Concussed athletes walk slower than non-concussed athletes during cognitive-motor dual-task assessments but not during single-task assessments 2 months after sports concussion: a systematic review and meta-analysis using individual participant data

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ABSTRACT

Objectives To determine whether individuals who sustained a sports concussion would exhibit persistent impairments in gait and quiet standing compared to non-injured controls during a dual-task assessment .

Design Systematic review and meta-analysis using individual participant data (IPD).

Data sources The search strategy was applied across seven electronic bibliographic and grey literature databases: MEDLINE, EMBASE, CINAHL, SportDISCUS, PsycINFO, PsycARTICLES and Web of Science, from database inception until June 2017.

Eligibility criteria for study selection Studies were included if; individuals with a sports concussion and non-injured controls were included as participants; a steady-state walking or static postural balance task was used as the primary motor task; dual-task performance was assessed with the addition of a secondary cognitive task; spatiotemporal, kinematic or kinetic outcome variables were reported, and; included studies comprised an observational study design with case–control matching.

Data extraction and synthesis Our review is reported in line with the Preferred Reporting Items for Systematic review and Meta-Analyses-IPD Statement. We implemented the Risk of Bias Assessment tool for Non-randomised Studies to undertake an outcome-level risk of bias assessment using a domain-based tool. Study-level data were synthesised in one of three tiers depending on the availability and quality of data: (1) homogeneous IPD; (2) heterogeneous IPD and (3) aggregate data for inclusion in a descriptive synthesis. IPD were aggregated using a ‘one-stage’, random-effects model.

Results 26 studies were included. IPD were available for 20 included studies. Consistently high and unclear risk of bias was identified for selection, detection, attrition, and reporting biases across studies. Individuals with a recent sports concussion walked with slower average walking speed (χ^2=51.7; df=4; p<0.001; mean difference=0.06 m/s; 95% CI: 0.004 to 0.11) and greater frontal plane centre of mass displacement (χ^2=10.3; df=4; p=0.036; mean difference −0.0039 m; 95% CI: −0.0075 to −0.0004) than controls when evaluated using a dual-task assessment up to 2 months following concussion.

Summary/conclusions Our IPD evidence synthesis identifies that, when evaluated using a dual-task assessment, individuals who had incurred a sports concussion exhibited impairments in gait that persisted beyond reported standard clinical recovery timelines of 7–10 days. Dual-task assessment (with motion capture) may be a useful clinical assessment to evaluate recovery after sports concussion.

Protocol pre-registration This systematic review was prospectively registered in PROSPERO CRD42017064861.

INTRODUCTION

Sports concussion is an international sports medicine priority. Typically, diagnosis of sports concussion is informed by athlete self-reported symptoms, computerised cognitive testing, and clinician-assessed static postural balance performance.[1 2] The discriminative capacity of these assessments, however, diminishes dramatically with increasing time following injury.[3 4] The fifth Concussion in Sport Consensus Statement identifies innovative assessment techniques to evaluate the time-course of concussion-induced impairments as a research priority.[5]

A cognitive-motor dual-task is one where an individual performs a physical task (such as walking or quiet stance) while simultaneously performing a cognitive task (eg, subtracting numbers backwards). Cognitive-motor dual-task evaluations can detect latent gait impairments following sports concussion that extend beyond the reported recovery timelines for clinical symptoms, cognitive impairments, and static postural balance impairments.[6 7 8–10] Everyday movement tasks such as walking and quiet standing are completed regularly with little-to-no conscious effort, and participant performance does not tend to improve on these tasks with practice.[11] Therefore, walking and quiet standing are ideal tasks with which to simultaneously present a cognitive task to assess dual-task performance.

Previous systematic reviews have investigated the psychometric properties of dual-task assessments,[12] described the constituents of dual-task protocols[13] and quantified the dual-task deficit of biomechanical outcomes in concussed and non-concussed athletes.[14] These systematic reviews concluded that wide variability existed in the reliability of dual-task assessment measures, that studies were of poor quality, but also that athletes walked with slower walking speed and greater frontal plane centre of mass (CoM) sway following sports concussion. Due to low study quality and large between-study differences,[8–10 15] these systematic reviews can make only tentative conclusions about the persistence of impairments under dual-task assessment in athletes following sports concussion. Given the inherent limitations of descriptive and quantitative aggregate data evidence syntheses, a meta-analysis using individual participant data (IPD)—in which the original data for each participant in relevant studies are centrally collected, validated, harmonised and re-analysed—is the gold-standard approach to evidence synthesis.[16 17] We conducted a systematic review with IPD and posed the following review questions:

In individuals who have recently sustained a sports concussion and are compared with control participants:

1. Are there greater walking and quiet standing impairments in dual-task assessments compared with single-task assessments?
2. Are there persistent walking and quiet standing impairments in single-task and dual-task assessments?

