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Relationship Between Cognitive Performance and Lower Extremity Biomechanics

Implications for Sports-Related Concussion

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Investigation performed at Michigan State University, East Lansing, Michigan, USA

Background: Collegiate athletes with prior sports-related concussion (SRC) are at increased risk for lower extremity (LE) injuries; however, the biomechanical and cognitive mechanisms underlying the SRC-LE injury relationship are not well understood.

Purpose: To examine the association between cognitive performance and LE land-and-cut biomechanics among collegiate athletes with and without a history of SRC and to determine the association among multiple cognitive testing batteries in the same athlete cohort.

Study Design: Controlled laboratory study.

Methods: A cohort of 20 collegiate athletes with prior SRC (9 men, 11 women; mean ± standard deviation [SD] age, 20.5 ± 1.3 years; mean ± SD time since last SRC, 461 ± 263 days) and 20 matched controls (9 men, 11 women; mean ± SD age, 19.8 ± 1.3 years) completed land-and-cut tasks using the dominant and nondominant limbs. LE biomechanical variables and a functional visuomotor reaction time (FVMRT) were collected during each trial. Athletes also completed the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) and Senaptec Sensory Station assessments.

Results: In the SRC cohort, Pearson correlation coefficients indicated slower FVMRT was moderately correlated with decreased dominant limb ($r = -0.512$) and nondominant limb ($r = -0.500$) knee flexion, while increased dominant limb knee abduction moment was moderately correlated with decreased ImPACT Visual Memory score ($r = -0.539$) and slower ImPACT Reaction Time ($r = 0.515$). Most computerized cognitive measures were not associated with FVMRT in either cohort ($P > .05$).

Conclusion: Decreased reaction time and working memory performance were moderately correlated with decreased sagittal plane knee motion and increased frontal plane knee loading in collegiate athletes with a history of SRC. The present findings suggest a potential unique relationship between cognitive performance and LE neuromuscular control in athletes with a history of SRC injury. Last, we determined that computerized measures of cognitive performance often utilized for SRC management are dissimilar to sport-specific cognitive processes.

Clinical Relevance: Understanding the relationship between cognitive performance and LE biomechanics in athletes with prior SRC may inform future clinical management strategies. Future research should prospectively assess cognitive and biomechanical measures, along with LE injury incidence, to identify mechanisms underlying the SRC-LE injury relationship.

Keywords: reaction time; visual memory; multiple object tracking; musculoskeletal injury

Sports-related concussion (SRC) represents a serious public health concern for competitive athletes, as evidence suggests that upward of 4 million sports- and recreational-based concussive events occur annually in the United States.[23] Specific to the active collegiate competitor, SRCs account for approximately 6.2% of all injuries, signifying an overall incidence of around 11,000 reported concussive injuries each year.[49] After the occurrence of a single SRC, it appears that adolescent, collegiate, and professional athletes are at greater future risk for both concussive and lower extremity (LE) injuries.[29,30,35] Recent systematic reviews have suggested that previously concussed athletes had approximately 2 times greater odds for LE injury compared with nonconcussed competitors.[35,42] Overall, it appears the elevated risk for LE injury post-SRC is present in both short and long terms after an athlete returns to unrestricted participation.[4,5,12,14,29] Compared with previous decades, it appears that SRCs are increasing within the collegiate athlete population,[9] which may predispose more competitors to subsequent LE injuries.

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A hallmark of SRC is a temporarily altered cognitive state that may last days or weeks after a concussive event[7,39] in spite of athletes reporting no symptoms.[3] Interestingly, lower preseason baseline cognitive performance (defined as mental processes related to visual recognition, processing speed, and response initiation[48]) in collegiate athletes has been prospectively[34,47,48] and retrospectively[46] associated with higher risk for LE injury. However, traditional post-SRC measures of cognitive performance were unable to predict LE injury occurrence in recently concussed male and female collegiate competitors.[5] Nonetheless, there does appear to be clinical utility in assessing cognitive performance for the dual purposes of SRC management and LE injury risk in collegiate athletes with and without a recent history of SRC. To further elucidate the relationship between cognitive performance and LE biomechanics associated with injury, recent studies have determined that athletes with slower reaction time and reduced working memory perform landing maneuvers with biomechanical patterns associated with LE injury, such as increased vertical ground-reaction force (vGRF),[16] greater knee valgus angle,[16,37] and decreased landing stability.[13]

The majority of traditional SRC management strategies, including symptom reporting, cognitive assessment, and postural control analysis, fail to provide quantitative and objective measures of motor performance when athletes return to sports activity.[2] Recent biomechanical research has suggested that athletes with a history of SRC adopt a more conservative gait strategy[20] or display altered LE neuromuscular control during high-impact loading tasks[1,10] compared with nonconcussed athletes that, in turn, may heighten the risk for LE injury. While these recent investigations provide novel information related to motor patterns in previously concussed athletes, it is unknown if LE biomechanical performance during sport-specific tasks is associated with clinical and functional measures of SRC, such as cognitive performance. The addition of objective motor performance tests, in conjunction with currently implemented clinical strategies, supports the need for multidimensional assessment to identify recovery trajectories and mitigate future injury risk in athletes with SRC.[33]

