

Assessment of Postural Stability During an Upper Extremity Rapid, Bimanual Motor Task After Sport-Related Concussion

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Context: Sport-related concussion (SRC) often presents with multidimensional and subtle neurologic deficits that are difficult to detect with standard clinical tests. New assessment approaches that efficiently quantify deficits across multiple neurologic domains are needed.

Objective: To quantify impairments in postural movements during an assessment of rapid, bimanual motor ability in athletes within 10 days of experiencing an SRC and evaluate relationships between impairments in upper extremity and postural performance.

Design: Cohort study.

Setting: Sports medicine clinic.

Patients or Other Participants: Initial baseline assessments were completed for 711 athletes. Seventy-five athletes (age = 15.8 ± 3.3 years at baseline) sustained SRCs and were reassessed within 10 days. Seventy-eight athletes (age = 15.5 ± 2.0 years) completed 2 assessments in a healthy state.

Main Outcome Measure(s): Athletes stood on force plates and performed a rapid, bimanual motor task, termed the *object-hit task*, delivered using a Kinesiographical Instrument for Normal and Altered Reaching Movements endpoint robot. Measures of postural stability that quantified center-of-pressure movements

and measures of upper extremity performance were used to characterize task performance.

Results: Performance changes across assessments were converted to reliable change indices. We observed a difference in reliable change indices values between athletes with SRC and healthy control athletes on the combined postural measures ($P = .01$). Using measures to evaluate the change in postural movements from the early, easier portion of the task to the later, more difficult portion, we identified the highest levels of impairment (19%–25% of the sample impaired). We also noted a difference between individuals with concussion and healthy individuals on the combined upper extremity measures ($P = .003$), but these impairments were largely unrelated to those identified in the postural movements.

Conclusions: Measurement of postural movements during the object-hit task revealed impairments in postural stability that were not related to impairments in upper extremity performance. The findings demonstrated the benefits of using assessments that simultaneously evaluate multiple domains of neurologic function (eg, upper extremity and postural control) after SRC.

Key Words: traumatic brain injury, balance, robotics, sports medicine, motor control

Key Points

- Neurologic deficits after sport-related concussion are often multidimensional, subtle, and difficult to detect.
- Simultaneous evaluation of postural and upper extremity movement revealed specific impairments in athletes with sport-related concussion.
- Further development of efficient, multidimensional functional assessment tools for sport-related concussion is needed.

Sport-related concussion (SRC) is defined as a traumatic brain injury induced by biomechanical forces that are transmitted to the brain through an impact to the head, neck, or body.¹ As with all types of traumatic brain injury, SRC is associated with wide-ranging clinical signs and symptoms (eg, sensory, motor, cognitive, emotional).² However, it is distinct from other traumatic brain injuries in being generally associated with subtle neurologic impairments reflective of a functional disturbance rather than a structural injury (ie, no abnormalities detected on standard structural clinical neuroimaging).¹ The

multidimensional, subtle nature of the deficits involved in SRC present a unique challenge to neurologic assessment and return-to-sport decision making.² For example, if undetected, such subtle impairments could impair sport performance enough to increase the risk of further injury,^{3,4} particularly in a high-risk, high-speed sporting context. Currently, many neurologic assessments used for SRC rely on reporting of patient symptoms and subjective identification of clinical signs,⁵ which, although clinically efficient, lack precision and are susceptible to both patient and clinician bias. Therefore, better tools are needed to

efficiently, precisely, and objectively assess multiple domains of neurologic function after SRC.

In previous studies, Mang et al⁶ and Whitten et al⁷ examined the potential utility of a robotic device, termed the *Kinesiological Instrument for Normal and Altered Reaching Movements* (KINARM; BKIN Technologies, Kingston, ON, Canada), for assessing neurologic function after SRC. Relative to traditional clinical tools, the potential benefits of applying robotic technology to SRC assessment include high levels of accuracy, precision, and objectivity.⁸ In initial work^{7,9} with healthy athletes, moderate to good test-retest reliability of several robotic tests (KINARM Standard Tests) designed to evaluate motor, sensory, and cognitive function was demonstrated. Briefly, researchers from our laboratory investigated 6 tests that together were designed to assess elements of upper extremity visuomotor capability, upper extremity proprioceptive capability (ie, position sense), rapid bimanual motor control, attention, rapid motor selection, response inhibition, task switching,^{6,9–11} and spatial working memory performance.⁷ These tests are efficient (approximately 2 minutes each) and collectively compose a multidimensional neurologic assessment. Moreover, compared with healthy control athletes, the percentage of athletes identified as impaired was generally higher among athletes who self-reported as symptomatic and were within 10 days of SRC.⁶ Nevertheless, the SRC-related impairments were fewer on these tests than we expected to observe in subjectively symptomatic athletes (range = 4%–27% using reliable change indices [RCIs] with an impairment cutoff of >80% confidence limit),^{6,7} suggesting that more complex tasks that engage additional neurologic functions may be required to objectively detect impairments after SRC.

Across the KINARM Standard Tests studied in the context of SRC, the highest proportions of impairment have been detected using the object-hit task.⁶ During the object-hit task, participants grasp 2 handles that are represented on a screen as small paddles. Small red objects (ie, balls) are “dropped” from the top of the screen, and participants use both hands to hit away as many of the objects as possible before they reach the bottom.¹² Performance measures include the number of objects successfully hit away, the speed of hand movements, and the size of the area in which the hands moved, among others. Successful performance of the test depends on motor (ie, rapid bimanual movement, coordination), sensory (ie, vision, proprioception), and cognitive (ie, movement selection, decision-making) functions. The relatively large number of athletes identified as impaired using the object-hit task compared with other KINARM tests might relate to the particularly high and varied demands of the test.⁶

A neurologic function that is commonly impaired in SRC but has not been assessed using the aforementioned KINARM Standard Tests is postural stability.^{1,13,14} Clinical tools, such as the Balance Error Scoring System, and more comprehensive approaches, such as the Sensory Organization Test, have been used to identify SRC-related impairments in static balance by numerous investigators.^{13,15} Other researchers have identified deficits in postural stability involved in gait¹⁶ and altered postural movements while participants simultaneously performed cognitive tasks (ie, dual tasking) after SRC.^{17,18} Notably, postural stability plays an important role in virtually all forms of human movement, including those that involve the

upper extremity. For example, the act of reaching an upper extremity into space exerts forces on our own bodies, for which postural movements that serve to maintain equilibrium must compensate.¹⁹ However, to our knowledge, postural stability during upper extremity movement has not been thoroughly studied in individuals with SRC. Given other deficits related to SRC, it is plausible that postural movements that support upper extremity motor performance may also be impaired.

Therefore, the primary objective of our study was to quantify impairments in postural movements involved in performing an upper extremity rapid, bimanual motor task (ie, the object-hit test) while standing in athletes who were symptomatic and within 10 days of sustaining an SRC. We postulated that the added complexity and multidimensional nature of performing the object-hit test in a standing posture would provide an efficient and effective method of simultaneously evaluating multiple neurologic functions after SRC. We hypothesized that we would detect impairments in postural movements among a relatively high percentage of athletes with SRC compared with healthy athletes. We also expected that impairments in postural movements would be associated with impairments in upper extremity performance.

METHODS

Participants

Study participants were recruited through and tested at the Benson Concussion Institute, Group23 Sports Medicine Clinic (formerly WinSport Medicine Clinic) in Calgary, Alberta, Canada, between April 1, 2015, and July 31, 2018. Volunteers were included if they were between the ages of 10 and 40 years and participating in a contact, collision, or high-speed sport or a combination of these. They were excluded from the study if they had a neurologic disorder, an uncorrected visual impairment, or an ongoing musculoskeletal injury. Athletes with a history of concussion or musculoskeletal impairment were included if all symptoms had resolved and they were participating fully in sport at the time of the initial assessment.