METHODS

Review authorship

Two authorship groups undertook this systematic review. The ‘review authors’ comprised authors who initiated the review as well as selected studies, and collected, synthesised, verified, and analysed aggregate and IPD . The ‘contributing authors’ were the lead and supervising authors of included original research studies. Contributing authors provided IPD for review authors to independently validate, harmonise, and analyse. One author (DRH) was a member of both groups. Members of the ‘contributing authorship’ group did not manage datasets provided for IPD analysis. All authors approved the final manuscript.

Protocol registration

This systematic review was reported in line with the Preferred Reporting Items for Systematic review and Meta-Analyses using IPD statement.[18] A review protocol was completed *a priori* and pre-registered at the International Prospective Register of Systematic Reviews (PROSPERO ID=CRD42017064861) http://www.crd.york.ac.uk/PROSPERO/display_record.php?ID=CRD42017064861.

Literature identification and screening

Two ‘review authors’ (FCB and ED) developed the search strategy (online supplementary file – search strategy). Search terms were mapped to Medical Subject Headings where possible. Search terms were entered under four concepts: (1) injury terminology; (2) motor task; (3) cognitive task and (4) sporting code. Search terms within each concept were grouped with the ‘OR’ Boolean operator and concepts were combined using the ‘AND’ Boolean operator to produce the search strategy and final yield. The search strategy was applied across seven electronic bibliographic and grey literature (non-formally published literature) databases; MEDLINE via PubMed; EMBASE via Ovid; CINAHL via Ebsco (for grey literature); SportDISCUS (for grey literature); PsycINFO (for grey literature); PsycARTICLES and Web of Science. Search terms were applied from inception of each database to June 2017. Following dual-assessor (FCB and ED) screening of titles and abstracts, the full-length texts of remaining articles were retrieved to determine a study’s inclusion eligibility if ambiguity existed. Reference lists of relevant articles were hand-searched by one author (FCB) for other potentially relevant references. A content expert (DRH) provided feedback about whether ongoing or previously published studies were not identified following the electronic database search.

Study selection

Studies were included if:

1. Individuals with a sports concussion *and* non-injured controls were included as participants. We accepted studies that included clinician- or investigator-determined concussion injury. Studies including patients with moderate and/or severe traumatic brain injury were excluded.
2. A steady-state walking task or a static postural balance task was used. Complex walking tasks, such as walking over or around an obstacle while responding to a cognitive task, were excluded.
3. Dual-task performance was assessed using a motor task and simultaneous a cognitive task.
4. Spatiotemporal or kinematic walking outcome measures or kinetic balance outcome measures were reported.
5. Motor outcomes in single-task and dual-task conditions were reported.
6. An observational study design (prospective, retrospective or cross-sectional) with case–control matching was used. Case report and case series research designs were excluded.

Outcome measures

Primary and secondary outcome measures were classified into one of the three outcome domains (table 1) (online supplementary tables A–C). The absolute single-task and dual-task performances of each outcome measure were computed. Dual-task costs were calculated by subtracting the absolute single-task value from the absolute dual-task value, normalising for single-task performance, and interpreted as the percentage change between single-task and dual-task conditions.[19]

Table 1 Outcome measurement domains and associated outcome measures

Spatiotemporal	Kinematic	Kinetic
Walking velocity*	CoM displacement in frontal and sagittal planes*	95% CoP ellipse area*
Tandem walking completion time†	CoM velocity in frontal and sagittal planes*	Mean CoP velocity in frontal and sagittal planes*
Stride length†	Maximum horizontal CoP-CoM separation in frontal and sagittal planes†	
Stride time†	Peak CoM mediolateral acceleration†	
Step width†		

*Primary outcome.
†Secondary.
CoM, centre of mass; CoP, centre of pressure.

Table 2 Responses of primary authors to requests for IPD

Primary author responses:	Primary authors contacted N=12 (K=26)
Satisfied to provide IPD unconditionally	n=3 (k=11)
Provision of IPD conditional on authorship	n=1 (k=4)
Provision of IPD conditional on approval by supervisory author	n=1 (k=4)
Provision of IPD prohibited by ethics institutional board	n=1 (k=1)
No response from author	n=4 (k=4)
IPD no longer available	n=2 (k=2)

IPD, individual participant data; k, number of studies; n, number of authors.

IPD acquisition, data cleaning, and harmonisation

Authors of included studies were contacted by two members of the 'review authorship' group (FCB and DRH). We provided the contributing authors with template datasets, which indicated the independent and dependent variables we sought for analysis. All data were anonymised before providing IPD to the 'review authors'. Duplicate samples were either (i) removed or (ii) combined into a single dataset to ensure data from each participant were included in the analysis only once.

