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Original Research

Using functional movement tests to investigate the presence of sensorimotor impairment in amateur athletes following sport-related concussion: A prospective, longitudinal study

Fionn Büttner [a, *], David Howell [b, c, d], Giacomo Severini [e, f, g], Cailbhe Doherty [a], Catherine Blake [a], John Ryan [h], Eamonn Delahunt [i, a]

[a] School of Public Health, Physiotherapy and Sports Science, University College Dublin, Dublin, Ireland
[b] Sports Medicine Center, Children's Hospital Colorado, Aurora, CO, USA
[c] Department of Orthopedics, University of Colorado School of Medicine, Aurora, CO, USA
[d] The Micheli Center for Sports Injury Prevention, Waltham, MA, USA
[e] School of Electrical and Electronic Engineering, University College Dublin, Dublin, Ireland
[f] Insight Centre for Data Analytics, University College Dublin, Dublin, Ireland
[g] UCD Centre for Biomedical Engineering, University College Dublin, Dublin, Ireland
[h] Emergency Department, St. Vincent's University Hospital, Elm Park, Dublin 4, Ireland
[i] Institute for Sport & Health, University College Dublin, Dublin, Ireland

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ABSTRACT

Objective: To longitudinally investigate the presence of sensorimotor impairments in amateur athletes following sport-related concussion using two functional movement tests.
Design: Prospective, longitudinal study.
Setting: Human movement analysis laboratory.
Participants: Athletes who presented to a hospital emergency department and were diagnosed with sport-related concussion, and sex-, age-, and activity-matched non-concussed, control athletes. Concussed participants were assessed within one-week following sport-related concussion, upon clearance to return-to-sporting activity (RTA), and two weeks after RTA. Control participants were assessed at an initial time-point and approximately two and four weeks following their initial study assessment.
Main outcomes measures: At each laboratory assessment, participants completed two functional movement tests: the Star Excursion Balance Test to evaluate anterior reach distance (normalised for leg length) and fractal dimension (centre of pressure path complexity), and the Multiple Hop Test to evaluate corrective postural strategies and time-to-stabilisation.
Results: Fifty concussed athletes and 50 control athletes completed the study. There were no significant differences at any study assessment between the concussion and control group on the Star Excursion Balance Test anterior reach distance or fractal dimension (centre of pressure path complexity). During the Multiple Hop Test, the concussion group used a significantly greater number of corrective postural strategies than the control group one-week following sport-related concussion and upon clearance to RTA, but not two weeks following RTA.
Conclusion: Recently concussed athletes made a greater number of corrective postural strategies than control participants during the Multiple Hop Test upon clearance to RTA but not two weeks after RTA. The Multiple Hop Test may offer a clinically useful tool for practitioners to examine the recovery of subtle sensorimotor impairments and related RTA readiness.

1. Introduction

Sport-related concussion is a trauma-induced, functional disturbance of the brain causing transiently altered mental status

* Corresponding author. , School of Public Health, Physiotherapy and Sports Science, University College Dublin, Dublin, Ireland.
E-mail addresses: fionn.cleirigh-buttner@ucdconnect.ie (F. Büttner), david.howell@cuanschutz.edu (D. Howell), giacomo.severini@ucd.ie (G. Severini), cailbhe.doherty@ucd.ie (C. Doherty), c.blake@ucd.ie (C. Blake), j.ryan@svuh.ie (J. Ryan), eamonn.delahunt@ucd.ie (E. Delahunt).

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(Harmon et al., 2019; McCrory et al., 2017). Accumulating evidence suggests that sport-related concussion may be associated with subsequent lower extremity, musculoskeletal injury (McPherson et al., 2019; Reneker, Babl, Flowers 2019). Theory, clinical intuition, and preliminary research propose that post-concussive sensorimotor impairments may be an important mediating variable in this potentially causal pathway (Eagle et al., 2020; Howell et al., 2018a, 2018b). However, despite plausible hypotheses, an explanatory mechanism remains elusive.

Developing evaluative tests that can detect persistent clinical and neuro-biological impairments following sport-related concussion is a field-wide priority (Feddermann-Demont et al., 2017; Kristman et al., 2014). Currently-recommended side-line assessment strategies evaluate clinical symptoms, cognitive deficits, and balance impairments after sport-related concussion that resolve in most concussed athletes to within 10–14 days following injury to approximate preinjury values (McCrea et al., 2003, 2005, 2013; William et al., 2011). The majority of collegiate and adult athletes exhibit normal static balance performance and report symptom resolution within five and ten days, respectively, following sport-related concussion (Garcia et al., 2018; Gessel et al., 2007; McCrea et al., 2013). Consequently, return-to-play timelines remain brief ($\leq$21 days) for most professional, amateur, and recreational athletes after sport-related concussion, irrespective of the sport played (Bahr et al., 2017; Gessel et al., 2007; Kerr et al., 2016; Marar et al., 2012; McCrea et al., 2020; Roberts et al., 2013; Wasserman et al., 2016; William et al., 2011). However, the sensitivity of multi-faceted assessments diminishes with increasing time following sport-related concussion, creating uncertainty about whether resolved post-concussive impairments reflect full recovery of normal performance capabilities (Broglio et al., 2007, 2017; Buckley et al., 2018; Kamins et al., 2017; Putukian et al., 2015; Resch et al., 2016).

