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Use of Reactive Balance Assessments With Clinical Baseline Concussion Assessments in Collegiate Athletes

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Context: Current clinical concussion evaluations assess balance deficits using static or dynamic balance tasks while largely ignoring reactive balance. Including a reactive balance assessment might provide a more comprehensive concussion evaluation.

Objectives: To identify redundancy in current clinical baseline assessments of concussion and determine whether reactive balance adds unique information to these evaluations.

Design: Cross-sectional study.

Setting: Clinical assessment.

Patients or Other Participants: A total of 279 healthy National Collegiate Athletic Association Division I athletes.

Intervention(s): Two cohorts of data were collected at the beginning of the athletic season. For cohort 1 (n = 191), the Immediate Post-Concussion Assessment and Cognitive Tool, instrumented modified push and release (I-mP&R), and Balance Error Scoring System (BESS) were administered. For cohort 2 (n = 88), the I-mP&R, BESS, timed tandem gait, walking with eyes closed, and clinical reaction time were administered.

Main Outcome Measure(s): The strengths of the relationships between the Immediate Post-Concussion Assessment and Cognitive Tool cognitive indices, mP&R clinical score, instrumented measures (BESS sway; I-mP&R time to stability, latency, and step length), BESS score, timed tandem gait, walking time to completion, and clinical reaction time were characterized.

Results: The strongest interinstrument correlation value was between single-task time to stability from the I-mP&R and clinical reaction time but was considered weak ($r = 0.35$, $P = .001$). The mP&R and I-mP&R clinical scores were weakly associated with the other assessments.

Conclusions: Weak correlations between interassessment variables indicated that little redundancy was present in the current clinical evaluations. Furthermore, reactive balance represents a unique domain of function that may improve the comprehensiveness of clinical assessments.

Key Words: mild traumatic brain injury assessment, ImPACT, Balance Error Scoring System, timed tandem gait, clinical reaction time

Key Points

- Results on the Immediate Post-Concussion Assessment and Cognitive Tool and the Balance Error Scoring System (current clinical assessments) were not associated with the instrumented modified push-and-release task (reactive balance assessment).
- Weak interinstrument associations suggested reactive balance tests are needed to fully evaluate balance in a concussion evaluation.
- The lack of redundancy between instruments highlighted that each instrument measures a unique aspect of the concussion assessment.

Current clinical tools used after sport-related concussion (SRC) assess the presence of symptoms, cognitive functioning, balance control, or a combination of these to evaluate and determine recovery from SRC.[1] Some of the most common tools include computerized neurocognitive testing, such as the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT; ImPACT Applications Inc); static and dynamic balance tests, such as the Balance Error Scoring System (BESS) and timed tandem gait (TTG) test; and tests of clinical reaction time. The combination of neurocognitive, balance, and self-reported symptom assessments can achieve >90% sensitivity in detecting acute concussion (<24 hours).[2] However, a comprehensive assessment battery introduces the possibility of redundancy across assessments. Therefore, we need to identify brief tests that evaluate nonoverlapping domains of recovery to create a comprehensive postconcussion battery while minimizing the burden on the patient and the health care professional (eg, athletic trainer [AT], physician).[3]

Balance assessments have been a hallmark of concussion batteries, but they have focused on static balance, with only recent attention to dynamic balance. Even though the BESS, a measure of static balance performance, is often used as a baseline or sideline screen by ATs, it has low sensitivity as a diagnostic test for symptoms of acute SRC[4] and poor interrater and intrarater reliability.[5] In the past few years, the TTG test has demonstrated an ability to identify balance deficits after SRC.[4] Static and dynamic balance assessments, therefore, offer different, complementary information that may be used in clinical decisions after SRC.[4]

Reactive balance is another domain of balance that may further complement existing clinical evaluations. *Reactive balance* involves a rapid, time-constrained response to a sudden external destabilizing perturbation.[6,7] Capturing this ability to recover balance after destabilization is a core component of multidimensional assessments of balance in other populations, such as participants who are older or have age-related balance disorders, Parkinson disease, multiple sclerosis, or neuromuscular disease[8,9]; the Balance Evaluations Systems Test (BEST) and shortened mini-BEST incorporate valid and reliable clinical measures of reactive balance using a compensatory stepping task known as the push and release (P&R).[8,9] Yet reactive balance is seldom, if ever, included in clinical concussion assessments.