Aggregate data extraction

If IPD were unavailable (table 2), review authors (FCB and ED) extracted aggregate data to systematically identify, compare and report the characteristics of study methodologies and population demographics.[20] A template for aggregate data extraction within the following domains was developed: [21–2523 24 26–2824 29–322424 33 3424 35]

1. methodological characteristics: risk of bias (including selection of participants, confounding (such as sex,[21–25] age,[23 24 26–28] concussion history,[24 29–32] diagnosed learning disability or attention disorder,[24] diagnosed mood disorder[24 33 34] or history of migraine headaches),[24 35] measurement of injury, blinding of outcome assessment, incomplete outcome data, and selective outcome reporting).
2. participant characteristics: sex, age, height, body mass, sport-type, and previous concussion history.
3. study characteristics: observational study design, frequency of and interval between assessment time-points, sample size, and type of dual-task paradigm.
4. outcome domain and associated outcome measures: spatiotemporal, kinematic, and kinetic outcome variables.

table 2 .

Risk of bias assessment within-studies and across-studies

We implemented the Risk of Bias Assessment tool for Non-randomised Studies to assess the risk of bias within and across included studies (online supplementary file A). Two authors (FCB and ED) independently performed separate outcome-level risk of bias assessments for spatiotemporal, kinematic and kinetic outcome domains.[36] We could not assess publication bias due to the observational design of included studies and because too few studies contributed to a common outcome measure.[20 37] We implemented the Strength of Recommendation Taxonomy to determine the strength of recommendation for the use of dual-task assessments to evaluate the recovery of walking and quiet standing impairments following sports concussion.[38]

Statistical analysis

We performed χ^2 tests to compare the proportion of men and women in sports concussion and control groups.

We undertook a three-tiered approach to data synthesis:

1. Meta-analysis of homogeneous IPD that were harmonised across datasets to compile a 'mega-dataset'. We used a 'one-stage' approach to combine IPD into a single meta-analysis, using a linear mixed model (LMM), for each outcome measure. Fixed effects and their interactions for each outcome measure were examined while accounting for grouping factors (clusters) by implementing linear mixed-effects modelling[39–41] using the 'lme4' package in R and an unstructured variance–covariance matrix.[42 43] Each model initially specified random effects (intercepts) to account for clustering of participants within each dataset and for repeated measures within each participant, with fixed effects specified for group membership (concussion and control) and time. Model selection confirmed that the participant random intercept improved model fit and was necessary using a likelihood ratio test and the Akaike Information Criterion. Thereafter, LMMs were constructed with maximum likelihood estimation to evaluate both main effects for group and group*time interactions. The results of the likelihood ratio test followed a χ^2 distribution and results are expressed as χ^2 statistics with p values. We calculated mean differences with 95% CIs to assess post-hoc differences between the concussion and control groups at each time-point. 95% CI were selected to minimise type I and type II errors.
2. IPD that were too heterogeneous or sparse to harmonise were analysed within their original dataset to reproduce the originally reported findings.[44 45] 'Review author' s statistically analysed data for the research questions for which IPD were collected. Results were described narratively.
3. For unavailable IPD and excessively heterogeneous data, aggregate data were extracted from included articles and narratively synthesised.[20] Outcome-level narrative syntheses were reported, systematically, in order of:

i) population characteristics (sample sizes)
ii) assessment time-points (quantity and intervals)
iii) assessment protocol (single-task and dual-task conditions)
iv) results of specific outcome domains (spatiotemporal, kinematic, kinetic).

RESULTS

The search identified 701 studies. After we identified and removed duplicate items, 372 studies remained. 36 studies were eligible for inclusion following title and abstract screening. Full-text screening eliminated 12 studies. A content expert identified one additional eligible study. Hand-searching identified one study. In all, 26 studies were included for aggregated data extraction (online supplementary file C – PRISMA flow-diagram).

Study characteristics

There were 14 prospective longitudinal studies,[46–59] 11 cross-sectional studies[60–70] and one retrospective longitudinal study.[71] Data for 1039 participants (concussed participants (n=516); control participants (n=523)) were included in this review. Six individual patient datasets were contributed for IPD analysis by five authors, accounting for 20 of 26 identified studies (online supplementary table D).

Study time-points

In all, 21 studies assessed participants within 2 days[46–51 53–63] to 1 week[52 67 68 71 72] following concussion. Five studies assessed participants for the first time approximately 1 month or greater following concussion.[64–66 69 70] Duration of prospective longitudinal studies (k=12) ranged from 1–2 months[46–51 53–58] to 12 months[52] post-injury. In total, 22 studies reported concussion diagnosis by a physician, physiotherapist, or certified athletic trainer and in accordance with a best-evidence practice guideline/expert-led consensus statement.

Participants

Sex

From aggregate data alone, there were 277 concussed male participants and 269 non-injured male control participants. There were 211 concussed female and 226 non-injured female control participants across 25 studies (online supplementary tables E–F) (one study did not report participant sex). IPD were obtained for 187 concussed participants (102 men; 54.5%, 85 women; 45.5%) and 175 non-injured control participants (87 men; 49.7%, 88 women; 50.3%) (χ^2=0.85; p=0.35).