Functional movement tests can pose physical and cognitive challenges that more closely mimic the demands imposed upon athletes during sport-specific activity than isolated, clinical tests. Using functional movement tests when assessing athletes following sport-related concussion may identify subtle, yet persistent, sensorimotor impairments that evade detection on clinical static balance tests (Buckley, Oldham, et al., 2016; Büttner et al., 2019; Howell et al., 2018a; Oldham et al., 2018). For example, divided attention walking and sport-specific functional movement tasks have demonstrated promise in detecting dynamic postural control impairments beyond one-month following sport-related concussion (Büttner et al., 2019; Howell et al., 2015). Postural control impairments may be exacerbated in more physically dynamic and cognitively challenging environments that require athletes to distribute their attentional resources across internal and external cognitive stimuli (Howell et al., 2018a). The physical and cognitive challenges of sports performance place a high demand on the athlete's ability to process and respond to incoming stimuli (Riemann and Lephart, 2002a, 2002b). Given that reduced internal processing abilities and sensorimotor impairments may co-exist following sport-related concussion (Herman et al., 2015; Swanik et al., 2007), participating in a dynamic and complex sporting environment with aberrant movement patterns may increase an athlete's injury risk (Eagle et al., 2020; Howell et al., 2018a, 2018b; Lynall et al., 2015, 2017a, 2017b).

Applying functional movement tests, which are more challenging than static tasks, when assessing athletes following sport-related concussion may detect subtle sensorimotor impairments that have important implications for return-to-play decision-making and future lower extremity musculoskeletal injury risk. (Eagle et al., 2020; Howell et al., 2018a; McPherson et al., 2019). This study aimed to longitudinally investigate the presence of sensorimotor impairments in amateur adult athletes following sport-related concussion using two functional movement tests. We hypothesised that concussed athletes would exhibit persistent sensorimotor impairments on challenging, functional movement tests up to two weeks after return-to-sporting activity following sport-related concussion compared with control athletes.

2. Methods

This prospective, longitudinal study received ethical approval from the Human Resources Ethics Committee for Life Sciences at University College Dublin (UCD), Ireland and was performed in accordance with the Declaration of Helsinki. Study design, conduct, analysis, and results are reported according to the STatement for Reporting OBsErvational Studies guidelines (Vandenbroucke et al., 2007; von Elm et al., 2008).

2.1. Participant identification

Concussed patients were recruited from the emergency department of a national, university-affiliated, teaching hospital over a 20-month rolling recruitment period from January 2017 until August 2018. Patients were diagnosed with sport-related concussion by an emergency medicine physician using the injury definition developed by the 5th Concussion in Sport Consensus Statement (McCrory et al., 2017). For the current study, we defined sport-related concussion as a traumatic brain injury induced by biomechanical trauma transmitting an impulsive force to the brain and manifesting in transiently altered mental status (McCrory et al., 2017).

Upon identification of a concussed patient, the patient was approached by a study investigator who applied study eligibility criteria and, if eligible, sought the patient's interest in participating in the study. Concussed participants were included if they were amateur athletes who attended the emergency department and were diagnosed with a concussion occurring during sports competition or practice, and were 16–38 years old. Participants were excluded if they reported: sustaining a sport-related concussion in the preceding 12 months; a history of greater than three lifetime concussions; loss of consciousness greater than 1 min following the current sport-related concussion, a lower extremity physical complaint in the preceding twelve months that resulted in at least 24 h of missed training and/or match-play from midnight at the end of the day that the physical complaint was sustained, or; a history of vestibular disorder. Sex-, age-, and activity-matched volunteer control participants were recruited by advertising the study across competitive and intramural athletic teams in the university and local catchment area, and by applying the same exclusion criteria as were used for the concussion group.

2.2. Assessment timeline

Study participants, who consented to participate, attended three study assessments at the human movement analysis laboratory at the UCD School of Public Health, Physiotherapy and Sports Science. We assessed concussed participants 1) within one week following sport-related concussion, 2) upon medical clearance to return-to-sporting activity (RTA), and 3) two weeks after RTA following sport-related concussion. Control participants were assessed at an initial study assessment and subsequently tested approximately two weeks and four weeks following their initial study assessment. We aimed to assess control participants at matched time points within three days of concussion participants.