Characterizing reactive balance during the P&R task relies on clinical scoring that captures global measures, such as whether the patient needed assistance to recover balance. However, this scoring scale does not yield more sensitive information about the time-constrained responses of reactive balance, such as response latency, step length, and time to stability (ie, recovery time), that may be most relevant to athletes. To solve this problem, inertial measurement units (IMUs; ie, inertial sensors) can be used to improve clinical tests by objectively quantifying kinematics in standard clinical settings with minimal added time or expense.[10,11] For example, IMUs can enhance the diagnostic accuracy of the BESS[12] and are used in smartphone applications for clinical assessments of static balance.[13] Similarly, IMUs can capture validated, granular measures of stepping response latency, step length, and time to stability during the P&R task.

We need to identify whether the information generated by reactive balance tests, with or without IMUs, offers complementary, nonoverlapping information to that in current protocols before such tests of reactive balance can be recommended for clinical use. Reactive balance integrates proprioceptive, vestibular, and visual sensory stimuli; a fast-stepping response; cognitive processing to prime and select the appropriate stepping response based on the sensory stimuli; and precise foot placement to arrest the fall and regain balance. However, some or all of these specific components may already be captured by individual elements in the current concussion battery. For example, the latency of a stepping response during reactive balance may reflect processing speed and be associated with clinical or computerized reaction times.[14] Step length may be linked with neurocognitive performance due to the cognitive processes needed to integrate sensory information, select an appropriate motor plan based on one's instantaneous body state, and execute a precise step. Time to stability may be related to other measures of balance control that require steps to be taken, such as TTG. If specific components of reactive balance (eg, step latency) are already being captured through other means (eg, reaction time), then reactive balance may offer another way of assessing these domains of function. Alternatively, measures of reactive balance may provide new information, so adding reactive balance assessments could improve the comprehensive, multidimensional nature of clinical evaluations.

Thus, the purposes of our study were to determine whether redundancy existed in current clinical baseline assessments of concussion and to examine whether reactive balance added unique information about reaction time, cognitive function, and motor function that was not captured in current baseline concussion batteries. We hypothesized that outcomes from an instrumented test of reactive balance (instrumented modified P&R task [I-mP&R])[15] would be weakly correlated with current clinical evaluations, indicating the potential for complementary information that may improve clinical batteries.

METHODS

Participants

We enrolled 279 athletes in this study at or before the start of their competitive seasons. The participants were divided into 2 cohorts based on the year of enrollment (2019 and 2021; Table 1). Two cohorts were included because of changes in the assessments used for standard clinical baseline concussion batteries (ie, ImPACT data were no longer collected after 2019, and the TTG and walking task were added in 2021). Cohort 1 consisted of 191 athletes (104 females, 87 males; age = 19 ± 1.5 years, body mass index = 23.3 ± 3.1). Cohort 2 consisted of 88 athletes (35 females, 53 males; age = 19.5 ± 1.7 years, body mass index = 24.3 ± 3.8). Cohort 1 completed neurocognitive (ImPACT), reactive balance (I-mP&R), and static balance (BESS) tests before their competitive seasons. Cohort 2 completed reactive balance (I-mP&R), static balance (BESS), dynamic balance (TTG and walking with eyes closed assessment), and clinical reaction time tests before their competitive seasons. Inclusion criteria were as follows: (1) aged 18–30 years and (2) current participation in National Collegiate Athletic Association Division I athletics. Exclusion criteria were as follows: (1) recent (within 6 months) or planned surgery that would result in future time loss from practice or competition exposure and (2) a chronic condition that could confound testing procedures (overuse injuries, medical conditions).[6] All participants provided written informed consent, and the study was approved by the institutional review board of the University of Utah.

Immediate Post-Concussion Assessments and Cognitive Test

We administered the ImPACT according to standardized instructions under supervision of a certified administrator (R.P. or J.B). Seven composite scores were calculated by the ImPACT software to assess aspects of cognitive functioning: verbal memory, visual memory, visual motor speed, reaction time, impulse control, symptom severity, and cognitive efficiency index.

Table 1. Descriptive Statistics for Each Variable Stratified by Cohort and Combined