There appears to be a complex relationship among cognitive performance, SRC, and LE injury in athletes, which may alter future concussive management strategies. While an increasing number of research studies suggest that previously concussed athletes are at greater risk for LE injury,[4,5,12,29] there is a need for more multifaceted clinical assessments of recovery that emphasize dynamic motor performance to ensure athlete safety upon resuming sports.[29,35,41] The relationship between cognitive performance and LE injury risk in collegiate athletes with previous SRC is presently unknown. If clinicians are provided with information related to measures of cognitive performance and LE biomechanical performance, they may be able to make a more accurate assessment of LE injury risk regardless of SRC history. Therefore, the primary aim of this investigation was to examine the association between cognitive performance and LE land-and-cut biomechanics during a sport-specific task among collegiate athletes with and without a history of SRC. While cognitive assessment is integral to SRC management,[33] preliminary evidence suggests that clinical (ie, computerized) and functional measures of cognitive performance (ie, during movement tasks such as jump-cutting)[24] are not associated with each other in recreational athletes[24]; however, further research is necessary to confirm these findings in higher-level athletic competitors and those with prior SRC injury. Therefore, a secondary aim was to determine the association among multiple cognitive testing batteries in the same athlete cohort. Based upon recent findings,[37] we hypothesized that cognitive assessments of reaction time and working memory would be significantly correlated with higher-risk biomechanical land-and-cut patterns in both athlete cohorts; however, the associations would be stronger in previously concussed athletes. In line with prior investigators,[24] we also hypothesized that functional measures of cognitive performance would not be significantly correlated with computerized measures of cognitive performance.

METHODS

Design and Setting

Based upon previous literature[37] and an a priori power analysis (coefficient of determination = 0.70; alpha = .05; power = 0.95) based upon data pertaining to the association between computerized cognitive and LE biomechanical performance, we determined that a sample size of ≥15 athletes for each group was sufficient to detect significant associations between cognitive and biomechanical performance. A sample of 40 collegiate athletes (20 with a history of SRC, 20 matched controls) were enrolled in this study and completed all cognitive and biomechanical assessments during a single testing session. To control for potential confounding factors, each participant in the SRC group was matched to a participant in the control group by sport, position, sex,

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Ethical approval for this study was obtained from Michigan State University (study ID: STUDY00003692).

and age (±1 year).[10] Participants were excluded if they reported an LE injury or any visual, physiological, or neurological conditions that would limit one from completing all assessment batteries. The study protocol was approved by the institutional review board at Michigan State University, and all participants provided written consent for study participation.

Instrumentation and Procedures

All participants reported to the laboratory for a single testing session and were instructed to complete a questionnaire pertaining to their SRC history during their collegiate athletic career (number of diagnosed SRCs and time since the latest SRC). All participants in the control group did not report a previous SRC during their collegiate athletic career. We choose the collegiate sporting career for group classification because of limitations with athletes self-reporting SRCs from previous sports participation (eg, high school)[15] and because each collegiate SRC in this investigation was confirmed by a health care professional at the university. After collecting the completed informed consent form and health history questionnaire, the research team provided a verbal overview of all biomechanical and cognitive testing procedures.

Definition of SRC

Athletes in the SRC group sustained their injury while participating in a National Collegiate Athletic Association Division I sport during any year of their collegiate career. SRC was operationally defined as an altered mental status induced by biomechanical forces resulting in a variety of clinically overt signs and symptoms.[15] All SRCs were assessed by health care professionals and diagnosed by a physician using the criteria of observed and/or reported mechanism of injury and the presence of at least 1 of the following: (1) on-field signs (eg, loss of consciousness, amnesia, disorientation/confusion, balance difficulties), (2) symptoms (eg, headache, nausea, dizziness), and/or (3) any impairment on sideline assessments (eg, Sport Concussion Assessment Tool).