For athletes enrolled in the study, baseline assessments were conducted in the preseason of their respective sport. They were instructed to return for a postconcussion assessment as soon as possible after sustaining an SRC. When the team certified athletic therapist or physiotherapist suspected a concussion, the athlete reported to the clinic, where he or she was evaluated by a sports medicine physician experienced in SRC (B.W.B.). This physician diagnosed all concussions based on a comprehensive history, including the mechanism of injury, patient's postconcussion symptom reporting, physical examination using the Sport Concussion Assessment Tool (SCAT: versions 3 and 5), and detailed neurologic examination. Some athletes completed multiple baseline assessments because of enrollment in the study over consecutive seasons. For this investigation, we only evaluated postconcussion assessments in athletes who had completed a single baseline assessment before sustaining an SRC.

A subset of athletes completed 2 KINARM (model 10288) assessments while in a healthy state during the study period and served as a control group. A *healthy state* was defined as having no symptoms of any previous injuries, fully

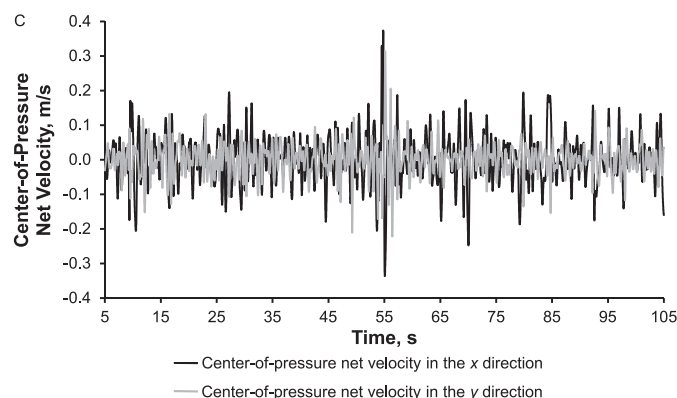
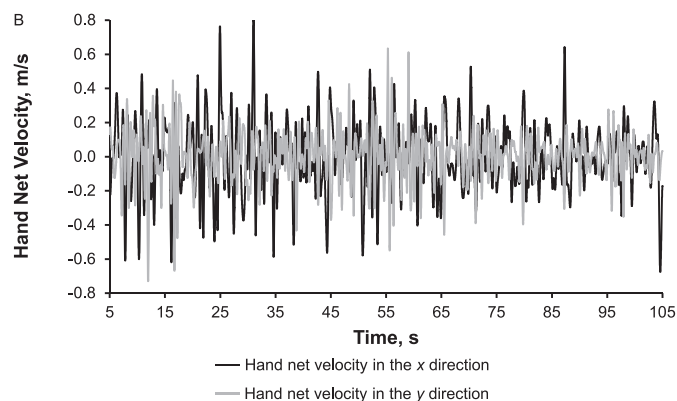
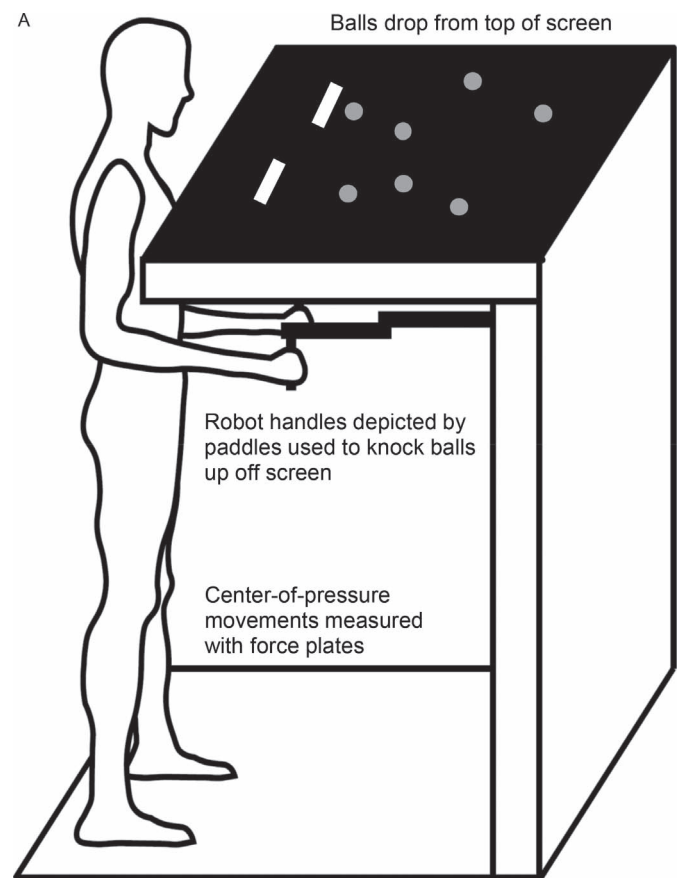


Figure 1. Experimental apparatus and setup. A, The adjustable-height Kinesiological Instrument for Normal and Altered Reaching Movements (BKIN Technologies, Kingston, ON, Canada)

participating in sport, and having no injuries that could affect KINARM performance between assessments. Data from these athletes were used to determine the “normal” range of performance on the assessments, such that the performance of athletes with SRC could be identified as *normal* or *impaired*. Given the goal of comparing performance of individual athletes with SRC with a normal range, we included only athletes with no self-reported history of concussion in this subset of healthy athletes. These data were largely obtained from athletes who completed preseason baseline assessments in consecutive seasons without sustaining an injury; a minority were from a single season but >12 weeks apart. All participants or their parents or guardians provided written informed consent, and the study was approved by the University of Calgary Conjoint Health Research Ethics Board (Ethics ID: 23963).

Experimental Apparatus and Setup

Data were collected using an adjustable-height KINARM endpoint robotic device (Figure 1). The KINARM was adjusted vertically to allow each participant to stand and grasp the endpoint handles with the shoulders relaxed and elbows flexed to approximately 90° while viewing the augmented reality display in the horizontal plane. Participants stood in athletic footwear with each foot on a force plate (model FP4060-07-1000; Bertec Corp, Columbus, OH) that was used to measure ground reaction forces and moments in the medial-lateral (*x*), anterior-posterior (*y*), and vertical (*z*) axes. The position and velocity of the robot handles and ground reaction forces and moments from the force plates were collected at a sampling frequency of 1000 Hz.

Object-Hit Test

The object-hit test (Figure 1) was the focus of our study but was conducted as 1 component of a larger robotic testing battery (approximately 30 minutes of assessments in total) in a large prospective study of SRC.⁶ Using this test, researchers can assess upper extremity rapid, bimanual motor ability and visuospatial attention.¹² By conducting the test with participants in a standing posture, we were also able to gain information about postural movements during test performance.

On approaching the KINARM device, participants were instructed to place their feet approximately hip-width apart, with 1 foot on each force plate. They were told to keep their feet in the same position over the course of the test but otherwise were given no further instruction related to postural control. They grasped the robot handles, which were represented by green paddles on the screen. During the test, objects (red circles) were “dropped” from 10 bins that were evenly spaced across the top of the screen. Participants were then provided the simple instruction to “use both hands to hit as many objects away from the bottom of the screen as possible.” Haptic feedback (ie, a small perturbation) was

endpoint robotic device and the object-hit task. The paddles are depicted in white, and the objects that are “dropped” are depicted in gray. B and C, Representative data of hand net velocity and center-of-pressure net velocity in the *x* and *y* directions over the course of the test are shown. These data were used to derive the new upper extremity measures and the postural measures described in Table 1.