Assessment	Variable	Mean ± SD		
		Cohort 1	Cohort 2	Total
Immediate Post-Concussion Assessment and Cognitive Test	Verbal memory, unitless	90.6 ± 8.9	NA	NA
	Visual memory, unitless	78.7 ± 11.9	NA	NA
	Visual motor speed, unitless	41.634 ± 5.572	NA	NA
	Reaction time, s	0.602 ± 0.076	NA	NA
	Impulse control, unitless	5.4 ± 3.7	NA	NA
	Symptom severity, unitless	5.6 ± 7.4	NA	NA
	Cognitive efficiency index, unitless	0.4 ± 0.1	NA	NA
Instrumented, modified push-and-release task	Single-task latency, s	0.19 ± 0.05	0.21 ± 0.05	0.19 ± 0.05
	Dual-task latency, s	0.25 ± 0.07	0.27 ± 0.07	0.26 ± 0.07
	Single-task step length, step length and height, m	0.28 ± 0.04	0.26 ± 0.04	0.28 ± 0.04
	Dual-task step length, step length and height, m	0.28 ± 0.04	0.27 ± 0.04	0.28 ± 0.04
	Single-task time to stability, s	1.00 ± 0.22	1.00 ± 0.19	1.00 ± 0.25
	Dual-task time to stability, s	1.13 ± 0.26	1.11 ± 0.24	1.12 ± 0.25
	Single-task clinical score, unitless	6 [1][a]	6 [1][a]	6 [1][a]
	Dual-task clinical score, unitless	5 [1][a]	6 [1][a]	5 [1][a]
Balance Error Scoring System	Firm clinical score, unitless	2 [3][a]	2 [3][a]	2 [3][a]
	Foam clinical score, unitless	6 [4][a]	6 [5][a]	6 [4][a]
	Firm mediolateral root mean square sway, m/s^2	0.06 ± 0.02	0.06 ± 0.02	0.06 ± 0.02
	Foam mediolateral root mean square sway, m/s^2	0.17 ± 0.06	0.19 ± 0.10	0.18 ± 0.08
Timed tandem gait	Timed tandem gait, s	NA	12.8 ± 2.2	NA
Walking with eyes closed	Walking with eyes closed (time[s]/height[m])[b]	NA	3.6 ± 0.8	NA
Clinical reaction time	Clinical reaction time, ms	NA	201.8 ± 23.9	NA

Abbreviation: NA, not applicable.

[a] Data are reported as median [interquartile range].

[b] Time to complete the 6-m walk test was normalized to participant height in meters.

Modified P&R Task

We administered the mP&R task as described by Morris et al.[6] Given the predominant use of the P&R task in older adults and populations prone to falls,[8] we made 2 modifications to the original test[6] to scale the difficulty of the reactive balance task to match the capacity of elite athletes: (1) having participants close their eyes before being released and (2) adding a dual-task component. For each trial, the administrator (R.P. or B.C.) leaned participants, in a plank-like position, until they were past the point at which they could maintain balance on their own. The administrator visually inspected the position of the body relative to the base of support and felt for a significant shift in force from the participants to the administrator's hands. For forward and backward directions, the correct leaning angle was noted when the midline of the body in the sagittal plane, roughly equivalent to the position of the greater trochanter, was just beyond the participants' toes and heels, respectively. For the right and left directions, the correct leaning angle was identified when the midline of the body in the frontal plane was just beyond the participants' lateral malleoli.[15] This point of destabilization was most accurately felt as an inflection point in the force supported by the administrator, which occurred when the ground reaction force switched from producing a restoring moment to an overturning moment. After being held in this position, participants were instructed to close their eyes, and the administrator's support was unexpectedly removed (within 5 seconds of participants maintaining the correct position). Participants were then required to regain their balance through any means necessary, including taking a step or steps. They were allowed to open their eyes when they were released to accommodate taking a step. The mP&R was performed in 4 directions (forward, backward, left, and right) under single-task and dual-task conditions. The dual-task condition consisted of a different cognitive task for each of the 4 directions: serial subtraction by 3s, phonemic verbal fluency (F-A-S test), categorical verbal fluency (naming animals or fruits), or reciting every other letter of the alphabet during the trial.[6] Clinical scores were 0 (*fall*; participant needed assistance from the administrator to avoid falling), 1 (*recovered independently but required >1 step*), and 2 (*recovered independently with 1 step*). The final clinical score was calculated using the following equation, yielding a maximum possible score of 6 points[16]:

$$\text{Total Score} = \text{Forward Score} + \text{Backward Score} + \min(\text{Left Score}, \text{Right Score}),$$

where min(Left Score, Right Score) was the score of the side with the lowest score.