Biomechanical Assessment

All participants completed the biomechanical assessment in compression clothing and athletic footwear worn during sports training. Anthropometric measurements (height and mass) as well as each participant's self-defined dominant limb for one's respective sport were recorded before testing. Each participant was outfitted with clusters of 4 passive retroreflective markers on the upper thoracic and lumbar spine, lateral thighs and shanks, and dorsal surfaces of each foot.[27] Joint locations were identified during the static calibration trial using a stylus to digitize anatomic landmarks at the C7 spinous process, L5 spinous process, medial and lateral femoral condyles, medial and lateral malleoli, and bases of the second and fifth metatarsals.[27]

After the static calibration trial, participants performed the land-and-cut assessment. Participants started each trial on a 60-cm box and faced a visual stimulus via a light disc (FITLIGHT Corp) that was placed 3 m in front of the landing apparatus. Participants were shown a series of flashing colors (green, red, pink, blue) on the light disc as the visual stimulus; however, participants were instructed to respond to only a final green or red light. If a green or red light was presented, participants stepped off the box, landed on both feet, and then performed an approximately 45° cutting maneuver to the left (green light) or right (red light) as quickly as possible. The limb (dominant or nondominant) that performed the cutting maneuver was the limb of biomechanical interest for each trial. An additional light disc, placed 0.3 m adjacent to each participant's starting position, was triggered once the participant initiated the land-and-cut maneuver. Functional visuomotor reaction time (FVMRT), defined as the time to trigger the adjacent light disc once the green or red light was presented, was recorded during each trial. The order of trials was randomized, as well as the temporal latencies (ie, short, medium, long) for when the green or red light was presented during each individual trial. This land-and-cut task was developed to challenge participants from both a motor and a cognitive perspective by imposing temporal, decision-making, and movement constraints on task performance. In sports, athletes are required to rapidly perform high-impact, multidirectional landing maneuvers while simultaneously engaging and responding to the external environment.[45] Because athletes in the present study were instructed to perform the unanticipated land-and-cut task as rapidly as possible, we believed our implemented task was more ecologically valid and sport-specific compared with previous LE landing biomechanics protocols without imposed cognitive constraints.[17] All participants were allowed up to 4 practice trials before data collection. Four trials for each directional condition (dominant and nondominant limb land-and-cuts) were collected to ensure land-and-cut performance stability for subsequent data analysis.[36] The average of these 4 trials was used for each biomechanical parameter of interest.

Biomechanical data were collected using a 10-camera motion capture system (Vicon Motion Systems Ltd.) sampling at 240 Hz and embedded force platforms (Advanced Medical Technology Inc) sampling at 1200 Hz. For the land-and-cut maneuvers using dominant or nondominant cutting limb, biomechanical variables of interest included select peak kinetic (vGRF, knee extensor moment, knee abduction moment) and peak kinematic (ankle dorsiflexion, knee flexion, knee abduction angle) parameters that have been prospectively associated with LE injury during high-impact loading tasks.[16,17,26,37] Each kinetic and kinematic variable was assessed during the first 100 milliseconds of ground contact with the force platform, as it has been previously demonstrated that LE injuries, such as anterior cruciate ligament rupture, occur within that time period when performing landing-type sports maneuvers.[22] Biomechanical computations were performed using the Motion Monitor software (Innovative Sports Training Inc), in which marker trajectory and force plate data were smoothed via a fourth-order, low-pass Butterworth filter at 10 Hz. Kinetic moment parameters were computed using inverse dynamics and normalized to each participant's height and mass.

Cognitive Assessments

Computerized cognitive performance was assessed using 2 instruments: Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; ImPACT Applications, Inc) and the Senaptec Sensory Station (Senaptec LLC). Participants performed both assessments in a quiet room to minimize any external distractions, and a member of the research team was present to ensure that participants understood all testing instructions. Briefly, the ImPACT is a computerized assessment that requires approximately 20 to 30 minutes to complete and consists of a symptom inventory (Post-Concussion Symptom Scale) and 6 cognitive modules designed to provide measures of attention, working memory, processing speed, and reaction time. From these modules, ImPACT provides the following 4 cognitive performance scores: Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time. The procedures for each module and the methods of calculating performance scores can be viewed in the manufacture's manual.[28] The ImPACT assessment has previously demonstrated adequate reliability for individuals with and without a history of concussion[11,38] and is one of the most commonly utilized cognitive tools for SRC management in the collegiate athlete setting.[8]

In addition to the ImPACT, participants also completed tasks using the Senaptec Sensory Station. This cognitive assessment tool utilizes a smartboard-based interface system that measures various sensorimotor skills such as multiple object tracking (MOT), eye-hand coordination (EHC), and peripheral/central reaction time. For the present investigation, participants performed the following 3 tasks: EHC, Go/No Go, and MOT, which provide measures of visuomotor speed, response execution/inhibition, and working memory.[6] The detailed descriptions of the EHC and Go/No Go tasks are provided in previous open-access literature.[6] The outcomes of interest for the EHC, Go/No Go, and MOT tasks were total time, total score, and composite score, respectively.[6]

Statistical Analysis

To ensure matching criteria, group characteristics were first compared using the independent-sample *t* test. Multiple correlational analyses were performed to determine the associations between land-and-cut biomechanics and cognitive performance for the complete athlete data set as well as for each subgroup (SRC and control). Specifically, we assessed the associations between dominant and nondominant limb land-and-cut biomechanics and FVMRT, ImPACT, and Senaptec Sensory Station performance. Additionally, we performed correlational analyses among FVMRT, ImPACT, and Senaptec Sensory Station to determine the associations between each cognitive testing battery. Correlational analyses were computed via Pearson correlation coefficients and were interpreted as negligible (<0.30), low (0.31-0.50), moderate (0.51-0.70), high (0.71-0.90), and strong (>0.90) correlation based upon previously established correlational heuristics.[18] All statistical analyses were conducted using SPSS Version 27.0 (IBM Corp). An a priori α level of .05 was set to determine statistical significance.