Table 1. Upper Extremity and Postural Measures Evaluated During the Object-Hit Test^a

| Measure | Abbreviation | Definition |
|--|------------------|---|
| Standard upper extremity measures reported | | |
| Total hits | TH | No. of balls hit off the screen in the opposite direction from the original path |
| Hits nondominant | H _{ND} | No. of balls hit with the nondominant hand |
| Hand speed nondominant (in m/s) | HS _{ND} | Mean speed of the nondominant hand throughout the entire task |
| New upper extremity measures ^b | | |
| Maximum hand velocity (in m/s) | HAND max | Absolute maximum net velocity of the hands reached during the task |
| Variability of hand velocity | HAND var | Standard deviation of the net velocity of the hands during the task |
| Maximum hand velocity ratio | HAND MR | Ratio of absolute maximum net velocity of the hands reached during the last 40 s and first 40 s of the task, excluding the first 5 s |
| Variability of hand velocity ratio | HAND VR | Ratio of the standard deviation of net velocity of the hands during the last 40 s and first 40 s of the task, excluding the first 5 s |
| Maximum hand velocity time | HAND MT | Point in task (% complete) when the absolute maximum net velocity of the hands was reached, expressed as a value between 0 and 1 |
| Postural measures ^b | | |
| Maximum center-of-pressure velocity (in m/s) | COP max | Absolute maximum velocity of the center of pressure reached during the task |
| Variability of center-of-pressure velocity | COP var | Standard deviation of velocity of the center of pressure during the task |
| Maximum center-of-pressure velocity ratio | COP MR | Ratio of the absolute maximum velocity of the center of pressure reached during the last 40 s and first 40 s of the task, excluding the first 5 s |
| Variability of center-of-pressure velocity ratio | COP VR | Ratio of the standard deviation of velocity of the center of pressure during the last 40 s and first 40 s of the task, excluding the first 5 s |
| Maximum center-of-pressure velocity time | COP MT | Point in task (% complete) when the absolute maximum velocity of the center of pressure was reached, expressed as a value between 0 and 1 |

^a Adapted with permission from Mang CS, Whitten TA, Cosh MS, et al. Robotic assessment of motor, sensory, and cognitive function in acute sport-related concussion and recovery. *J Neurotrauma*. 2019;36(2):308–321.

^b New upper extremity and all postural measures are reported for velocity in the x and y directions.

provided when an object was hit. They were allowed 105 seconds to hit 30 objects dropped randomly from each bin (300 objects total), and as the test progressed, the objects dropped faster and more frequently. The original test was designed for neurologic assessment after stroke¹² and has since been modified to increase the difficulty for use in athletes with SRC.^{6,9–11} In the modified “athlete” version of the test used in this study, the width of the paddles is 2 cm, the objects have a 2-cm radius, and the initial speed of the objects is faster than that in the original test.

Data Analyses

Unless otherwise stated, all data analyses were performed using MATLAB software (version 2016a; The MathWorks Inc, Natick, MA). Raw KINARM data were low-pass filtered at <10 Hz using a zero-phase lag (forward and backward) third-order filter.

Upper Extremity Data. We used Dexter-E software (version 3.6; BKIN Technologies) to export multiple standard measures of upper extremity object-hit test performance based on kinematics of the robot handles (Table 1). However, we focused on only the total hits (TH), hits with the nondominant hand (H_{ND}), and nondominant hand speed (HS_{ND}) standard measures in the current study, as these were the only measures previously found to reflect higher levels of impairment in athletes with acute SRC than in healthy athletes.⁶ We also derived a new set of measures from the robot-handle kinematics that more closely mirrored the postural measures that we will describe. All performance measures derived from consideration of upper extremity movement are herein referred to as *upper extremity measures* and are described in detail in Table 1.

Postural Data. Using the force-plate data, we calculated the center-of-pressure (COP) position in the x (medial-lateral; COP_x) and y (anterior-posterior; COP_y) directions for each foot using the following equations:

$$\text{COP}_x = \frac{-M_y + F_x \times d}{F_z}$$

and

$$\text{COP}_y = \frac{M_x - F_y \times d}{F_z}$$

where F_x , F_y , and F_z are ground reaction forces in the x, y, and z directions; M_y and M_x are moments about the y and x axes; and d is the distance from the top to the center of the force plate (true origin = 0.0471 cm). The distance is used to calculate the contribution of the horizontal forces (F_x and F_y) to the horizontal moments generated about the y and x axes. The net COP (COP_{net}) position was calculated using the COP from each limb (COP_{left}, COP_{right}) to provide a measure of full-body COP movement. The COP_{net} position in the x and y directions was calculated as a weighted average of the F_z (vertical ground reaction forces for each foot collected from each force plate) using the following equation²⁰:

$$\begin{aligned} \text{COP}_{\text{net}} = & \text{COP}_{\text{left}} \times \frac{F_z(\text{Left})}{F_z(\text{Left}) + F_z(\text{Right})} \\ & + \text{COP}_{\text{right}} \times \frac{F_z(\text{Right})}{F_z(\text{Right}) + F_z(\text{Left})} \end{aligned}$$

Hereafter, *COP* is used to represent COP_{net}, and performance measures derived from examination of these force-plate data are termed *postural measures* (Table 1).

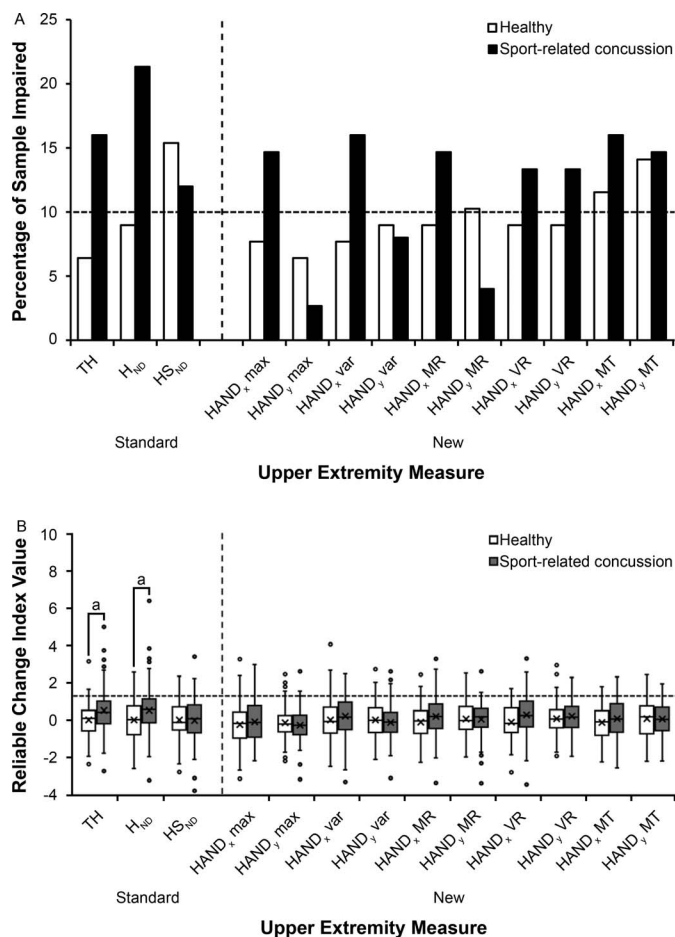


Figure 2. Upper extremity measures. A, Percentages of healthy athletes and those with acute concussions impaired in each measure. The horizontal dashed line depicts the percentage of the sample (10%) that, using the current reliable change index approach, would be expected to be categorized as impaired on any given measure based on normal variation in performance across the group. B, Box-and-whisker plots depicting reliable change index values for each measure in healthy athletes and those with acute concussions. ^a Indicates difference ($P = .0167$). Abbreviations: HAND_y max, maximum hand velocity in the y direction; HAND_x var, variability of hand velocity in the x direction; HAND_y var, variability of hand velocity in the y direction; HAND_x MR, maximum hand velocity ratio in the x direction; HAND_y MR, maximum hand velocity ratio in the y direction; HAND_x VR, variability of hand velocity ratio in the x direction; HAND_y VR, variability of hand velocity ratio in the y direction; HAND_x MT, maximum hand velocity time in the x direction; HAND_y MT, maximum hand velocity time in the y direction; HND, hits nondominant; HSND, hand speed nondominant; TH, total hits.