Instrumented mP&R

We placed IMUs (Opal; APDM Wearable Technologies Inc) on the left and right feet, right shank, lumbar spine (L3–L5), and sternum (over the manubrium) of participants to capture objective measures of reactive balance during the mP&R. An IMU was placed on the administrator's hand to determine the release time. Raw linear acceleration and angular velocity data were sampled at 128 Hz and used to calculate step latency, step length, and time to stability using established, validated algorithms (MATLAB version r2020a; The MathWorks).[6] *Step latency* was calculated as the time from release of support to the time that first movement was initiated. Maximum latency from the 4 directions was used for analysis.[15] *Step length* was the length, in meters, of the recovery step after release and was normalized to height before analysis. *Time to stability* was the time, in seconds, after release to stability.[6] *Stability* was defined as the point in time after release when the magnitude of acceleration at the lumbar sensor was $<1.07g$, the magnitude of rotational velocity was $<14°/s$, and both foot sensors reached zero velocity criteria.[15] The time to stability and step-length data used in the analysis were calculated as the median of all 4 directions.[6]

Balance Error Scoring System

Participants completed clinical assessments of static balance using the BESS.[17] They were instructed to maintain their balance in 3 stances (single-legged, tandem, and double-legged) on both firm and foam surfaces with their hands on their hips and eyes closed. *Errors* were defined as opening the eyes, taking the hands off the hips, stepping, falling out of position, lifting the forefoot or heel, abducting the hip $>30°$, or not returning to the test position for >5 seconds.[17] The clinical score was computed as the sum of errors across all stances. If a participant was unable to maintain balance for 5 consecutive seconds, then the maximum score of 10 was assigned.[17] Each stance was maintained for a total of 30 seconds, but only the first 20 seconds were used for clinical scoring.[12,17] To score the BESS, all raters were trained on protocols by either a physical therapist (R.P.) or an AT (B.C.) with extensive experience administering the test. Two raters (A.M., T.P., R.P., S.H., or B.C.) evaluated each trial to confirm the score, and any disagreement was resolved by reviewing a video recording to reach consensus.

Instrumented BESS

For objective measures of static balance, participants wore an IMU that was placed on the lumbar spine in the L3–L5 area. The root-mean square of mediolateral acceleration for the double-legged stance of the BESS (both firm and foam surfaces) was calculated using Mobility Lab software (version 2017; APDM Wearable Technologies Inc) and extracted for analysis on the basis of previous recommendations.[18]

Timed Tandem Gait

Participants completed a clinical assessment of dynamic balance using the TTG.[4] They were instructed to walk with alternating feet, heel to toe, as quickly and as accurately as possible down a line of tape that was 3-m long and 38-mm wide, turn 180°, and return to the starting point using the same gait.[4] Participants were timed, and the average time of 3 trials was used as the measure of dynamic balance.

Walking With Eyes Closed

For the walking-with-eyes-closed task, participants were instructed to walk at their normal speed with their eyes closed down a 6-m walkway that was 12-in (30.48-cm) wide.[19] An oral command of "stop" was provided when the participant reached the end of the second marker as an alert that the task was completed. Time to completion was used as the performance measure and normalized to height before analysis.

Clinical Reaction Time Test

Participants completed a clinical assessment of reaction time.[20] While sitting, they rested the wrist of their dominant hand on the end of the table and formed a C shape with their fingers going around, but not touching, a hockey puck into which a stick was inserted. After a random interval of time (<5 seconds), the hockey puck was released, and the individual caught the stick as quickly as possible. The administrator (A.M., T.P., R.P., S.H., or B.C.) then measured the distance (in centimeters) that the stick fell, and the distance was used to calculate reaction time. If the stick was dropped entirely, the trial was repeated. Participants were given 2 practice trials, and 8 trials were collected for data analysis. The average of the 8 trial times was the performance measure.

Statistical Analysis

To determine whether reactive balance added unique information about cognitive and motor function that was not being captured in current baseline concussion batteries, we calculated the associations between the outcomes of each clinical assessment. Pearson correlation coefficients were generated for each pair of continuous outcomes using the function *corrcoef* in MATLAB (version R2021a). Spearman correlation coefficients were computed across each pair of categorical variables: the clinical scoring of the mP&R and the BESS error count on firm and foam surfaces. A correlation coefficient ≤ 0.35 was considered a *weak association*; between 0.36 and 0.67, *moderate*; and ≥ 0.68, *strong*.[21] The α level was set at .05.

RESULTS

Descriptive statistics for outcome measures from cohort 1 and cohort 2 are listed in Table 1.

Cohort 1

Only weak associations were found between the variables of the ImPACT, I-mP&R, and BESS (Figure 1). The strongest correlation between variables of separate assessment tools was between the verbal memory composite score from the ImPACT and root mean square sway in the foam condition of the BESS ($r = -0.18$, $P = .02$). Interassessment correlation values ranged from 0 to 0.18. Pairwise correlation coefficients are presented in Table 2.