TABLE 1
Participant Characteristics for Each Athlete Group[a]

Characteristics	SRC Group (n = 20)	Control Group (n = 20)	*P*
Age, y	20.5 ± 1.28	19.75 ± 1.29	.073
Height, m	1.81 ± 0.10	1.82 ± 0.09	.746
Mass, kg	85.96 ± 25.42	82.08 ± 23.40	.618
Time since last SRC, d	461 ± 263	NA	NA
Sport, n			
Men's football	6	6	
Women's volleyball	4	4	
Men's soccer	3	3	
Women's soccer	3	3	
Women's rowing	2	2	
Women's field hockey	1	1	
Women's diving	1	1	

[a]Data are reported as mean ± SD unless otherwise indicated. NA, not applicable; SRC, sports-related concussion.

RESULTS

The 40 participating athletes were representative of 7 collegiate sports, equally represented between the SRC and control groups. There were no significant differences between the study groups in age, height, or mass (Table 1).

Cognitive-Biomechanics Correlations

All Athletes. All Pearson correlation coefficients between cognitive and biomechanics performance for all athletes in the data set are presented in Table 2. For ImPACT, a lower Visual Memory score had low correlation with greater dominant limb knee abduction moment ($r = -0.371$; $P = .020$), and lower Visual Motor Speed had low correlation with greater dominant limb ankle dorsiflexion ($r = -0.421$; $P = .008$). For the Senaptec Sensory Station, higher MOT score had low correlation with decreased dominant limb ($r = -0.457$; $P = .004$) and nondominant limb ($r = -0.359$; $P = .029$) ankle dorsiflexion as well as with decreased nondominant limb knee abduction moment ($r = -0.410$; $P = .015$). Additionally, several significant correlations were identified between FVMRT and biomechanical variables. Slower dominant limb FVMRT had low correlation with decreased dominant limb knee extension moment ($r = -0.462$; $P = .003$), while slower nondominant limb FVMRT had low correlation with decreased nondominant limb knee flexion ($r = -0.408$; $P = .012$) and nondominant limb knee extension moment ($r = -0.369$; $P = .025$). No other limb-specific significant cognitive-biomechanics performance associations were present for the entire athlete cohort (Table 2).

SRC Group. All Pearson correlation coefficients between cognitive measures and biomechanics performance in the

TABLE 2
Cognitive-Biomechanics Performance Correlation Matrix for All Athletes (N = 40)[a]

	vGRF		Ankle Dorsiflexion		Knee Flexion		Knee Extension Moment		Knee Abduction		Knee Abduction Moment	
Cognitive Assessment	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM
ImPACT												
Verbal Memory	0.123	–0.065	–0.099	0.037	0.225	0.186	–0.020	–0.084	0.085	0.032	–0.139	–0.226
Visual Memory	–0.040	–0.163	–0.214	–0.099	0.227	–0.018	0.055	–0.182	–0.063	–0.088	**–0.371**	–0.190
Visual Motor Speed	–0.130	–0.087	**–0.421**	–0.221	0.253	–0.085	0.075	0.071	–0.054	–0.167	–0.292	–0.062
Reaction Time	0.167	0.033	0.032	–0.070	–0.137	–0.121	–0.234	–0.238	0.088	0.238	0.273	0.311
Senaptec												
EHC total time	0.048	0.078	0.005	–0.150	0.177	0.066	–0.167	–0.217	–0.195	–0.021	–0.075	–0.306
Go/No Go	0.108	–0.216	–0.035	–0.039	–0.278	–0.057	–0.020	–0.120	0.216	0.266	0.203	0.326
MOT	–0.114	–0.237	**–0.457**	**–0.359**	–0.032	–0.028	–0.313	–0.330	0.023	–0.168	–0.074	**–0.410**
Whole-body FVMRT												
DOM	–0.035	–0.178	**–0.229**	–0.156	–0.109	–0.380	**–0.462**	–0.467	0.200	–0.117	0.025	–0.227
NDOM	–0.014	–0.154	–0.113	–0.164	–0.152	**–0.408**	–0.187	**–0.369**	0.089	0.100	–0.040	–0.076

[a]Bolded values indicate statistical significance ($P < .05$). DOM, dominant; EHC, eye-hand coordination; FVMRT, functional visuomotor reaction time; ImPACT, Immediate Post-Concussion Assessment and Cognitive Test (ImPACT Applications, Inc); MOT, multiple object tracking; NDOM, nondominant; Senaptec, Senaptec Sensory Station (Senaptec LLC); vGRF, vertical ground-reaction force.