We defined medical clearance to RTA as clearance of the concussed athlete by a physician to initiate organised sporting activity following sport-related concussion. RTA decision-making by physicians was independent of the current observational study, and physicians and patients were unaware of study hypotheses. RTA criteria were physician-specific and comprised time-dependent (such as ensuring that the athlete adhered to a time-defined rest period) and criterion-dependent (such as a symptom-free waiting period) approaches. Physicians typically recommended athletes to RTA using a stepwise RTA protocol that increased sport-specific physical activity in volume and intensity.

2.3. Participant demographic information

We collected the following demographic characteristics that are considered to potentially mediate, and/or confound, the relationship between sport-related concussion and clinical recovery duration: medically diagnosed concussion history, migraine history, diagnosed attention disorder or learning disability, history of diagnosed anxiety or depression (Abrahams et al., 2014; Iverson et al., 2017; Makdissi et al., 2013; Zemek et al., 2016). We ascertained participant concussion history by asking participants whether they had previously sustained a medically diagnosed sport-related concussion. Migraine history was ascertained by asking participants whether they had a history of physician-diagnosed migraines. Diagnosed attention disorder or learning disability was ascertained by asking study participants whether they had ever been medically diagnosed with an attention disorder (e.g., ADD or ADHD) or a learning disability (e.g., dyslexia). History of diagnosed mood disorder was ascertained by asking study participants whether they had ever been medically diagnosed with anxiety or depression.

2.4. Assessment protocol

At each study assessment, concussion and control participants completed the following clinical tests (Table 1):

2.5. Star excursion balance test

The Star Excursion Balance Test (SEBT) is a clinical assessment of dynamic postural control. During the SEBT, the participant performs single-leg squats using the non-weightbearing limb to reach maximally and touch a point along one of eight lines on the floor that extend from a fixed centre point and are spaced at 45° from each other (Kaminski & Gribble, 2003). Participants were instructed to perform the SEBT in the anterior reach direction, as described by Gribble et al. (Gribble et al., 2012) In brief, participants maintain a stable base of support on the weightbearing stance foot while performing a maximal reach in the anterior direction with the non-weightbearing leg (further explanation in *supplemental file*).

We computed the average of three test trials to calculate the anterior reach distance for each participant. The anterior reach component of the SEBT was selected due to its similarity with a single-leg squat but also because it has a clinician-based outcome (i.e., reach distance) as well as a laboratory-based outcome (i.e., forceplate-instrumented postural control) when performed in the laboratory. Anterior reach distance was normalised for participant leg length (as measured from the ASIS to the medial malleolus) to account for systematic leg length differences between participants in the concussion and control group (Gribble & Hertel, 2003). We measured closed-chain ankle dorsiflexion range of motion of the weightbearing limb by performing a knee-to-wall lunge test and included this variable as a confounding variable to minimise the influence of this variable on normalised anterior reach distance performance (Gribble & Hertel, 2003; Hoch et al., 2011).

The SEBT has demonstrated discriminative capacity to differentiate the level of postural control in injured and uninjured participants with chronic ankle instability, anterior cruciate ligament reconstruction, and patellofemoral pain syndrome (Gribble et al., 2012; Hegedus et al., 2015). Consistent intra-tester (0.78–0.96), inter-tester (0.81–0.93) and inter-session (0.84–0.92) reliability has been demonstrated for the SEBT when practice trials were accounted for (Gribble et al., 2012).

Additionally, we acquired centre of pressure data for the weightbearing, stance limb to calculate fractal dimension combining anteroposterior and mediolateral centre of pressure (CoP) paths (Doherty et al., 2015a, 2015b). Fractal dimension is a unit-less measure that characterises the complexity of the CoP signal (Katz & George, 1985), thereby providing an indication of the extent to which the participant is using their available base of support (Prieto et al., 1996). Fractal dimension describes its shape using a value ranging from 1 (i.e., low complexity or reduced capacity to avail of the supporting base) to 2 (i.e., high complexity). (Katz & George, 1985).

2.6. Multiple hop test

The Multiple Hop Test (MHT) is a functional assessment of dynamic postural control developed by Riemann et al. (Riemann et al., 1999) Participants performed the MHT as described by Eechaute et al. (Eechaute, Vaes, & Duquet, 2008a, 2008b). In brief, participants hop and land, with a stable landing, along a multi-directional pattern of ten, numbered, floor markers. Participants pause momentarily when landing on each tape marker to sufficiently stabilise. When the participants' weightbearing knee and hip are aligned, and foot, chest and head are pointing anteriorly, the participant can hop to the next marker. Participants aim to cover each tape marker with their weightbearing foot upon landing (further explanation in *supplemental file*).