Age

Nine studies implemented dual-task assessments in an adolescent population only (<18 years), and 17 studies in an adult population (>17 years). The mean age of participants in individual patient datasets (k(number of datasets)=6, n(number of participants)=362) was 17.3±3.9 years (concussion group=17.5 ±3.9 years; control group=17.2 ±3.9 years). The mean age of adolescents (k=3, n=218) was 14.9±1.9 years (concussion group=15.0 ±2.0 years; control group=14.9 ±1.8 years). The mean age of adult participants (k=4, n=144) was 21.1±3.1 years (concussion group=21.1 ±3.2 years; control group=21.1 ±3.0 years) (online supplementary table E).

Assessment protocols

Walking was the most frequently used motor task.[46–68] Three studies used quiet standing tasks conducted on a strain gauge force-plate[71] or a Wii balance board.[69 70] Individual patient datasets required participants to walk on an 8–10 m level walkway at a self-selected pace while completing 'question and answer' tasks (k=5), or stand quietly on a Wii balance board while concurrently performing a Stroop test (k=1) (online supplementary file B). 'Question and answer' tasks[46–63 67 68 72] were secondary cognitive tasks for 23 (82%) studies. Visual[69–71] or auditory[49 54] Stroop tasks were the cognitive task in five studies.

Outcome measures

Table 3 details the outcome measures that were assessed in three broader outcome domains.

We present quantitatively aggregated IPD (tier 1) for primary outcome measures in the main manuscript and include tier 3 (aggregate data) synthesis for primary outcome measures and tier 1 (IPD meta-analysis), tier 2 (heterogeneous IPD verification) and tier 3 (aggregate data) syntheses for secondary outcome measures in online supplementary file B. We report separate statistical analyses and results of tier 2 (independently verified heterogeneous IPD) in online supplementary files D–J.

Table 3 Outcome measure allocation to outcome domains as determined by pre-specified criteria [online supplementary tables A–C].

Tier	Spatiotemporal	Kinematic	Kinetic
1) Individual patient data	Walking velocity* Stride length† Stride time†	CoM displacement and velocity in frontal and sagittal planes* Maximum CoP-CoM separation in frontal and sagittal planes†	–
2) Verification analysis contributing to descriptive synthesis	Walking speed* Tandem walking completion time† Step length† Step width†	Peak CoM M/L acceleration†	95% CoP ellipse* Mean A/P CoP velocity* Mean M/L CoP velocity*
3) Descriptive synthesis	Walking speed* Stride length† Step width†	–	95% CoP ellipse area* CoP velocity*

*Primary outcome.
†Secondary outcome.
A/P, anterior-posterior; CoM, centre of mass; CoP, centre of pressure; M/L, mediolateral.

Spatiotemporal walking outcomes

Walking velocity

Absolute single task and dual task, and dual-task cost

On analysis of IPD, the concussion group walked slower than the control group, averaged across all time-points, during single-task (main effect: χ^2=13.3, df=1, p<0.001) and dual-task conditions (main effect: χ^2=23.6, df=1, p<0.001). During the single-task assessment, the difference varied by time of assessment (interaction effect: χ^2=38.2, df=4, p<0.001), with slower walking speed evident at 48 hours (time-point 1) and 1 week (time-point 2) assessments in the concussion group. In dual-task assessments, the difference in walking speed between concussion and control groups also varied by time (interaction effect: χ^2=51.7, df=4, p<0.001), with the concussion group walking slower from 48 hours up to 2 months (time-point 5) following injury (interaction effect: χ^2=51.7, df=4, p<0.001) (figure 1) [online supplementary IPD table 1]. Overall, the concussion group demonstrated greater dual-task costs compared with the control group across all time-point assessments (main effect: χ^2=9.96, df=1, p=0.002) and this was consistent over time (interaction effect: χ^2=4.76, df=4, p=0.31).

Risk of bias: spatiotemporal outcomes

Ten studies (56%) were at low risk of selection bias due to inadequate selection of participants (table 4). One study (6%) was at low risk of selection bias due to inadequate identification of or adjustment for confounding variables, with remaining studies at unclear (k=2; 11%) or high risk (k=15; 83%). All studies (100%) with spatiotemporal outcomes were at high risk of detection bias due to lack of investigator blinding, and the majority of studies (94%) were at unclear risk of bias for attrition bias due to a lack of transparency into the extent of missing data. In all, 15 studies (83%) were at unclear risk of selective outcome reporting due to unavailability of a study protocol or due to the ambiguous selection of study outcomes for presentation (online supplementary table G).