Cohort 2

Similar to the findings in cohort 1, we observed only weak correlations between variables in different tests; however, variables within the same test were more than

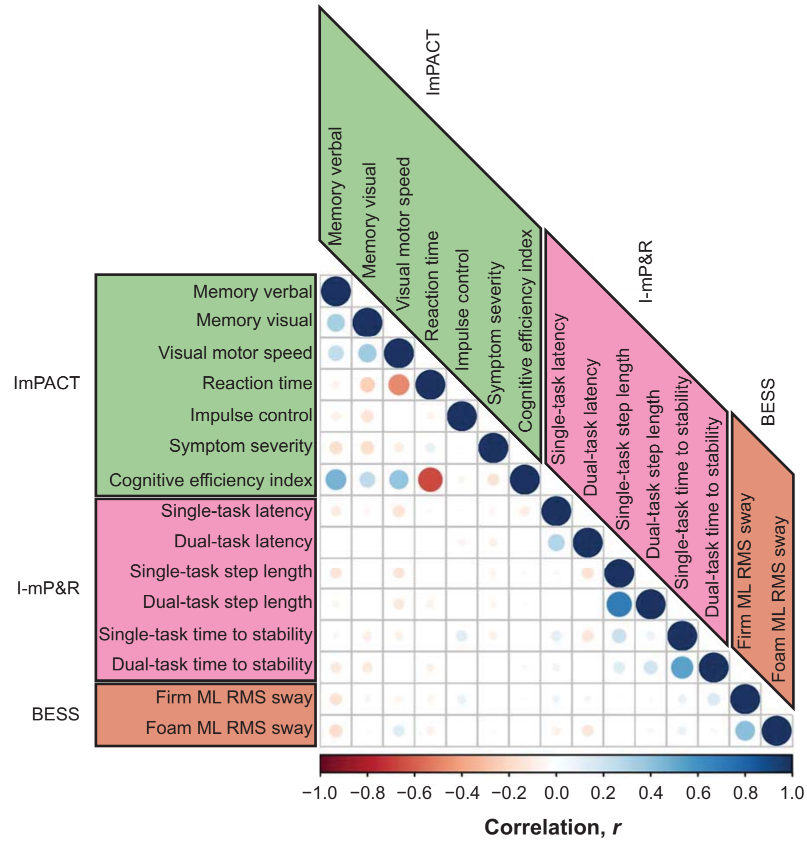

Figure 1. Correlation matrix between continuous variables from the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT; Impact Applications Inc); instrumented, modified push and release (I-mP&R), and instrumented Balance Error Scoring System (BESS) in cohort 1. Darker circles reflect a stronger correlation, with blue indicating a positive correlation and red indicating a negative correlation. Shaded boxes reflect the measures extracted from each instrument. Abbreviations: ML, mediolateral; RMS, root mean square.

minimally associated with one another (Figure 2). The strongest interinstrument correlation value was between time to stability on the single-task I-mP&R and clinical reaction time ($r = 0.35$, $P = .001$). Interassessment correlation values ranged from 0 to 0.35. Pairwise correlation coefficients are shown in Table 3. Across cohorts 1 and 2, we noted only weak associations between the clinical mP&R scores and BESS error counts (Table 4).

DISCUSSION

In this study, we wanted to determine whether a reactive balance test added unique information about cognitive or motor function not currently captured in standard baseline concussion batteries. The weak correlations between the variables of the ImPACT, I-mP&R, and BESS suggested that the reaction time assessed by I-mP&R latency was distinct from the reaction time composites presented in the ImPACT and that the I-mP&R tested domains of function distinct from the static balance evaluated on the BESS. In cohort 2, these results extended to dynamic balance (TTG and walking with eyes closed) through negligible-to-weak associations between the variables of the I-mP&R and standard assessments. Together, these findings indicated that including an assessment of reactive balance, such as the I-mP&R, may capture aspects of function that are not captured in current assessment batteries.

The weak relationships between the I-mP&R and current assessments align with an evolving understanding of balance and a complex organization of separate systems in the body. Balance requires numerous resources: reactive movement strategies, sensory strategies including sensory integration and reweighting, biomechanical constraints, dynamic control, and orientation in space. A comprehensive assessment of balance requires testing each aspect separately.[8] Even though this balance-systems approach has been successfully applied to older adults and other populations at high fall risk,[22] it has not been considered in collegiate athletes despite the importance of balance testing for clinical decisions in this population.