Participants were instructed to maintain balance and to minimise corrective postural strategies upon landing. Corrective postural strategies included: (1) falling or stumbling; (2) displacing the supporting foot (through shuffling or jumping); (3) touching the ground with the non-weightbearing foot; (4) removing the hand(s) from the iliac crest(s); (5) moving the trunk medially or laterally in the frontal plane or anteriorly in the sagittal plane; (6) holding the legs together to maintain stability, and (7) swinging the

Table 1
Study outcome measures and metrics.

Clinical test	Outcome measure	Outcome metric (unit)
SEBT	Anterior reach distance performance normalised for leg length	Percentage (%)
	Fractal dimension	N/A (unitless)
MHT	Performance time	Seconds (s)
	Corrective postural strategies	Count
	Time-to-stabilisation (x-axis)	Seconds (s)
	Time-to-stabilisation (y-axis)	Seconds (s)

SEBT = Star excursion balance test; MHT = Multiple hop test.

non-weightbearing leg into greater than 30° of adduction or abduction. Participants were instructed to minimise corrective postural strategies. Participants performed four practice trials and three test trials, with 3-minute rest intervals between trials. Participants performed the MHT using only the dominant limb (further explanation in *supplemental file*). (Eechaute et al., 2008a, 2008b, 2009).

MHT trials were video-recorded using a tripod-mounted video camera facing the participant antero-posteriorly (Canon, Tokyo). Two independent assessors (one blind and one not blind to participant concussion status) assessed video recordings of MHT performance. Assessors evaluated the number of corrective postural strategies made by participants during the test when landing on each floor marker. The sum of corrective postural errors across trials was used to calculate the postural error outcome score for each MHT assessment (further explanation in *supplemental file*). An unweighted mean of assessor one and assessor two error ratings for each participant was calculated.

The MHT has not been validated in a concussion cohort but has demonstrated good-to-excellent intersession reliability (time in seconds: Intra-Class Correlation (ICC) = 0.87–0.97; corrective strategies: ICC = 0.64–0.83) and moderate-to-good intra- (corrective strategies: ICC = 0.83–0.94) and inter-rater reliability (corrective strategies: ICC = 0.91–0.94) in healthy and other clinical populations (Eechaute et al., 2008a, 2009). The MHT has demonstrated good discriminative properties to differentiate individuals with and without chronic ankle instability using the number of corrective strategies (receiver operating characteristic area under the curve = 0.79 (95%CI 0.67–0.89)) (Eechaute et al., 2012, 2017; Rosen et al., 2019).

At the end of the MHT, participants stabilised on the final tape marker, which was positioned on a force-plate. Data from the force-plate was recoded using a sampling frequency of 1 kHz and was segmented, for each trial, from the instant of landing to exactly 5 seconds after landing. The time-to-stabilisation parameter was calculated from the force-plate data for both the anteroposterior and mediolateral directions using the sequential estimation method (Shaw et al., 2008). In the sequential estimation method, the cumulative average of the ground reaction force data in both directions was calculated, for each time point, as the average of all samples up to that point. Then, a threshold was calculated, for each direction, as the average + 0.25 times the standard deviation of the whole ground reaction data for the trial. The time-to-stabilisation parameter was then identified as the instant in which the cumulative average first fell below the threshold value. Data processing was performed using Matlab (Mathowks, US).

2.7. Statistical analysis

We performed descriptive statistics to summarise group-level demographic characteristics and outcomes. Continuous variables are expressed as means or medians, and standard deviations (SD) or inter-quartile ranges (IQR). Dichotomous variables are presented using frequencies (n) and percentages (%). Equivalence tests were performed to test the null hypothesis that concussion and control groups were statistically equivalent on baseline and demographic variables (Lakens, 2017; Lakens et al., 2018).

We constructed a multi-level model to investigate whether SEBT and MHT outcome measures differed between the concussion group and the control group at each study assessment (further explanation in *supplemental file*). We selected a maximum-likelihood estimation method to compare models with fixed and random coefficients (i.e., intercepts and slopes) and to assess which models provided the best fit to the data. We constructed an initial baseline model including only a fixed intercept and then added a random intercept for individual participants to assess whether allowing scores at each study assessment time-point to vary across individuals improved model fit (because participants likely recover from different "starting points"). Random intercepts improved model fit for each outcome variable and was retained. Allowing outcome scores to vary across individual participants significantly improved model fit and was retained in each statistical model.

Group, time, and group-by-time were entered, in that order, into each model as fixed effects and interaction terms, respectively. We allowed study assessment time-points to cluster within each patient due to the dependency of these scores on the same patient over time. We interpreted Akaike Information Criterion (AIC) values to evaluate improvements in the fit of each model. We calculated a -2 Log-Likelihood ratio value to assess significant improvements in model fit with each added parameter. Alpha level was set at 0.05.