Kinematic walking outcomes

Mediolateral CoM displacement

Absolute single task and dual task, and dual-task cost

There was neither a significant overall difference in mediolateral CoM displacement during single-task walking between

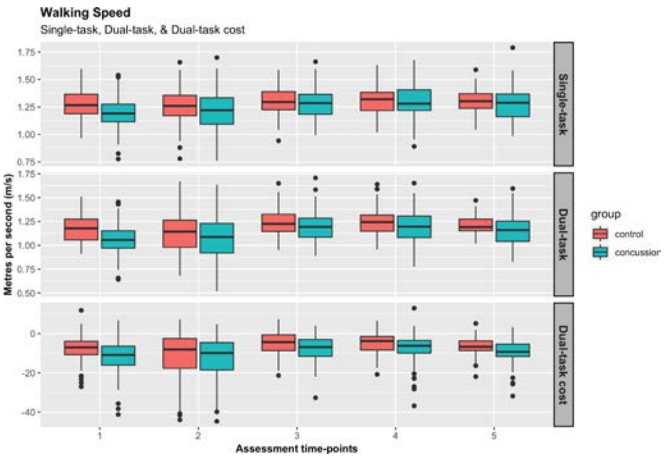

Figure 1 Single task, dual task and dual-task cost walking velocity. Time-point 1 = 48 hours following sports concussion, time-point 2 = 1 week following sports concussion, time-point 3 = 2 weeks following sports concussion, time-point 4 = 1 month following sports concussion, and time-point 5 = 2 months following sports concussion.

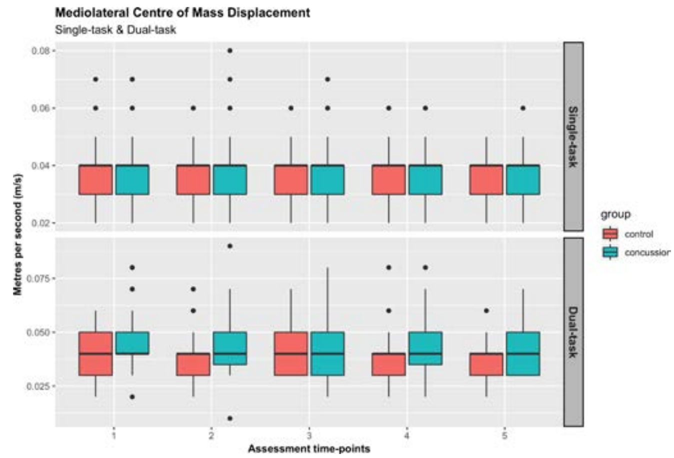

Figure 2 Single-task and dual-task frontal plane CoM displacement. Time-point 1 = 48 hours following sports concussion, time-point 2 =1 week following sports concussion, time-point 3 = 2 weeks following sports concussion, time-point 4 = 1 month following sports concussion, and time-point 5 = 2 months following sports concussion.

the concussion and control groups (main effect: $\chi^2=0.2$; df=1; p=0.7) nor a significant group*time interaction (interaction effect: $\chi^2=2.2$; df=4 ; p=0.7) from 48 hours up to 2 months following injury. However, during dual-task walking, the concussion group walked with greater mediolateral CoM displacement than the control group (main effect: $\chi^2=6.2$; df=1; p=0.013). This varied across the assessment time-points (interaction effect: $\chi^2=10.3$; df=4; p=0.036) as the concussion group walked with greater mediolateral CoM displacement up to 2 months following injury (online supplementary IPD table 4). The concussion and control groups did not differ significantly in dual-task cost at each time-point (interaction effect: $\chi^2=9.4$; df=4; p=0.052). However, the concussion group demonstrated greater mediolateral CoM displacement dual-task cost than the control group when values were averaged across all time-points (main effect: $\chi^2=8.0$; df=1; p=0.005).

Mediolateral CoM velocity

Absolute single task and dual task, and dual-task cost

IPD analysis demonstrated that the concussion group did not exhibit significantly different mediolateral CoM velocity than the control group during single-task (interaction effect: $\chi^2=3.6$; df=4; p=0.5) or dual-task walking (interaction effect: $\chi^2=8.9$; df=4; p=0.1) up to 2 months following concussion (online supplementary IPD table 5). Dual-task cost (interaction effect: $\chi^2=6.2$; df=4; p=0.2) was not significantly different at all time-points up to 2 months following concussion (figure 2) (online supplementary IPD table 5).