TABLE 3
Cognitive-Biomechanics Performance Correlation Matrix for the SRC Group (n = 20)[a]

	vGRF		Ankle Dorsiflexion		Knee Flexion		Knee Extension Moment		Knee Abduction		Knee Abduction Moment	
Cognitive Assessment	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM
ImPACT												
Verbal Memory	0.163	–0.148	–0.201	0.094	–0.014	–0.269	–0.369	**–0.489**	–0.009	0.037	–0.291	–0.138
Visual Memory	–0.004	0.072	–0.173	0.039	–0.068	–0.235	0.049	–0.081	–0.154	–0.131	**–0.539**	–0.281
Visual Motor Speed	0.042	–0.090	**–0.473**	–0.057	0.203	–0.231	0.163	–0.077	–0.212	–0.115	–0.332	–0.096
Reaction Time	–0.028	–0.201	0.142	–0.102	–0.046	0.085	–0.348	–0.251	0.366	0.263	**0.515**	0.347
Senaptec												
EHC total time	0.261	0.369	–0.035	–0.312	0.273	–0.027	0.015	–0.042	**–0.554**	–0.144	–0.240	–0.450
Go/No Go	–0.359	**–0.700**	–0.052	0.147	–0.329	0.015	–0.319	–0.353	0.123	0.250	0.373	0.134
MOT	–0.208	**–0.471**	–0.310	–0.190	–0.076	–0.133	**–0.475**	**–0.619**	0.086	0.053	–0.032	–0.395
Whole-body FVMRT												
DOM	0.149	–0.050	–0.350	–0.102	**–0.514**	–0.847	**–0.512**	–0.469	0.230	0.212	–0.132	–0.193
NDOM	0.069	–0.299	–0.241	–0.201	–0.343	**–0.500**	–0.304	**–0.548**	0.046	0.158	–0.301	–0.361

[a]Bolded values indicate statistical significance ($P < .05$). DOM, dominant; EHC, eye-hand coordination; FVMRT, functional visuomotor reaction time; ImPACT, Immediate Post-Concussion Assessment and Cognitive Test (ImPACT Applications, Inc), MOT, multiple object tracking; NDOM, nondominant; Senaptec, Senaptec Sensory Station (Senaptec LLC); vGRF, vertical ground-reaction force.

SRC group are presented in Table 3. Several significant correlations were identified using the ImPACT battery. Specifically, higher Verbal Memory score had low correlation with decreased nondominant limb knee extension moment ($r = –0.489$; $P = .039$), higher Visual Memory score was moderately correlated with decreased dominant limb knee abduction moment ($r = –0.539$; $P = .017$), faster Visual Motor Speed score had low correlation with decreased dominant limb ankle dorsiflexion ($r = –0.473$; $P = .041$), and faster Reaction Time was moderately correlated with increased dominant limb knee abduction moment ($r = 0.515$; $P = .024$). Several low and moderate correlations were identified using the Senaptec Sensory Station. Specifically, increased EHC total time was moderately correlated with decreased dominant limb knee abduction ($r = –0.554$; $P = .017$). Higher Go/No Go score was moderately correlated with decreased nondominant limb vGRF ($r = –0.700$; $P = .001$). Higher MOT score had low correlation with decreased nondominant limb vGRF ($r = –0.471$; $P = .048$) and decreased dominant limb knee extension moment ($r = –0.475$; $P = .046$) and was moderately correlated with decreased nondominant limb knee extension moment ($r = –0.619$; $P = .008$). Additionally, several significant correlations were identified between FVMRT and biomechanical variables. Slower dominant limb FVMRT was moderately correlated with decreased dominant limb knee

TABLE 4
Cognitive-Biomechanics Performance Correlation Matrix for the Control Group (n = 20)[a]

	vGRF		Ankle Dorsiflexion		Knee Flexion		Knee Extension Moment		Knee Abduction		Knee Abduction Moment	
Cognitive Assessment	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM	DOM	NDOM
ImPACT												
Verbal Memory	0.200	0.125	–0.064	–0.025	0.311	**0.508**	0.133	0.125	0.211	0.132	0.074	–0.182
Visual Memory	–0.055	–0.294	–0.239	–0.171	0.405	0.052	0.077	–0.252	0.053	0.014	–0.244	–0.054
Visual Motor Speed	–0.428	–0.111	–0.362	–0.315	**0.525**	0.229	0.130	0.256	0.086	–0.236	–0.301	–0.145
Reaction Time	0.378	0.283	–0.058	–0.019	–0.058	–0.217	–0.118	–0.205	–0.346	0.071	–0.262	0.031
Senaptec												
EHC total time	–0.088	–0.250	0.014	0.006	–0.082	–0.048	–0.424	**–0.489**	0.137	0.207	0.159	–0.033
Go/No Go	0.392	0.085	0.026	–0.182	0.013	0.305	0.289	0.175	0.231	0.161	–0.013	0.283
MOT	0.019	–0.011	**–0.648**	**–0.618**	0.002	0.109	–0.284	–0.125	–0.142	**–0.513**	–0.225	**–0.673**
Whole-body FVMRT												
DOM	–0.238	–0.290	–0.138	–0.204	0.224	0.007	**–0.477**	–0.508	0.270	–0.372	0.299	–0.213
NDOM	–0.303	0.042	0.072	–0.072	0.297	–0.191	–0.006	–0.148	0.153	–0.033	0.384	0.196