When calculating the postural measures, we excluded the first 5 seconds of the test to allow a brief period of postural stabilization as individuals became familiar with the test demands. In addition, all measures were determined for COP movements in both the *x* and *y* directions. Postural measures included the absolute maximum velocity of the COP (COP max) and the standard deviation of the velocity of the COP (COP var) over the course of the test. To capture how COP movements changed as the test became more difficult, we derived ratios of the COP max (COP MR) and COP var (COP VR) from the later, more challenging portion of the test to the earlier, easier portion of the test. After the first 5 seconds of the test were

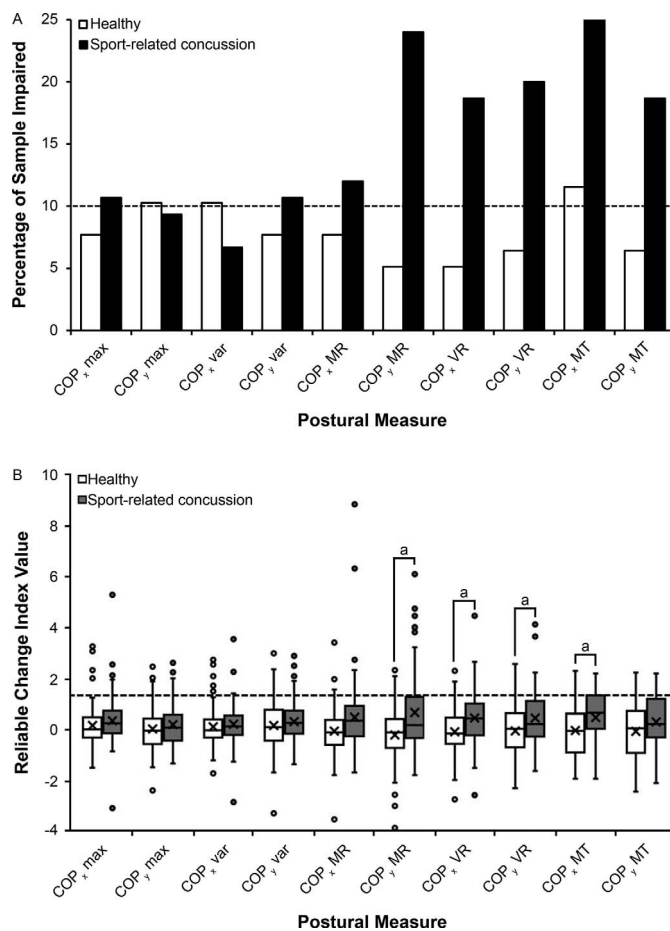


Figure 3. Postural measures. A, Percentages of healthy athletes and those with acute concussions impaired in each measure. The horizontal dashed line depicts the percentage of the sample (10%) that, using the current reliable change index approach, would be expected to be categorized as impaired on any given measure based on normal variation in performance across the group. B, Box-and-whisker plots depicting reliable change index values for each measure in healthy athletes and those with acute concussions. ^a Indicates difference ($P = .005$). Abbreviations: COP_x max, maximum center-of-pressure (COP) velocity in the x direction; COP_x MR, maximum COP velocity ratio in the x direction; COP_x MT, maximum COP velocity time in the x direction; COP_x VR, variability of COP velocity ratio in the x direction; COP_y max, maximum COP velocity in the y direction; COP_y MR, maximum COP velocity ratio in the y direction; COP_y var, variability of COP velocity in the y direction; COP_y MT, maximum COP velocity time in the y direction; COP_y VR, variability of COP velocity ratio in the y direction.

excluded as described, 100 seconds remained for analysis. With these data, we opted to calculate the ratios based on the first and last 40 seconds of the test, and these data are presented in the text and Figures 2 through 5. With the gradual increase in test demands, the 20-second gap between the portions of the test contributing to the ratio measures ensured that performance changes on portions of the test with distinct difficulty levels were characterized. Nevertheless, the choice to specifically use the first and last 40 seconds of the test for these calculations was largely arbitrary. As such, we also ran variations of the ratio calculations, comparing the first and last thirds of the test and the first and last quarters of the test. These results were similar across approaches; the proportion of the sample identified as impaired across approaches is presented in the

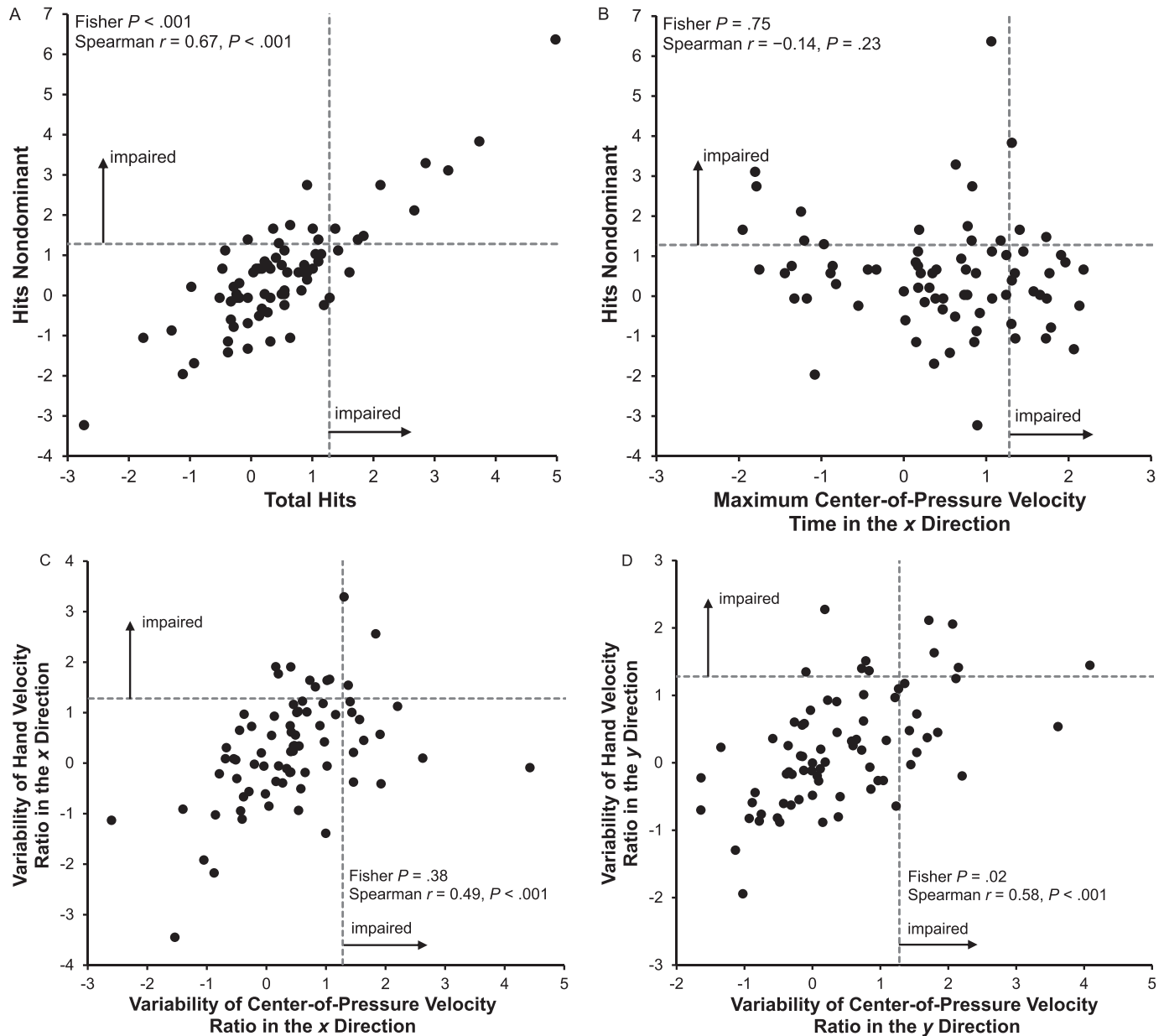


Figure 4. A–D, Representative associations between performance on upper extremity and postural measures.

Supplemental Figure. Finally, the percentage of the test completed when COP max was reached was also evaluated (COP MT). More information is provided in Table 1.

Clinical Variables

All enrolled participants were instructed to inform the study personnel of any self-reported history of concussion. The Postconcussion Symptom Severity (PCSS) scale from the SCAT (versions 3 and 5) was administered by a qualified health professional (M.S.C., B.W.B.) at baseline and at the initial postconcussion appointment. Participant age and number of days between the concussion and postconcussion clinic appointment were also recorded.

Statistical Analyses

Participant Characteristics. A series of independent-samples *t* tests were conducted to compare descriptive data

between the subset of healthy control individuals and participants who experienced an SRC during the study period. The *t* tests were used to compare the groups by age at baseline, age at the second test (retest for healthy control athletes and postconcussion assessment for athletes with SRC), height, mass, body mass index, and baseline SCAT PCSS score. We computed an additional *t* test to compare the number of days between the first and second tests in the athletes with SRC versus healthy athletes.

