in the maintenance of any upright posture (26). These corrections are made on the basis of contributions from a somatosensory system appropriating afferent information with an efferent motor response, and generates a pattern of sway (27). Measurement of this pattern of sway offered the mechanism by which we sought to quantify performance without the necessity that an individual 'fails' their attempt at the task. Our results suggest that the postural corrections required to maintain upright posture increase as the individual progresses from the bilateral stance position (where the sway area/volume values were smallest) to the unilateral stance position (where the sway area/volume values were largest).

Our use of two acquisition methods (the force plate and IMU) to measure the same construct (sway) revealed a high degree of similarity between the sway pattern of the COP, and that of the trunk; the concussion cohort demonstrated increased sway on the basis of both the COP and the IMU data. This similarity is in agreement with previous literature comparing the relationship of the COP to trunk sway (28), and is important because it qualifies the IMU as a cheap clinical balance assessment tool (29), the use of which may facilitate an objective, biomechanical approach to pitch-side assessment of concussion. This substantiates the recent recommendations of the National Institutes of Health (NIH) Balance Toolbox which has encouraged the use of IMUs to assess general balance through postural sway (30). With the advent of online cloud computing and the ubiquity of smart-phones among the general

population, the current results are one step towards remote concussion assessment, whereby the accelerometers in a smart-phone may be leveraged in a similar manner to the IMUs in the current study, towards empowering the clinician with an objective metric of BESS performance, which overcomes its floor/ceiling effects. Specifically, converse to the floor effect that is evident during bilateral stance, a ceiling effect has been reported during the unilateral stance variant of the BESS (31), with healthy individuals scoring the maximum number of 'fails'(32). In such situations (of task failure), the provision of an objective metric on a continuous scale in the form of sway volume derived from a tri-axial accelerometer placed on the trunk for a successfully completed trial, that could also be used to identify task failures, may have significant clinical value. Indeed, on the basis of the ROC analysis, the sway volume metric in the current study exhibited excellent accuracy on the basis of the AUC statistic (90%) in identifying task failures in the tandem and unilateral stance positions. While no between-groups differences were evident for these stance positions, there was a trend of increased sway in the tandem stance position in the concussion group, however this was not statistically significant.

Future research is required to determine the accuracy of the sway volume metric in accruing the total number of errors in a given task attempt, but it is reasonable to expect that this metric could 'bridge the gap' between the clinical outcome of the BESS and an objective measure of performance technique, on the basis of the current findings.

Recently Brown et al used a single IMU as a means to quantify the number of task errors that were accrued during the BESS (13). The algorithm that was developed fit accurately with error scores under the foam conditions of the BESS, but not for the subset of the firm conditions (as described in the SCAT3 and as was assessed in this study). Furthermore, the IMU that was utilized was placed on the forehead and could not provide a true measure of

postural stability (13). To resolve this issue, Alberts et al developed the volume of sway metric adopted in the current study (14). We have developed on the findings of these groups by using the same metric to both quantify postural control performance and identify task errors. We have also provided preliminary evidence of the relationship the sway volume metric has with a traditional measure of postural sway from COP analysis and its ability to differentiate patients with a recent concussion from a control cohort.

Despite its strengths, there are a number of study limitations that must be acknowledged. First, as has previously been alluded to, there was substantial heterogeneity in the concussion cohort regarding 'time-since-injury'. The inferences that can be made about how concussion affects self-reported general health and motor control are therefore limited; the trajectory of recovery of the variables tested in this study remain unclear, albeit we can deduce [in conjunction with a number of recently published articles (25, 33-35)] that any consensus that concussion-induced impairment will resolve within a 7-day period (36) should probably be abandoned. Another limitation of this study is that we cannot identify if any causal relationship between deficits in postural control and the incidence of concussion.

2.5 CONCLUSIONS

This study has elucidated that individuals with concussion display increased postural sway during bilateral stance as determined via a traditional 'gold-standard' method of postural control quantification (the force plate), and an emerging technology (the IMU). The sway volume that was calculated from the accelerometer data acquired from the IMU not only differentiated a group with concussion from a healthy control group, but also successfully identified errors that were accrued during each task attempt. This may be of value in the development of a pitch-side assessment system for concussion. Future research is required to elucidate the recovery trajectory of postural sway in a concussion cohort.