Significant interaction terms were interpreted by performing separate multi-levels models at each study assessment to evaluate whether there were significant differences between the concussion group and the control group at study assessment time-points one, two, and three. We adjusted the alpha level for family-wise comparisons of significant interaction terms using a Bonferroni correction (0.05/3 time-points = 0.0167). Statistical analyses and data visualisation were performed in RStudio (Vienna, Austria).

3. Results

Fifty-two concussion patients and 52 control participants were eligible to participate, provided informed consent, and enrolled in the study. Two participants in each group were lost to follow-up and excluded from the study. Fifty concussed athletes and 50 sex-, age-, and activity-matched control athletes, who were similar on collected demographic characteristics, completed the study (Table 2).

3.1. Star excursion balance test anterior reach distance normalised for leg length

The concussion group and the control group did not differ on anterior reach distance (normalised for leg length) when aggregating across study assessment time-points and when group was included in the model as a fixed effect (main effect for group: χ^2 (1) = 0.70; p = 0.4). Adding dorsiflexion range of motion as a confounding variable to the model, with group, significantly improved model fit (χ^2 (1) = 20.86; p < 0.0001). The concussion group did not demonstrate significantly different anterior reach distance normalised for leg length on the SEBT compared with the control group at any study assessment (group-by-time interaction: χ^2 (5) = 0.00001; p = 0.99) (Table 3) (Supplemental Table 1).

3.2. Fractal dimension

The concussion group exhibited significantly different complexity in centre of pressure trajectory compared with the control group regardless of the study assessment time-point (main effect for group: χ^2 (1) = 11.35; p = 0.0008). The concussion group did not demonstrate significantly different complexity in postural stability than the control group at any study assessment (group-by-time interaction: χ^2 (2) = 1.55; p = 0.46) (Table 3).

3.3. Multiple hop test corrective postural strategies

There was a significant group-by-time interaction (χ^2 (2) = 14.16; p = 0.008) for corrective postural strategies on the MHT (Supplemental Table 3), whereby the concussion group used a significantly greater number of corrective postural strategies than

Table 2
Participant demographic information.

	Concussion group (n = 50)	Control group (n = 50)	Equivalence testing	Upper & lower bounds
Sex (female), n (%)	14 (28%)	14 (28%)	p = 0.013[a]	± 0.2%
Age (years), mean (SD)	22.9 (5.1)	23.8 (4.6)	p < 0.001[a]	± 4 years
Height (cm), mean (SD)	177.4 (10.4)	177.0 (9.0)	p = 0.034[a]	± 4.0 cm
Mass (kg), mean (SD)	79.2 (15.4)	79.0 (13.1)	p = 0.023[a]	± 6.0 kg
Sports participation per week (hours), mean (SD)	8.3 (3.7)	8.5 (3.4)	p = 0.006[a]	± 2 h
Assessment 1 (days), mean (SD)	4.3 (1.70)	N/A	–	–
Assessment 2 (days), mean (SD)	14.3 (4.6)	14.4 (3.4)	p < 0.001[a]	± 3 days
Assessment 3 (days), mean (SD)	30.3 (7.2)	31.5 (6.9)	p = 0.004[a]	± 5 days
Prior concussion history (yes), n (%)	26 (52%)	18 (36%)	p = 0.342[b] p = 0.102[b]	± 0.2
History of migraine (yes), n (%)	7 (14%)	7 (14%)	p = 0.002[a]	± 0.2
History of diagnosed learning disability (yes), n (%)	6 (12%)	1 (2%)	p = 0.049[a]	± 0.2
History of diagnosed mood disorder (yes), n (%)	8 (16%)	4 (8%)	p = 0.031[a]	± 0.2

N/A = Time calculated since injury meaning that control group could not produce a numeric value. Control group study assessment time-points are subtracted from the first control group study assessment.
[a] In equivalence testing using two one-sided significance tests, p < 0.05 indicates that both the concussion group and control group are statistically equivalent.
[b] For prior concussion history, the concussion group and the control group are not statistically equivalent but also not statistically different due to a lack of statistical power.

the control group within one-week following sport-related concussion ($\beta = 4.85$; SE = 1.05; $p < 0.0001$) and upon clearance to RTA ($\beta = 4.65$; SE = 1.00; $p < 0.0001$) (Fig. 1) (Supplemental Table 4). The number of corrective postural strategies employed by the concussion group were not significantly different compared with the control group two weeks following RTA after sport-related concussion ($\beta = 2.26$; SE = 1.10; $p = 0.043$) (Table 3).

3.4. Multiple hop test time-to-stabilisation in the sagittal plane

There was a significant group-by-time interaction for time-to-stabilisation in the anteroposterior direction (χ^2 (2) = 10.8; $p = 0.0045$), whereby adding this interaction term significantly improved model fit to the data (Supplemental Table 5). However, when applying a Bonferroni correction for multiple comparisons between the concussion and the control group, there were no significant differences in the time taken for participants to stabilise in the anteroposterior direction at the end of the MHT (Table 3) (Supplemental Table 6).