Table 4 Outcome domain-level risk of bias assessment findings across studies using RoBANS

	Selection bias	Selection bias	Performance bias	Detection bias	Attrition bias	Reporting bias
Risk of bias	Selection of participants n (%)	Confounding variable n (%)	Exposure measurement n (%)	Blinding outcome assessment n (%)	Incomplete outcome data n (%)	Selective outcome reporting n (%)
Spatiotemporal outcomes (k=18)						
Low	10 (56%)	1 (6%)	11 (61%)	0 (0%)	1 (6%)	3 (16%)
Unclear	6 (33%)	2 (11%)	5 (28%)	0 (0%)	17 (94%)	15 (83%)
High	2 (11%)	15 (83%)	2 (11%)	18 (100%)	0 (0%)	1 (6%)
Kinematic outcomes (k=13)						
Low	10 (77%)	0 (0%)	13 (100%)	0 (0%)	0 (0%)	2 (15%)
Unclear	2 (15%)	1 (8%)	0 (0%)	0 (0%)	13 (100%)	10 (77%)
High	1 (8%)	12 (92%)	0 (0%)	13 (100%)	0 (100%)	1 (8%)
Kinetic outcomes (k=3)						
Low	0 (0%)	0 (0%)	2 (67%)	0 (0%)	0 (0%)	0 (0%)
Unclear	0 (0%)	0 (0%)	1 (33%)	0 (0%)	3 (100%)	1 (33%)
High	3 (100%)	3 (100%)	0 (0%)	3 (100%)	0 (0%)	2 (67%)
All outcome types (k=26)						
Low	14 (54%)	1 (4%)	18 (69%)	0 (0.0%)	1 (4%)	3 (11.5%)
Unclear	6 (23%)	3 (11%)	6 (23%)	0 (0.0%)	25 (96%)	20 (77.0%)
High	6 (23%)	22 (85%)	2 (8%)	26 (100%)	0 (0.0%)	3 (11.5%)

Anteroposterior CoM displacement

Absolute single task and dual task, and dual-task cost

The concussion group walked with less anteroposterior CoM displacement compared with the control group at 48 hours post-injury during the single-task condition (interaction effect: χ^2=13.13, df=3, p=0.004) and up to 1 week post-injury during the dual-task condition (interaction effect: χ^2=19.26, df=3, p<0.001). Irrespective of time-point assessment, the concussion group walked with less anteroposterior CoM displacement for the dual-task condition (main effect: χ^2=5.1, df=1, p=0.023) but not during the single-task condition (main effect: χ^2=2.0, df=1, p=0.2) (online supplementary IPD table 7). The concussion group did not walk with significantly different anteroposterior CoM displacement dual-task costs compared with the control group (main effect: χ^2=3.4, df=1, p=0.06). There were no significant between-group differences in dual-task cost over time (interaction effect: χ^2=6.5, df=3, p=0.09).

Anteroposterior CoM velocity

Absolute single task and dual task, and dual-task cost

Participants with sports concussion walked with slower anteroposterior CoM velocity compared with the control participants at 48 hours following injury during the single-task condition (interaction effect: χ^2=38.3, df=4, p<0.001). During dual-task walking, the concussion group walked with slower anteroposterior CoM velocity from 48 hours through 1 month following concussion (χ^2=45.4, df=4, p<0.001) (online supplementary IPD table 8). Irrespective of time-point assessment, the concussion group walked with slower CoM velocity for the dual-task condition (main effect: χ^2=11.8, df=1, p<0.001) but not during the single-task condition (χ^2=2.6, df=1, p=0.1). No significant between-group differences in dual task cost were observed over time following concussion (interaction effect: χ^2=6.5, df=4, p=0.7).

Risk of bias: kinematic outcomes

In all, 13 studies were at high (k=12; 92%) or unclear (k=1; 8%) risk of selection bias due to inadequate adjustment for confounding (table 4). Every study (k=13; 100%) was at low risk of performance bias, high risk of detection bias, and at unclear risk of attrition bias. Reporting bias was unclear in 10 studies (77%) and high in one study (8%) (online supplementary table H).

Kinetic balance outcomes

95% centre of pressure (CoP) ellipse area and CoP velocity. The concussion group swayed over a greater stance area than the control group in dual-task compared with single-task quiet stance up to 1 month following concussion (based on results of IPD analysis and narrative synthesis of 95% CoP ellipse area) (online supplementary table C).[69 70] Similarly, Rochefort *et al*[69] observed that concussed individuals swayed faster than a non-injured control group in dual-task quiet stance compared with single-task quiet standing at 1 month following concussion (online supplementary file K). In contrast, Dorman *et al*[71] identified between-group differences in dual-task quiet stance at 10 days following injury. However, no significant between-group differences existed at 1 month following sports concussion.

Risk of bias: kinetic outcomes

All three studies were at high or unclear risk of selection, detection, attrition or reporting bias due to suboptimal adjustment for confounding variables, lack of investigator blinding, unreported missing data and ambiguous selection of outcomes, respectively (table 4).

DISCUSSION

We undertook an IPD meta-analysis to answer two pre-specified questions. When comparing concussed and control participants:

1. Are there greater walking and quiet standing impairments in dual-task assessments compared with single-task assessments?
2. Are there persistent walking and quiet standing impairments in single-task and dual-task assessments?