[a]Bolded values indicate statistical significance ($P < .05$). DOM, dominant; EHC, eye-hand coordination; FVMRT, functional visuomotor reaction time; ImPACT, Immediate Post-Concussion Assessment and Cognitive Test (ImPACT Applications, Inc); MOT, multiple object tracking; NDOM, nondominant; Senaptec, Senaptec Sensory Station (Senaptec LLC); vGRF, vertical ground-reaction force.

extension moment ($r = -0.512$; $P = .025$) and decreased dominant limb knee flexion ($r = -0.514$; $P = .024$). Slower nondominant FVMRT had low correlation with decreased nondominant knee flexion ($r = -0.500$; $P = .035$) and was moderately correlated with decreased nondominant knee extension moment ($r = -0.548$; $P = .019$). No other significant limb-specific cognitive-biomechanics performance associations were present for the SRC group (Table 3).

Control Group. All Pearson correlation coefficients between cognitive and biomechanics performance for all athletes in the data set are presented in Table 4. For ImPACT, lower Verbal Memory score had low correlation with decreased nondominant limb knee flexion ($r = 0.508$; $P = .031$), and faster Visual Motor Speed was moderately correlated with increased dominant limb knee flexion ($r = 0.525$; $P = .021$). For the Senaptec, decreased EHC score had low correlation with decreased nondominant knee extension moment ($r = -0.489$; $P = .046$), while increased MOT score was moderately correlated with decreased dominant limb ankle dorsiflexion ($r = -0.648$; $P = .004$), decreased nondominant limb ankle dorsiflexion ($r = -0.618$; $P = .006$), decreased nondominant limb knee abduction ($r = -0.513$; $P = .035$), and decreased nondominant limb knee abduction moment ($r = -0.673$; $P = .003$). Additionally, slower dominant limb FVMRT had low correlation with decreased dominant limb knee extension moment ($r = -0.477$; $P = .039$). No other significant limb-specific cognitive-biomechanics performance associations were present for the control group (Table 4).

Cognitive Correlations

All Athletes. Higher Verbal Memory score had low correlation with higher Visual Memory ($r = 0.412$; $P = .009$) and higher MOT ($r = 0.343$; $P = .038$) scores. Faster Visual Motor Speed had low correlation with higher Visual Memory score ($r = 0.507$; $P = .001$), faster Reaction Time ($r = -0.382$; $P = .016$), and higher MOT ($r = 0.344$; $P = .037$) scores. Within the Senaptec Sensory Station, decreased EHC score had low correlation with Go/No Go score ($r = -0.457$; $P = .004$). Additionally, there was a moderate correlation between faster dominant and nondominant limb FVMRT ($r = 0.613$; $P < .001$). No other significant cognitive performance correlations were present for the entire athlete cohort.

SRC Group. There was a low correlation between higher Visual Memory score and faster Visual Motor Speed ($r = 0.500$; $P = .029$), a low correlation between higher MOT score and slower dominant limb FVMRT ($r = 0.484$; $P = .042$), a moderate correlation between MOT score and nondominant limb FVMRT ($r = 0.597$; $P = .009$), and a high correlation between faster dominant limb FVMRT and faster nondominant limb FVMRT ($r = 0.742$; $P < .001$). No other significant cognitive performance correlations were present for the SRC group.

Control Group. Higher Verbal Memory score had low correlation with higher Go/No Go score ($r = 0.479$; $P = .044$), and faster Visual Motor Speed moderately was correlated with higher MOT score ($r = 0.566$; $P = .017$). There was a low correlation between faster dominant and nondominant limb FVMRT ($r = 0.473$; $P = .041$). No other significant cognitive performance correlations were present for the control group.

DISCUSSION

The primary purpose of the present study was to determine the associations between cognitive performance and LE land-and-cut biomechanics during a sport-specific maneuver in collegiate athletes with and without previous SRC. Additionally, we sought to determine the associations between multiple cognitive testing batteries in the same athlete cohort. We hypothesized that cognitive performance markers specific to reaction time and working memory would be significantly correlated with higher-risk biomechanical land-and-cut patterns in both athlete cohorts; however, these associations would be stronger in the SRC cohort. We also hypothesized that functional measures of cognitive performance (defined as FVMRT in the present study) would not be significantly correlated with computerized measures of cognitive performance (ie, ImPACT and Senaptec).