3.5. Multiple hop test time-to-stabilisation in the frontal plane

There was a significant group-by-time interaction for time-to-stabilisation in the mediolateral direction (χ^2 (2) = 2.52; $p = 0.019$) (Supplemental Table 7). However, the concussion group did not take significantly longer than the control group to stabilise in the mediolateral direction after the MHT one week following sport-related concussion ($\beta = 0.06$; SE = 0.05; $p = 0.2$), upon medical clearance to RTA ($\beta = 0.04$; SE = 0.04; $p = 0.3$), and two weeks following RTA after sport-related concussion ($\beta = -0.07$; SE = 0.04; $p = 0.08$) when a Bonferroni correction was applied to account for multiple comparisons (Table 3) (Supplemental Table 8).

4. Discussion

Using two functional movement tests, we assessed for the presence of sensorimotor impairments in a group of recently concussed amateur athletes compared with control athletes. Upon clearance to RTA, concussed athletes demonstrated a greater number of corrective postural strategies than control athletes when performing the MHT. However, the concussion group recorded a similar time-to-stabilisation as the control group when completing the MHT from one-week following sport-related concussion through two weeks after RTA. Similarly, the concussion group did not perform significantly differently during the SEBT compared with the control group from one-week following sport-related concussion up to 2 weeks after RTA. Our results contradict our pre-study hypotheses, which anticipated that acutely concussed athletes would exhibit persistent sensorimotor impairments on the SEBT and the MHT up to two weeks following RTA.

We used the number of corrective postural strategies exhibited during the MHT as a surrogate marker of sensorimotor performance. The dynamic and multi-directional demands of the MHT require high levels of sensorimotor control to confer postural

Table 3
Descriptive statistics of SEBT & MHT outcome measures.

	Time-point 1		Time-point 2		Time-point 3	
	Concussion Mean (SD)	Control Mean (SD)	Concussion Mean (SD)	Control Mean (SD)	Concussion Mean (SD)	Control Mean (SD)
DF RoM (cm)	8.39 (3.36)	6.41 (3.26)	8.23 (3.05)	6.36 (3.43)	8.41 (3.39)	6.33 (3.23)
LL (cm)	92.7 (6.27)	92.5 (5.34)	92.1 (6.17)	92.5 (5.56)	92.8 (6.51)	92.1 (5.29)
SEBT						
Anterior reach distance[a] (cm)	62.6 (5.32)	64.0 (5.92)	63.9 (5.89)	64.1 (6.42)	63.5 (6.53)	64.0 (5.87)
Fractal dimension	1.07 (0.08)	1.11 (0.07)	1.05 (0.08)	1.10 (0.06)	1.05 (0.07)	1.10 (0.07)
MHT						
Time (s)	39.0 (6.88)	31.3 (6.18)	36.8 (7.90)	32.0 (7.86)	35.9 (8.02)	32.1 (8.08)
Corrective postural strategies (number)	14.8 (5.74)	10.0 (4.57)	15.1 (5.07)	10.5 (4.42)	12.8 (5.21)	10.5 (5.21)
TTSx[b] (s)	2.67 (0.11)	2.73 (0.22)	2.70 (0.18)	2.74 (0.08)	2.77 (0.13)	2.73 (0.06)
TTSy[b] (s)	2.56 (0.24)	2.62 (0.18)	2.61 (0.18)	2.65 (0.18)	2.68 (0.23)	2.60 (0.16)

DF RoM = Dorsiflexion range of motion, cm = centimetres, LL = Leg length.
[a] Star Excursion Balance Test anterior reach distance normalised for leg length.
[b] TTSx = Time-to-stabilisation (x-axis), anteroposterior direction, sagittal plane; TTSy = Time-to-stabilisation (y-axis), mediolateral direction, frontal plane.