Dual-task assessments revealed persistent walking speed differences between the sports concussion and control groups that extended beyond standard clinical recovery timelines following sports concussion. This difference between the sports concussion and control group in the current IPD meta-analysis differs from many aggregate data review findings wherein group and task effects predominate. Our findings indicate that concussed individuals walk slower than control participants during dual-task assessment conditions but not necessarily during single-task conditions. However, high risk of selection bias and detection bias across studies likely reduces the size of observed between-group differences in walking outcomes.

Plausible explanations exist for conflicting results between aggregate data systematic reviews and this IPD meta-analysis. Our use of IPD increased the statistical power of analyses, empowering the identification of statistically significant differences that may have been previously too small in underpowered studies to achieve a threshold of statistical significance. Additionally, our analyses of IPD were independent of original authors, reducing the likelihood of detection bias and increasing the credibility of current findings.

Verification of original study findings using original data

We were unable to reproduce certain findings of original studies by re-performing the statistical analyses reported in the original articles. Low reproducibility rates are unsurprising,[73 74] as observational study findings are notoriously difficult to reproduce.[75] Disagreement between original study findings and independent re-analyses may be attributable to factors that include different sample sizes in the independent re-analysis,[76] flexible *post-hoc* analyses in original studies,[77] suboptimal reporting of statistical methods,[78] and lacking a reproducible workflow.

Exploratory research

Meta-analyses are frequently not possible in the area of sports concussion due to important differences between study methodologies. Studies contributing IPD were sufficiently similar to enable meta-analysis; however, studies from which only aggregate data were available varied across subpopulations studied, follow-up time-points, assessment protocols implemented and outcome measures evaluated.[8] Consequently, we undertook independent analyses of these data but could not account for *post-hoc* decisions that are frequently made by authors in the data collection, processing, analysis, and reporting of laboratory-oriented outcome measures.[77 79]

Spatiotemporal outcomes

The concussion group walked slower than the control group under dual-task conditions up to 2 months following sports concussion. The sports concussion group had reduced walking speed up to 2 weeks post-injury under single-task conditions, which reflects standard clinical recovery time-frames following sports concussion using traditional evaluations.[3 80 81]

Differences in mean recovery times between single-task and dual-task assessments likely reflect a reduced ability of concussed athletes to complete more complex laboratory tasks that require greater attentional resources compared with a single-task assessment. As sport involves the integration of multiple cognitive and physical tasks simultaneously, dual-task paradigms may better reflect the demands of sport than single tasks. Therefore, using cognitive-motor dual tasks in the clinical rehabilitation setting may facilitate a better understanding about how athletes will perform on return-to-sporting participation following sports concussion.

Kinematic outcomes

The concussion group had greater frontal plane CoM sway up to 2 months following sports concussion that were not evident during the performance of a single motor task. The concussion group also exhibited less and slower anteroposterior CoM movement compared with the control group up to 1 week and 1 month, respectively, during dual-task walking following sports concussion. These findings contrast to individual aggregate data studies, wherein main effects of group, time, or task predominate, reflected by previously-published aggregate data evidence syntheses.[9 10 13]

Kinetic outcomes

Both sports concussion and control groups demonstrated greater 95% ellipse sway area during dual-task assessments compared with single-task quiet standing. However, while the concussion group demonstrated worse postural balance than the control group under the dual-task condition, included studies were not in complete agreement. Disagreement between studies may be attributable to conceptual differences in study design, participant age, test instrumentation or medical support. This body of evidence, although small, opposes the 'constrained-action' hypothesis, which suggests that a conscious focus on postural control interferes with automatic motor control regulating standing balance.[82 83] Under the 'constrained-action' hypothesis, adding a cognitive stimulus enhances dual-task balance performance in healthy individuals compared with single-task performance by reducing sustained attention regulating standing balance.[84 85] However, the constrained-action hypothesis has a varied effect in ageing and neurologically impaired populations depending on the type and complexity of secondary task.[86 87–90]

Methodological artefacts of dual-task paradigms

Very simple or overlearned single tasks are easily completed when performed simultaneously with another task, minimising the divided attention effect of a dual-task. A 'question and answer' task, as described by the Mental Status Examination,[91] was the most frequently implemented cognitive task across selected studies. Novel cognitive or movement tasks possess substantial practice effects that contaminate the measurement of impairment recovery following sports concussion. However, non-novel motor tasks such as walking have clinical value due to minimal practice effects.[92 93] Challenging cognitive tasks require additional attention, withdrawing attention from other performance domains.[49 60] Across studies in this systematic review, participants were not consistently instructed to allocate equal attention to both conditions in a dual task. In the absence of an instruction to prioritise one task, or both tasks equally, participants may subconsciously favour and prioritise one task. Consequently, individualised participant preferences in task prioritisation may have important implications on performance in single-task and dual-task paradigms.