Conflict of interest

This study was supported by Fujitsu Laboratories Ltd. Japan as part of the KIDUKU project. We have not conflicts of interest to declare.

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Figure 1. Experimental setup for intertial measurement unit.

Figure 2. Receiver operating characteristic curve analysis for fails detection on the basis of the sway volume metric calculated from the accelerometer data of the inertial measurement unit.

The AUC statistic for the tandem stance condition was 0.91 (95% CI: 0.85 to 0.96) with a sensitivity and specificity of 0.92 and 0.79 respectively at the threshold of $28.22 m^3 s^{-6}$ (denoted with the grey cross). The AUC statistic for the unilateral stance condition was 0.91 (95% CI: 0.86 to 0.96) with a sensitivity and specificity of 0.72 and 0.96 respectively at the threshold of $266.48 m^3 s^{-6}$ (denoted with the black cross).

Figure 3. Representative sway volume for the concussion (black) and control (grey) groups.

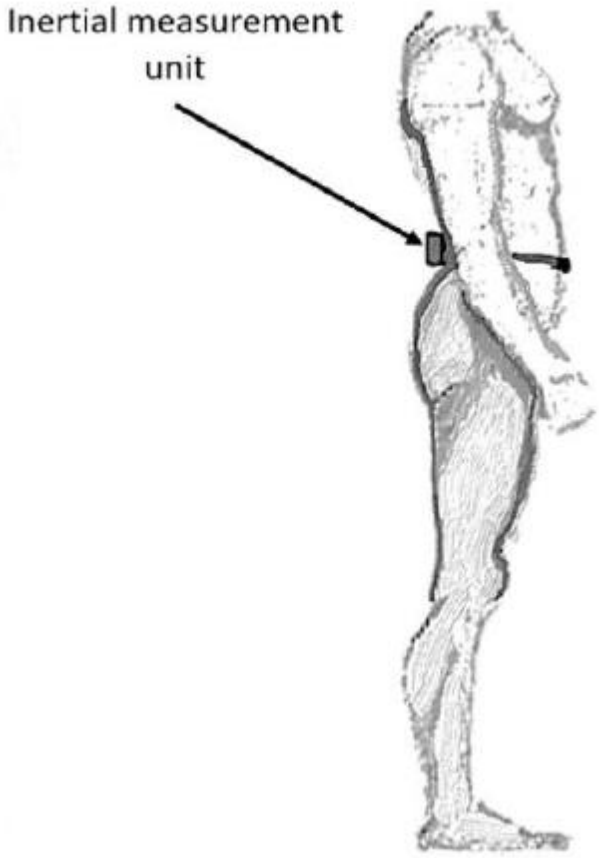

Fig. 1

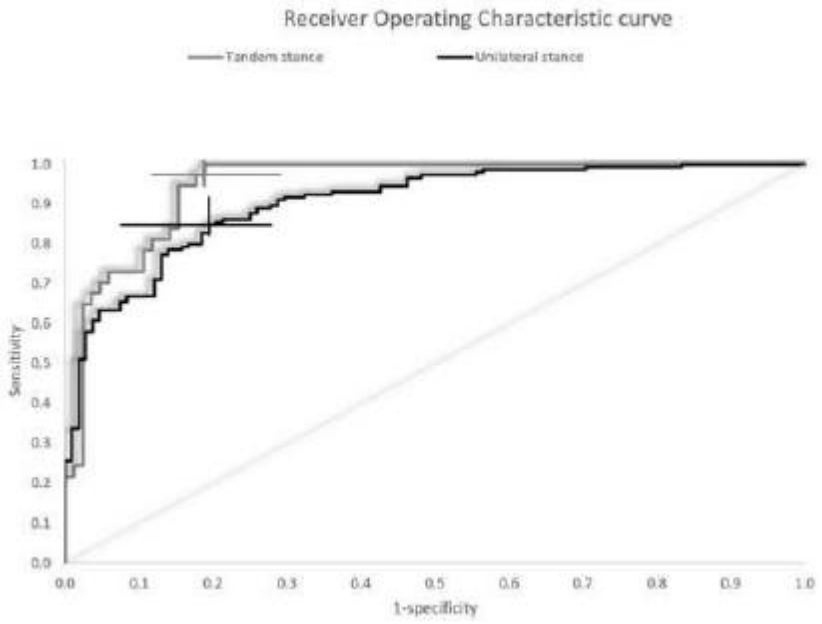

Fig. 2

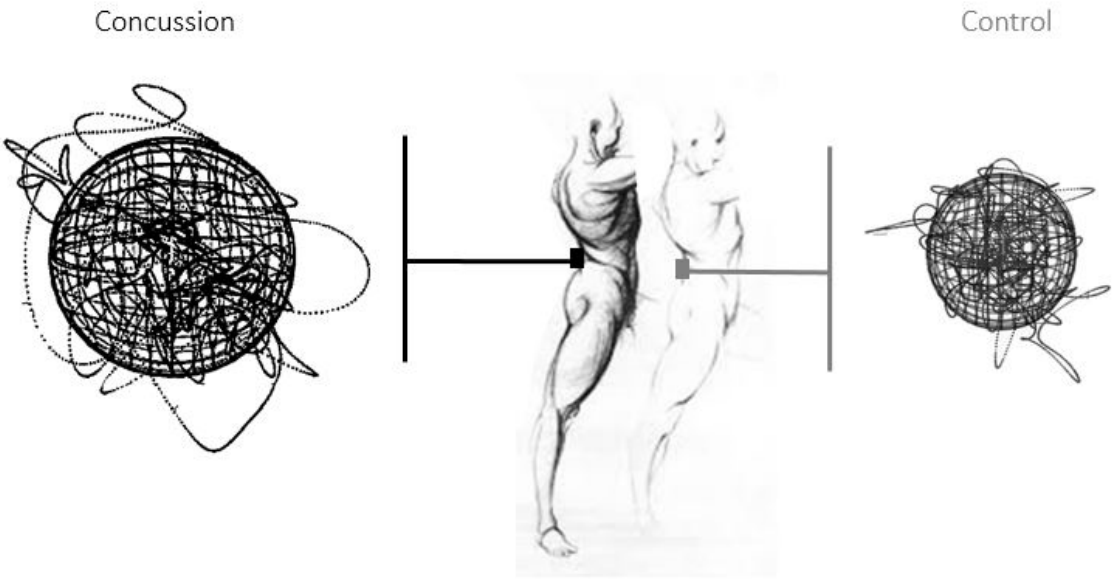

Fig. 3

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.

	SCAT3			
	Symptom severity (/132)		Symptom number (/22)	
	Mean	SD	Mean	SD
Concussion	26.86	21.57	10.86	5.20
Control	6.19	7.95	4.00	4.75
P-value	0.001*		0.001*	

*indicates a statistically significant difference

SCAT3 = Sport Concussion Assessment Tool 3;