Our results suggest that current concussion assessments of cognition and motor function may be incomplete because they do not assess reactive balance. Maintaining static balance during the BESS requires sensory reweighting and integration of vestibular and proprioceptive inputs to account for the loss of visual feedback. This static balance relies heavily on feedback-driven control to maintain balance.[23] Similarly, tandem walking or walking with eyes closed requires dynamic control by integrating sensory information to internally generate movement in response to volitional movement. These dynamic balance tasks use both feedback and feedforward control to continually place the feet under the falling center of mass,[23] where anticipatory postural adjustments ensure accurate foot placement, and feedback initiates automatic postural responses to

Table 2. Pairwise Pearson Correlation Coefficients From the Immediate Post-Concussion Assessment and Cognitive Test, Instrumented, Modified Push-and-Release Task, and Balance Error Scoring System in Cohort 1[a]

	Immediate Post-Concussion Assessment and Cognitive Test							Instrumented, Modified Push-and-Release Task						Balance Error Scoring System	
								Latency		Step Length		Time to Stability		Medial-Lateral Root Mean Square	
Variable	Verbal Memory	Visual Memory	Visual Motor Speed	Reaction Time	Impulse Control	Symptom Severity	Cognitive Efficiency Index	ST	DT	ST	DT	ST	DT	Firm Surface	Foam Surface
Verbal memory	1														
Visual memory	0.34	1													
Visual motor speed	0.25	0.36	1												
Reaction time	−0.07	−0.22	−0.47	1											
Impulse control	−0.08	−0.15	0.00	−0.06	1										
Symptom severity	−0.17	−0.17	−0.09	0.09	0.02	1									
Cognitive efficiency index	0.47	0.25	0.38	−0.65	−0.05	−0.14	1								
Latency															
ST	−0.10	−0.04	−0.16	0.04	−0.02	−0.04	−0.10	1							
DT	−0.02	0.01	−0.01	−0.01	−0.07	−0.07	−0.01	0.31	1						
Step length															
ST	−0.14	0.02	−0.11	−0.03	0.01	−0.07	−0.004	0.06	−0.12	1					
DT	−0.06	0.02	−0.11	−0.09	−0.02	−0.06	0.04	−0.005	0.00	0.69	1				
Time to stability															
ST	−0.04	−0.08	−0.08	−0.02	0.13	−0.08	0.00	0.13	−0.12	0.22	0.09	1			
DT	−0.12	−0.11	0.02	−0.08	0.02	−0.01	0.03	0.08	0.03	0.13	0.21	0.53	1		
Medial-lateral root mean square sway															
Firm surface	−0.15	0.04	−0.06	−0.04	0.09	−0.02	0.02	0.07	0.05	−0.03	0.02	0.09	0.16	1	
Foam surface	−0.18	0.03	0.13	−0.07	0.02	0.04	−0.01	−0.09	−0.15	0.04	0.06	0.08	0.05	0.41	1

Abbreviations: DT, dual task; ST, single task.

[a] Correlation coefficients were classified as *weak* (0–0.35), *moderate* (0.36–0.67), or *strong* (>0.67).