Limitations

Outcome variability was large and group means obscured large differences within patient groups. Most included studies used prospective, longitudinal designs (with cases and controls). Without comparable pre-morbid data, reliably detecting concussion-induced impairments is challenging. CIs widened over time following concussion, indicating variable concussion recovery rates for individual participants. Few IPD were available for cognitive outcome measures due to a lack of cognitive data collected in original studies. Thus, we examined only motor outcome domains in this systematic review. The likelihood of publication bias within this body of evidence, while unamenable to statistical assessment due to large outcome variability, is high, as reasoned based on highly-exploratory and 'positive' findings across included studies.

Strengths

We pre-registered our review protocol, whereas related reviews did not publish a review protocol.[13 15] Since the pre-registration of this meta-analysis, four systematic reviews were published that explore the use of dual-task assessments to identify impairments following sports concussion.[9 10 13 15] These reviews do not directly address the same research question but demonstrate considerable conceptual overlap.[94] Our use of IPD enabled us to identify and remove duplicate samples, and to statistically analyse original data rather than summary data. Our IPD meta-analysis could quantitatively synthesise the results of included studies, whereas aggregate data systematic reviews could only apply methods of vote counting[10 13] and narrative synthesis.[9 15] Larger sample sizes of IPD facilitated greater statistical power, increasing the ability to identify true persistent effects over time.[76]

Strength of recommendation to inform the recovery of walking and quiet standing impairments following sports concussion

We synthesised only laboratory outcomes measures, which frequently possess limited meaning to patients.[95] However, laboratory outcome measures can be informative as surrogate outcomes by identifying subclinical changes that may become clinical and meaningful to patients over time.[96 97] The findings of laboratory outcome measures in this review were inconsistent and thus determined a level 'C' strength of recommendation for this body of evidence and each associated outcome domain. Clinicians require clinical outcome measures, such as hand-timed average walking speed, that possess the clinical value to differentiate concussion and control groups over time. The acquisition and maintenance of motion analysis and force-plate laboratory equipment is expensive and, in conjunction with required operator expertise, exceeds the resources available to the majority of clinical practitioners. High risk of bias in each outcome domain increases the likelihood that differences between concussion and control groups and between single-task and dual-task conditions are less in magnitude than that observed in this IPD meta-analysis.

Future research

Consensus is required to establish minimum common data elements and core outcome sets for inclusion in observational studies in sports concussion dual-task research. This consensus will minimise between-study heterogeneity and facilitate meta-analysis

What is already known

- Concussion-induced impairments, as identified by athlete-reported symptoms, neurocognitive testing and static balance performance, typically recover within 7–10 days following sports concussion.
- Aggregate data systematic reviews and meta-analyses are important study designs that help to answer a pre-specified research question. If researchers can perform individual participant data (IPD) meta-analyses, they have more specific information with which to address pre-specified research questions.

What are the new findings

- Individuals who incurred a sports concussion presented with impaired gait characteristics, which persisted beyond standard clinical recovery timelines reported for other post-concussive signs and symptoms. Persistent walking impairments were only identified using a dual-task assessment. Dual-task assessments may prove to be an important part of clinical assessments after sports concussion.
- The harmonisation and analysis of IPD identified that concussed individuals, when asked to perform a cognitive-motor dual-task, walked slower and with greater frontal plane sway than non-concussed controls up to 2 months following sports concussion.

of exploratory research.[98] An improvement on current study designs to include an assessment of pre-morbid status is warranted for post-injury comparisons. Standardising research methodologies and improving their validity beyond the laboratory setting will facilitate a deeper understanding of dual-task walking and quiet standing balance impairments in different populations.

CONCLUSION

Analysing IPD from multiple sources, this systematic review identifies that individuals with sports concussion exhibit persistent walking impairments under a dual-task assessment compared with a single-task assessment. The concussion group demonstrated slower dual-task average walking speed compared with the control group up to 2 months following sports concussion. The heterogeneity of review findings and conflicting evidence across included studies does not support a comprehensive set of variables to use clinically at this time, requiring the development of minimum common data elements and core outcome sets to enable clinical inferences from dual-task concussion research.

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Contributors FCB conceived the present idea articulated in this manuscript and initiated the IPD meta-analytic process. FCB and CLA developed, edited, and reviewed the pre-specified review protocol and risk of bias assessment criteria. FCB and ED formulated the review search strategy, screened subsequent search results for inclusion, abstracted aggregate data, and completed risk of bias assessments of included studies. FCB and DRH contacted 'contributing authors' to request the provision of IPD. FCB, DRH, and CD performed re-analyses of within-study IPD. FCB and CB statistically harmonised, re-checked, and analysed IPD. DRH, RDC, LC, PF, CR, HS and TP contributed IPD for harmonisation, re-checking, and analysis. FCB composed the first draft of this manuscript. FCB, DRH, CLA, CD, CB, JR, and ED contributed towards the composition and revision of subsequent manuscript drafts. All co-authors edited and approved the final manuscript.

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