Table 3. Results of the postural sway analysis from the force plate (sway area) and inertial measurement unit (sway volume) data.

		Concussion		Control		Concussion vs Control	
		Mean	SD	Mean	SD	P-value	Effect size (η^2)
Bilateral stance	Sway volume (m^3s^6)	9.46	20.71	2.68	1.72	0.01*	0.25
	Sway area (mm^2)	1513.61	1142.16	646.22	249.70	0.02*	0.26
Tandem stance	Sway volume (m^3s^6)	95.78	183.71	65.91	166.90	0.42	0.03
	Sway area (mm^2)	2471.41	1855.00	1208.04	627.04	0.03	0.18
Unilateral stance	Sway volume (m^3s^6)	2857.99	1573.64	2709.95	821.61	0.24	0.06
	Sway area (mm^2)	727.26	1012.71	768.49	1075.09	0.76	0.00

*indicates a statistically significant difference. SD = Standard Deviation.

Table 4. Results of the exploratory analysis investigating failure accrual between the concussion and control groups during performance of the balance task.

	Number of errors				
	Concussion		Control		Concussion vs control
Stance position	Mean	SD	Mean	SD	p-value
bilateral	0.00	0.00	0.00	0.00	0.15
tandem	0.40	0.52	0.72	0.66	0.08
unilateral	1.08	0.99	1.59	1.06	0.19

SD = Standard Deviation.

Highlights

- Postural control performance is evaluated in a cohort with recent concussion.
- Traditional and novel technologies were used to measure performance.
- Postural ‘sway’ was quantified with a force plate and a wearable sensor.
- Concussed patients exhibit increased sway in bilateral stance.
- These alterations are likely reflective of impaired sensorimotor control.