Baseline Assessment Performance. Before the main statistical analyses were carried out, a series of statistical tests was conducted to compare baseline performance on the object-hit test measures between the healthy control group and the SRC group. Given that the control group was free of a self-reported history of concussion, differences in baseline performance could have suggested an effect of concussion history on object-hit test performance. Three separate 1-way multivariate analyses of variance (MAN-

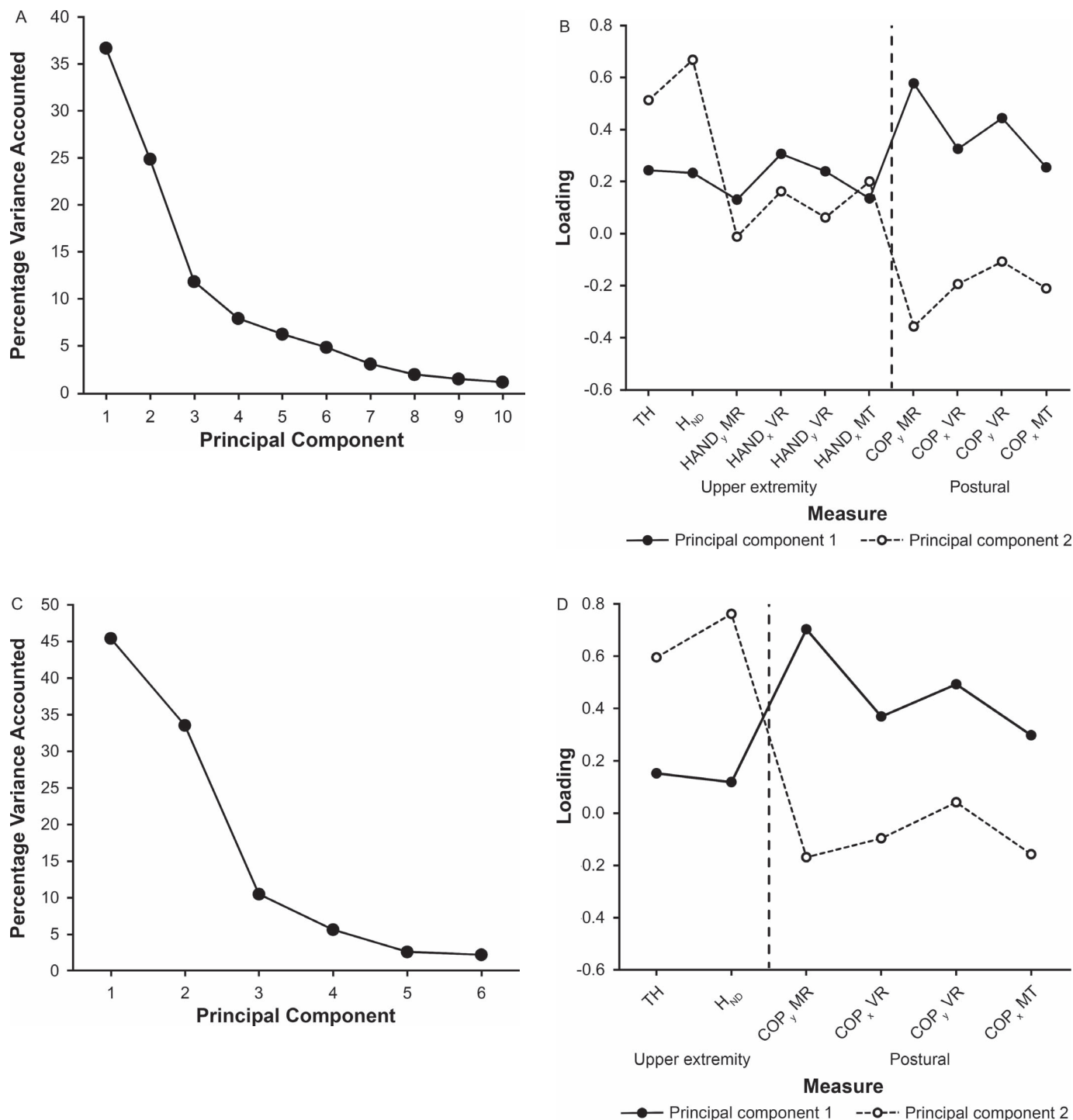


Figure 5. Results from the principal components analyses. **A**, The scree plot and, **B**, loadings of principal components 1 and 2 in the first principal components analysis. **C**, The scree plot and, **D**, loadings of principal components 1 and 2 in the second principal components analysis. Abbreviations: COP_x MT, maximum COP velocity time in the x direction; H_{ND}, hits nondominant; COP_x VR, variability of COP velocity ratio in the x direction; COP_y MR, maximum COP velocity ratio in the y direction; COP_y VR, variability of COP velocity ratio in the y direction; HAND_y MR, maximum hand velocity ratio in the y direction; HAND_x VR, variability of hand velocity ratio in the x direction; HAND_y VR, variability of hand velocity ratio in the y direction; HAND_x MT, maximum hand velocity time in the x direction; TH, total hits.

OVA) were conducted to compare baseline performance between these groups. The dependent variables for the first MANOVA were the 3 standard object-hit upper extremity measures highlighted in our previous work (TH, H_{ND}, HS_{ND}).⁶ The dependent variables in the second MANOVA were the new upper extremity measures (maximum hand velocity, variability of hand velocity, maximum hand

velocity ratio, variability of hand velocity ratio, and maximum hand velocity time in the x and y directions). The third MANOVA was used to consider the postural measures that we described (COP_x max, COP_y max, COP_x var, COP_y var, COP_x MR, COP_y MR, COP_x VR, COP_y VR, COP_x MT, and COP_y MT). If a main effect of SRC on the combined dependent variables was detected ($P < .05$)

using MANOVA, then we calculated post hoc univariate analyses of variance (ANOVAs) to determine which specific variables differed between the SRC and healthy groups using Bonferroni-corrected α levels of .0167 for the upper extremity measures and .005 for the postural measure.

Reliable Change Index Conversion. We identified impairments in performance relative to baseline through application of RCIs, which account for test-retest variance, in order to determine if an individual's change in performance from one assessment to another is abnormal.²¹ Data collected from the subset of healthy control athletes on 2 occasions were used to convert the change in object-hit test performance between assessments into RCIs for all participants (healthy control athletes: change from baseline to the second healthy test; athletes with SRC: change from baseline to the postconcussion test). We calculated RCIs using the equations provided by Jacobson and Truax²¹ and adjusted for practice effects. Higher values denoted impairment. The calculated RCI value can be interpreted against standard z -distribution critical values. Consistent with previous work,⁶ individuals with performance falling outside the RCI cutoff for an 80% confidence interval (CI; RCI value >1.28) were categorized as *impaired*. With this approach, approximately 10% of any sample, healthy or with concussion, would be categorized as impaired on any given measure based on normal variations in performance across the group. For all measures, an RCI value outside the cutoff indicated that the participant performed worse than expected on the second test, based on the baseline performance, test-retest variance, and reliability of the measure.

Reliable Change Index Comparisons. Using the RCI values, we conducted 3 separate 1-way MANOVAs to compare changes in performance between assessments in healthy athletes and those with SRC. Given the variability in the time of testing relative to injury in athletes with SRC, 3 additional 1-way MANOVAs were run to compare RCI values between athletes with SRC tested within 3 days and 4 to 10 days after their concussions. The dependent variables, α levels, and post hoc testing approaches for these MANOVAs were the same as those for the comparisons of baseline assessment performance.

Upper Extremity and Postural Performance Associations. We took multiple statistical approaches to examine potential associations between impairment on upper extremity and postural measures in athletes with SRC. These included a series of Fisher exact tests to examine associations between impairment category (impaired or not impaired) and Spearman correlations to examine relationships among RCI values for upper extremity and postural measures. The tests focused on measures that were different between healthy athletes and athletes with SRC in the previous MANOVAs. They were considered exploratory in nature, and the α levels were uncorrected ($P < .05$).