Our primary hypothesis was moderately supported by the present findings in that several moderate correlations were observed between decreased cognitive performance (Visual Memory score, Go/No Go score, and whole-body FVMRT) and LE biomechanical patterns (decreased knee flexion and increased knee abduction moment) associated with future LE injury risk within the SRC group but not in the control group. However, there were cognitive-biomechanics associations present in the control cohort that were absent in the SRC group, including increased MOT score being moderately correlated with decreased nondominant limb knee abduction ($r = -0.513$) and decreased nondominant limb knee abduction moment ($r = -0.673$). Additionally, many cognitive-biomechanics correlations were statistically similar (ie, no significant relationship) when comparing between groups (SRC vs control). Overall, our primary findings suggest that only a few select relationships between cognitive performance and LE land-and-cut biomechanics are modulated by a previous SRC history. Our secondary hypothesis was largely supported from the present results. Aside from the relationship between MOT score and dominant and nondominant limb FVMRT in the SRC group, no other significant associations were found between functional and computerized cognitive performance in any cohort analysis (all athlete, SRC, and control).

Athletes in the present study completed a biomechanical task that imposed constraints on the motor and cognitive systems. Athletes were instructed to rapidly perform sport-specific land-and-cut tasks under unanticipated conditions based upon directional light stimulus (green light, land-and-cut to the left; red light, land-and-cut to the right) while ignoring distractor colors. From a cognitive performance standpoint, athletes were required to make decisions based on attentional capacity, working memory, and response inhibition, all while performing a whole-body task. In a sporting environment, athletes must complete complex motor tasks while simultaneously engaging with a variety of visual stimuli that stress the aforementioned cognitive resources. We believe our study design represented a whole-body, dual-task scenario that conflicts with competing motor and cognitive demands for successful task completion, similar to sporting scenarios presented to athletes in training or competition. Previous findings from dual-task gait literature have demonstrated both cognitive and motor performance deficits in athletes up to 2 months post-SRC that are not present in control athletes.[19,21] All athletes in the present study were clinically cleared for sports and were well beyond 2 months post-SRC; however, we determined multiple cognitive-biomechanics performance relationships specific to the SRC cohort that suggest worse cognitive performance is associated with LE loading patterns that may increase the risk for future LE injury. These findings align with those of previous investigations of various athletic populations that largely did not account for SRC injury history.[13,16,37] In the present study, higher Visual Memory score was moderately associated with decreased dominant limb knee abduction moment ($r = -0.539$), slower FVMRT was moderately associated with decreased knee flexion (dominant limb: $r = -0.514$; nondominant limb: $r = -0.500$), decreased Go/No Go score was moderately associated with greater nondominant limb vGRF ($r = -0.700$), and decreased MOT score had low association with greater nondominant limb vGRF ($r = -0.471$) and low to moderate associations with increased knee extension moment (dominant limb: $r = -0.475$; nondominant limb: $r = -0.619$). These specific relationships were either not present or weaker when compared with those of the control cohort. While direct comparisons with the present study are difficult due to differences in statistical analyses and studied task, Herman and Barth[16] determined that recreational athletes with slower reaction time and processing speed performed drop-landing maneuvers with greater vGRF and frontal plane knee motion compared with a cohort with better cognitive performance. Additionally, Monfort et al[37] found decreased Visual Memory score was moderately associated with increased knee abduction ($r = 0.693$) and had low association with increased knee abduction moment ($r = 0.458$) in collegiate club male soccer athletes. Our results add further support to these findings, as improved Visual Memory and Reaction Time performance were moderately associated with decreased dominant limb knee abduction moment in the SRC cohort. Interestingly, 40% of the athletes reported a history of SRC but were clinically cleared to participate in sports,[37] further implicating SRC injury as a possible contributor to biomechanical loading patterns at the knee associated with greater risk for future injury.

It appears that kinetic LE loading patterns and sagittal plane movement at the knee may be uniquely associated with cognitive performance in athletes with a previous SRC injury history. In the SRC cohort, slower FVMRT was significantly correlated with decreased knee flexion on both limbs, while no such relationship was present in the control cohort. As decreased knee flexion has been extensively demonstrated to be a primary mechanism for LE injury, such as anterior cruciate ligament rupture during land-and-cut maneuvers,[26,32,43] we speculate that worse cognitive performance and associated reductions in knee flexion may represent a potential compensatory movement strategy to complete the task rapidly after a relative delay in FVMRT. Additionally, in the SRC group, we determined that decreased Go/No Go and MOT scores were associated with increased nondominant limb vGRF, while decreased MOT score was associated with increased knee extension moment on both limbs. Interestingly, these cognitive-biomechanics associations were not present in the control cohort. During landing maneuvers, increased vGRF and sagittal plane extension moments about the knee joint are both thought to create a higher tensile load on the anterior cruciate ligament[40,44] and have been prospectively identified as kinetic variables associated with future LE injury risk.[17,25] Similarly to FVMRT, both Go/No Go and MOT stress cognitive resources such as working memory and attentional capacity.[31] Overall, athletes with prior SRC who performed worse on Go/No Go, MOT, and FVMRT tended to display higher-risk biomechanical loading patterns during the jump-and-cut maneuvers compared with athletes in the same cohort with better performance on these cognitive measures. The present findings add evidence to suggest that the relationship between cognitive performance and LE neuromuscular control during dynamic tasks may be modulated by an athlete's prior SRC injury history. Prior prospective studies have determined the worse cognitive performance is predictive of LE injury[34,47,48]; therefore, subsequent management of SRC may consider the use of cognitive measures such as FVMRT and MOT to identify post-SRC athletes at-risk for future LE injury.