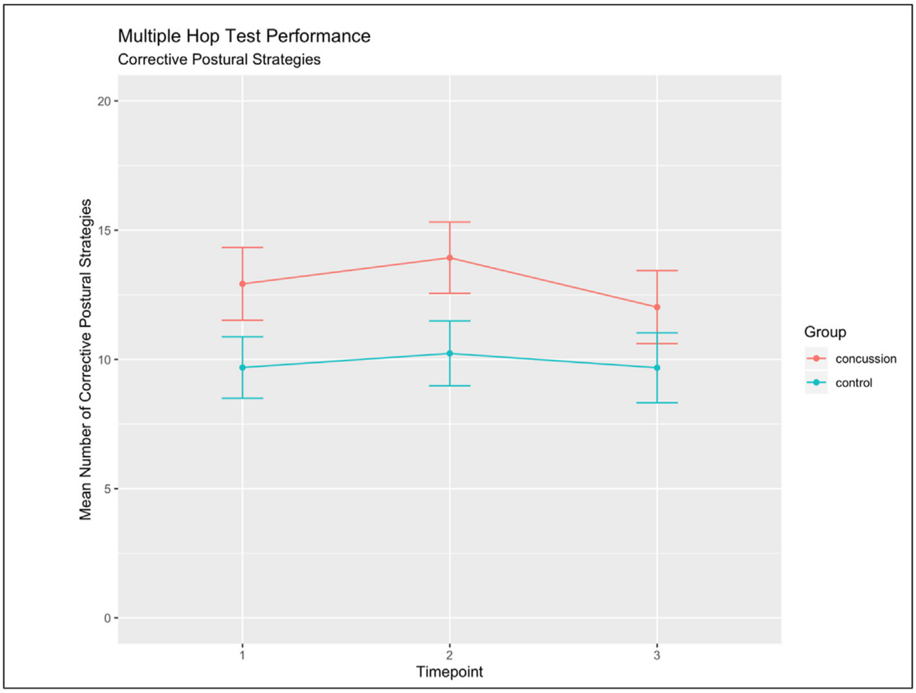

Fig. 1. Mean number of corrective postural strategies for the concussion group and the control group over time. Error bars represent 95% confidence intervals for each group mean at assessment time-points. Timepoint 1, within 1 week following sport-related concussion; Timepoint 2, upon medical clearance to return-to-sporting activity; Timepoint 3, 2 weeks after return-to-sporting activity.

stability. We speculated that performing a functional movement task such as the MHT, which is thought to be more challenging than a less functional, static balance task, would magnify underlying sensorimotor impairments that manifest only under high cognitive loads during sports performance. Our findings partially support the belief that subtle, persistent sensorimotor impairments are present when athletes RTA following sport-related concussion (Büttner et al., 2019; Howell et al., 2015; Parker et al., 2007; Parrington et al., 2018), which may mediate the relationship between concussion and subsequent lower extremity, musculoskeletal injury (McPherson et al., 2019). Future prospective studies are needed to examine this theory.

Dynamic balance impairments following sport-related concussion may impact walking and running gait control, potentially contributing to subsequent lower extremity, musculoskeletal injury risk (Fino et al., 2018; Howell et al., 2018a; Manaseer et al., 2017). Delayed reaction times and greater postural instability during a variety of functional walking tasks can persist beyond the resolution of clinical impairments and resumption of sporting activity following concussive injury (Belanger & Vanderploeg, 2005; Buckley, Vallabhajosula, et al, 2016; Büttner et al., 2019; Catena et al., 2009; Fait et al., 2013; Fino et al., 2016; Powers et al., 2014; Warden et al., 2001). It is probable that impaired sensorimotor control following sport-related concussion is only one of many risk factors that interact in a complex manner to manifest in subsequent lower extremity, musculoskeletal injury (Bittencourt et al., 2016; Roe et al., 2017). For example, underlying strength deficits and erratic training load prescriptions may further increase an athlete's susceptibility to lower extremity, musculoskeletal injury when combined with impaired sensorimotor control secondary to neurological alterations following sport-related concussion (Fino et al., 2019; Herman et al., 2015; Swanik et al., 2007).

Interestingly, the concussion group did not demonstrate a significantly greater number of corrective postural strategies than the control group (mean difference = 2.3 postural corrective strategies) two weeks after RTA following sport-related concussion. Continued recovery of the sensorimotor system following RTA and the (training) effect of organised sporting activity on sensorimotor control may explain improved MHT performance in the concussion group (Reneker, Babl, Pannell, et al., 2019). It is also possible that subtle, clinically undetectable, sensorimotor impairments persist following sport-related concussion and may become clinically meaningful, long-term outcomes over time.

When performing the MHT, the concussion group did not exhibit a significantly different time-to-stabilisation compared with the control group. These null findings align with the existing literature that explore the utility of functional movement tests to assess concussion-associated sensorimotor impairments using laboratory-based outcomes (Berkner et al., 2017; Büttner et al., 2019; Ford et al., 2018; Howell et al., 2019; Lynall et al., 2018, 2019). Specifically, athletes with and without a recent (<1.5 years) history of concussion demonstrated a similar time-to-stabilisation when landing from a single-leg hop (Lynall et al., 2020). Additionally, when completing jump landing tasks with and without anticipated cutting manoeuvres, athletes with a history of concussion did not perform significantly differently compared to athletes without a history of concussion after correcting for multiplicity (Lynall et al., 2018). Dynamic, cognitive-motor dual-task assessments did not consistently identify differences between concussion and control groups during single- and dual-task conditions (Berkner et al., 2017; Büttner et al., 2019; Howell et al., 2019; Lynall et al., 2018). Moreover, prospectively examined head impact exposure throughout one football season was not associated with pre-season to post-season changes in functional movement scores (Ford et al., 2018). Only a subset of, rather than all, athletes may experience persistently impaired sensorimotor performance following sport-related concussion – detecting this impaired subgroup is challenging when relying on statistically significant, group-level, mean differences, as the existing literature suggests.