Taking another approach, we conducted 2 principal components analyses using RCI values from the athletes with SRC. The goal of these analyses was to determine whether performance on any of the upper extremity measures shared variance with performance on the postural measures, as determined through visual inspection of the loading of the measures onto the retained components. The first principal components analysis was performed on

measures that were different between healthy athletes and athletes with SRC in the previous MANOVAs, as well as new upper extremity measures that corresponded to the postural measures that were different (eg, COP_x MT corresponds to maximum hand velocity time in the x direction). Although very few impairments were identified in SRC with these new upper extremity measures, we included them in this analysis to determine if they tended to share variance with the postural measures that they were derived to mirror. The second principal components analysis was conducted on only the measures that were different between healthy athletes and athletes with SRC in the previous MANOVAs. For both principal components analyses, we retained only the components that together explained at least 60% of the total variance.²² Additionally, we conducted bivariate correlation analyses (Spearman r) between individual scores on components retained from the second principal components analysis in athletes with SRC and age, change in PCSS score (baseline to postconcussion), and the number of days between the concussion and the postconcussion assessment.

Assumptions corresponding to each statistical test were satisfied.²² All analyses were performed using either MATLAB (version 2016a; The MathWorks, Inc) or SPSS (version 25; IBM Corp, Armonk, NY).

RESULTS

Participants

A total of 711 athletes (526 males, 185 females) completed initial baseline assessments for the study. Over the study period, 75 athletes sustained SRCs after their first baseline assessment. The upper extremity performance data from 24 of these 75 athletes with pre-SRC and post-SRC assessments were included in the analysis of the object-hit test in a past study in which only upper extremity performance was evaluated.⁶ Their postural data had not been previously explored. Seventy-eight athletes with no self-reported history of concussion completed 2 assessments in a healthy state. Of these individuals, 44 completed the assessments as preseason baselines in consecutive seasons, and 34 completed the 2 assessments within a single season (minimum of 88 days apart). Participants were involved in a variety of sports, but they were mainly hockey athletes from a local high school specializing in athletics and winter sport athletes (eg, skiing, speed skating, luge) competing at various levels. As a result, the age range of the participants in both the healthy and SRC groups was narrow. Participant demographic information is presented in Table 2.

Participant Characteristics

Age at baseline, age at the second test, height, mass, body mass index, and baseline SCAT PCSS score were not different between the healthy control and SRC groups (t_{151} range = 0.29–1.31, P range = .19–.94). In contrast, the number of days between the first and second tests was greater for the healthy control than for the SRC ($t_{151} = 10.37$, $P < .001$) group.

Baseline Performance and History of Concussion

Using 1-way MANOVAs, we observed no difference in baseline performance between the healthy control and SRC

Table 2. Characteristics of Athletes Who Completed Repeat Testing in a Healthy, Uninjured State and Athletes Who Sustained Concussions

| Characteristic | Group | |
|---|--|---|
| | Healthy (n = 78) | Concussed (n = 75) |
| Sex, male/female | 55/23 | 62/13 |
| Dominant hand, right/left | 72/6 | 72/3 |
| Sport, No., overall (females) | Hockey, 54 (8) Luge, 5 (4) Skiing, ^c 14 (8) Speed skating, 4 (2) Wrestling, 1 (1) | Bobsled, 1 (1) Cycling, 1 (1) Hockey, 52 (1) Luge, 2 (1) Motor cross, 1 (0) Skiing, ^c 8 (4) Snowboard, 1 (1) Speed skating, 9 (4) |
| Self-reported history of concussion at baseline | | |
| 0 | NA | 33 |
| 1 | NA | 26 |
| 2 | NA | 9 |
| ≥3 | NA | 7 |
| History of migraine, yes/no | 9/69 | 11/64 |
| History of attention-deficit hyperactivity disorder, yes/no | 2/76 | 3/72 |
| History of anxiety, yes/no | 1/77 | 2/73 |
| History of depression, yes/no | 0/78 | 1/74 |
| | Mean ± SD | |
| Age, y | | |
| At baseline | 15.5 ± 2.0 | 15.8 ± 3.3 |
| At retest or concussion | 16.7 ± 2.1 | 16.1 ± 3.4 |
| Height, cm | 169.9 ± 8.4 | 169.8 ± 9.0 |
| Mass, kg | 61.4 ± 10.4 | 61.9 ± 12.8 |
| Body mass index, kg/m ² | 21.2 ± 2.4 | 21.3 ± 2.8 |
| Time between tests, d | | |
| Baseline to retest | 423.6 ± 231.6 | NA |
| Baseline to sport-related concussion | NA | 113.8 ± 107.8 |
| Sport-related concussion to postconcussion assessment | NA | 4.9 ± 2.9 |
| Baseline to postconcussion assessment | NA | 118.6 ± 107.9 |
| Sport Concussion Assessment Tool postconcussion symptom severity scale score ^a | | |
| Baseline | 3.1 ± 5.1 | 3.9 ± 6.7 |
| Postconcussion assessment | NA | 16.2 ± 15.6 |
| Baseline to postconcussion assessment change | NA | 12.4 ± 15.6 |
| Time to asymptomatic state after sport-related concussion, ^b d | NA | 10.4 ± 6.7 |

Abbreviation: NA, not applicable.

^a The highest possible postconcussion symptom severity scale score is 132.

^b The number of days after the concussion when participants were free of concussion-related symptoms at rest, they had no return of symptoms with cognitive activity and exertion, and their postconcussion clinical assessments were within baseline normative (healthy, uninjured) levels in all testing domains, as judged by the consulting physician (6 athletes were lost to follow up such that we did not document their time to being asymptomatic).

^c A mix of alpine, ski-cross, freestyle, and moguls events.

groups (P range = .30–.63, Wilks Λ range = 0.90–0.99, partial η^2 range = 0.02–0.10).

Reliable Change Index

Upper Extremity Measures. The percentages of healthy athletes and athletes with SRC identified as impaired on the upper extremity measures, separated into the standard upper extremity measures (TH, H_{ND}, HS_{ND}) and new measures derived for this study, are shown in Figure 2A. On the standard upper extremity measures that were examined, the percentage of the sample identified as impaired varied from 6.41% to 15.38% in the healthy athletes and from 12.00% to 21.33% in the athletes with SRC. For the new upper

extremity measures, impairment percentages ranged from 6.41% to 14.10% in the healthy athletes and from 2.67% to 16.00% in the athletes with SRC.

Box-and-whisker plots of the RCI values for each upper extremity measure are depicted in Figure 2B. Using 1-way MANOVA, the 3 standard upper extremity measures indicated a difference in RCI values: worse performance in those with SRC relative to healthy control participants for the combined dependent variables ($F_{3,149} = 4.92$, $P = .003$, Wilks $\Lambda = 0.91$, partial $\eta^2 = 0.09$). Follow-up univariate ANOVAs with Bonferroni correction ($\alpha = .0167$) demonstrated that the RCI values were higher (ie, more impaired) in athletes with SRC than healthy athletes for the TH ($P = .003$) and H_{ND} ($P = .01$) measures. A second 1-

way MANOVA revealed no difference in RCI values on the combined new upper extremity measures between healthy athletes and athletes with SRC ($F_{10,141} = 0.95$, $P = .49$, Wilks $\Lambda = 0.94$, partial $\eta^2 = 0.06$). The MANOVAs used to compare RCI values between athletes with SRC tested within 3 days and between 4 and 10 days after their injury also showed no differences for the standard or new upper extremity measures (P range = .41–.76, Wilks Λ range = 0.91–0.98, partial η^2 range = 0.03–0.09).

Postural Measures. The percentages of healthy athletes and athletes with SRC identified as impaired on postural measures are provided in Figure 3A. Across measures, the percentage of athletes identified as impaired ranged from 5.13% to 11.54% in the healthy group and from 6.67% to 25.00% in the SRC group. Generally, the measures that characterized changes in postural movements from the early, easier portion to the later, more difficult portion of the test detected higher proportions of impairment than other measures (ie, COP_y MR, COP_x VR, COP_y VR). Notably, COP_x MT identified the largest proportion of individuals as impaired compared with all measures studied.