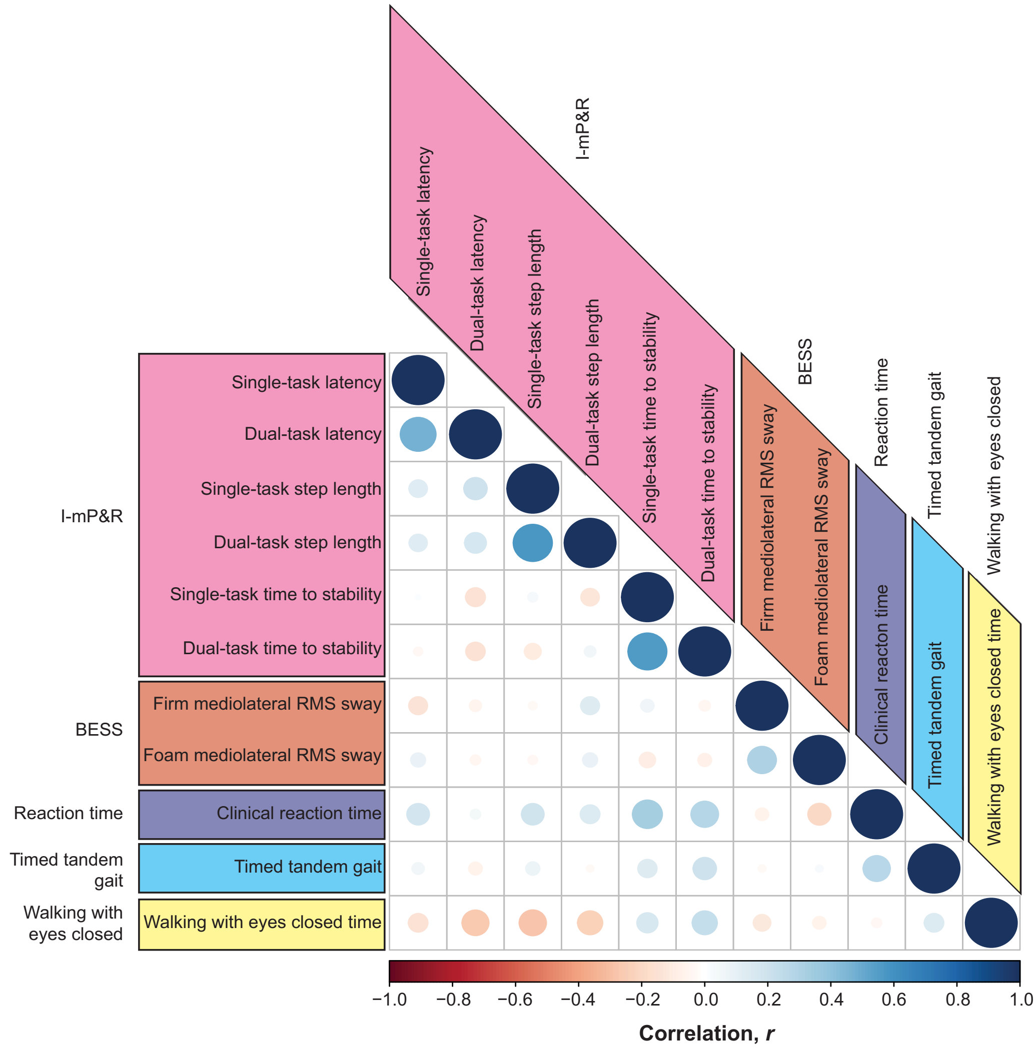

Figure 2. Correlation matrix for continuous variables from the instrumented modified push and release (I-mP&R), instrumented Balance Error Scoring System (BESS), timed tandem gait (TTG), walking with eyes closed, and the clinical reaction time test in cohort 2. Darker colors reflect a stronger correlation, with blue indicating a positive correlation and red indicating a negative correlation. Shaded boxes reflect the measures extracted from each instrument. Abbreviation: RMS, root mean square.

correct lateral trunk and foot movements.[23] In contrast to these static and dynamic balance tasks, the initial response to the I-mP&R relies on feedback, whereas the latter part of the response, time to stability, represents the ability to incorporate sensory information and an existing central plan set to a feedforward model for accurate, time-constrained foot placement.[24] Reactive balance is initiated via a feedback-driven, automatic response from the brainstem and spinal cord, with later input from transcortical loops, in response to an external perturbation.[7] Reactive balance, therefore, has 3 critical components: the primed motor response, the initial response latency, and the ensuing stepping response that determines the time to stability.

Few clinical tests can accurately re-create the demands of competitive sport, but the I-mP&R assesses an important component: the ability to prime a motor response in anticipation of a future event and then execute that whole-body response based on a stimulus. This anticipatory priming is critical to high-level performance in sport[25]; elite athletes often anticipate possible events before they occur, which allows them to prime a narrow selection of possible actions and select the most appropriate action based on instantaneous cues of their body and the environment.[25,26] Reactive balance tests such as the I-mP&R similarly feature this anticipatory priming and triggered selection[27] of a motor plan. Although obvious differences exist between a controlled clinical assessment and a fast-paced sport maneuver that may include contact and collision, these results support growing evidence that functional tests of reaction time and balance that better mimic competitive play, including anticipatory priming and whole-body responses, may be necessary to assess the specific neuromechanical systems used in sport.

The response latency on the I-mP&R is similar to a functional reaction time, and our outcomes are consistent with earlier weak associations seen between computerized and clinical reaction time measures and functional reaction time.[28] A key difference between the I-mP&R and the computerized and clinical reaction time tests is the stimulus and response execution. Both the computerized and clinical reaction time tests present a visual stimulus to the

Table 3. Pairwise Pearson Correlation Coefficients From the Instrumented Modified Push-and-Release Task, Balance Error Scoring System, Timed Tandem Gait, and Walking With Eyes Closed Task, and Clinical Reaction Time in Cohort 2[a]