In support of our secondary hypothesis, we determined that the majority of computerized measures were not associated with FVMRT in either athlete cohort. The only significant associations found were between MOT score and FVMRT on each limb in the SRC cohort. However, we determined that increased MOT score was associated with slower FVMRT, a finding that runs seemingly counter to our expectations. The overall lack of associations and conflicting results may stem from differences between computerized cognitive testing and the functional task in the present study. Although computer-based tests such as ImPACT are popular for SRC management,[8] they may not truly measure sports-based cognitive performance.[24] Utilizing a series of clinical-based and functional-based reaction time assessments, Lempke et al[24] determined no significant correlations between a computerized Stroop reaction time task and functional reaction time measures that included jump landings and unanticipated cutting maneuvers in reactional athletes. Taken together, these findings indicate that current clinical tests measure different constructs of cognitive performance that may not be related to the cognitive demands of a sport-specific scenario. It is possible that an athlete who sustains an SRC may return to preinjury performance on computerized cognitive measures but have lingering deficits in functional-based outcomes. During sporting maneuvers, slowed reaction time and processing speed, along with attentional deficiencies, are theorized to be key cognitive contributors to LE injury,[45] which may not be measured using computer-based modules. Future research should continue to delineate functional-based cognitive measures to determine their utility for SRC management and implications for LE injury risk, as well as their relationship to other cognitive tasks without an additional movement task.

Limitations must be considered when interpreting the results of the present study. The SRC history before a collegiate sporting career was not collected in the present athlete cohort, possibly underrepresenting the number of athletes with a previous SRC. Athletes in this study participated in various sports where land-and-cut maneuvers are either common (ie, soccer and football) or not typical (ie, rowing and diving), thus limiting generalizability to any single sport. Athletes in the SRC cohort were, on average, 461 days post-SRC. Future studies should examine the relationships between cognitive performance and LE biomechanics in a more acutely concussed athlete sample and monitor the relationship over the course of clinical recovery and return to sports. Additionally, the overall study design represents cross-sectional research on cognitive and motor behavior in collegiate athletes with and without a history of SRC. Future research would strengthen the current findings by determining pre- versus post-SRC biomechanical land-and-cut patterns, in conjunction with measures of cognitive performance, to determine the specific effects of SRC on LE injury risk. While it appears that decreased Visual Memory and MOT score, as well as slower FVMRT, are correlated with higher-risk biomechanical loading patterns, many of the cognitive-biomechanics correlations analyzed in this investigation were of low correlation or were not statistically significant. Furthermore, the collegiate athlete cohort studied may not be generalizable to other sporting populations such as adolescent and professional athletes. The reliability of FVMRT and Senaptec Sensory Station have yet to be elucidated in the present literature, and future research should confirm the reliability of these assessments in comparison with computerized measures such as ImPACT. Last, athletes in the present study were not excluded based upon medical diagnosis of attention-deficit/hyperactivity disorder, which may have influenced cognitive performance and their associations to LE land-and-cut biomechanics in the present study.

CONCLUSION

In the present study, collegiate athletes with a history of SRC demonstrated significant relationships between decreased cognitive performance and LE loading patterns associated with higher LE injury risk not found in the matched control cohort. In the SRC cohort, decreased performance on specific cognitive measures that stress reaction time, working memory, and attentional resources (Visual Memory score, Reaction Time score, MOT score, and FVMRT) were moderately correlated with increased vGRF, increased knee extension moment, and decreased knee flexion, suggesting that SRC may modulate the relationship between select measures of cognitive performance and LE motor performance. Additionally, we determined that clinical-based, computerized measures of cognitive performance were largely unrelated to functional, whole-body cognitive performance during a sport-specific land-and-cut task across both athlete cohorts. Our overall findings suggest that decreased cognitive performance may be associated with knee biomechanical patterns associated with higher risk for future LE injuries in athletes with a history of SRC and that computerized measures of cognitive performance utilized for SRC management are dissimilar to sport-specific cognitive processes.

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