Box-and-whisker plots of RCI values for each postural measure are illustrated in Figure 3B. One-way MANOVA reflected a difference in RCI values between groups: worse performance in the SRC athletes relative to the healthy athletes on the combined postural measures ($F_{10,141} = 2.34$, $P = .01$, Wilks $\Lambda = 0.86$, partial $\eta^2 = 0.14$). Using a Bonferroni-corrected α level of .005 on post hoc univariate ANOVAs, we found that the RCI values for the COP_y MR ($P < .001$), COP_x VR ($P = .001$), COP_y VR ($P = .002$), and COP_x MT ($P = .004$) measures were higher (ie, more impaired) in those with SRC than in healthy control individuals. The additional MANOVA used to compare RCI values between athletes with SRC tested within 3 days and between 4 and 10 days after their injury indicated no differences for the postural measures ($P = .65$, Wilks $\Lambda = 0.89$, partial $\eta^2 = 0.11$).

Relationships Among Measures in Athletes With SRC

Fisher Exact Tests. We used Fisher exact tests to focus on measures for which RCI values were different between healthy athletes and athletes with SRC, as determined by MANOVAs and follow-up univariate ANOVAs. A positive association between impairment on the TH and H_{ND} standard upper extremity measures was detected ($P < .001$; Figure 4A). In contrast, impairment in TH or H_{ND} was not associated with impairment on any of the tested postural measures (P range = .06–.99; example shown in Figure 4B). We also evaluated whether impairment on any of the postural measures from the MANOVAs that were different was associated with impairment on the corresponding new upper extremity measures. Most of these tests displayed a lack of association (P range = .14–.38; example shown in Figure 4C); only impairment in COP_y VR and variability of hand velocity ratio in the y direction was positively associated ($P = .02$; Figure 4D). The general lack of association between the upper extremity and postural measures indicated that many participants were impaired on the upper extremity (but not the postural) measures and vice versa. The results of all Fisher exact tests are reported in Table 3.

Spearman Correlations. We used Spearman correlations to examine relationships between the same measures as the Fisher exact tests but considering continuous RCI values rather than categorical data. As expected, a strong positive relationship between TH and H_{ND} was identified ($r = 0.67$, $P < .001$). Except for a relationship between TH and COP_y VR ($r = 0.28$, $P = .02$), TH and H_{ND} were not related to any of the tested postural measures (all other r values ≤ 0.17 , $P \geq .10$). Several moderately positive relationships were present between the tested postural measures and corresponding new upper extremity measures (r range = 0.37–0.58, $P < .001$). Only COP_x MT and maximum hand velocity time in the x direction displayed no relationship ($r = 0.06$, $P = .63$). The results of all Spearman correlations are provided in Table 3.

Principal Components Analyses in Athletes With SRC. We retained 2 components from the first principal components analysis, which explained 36.7% and 24.9% of the total variance (Figure 5A; see measures included in the analysis on the x -axis of Figure 5B). The first component loaded primarily onto the COP_y MR (0.58) and COP_y VR (0.44) postural measures and to a lesser degree onto TH (0.24), H_{ND} (0.23), and the new upper extremity measures (range = 0.13–0.31). For the second component (PC2), we observed strong positive loadings for the TH (0.51) and H_{ND} (0.67) measures, smaller loadings for the new upper extremity measures (range = –0.01 to 0.20), and negative loadings for the postural measures (range = –0.36 to –0.11; Figure 5B).

In the second principal component analysis we also retained 2 components, which explained 45.4% and 33.6% of the total variance (Figure 5C, see measures included in the analysis on the x -axis of Figure 5D). Again, the first component loaded primarily onto the COP_y MR (0.70) and COP_y VR (0.49) postural measures and minimally onto TH (0.15) and H_{ND} (0.12). The PC2 loaded mainly onto the TH (0.60) and H_{ND} (0.76) measures, with small or negative, or both, loadings onto the postural measures (range = –0.17–0.04; Figure 5D).

Clinical Relationships

Individual scores on components retained from the second principal components analysis in athletes with SRC were evaluated for bivariate correlation with age, change in PCSS score from baseline to postconcussion, and days between the SRC and postconcussion assessment. The principal components analysis scores were not correlated with any participant characteristics (r range = 0.03–0.18, P range = .13–.82).

DISCUSSION

We quantified impairments in performance of a KIN-ARM-based rapid bimanual motor task, termed the *object-hit test*, among athletes who were symptomatic from and within 10 days of sustaining an SRC. Impairments in upper extremity performance were identified in similar proportions as in past work.⁶ Extending this work, we determined that, when athletes with SRC performed the object-hit test in a standing posture, impairments in postural stability associated with test performance were also relatively common. Although several athletes were impaired in both upper extremity and postural measures, many showed

Table 3. Reliable Change Index Values and Associations in Impairment Categories Between Measures in Athletes With Sport-Related Concussion

| Measure 1 | Measure 2 | Fisher Exact P Value | Spearman | |
|---|---|-------------------------|----------|--------------------|
| | | | r Value | P Value |
| Total hits | Hits, nondominant hand | <.001 ^a | 0.67 | <.001 ^a |
| | Maximum center-of-pressure velocity ratio in y direction | >.99 | 0.19 | .10 |
| | Variability of center-of-pressure velocity ratio in x direction | .69 | 0.15 | .20 |
| | Variability of center-of-pressure velocity ratio in y direction | .06 | 0.28 | .02 ^a |
| | Maximum center-of-pressure velocity time | .49 | 0.12 | .32 |
| Hits, nondominant hand | Maximum center-of-pressure velocity ratio in y direction | >.99 | 0.002 | .99 |
| | Variability of center-of-pressure velocity ratio in x direction | .48 | −0.02 | .89 |
| | Variability of center-of-pressure velocity ratio in y direction | .08 | 0.17 | .15 |
| | Maximum center-of-pressure velocity time | .75 | −0.14 | .23 |
| Maximum center-of-pressure velocity ratio in y direction | Maximum hand velocity ratio in y direction | .14 | 0.37 | <.001 ^a |
| Variability of center-of-pressure velocity ratio in x direction | Variability of hand velocity ratio in x direction | .38 | 0.49 | <.001 ^a |
| Variability of center-of-pressure velocity ratio in y direction | Variability of hand velocity ratio in y direction | .02 ^a | 0.58 | <.001 ^a |
| Maximum center-of-pressure velocity time | Maximum hand velocity time | .17 | 0.06 | .63 |

^a Indicates difference ($P < .05$).

impairment in one domain (ie, upper extremity or postural) but not the other. As in previous research,⁶ the performance measures were largely unrelated to subjective symptom severity. Other investigators²³ have also described inconsistencies between symptom reports and objective measures of postural stability: only 25% of individuals reporting balance-related symptoms also demonstrated deficits in postural stability on the Sensory Organization Test.

Upper Extremity Measures

Recently, we quantified upper extremity performance impairments in athletes with SRC across several KINARM Standard Tests, including the object-hit test. For upper extremity performance measures evaluated in both the previous⁶ and current studies (Figure 2A), impairment percentages were generally lower in the current work (TH = 16%, decrease from 27%; H_{ND} = 21% in both studies; HS_{ND} = 12%, decrease from 24%). Given the high interindividual variability in the presentation of SRC,² slight differences in impairment percentages between studies were expected. Consistent with the previous study,⁶ the athletes with SRC exhibited worse performance than healthy control athletes on the second assessment (ie, post-SRC) relative to baseline for TH and H_{ND} (Figure 2B). Taken together, it appears that specific object-hit test measures may provide a means of quantifying deficits in upper extremity motor performance in a subset of athletes with SRC.

We included a number of additional measures quantifying upper extremity performance on the object-hit test that had not been studied in past work.⁶ As mentioned in the Methods section, these new upper extremity measures were developed to correspond with measures derived to quantify postural movements. The general tendency was for higher levels of impairment in these measures among athletes with SRC than healthy control participants (Figure 2A). However, the impairment percentages for these measures ranged from just 3% (maximum hand velocity in the y direction) to 16% (variability of hand velocity in the x direction), and RCI values for these measures were not

different between athletes with SRC and healthy control athletes (Figure 2B). Therefore, incorporating these measures did not add to the utility of the object-hit test in quantifying upper extremity motor deficits related to SRC. Notably, in both this study and related trials,^{6,24} the highest percentage of impairment in upper extremity object-hit test performance occurred in the number of objects hit, either with both hands or the nondominant hand, rather than measures of more specific aspects of performance. Possibly, simple evaluation of the number of objects hit may capture the summative effects of more subtle or specific (or both) deficits and lead to identification of higher percentages of impairment.