There were no significant differences between the concussion and control groups during the SEBT over time on either normalised anterior reach distance or fractal dimension. Although the SEBT is a novel, clinical assessment of postural control with both closed-chain and open-chain components (i.e., closed-chain controlling centre of mass while reaching outside of one's base of support) (Gribble et al., 2012), it has been suggested that more functional movement activities, such as gait tasks, are better at identifying deficits after a sport-related concussion than statically performed tasks (Buckley et al., 2017; Fino et al., 2016; Oldham et al., 2016; Parker et al., 2006). The SEBT was selected and administered in this investigation due to its prevalent use in clinical settings and responsiveness in, and prospective association with, other injuries (Gribble et al., 2012). However, the SEBT may be insufficiently dynamic to challenge athletes with persistent sensorimotor impairments following sport-related concussion. When performing clinician-administered static postural control tasks to assess balance impairments following sport-related concussion, athletes typically exhibit normative values within five days (McCrea et al., 2003, 2005, 2013). Similarly, athletes with a history of concussion exhibited similar performance on laboratory-based outcome measures (i.e., CoP path, speed, and velocity) compared to athletes without a history of concussion when performing a single-leg squat; similar to the movement involved in the anterior reach component of the SEBT (Lynall et al., 2020). These existing findings in the literature align with the null findings observed in the current study.

4.1. Limitations

Given our study design and resources, we could not collect pre-injury data for our cohort of concussed athletes. A prospective design with pre-morbid data may have resulted in different study findings due to an additional assessment time-point facilitating within-subject analyses. Additionally, our mixed-sport sample impacts the generalisability of our findings to cohorts of athletes who participate in a specific sport. We included a non-injured, athletic control group instead of a musculoskeletal injury, athletic control group. This may introduce a risk of selection bias in favour of greater corrective postural differences between the concussion and control groups during the MHT. Sensorimotor impairments have been identified as a risk factor for elevated non-contact, musculoskeletal injury risk (Hewett et al., 2005; McGuine et al., 2000; Padua et al., 2015; Plisky et al., 2006; Zazulak et al., 2007), and therefore dynamic postural control may be worse in athletes with a musculoskeletal injury compared with non-injured athletes. Two independent raters evaluated the number of participants' corrective strategies during the MHT using objectively set criteria. One-hundred participants negotiated ten numbered markers during the MHT and participants could make any one of seven corrective postural strategies, resulting in hundreds of potential combinations. Resolving inter-rater disagreement by discussion or third rater arbitration was not time feasible. Consequently, we computed an unweighted average for both raters.

5. Conclusion

Acutely concussed amateur athletes exhibited similar SEBT anterior reach distance (normalised for leg length) and fractal dimension values compared with control participants within one-week following sport-related concussion through two weeks after RTA following sport-related concussion. However, sensorimotor impairments may be present when athletes return to more dynamic, complex environments such as sport. The concussion group made a greater number of corrective postural strategies than control participants during the MHT upon clearance to RTA but not two weeks after RTA. Despite significant differences in the corrective postural strategies used by the concussion group and control group up to RTA, the concussion group and the control group recorded similar times-to-stabilisation at the end of the MHT. The MHT may offer a clinically useful tool for practitioners to examine the recovery of subtle sensorimotor impairments and related RTA readiness. Future longitudinal research using challenging, functional movement tests such as the MHT may elucidate the association, or lack thereof, between concussion-associated sensorimotor impairments and subsequent lower extremity, musculoskeletal injury.

6. Informed consent

This study was performed in accordance with the Declaration of Helsinki. Participants provided informed consent to participate in the reported study after reading a detailed study information leaflet, listening to a comprehensive explanation of the study's purposes and procedures, and asking questions about their involvement in the current study.

Declaration of competing interest

The authors report no conflict of interest relating to the current research study.

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Nil to report.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2020.10.012.

Authors contribution

FCB, ED, and JR developed the original study idea. FCB and ED developed the study protocol. FCB and JR directed participant recruitment. FCB, DRH, GS, CD, and CB were involved in the processing, analysis, and interpretation of study data. FCB composed the initial draft of the study manuscript. DRH, CD, CB, JR, and ED provided comments and edited subsequent manuscript drafts and contributed to the preparation of the final submission manuscript.

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Ethical approval

This prospective, longitudinal, matched-cohort study received ethical approval from the University College Dublin Human Resources Ethics Committee for Life Sciences (UCD HREC-LS).

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