	Instrumented Modified Push-and-Release Task						Balance Error Scoring System				
	Latency		Step Length		Time to Stability		Medial-Lateral Root Mean Square Sway				
Variable	ST	DT	ST	DT	ST	DT	Firm Surface	Foam Surface	Timed Tandem Gait	Walking With Eyes Closed Time	Clinical Reaction Time
Latency											
ST	1										
DT	0.47	1									
Step length											
ST	0.13	0.21	1								
DT	0.11	0.11	0.60	1							
Time to stability											
ST	0.02	−0.09	0.04	−0.04	1						
DT	−0.04	−0.15	−0.11	0.05	0.56	1					
Medial-lateral root mean square sway											
Firm surface	−0.15	−0.08	−0.03	0.11	0.10	−0.05	1				
Foam surface	0.08	−0.06	−0.03	0.08	−0.10	−0.08	0.30	1			
Timed tandem gait	0.07	−0.03	0.08	0.04	0.08	0.20	−0.004	0.03	1		0.27
Walking with eyes closed time	−0.13	−0.24	−0.28	−0.19	0.12	0.23	−0.10	−0.06	0.11	1	−0.05
Clinical reaction time	0.20	0.06	0.19	0.17	0.35	0.29	0.06	−0.19			1

Abbreviations: DT, dual task; ST, single task.

[a] Correlation coefficients were classified as *weak* (0–0.35), *moderate* (0.36–0.67), or *strong* (>0.67).

Table 4. Pairwise Spearman Correlation Coefficients Between the Clinical Scores on the Modified Push-and-Release Task and Errors During the Balance Error Scoring System (BESS) for the Firm and Foam Conditions[a]

	Clinical Score			
	Single Task	Dual Task	Firm Surface	Foam Surface
Single task	1	0.20	0.01	−0.07
Dual task	0.30	1	0.09	−0.04
Firm surface[b]	−0.08	−0.15	1	0.30
Foam surface[c]	0.03	−0.21	0.42	1

[a] Cohort 1 data are located below the identity diagonal. Cohort 2 data are located above the identity diagonal.
[b] The firm BESS condition is equivalent to the modified BESS scoring.
[c] The combined firm and foam scoring is equivalent to the total BESS scoring.

participant. In contrast, the I-mP&R presents a stimulus that is detected through proprioceptive inputs, vestibular inputs (ie, the motion of the body when the support is released), or both rather than visual input. Furthermore, computerized and clinical reaction time tests require a simple response from the upper extremity (either a button press or grasp), whereas the I-mP&R requires multijoint coordinated muscle activation of the lower extremities and core to complete the stepping response and arrest the fall. These brainstem–mediated responses[7] during reactive balance occur faster than computerized or clinical reaction times: the average maximum response latency for the I-mP&R in our sample was 190 milliseconds, compared with average computerized and clinical reaction times of 600 milliseconds and 201 milliseconds, respectively.

Both the clinical scoring on the mP&R and the instrumented outcomes from the I-mP&R complement the clinical scoring of BESS and objective measures of reaction time, cognition, and balance, respectively. However, the utility of the mP&R clinical score is questionable in this population given the potential ceiling effects of the mP&R (the median score was the maximum score of 6). In contrast, measures on the I-mP&R may have high clinical utility; IMUs can provide more sensitive and objective measurements of balance without the prohibitive cost and space limitations of a motion-capture system, making them a feasible clinical instrument.[10,11] The current implementation of the I-mP&R uses data from 4 sensors, a setup and data collection that take approximately 5 to 10 minutes total, and offline processing. Future work should focus on the clinical implementation of the I-mP&R by reducing the number of required sensors and improving the user-friendliness of the software and analysis. Similar strategies have been successfully applied to instrumented tests of static balance using widely available smartphone technology with embedded IMUs.[13]

We investigated a large sample of 279 National Collegiate Athletic Association Division I athletes. Even though we present the first assessment of the overlaps among static, dynamic, and reactive balance in collegiate athletes, it may not be appropriate to extrapolate these results to other populations. In addition, we obtained these measures as part of a baseline assessment, not after SRC; the utility of the I-mP&R and reactive balance in the clinical management of SRC remains unclear. Given that these tests were conducted as part of a baseline assessment in a controlled environment, the athletes were not exposed to a typical "sideline" testing environment. We did not consider an athlete's history of SRC; previous balance deficits may have been present due to SRC and influenced the balance outcomes.

CONCLUSIONS

Future researchers should examine the clinical utility of a reactive balance test such as the I-mP&R to improve the management of patients with SRC. Our results suggested that reactive balance may complement the current multidimensional battery of static balance, dynamic balance, and cognition after SRC. The clinical feasibility of the I-mP&R and utility of reactive balance are in predicting the fall risk in other populations, including those with stroke[29] or Parkinson disease[22] and those who are aging,[30] which further suggests its usefulness in SRC. Although not currently included in baseline or return-to-play assessments, a reactive balance assessment may improve the detection of acute and longitudinal neuromuscular deficits after SRC.

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