Postural Measures

Although postural movements have been evaluated using many paradigms after SRC,^{13,16,18} to our knowledge, we are the first to consider how SRC affects postural stability during performance of a demanding upper extremity motor task. Impairment levels in athletes with SRC were low for the simple measures of COP max and COP var during the test. In contrast, when considering COP MR and COP VR between the beginning and end of the test, impairment percentages were relatively high (up to 24%), and RCI values were greater (ie, worse) in athletes with SRC than in healthy control individuals. These ratio measures capture whether the participants increased their COP max and COP var in the later, more demanding portion relative to the earlier, easier portion of the test. Impairments were identified when the change in these ratios between the first and second tests (ie, baseline to post-SRC) was more negative, suggesting that SRC may have disrupted the athletes' ability to adapt their COP movements to increasingly complex upper extremity motor demands. The highest percentage of impairment (25%) was evident in the proportion of the test completed when the absolute maximum medial-lateral COP velocity was reached (COP_x MT). Impairments were identified when this maximum velocity was reached earlier in the second assessment relative to the first. Interestingly, impairments were not as

apparent when we considered the absolute maximum velocity, suggesting that impaired individuals were capable of similar maximum postural movement velocity after SRC but that this maximum velocity was elicited earlier in the test (ie, by less difficult upper extremity demands).

Maintenance of postural stability is a complex neurologic function that requires integration of feedback from the visual, somatosensory, and vestibular systems.¹⁴ Authors^{13,25} of previous studies of postural sway under varied sensory conditions (ie, eyes open or closed, standing on a flat or tilted surface) proposed that athletes with SRC may have impaired or inflexible weighting of this sensory information. During the object-hit test, participants are presented with continuous visual stimuli and experience extrinsic (ie, robot handles) and intrinsic (ie, arm movements) forces that stimulate the somatosensory and vestibular systems. Therefore, a deficit in processing such sensory information could certainly contribute to the altered postural movements we observed. Although no previous researchers to our knowledge have specifically evaluated postural movements during performance of an upper extremity motor task post-SRC, authors who focused on dual tasking noted SRC-related impairments in postural control related to gait during concurrent performance of cognitive tasks.^{26,27} Kleffelaar et al¹⁷ found that self-reported balance problems 1 year after a mild traumatic brain injury were associated with impaired postural stability during standing but only when participants concurrently performed an arithmetic task. Thus, the added complexity of dual- or multitask activities might unmask SRC-related impairments that are not obvious when performing simpler tasks. Our results align with this postulation and suggest that incorporating an upper extremity motor task during standing may provide another means of identifying postural-stability deficits after SRC.

Relationships Between Upper Extremity and Postural Measures

During the object-hit test, participants generate postural movements to compensate for upper extremity movements associated with test performance. Hence, we would expect that measures characterizing upper extremity and postural movement would be closely associated. However, we found that, whereas some athletes were impaired on both the upper extremity and postural measures, many individuals were impaired on the upper extremity but not the postural measures and vice versa (see Figure 4 and Table 3 for statistics). This finding was somewhat unexpected, yet it indicated that conducting the object-hit test in a standing posture allows the identification of a potentially separate subset of SRC-related impairments beyond those detected during upper extremity performance alone. This observation is consistent with the multidimensional and variable clinical presentation common in patients with SRC.¹

Among young, healthy adults, Ahmed and Wolpert²⁸ demonstrated that postural movements adapted at a slower rate than upper extremity movements during performance of a reaching task with novel forces applied to the arm. This outcome was taken as evidence that upper extremity movement and maintenance of postural stability may be supported by separate neural mappings that encode similar information but are adapted independently. Although the

object-hit test is very different from force-field reaching, the idea of distinct adaptation processes supporting upper extremity and postural movements could partly explain the lack of association in impairment categories across the upper extremity and postural measures. When performing the object-hit test, participants must continuously adapt their movements to the increasing test demands (ie, increasing speed and frequency of dropping objects). If control of the adaptation processes underpinning upper extremity and postural movements relies on separate neural mappings,²⁸ then they could be affected differently within and across athletes with SRC.

Despite the general lack of association between impairment categories across the upper extremity and postural measures, changes in performance on these measures were not entirely unrelated. For example, the Spearman correlations indicated moderately positive relationships between multiple postural measures and the corresponding new upper extremity measures (Table 3; Figure 4). Rather, the variability within and slope of these relationships tended to result in different individuals passing the RCI cutoff values for the different types of measures (examples given in Figure 4C). Nevertheless, principal component analyses showed that the principal components tended to load mainly onto either the upper extremity or postural measures instead of across both types of data, suggesting that most of the shared variance in performance was domain specific (ie, either upper extremity or postural). Therefore, although relationships were present between the upper extremity and postural movements involved in performing the object-hit test, evaluating measures from both domains added value. Given evidence of visual system disturbances after SRC,²⁹ eye tracking during the object-hit test could provide another approach to detecting specific SRC-related deficits. With this technology, a test that is completed by a participant in <2 minutes could provide a comprehensive picture of multiple neurologic functions (ie, upper extremity motor, postural, visual systems).

Relationships With Clinical Variables

In lieu of examining relationships between the clinical variables and each of the object-hit test measures separately, we evaluated their relationship with variables derived from a principal components analysis. In this analysis, the first component was mostly derived from information obtained from the upper extremity measures and the second component from the postural measures. Neither component was correlated with age or symptom severity, possibly because of study limitations. Although the number of days to the post-SRC assessment was relatively widespread (range = 1–10 days), given that most recovery typically occurs in the first 10 days after SRC,¹ it also was not associated with scores obtained from the principal components analysis of object-hit test performance. Similarly, we observed no differences in RCI values between athletes with SRC who were tested within 3 days and those tested 4 to 10 days after their SRC. These findings may suggest that the aspects of neurologic function we examined in the current study did not resolve as readily during this timeframe as many symptoms do. Consistent with this idea, a slower recovery timeframe for complex neurologic functions involved in dual tasking has been documented in other work.^{16,17} Therefore, a future clinical

application of this technology may be in determining when SRC-related deficits have resolved to inform return-to-sport decision making.

LIMITATIONS

Several study limitations should be considered. For example, the lack of an association between object-hit test performance and age could be partly due to the relatively narrow age range of participants in the healthy control and SRC groups. Additionally, the symptom severity score used here is a broad measure of many different symptoms, whereas the object-hit test is used to examine more specific aspects of neurologic function. A comprehensive symptom score specifically targeted at motor performance, coordination, balance, or all of these may be more likely to correlate with variance in object-hit test performance. Another important limitation was that the timeframes of reassessment in the healthy control and SRC groups were not well matched. Healthy control athletes were reassessed after a longer interval than the average time between the baseline and post-SRC assessment in athletes with SRC and often at different times within their athletic seasons. Although changes in performance on the upper extremity object-hit test were previously similar when athletes were retested within and between seasons,⁶ an ideal study design would match the timing of tests between groups to control for the potential effects of fatigue and conditioning. Finally, the size and expense of the equipment used in this study constitute barriers to its integration into many clinical settings. Nevertheless, in a feasibility study, Subbian et al³⁰ demonstrated that the KINARM device can be successfully integrated into an emergency department. Alternatively, other approaches could be developed to provide similar assessments with less expensive or more portable equipment (eg, tablets, wearable sensors).

CONCLUSIONS AND FUTURE DIRECTIONS

Sport-related concussion is a major public health concern, but advancements in the field are limited by the lack of a criterion-standard approach to assessment. We found that measurement of postural movements during performance of an upper extremity rapid, bimanual motor task (object-hit test) can provide an efficient and potentially valuable means of simultaneously identifying impairments in different domains of motor performance among athletes with SRC. These results highlight the importance of using simultaneous, multidimensional functional assessments for patients with SRC.

ACKNOWLEDGMENTS

This work was funded by Own the Podium Canada, the Canadian Academy of Sport and Exercise Medicine Research Fund, and the Canadian Sport Institute Calgary; postdoctoral fellowships from the Canadian Institutes of Health Research and Alberta Innovates Health Solutions (Dr Mang); and a Mitacs fellowship in partnership with Own the Podium Canada (Dr Whitten).

We thank the participating athletes, coaches, and team athletic therapists.

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