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The Relationship Between Neurocognitive Function and Noncontact Anterior Cruciate Ligament Injuries

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Background: Biomechanical analyses suggest that the loss of neuromuscular control is associated with noncontact anterior cruciate ligament sprains; however, previous research has not explored the link between neurocognitive function and unintentional knee injuries.

Purpose: To determine if athletes who suffer a noncontact anterior cruciate ligament injury demonstrate decreased baseline neurocognitive performance when compared with matched controls.

Study Design: Case control study; Level of evidence, 3.

Methods: The baseline scores from a computerized neurocognitive test battery (ImpACT) were analyzed to compare verbal memory, visual memory, processing speed, and reaction time. Eighty intercollegiate athletes who, subsequent to testing, experienced noncontact anterior cruciate ligament injuries, were matched with 80 controls based on height, weight, age, gender, sport, position, and years of experience at the collegiate level.

Results: Statistical differences were found between the noncontact anterior cruciate ligament injury group and the matched controls on all 4 neurocognitive subtests. Noncontact anterior cruciate ligament-injured athletes demonstrated significantly slower reaction time ($F_{1,158} = 9.66, P = .002$) and processing speed ($F_{1,158} = 12.04, P = .001$) and performed worse on visual ($F_{1,158} = 19.16, P = .000$) and verbal memory ($F_{1,158} = 4.08, P = .045$) composite scores when compared with controls.

Conclusion: Neurocognitive differences may be associated with the loss of neuromuscular control and coordination errors, predisposing certain intercollegiate athletes to noncontact anterior cruciate ligament injuries.

Keywords: neuropsychological functioning; ImpACT; knee; neuromuscular

Biomechanical and neuromuscular characteristics are currently the primary focus of research on noncontact knee injury mechanisms because these risk factors are modifiable.^{20,22} Although these characteristics may predispose individuals to noncontact injuries, the underlying neurocognitive influences that play a role in determining

motor behavior have not been investigated in this context. No previous study has attempted to link brain function with noncontact injuries, such as an anterior cruciate ligament (ACL) tear.

It has been reported that between 72% and 95%^{6,45} of ACL injuries occur through noncontact mechanisms, without player-to-player contact.^{16,49} A noncontact ACL (NCAACL) injury typically occurs shortly after foot strike when an athlete is decelerating, pivoting, or landing^{6,16,31,47,49} and where ground-reaction forces typically exceed 5 times the person's body weight.⁴² Successfully negotiating these high joint loads requires complex neuromuscular control strategies for dynamic joint stabilization.^{12,28,41,55,56}

Neuromuscular control is influenced by sensory information from proprioceptive, kinesthetic, visual, and vestibular sources, as well as cortical and spinal motor

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commands.^{19,30} Maintaining dynamic restraint during complicated, high-velocity movements such as athletics is contingent on both cortically programmed muscle pre-activation and reflex-mediated contractions. The cerebral cortex relies on feed-forward processing to initiate a motor program for coordinated execution of the desired task.¹⁸ The feedback mechanism then regulates reflexive motor responses to unanticipated events after ground contact. Although many peripheral and segmental reflexive pathways exist, ultimately the cerebral cortex is responsible for planning and regulating all of these motor control processes.^{5,17}

Neurocognitive tasks, such as those measuring reaction time, processing speed, visual memory, and verbal memory, are well established in the neuropsychology literature as indirect measures of cerebral performance. Situational awareness, arousal, and attentional resources of the individual may influence these areas of neurocognitive function, affecting the complex integration of vestibular, visual,¹¹ and somatosensory information needed for neuromuscular control.^{3,8,39,40,44}

Throughout the past decade, neurocognitive testing has become a standard, objective means for assessing subtle changes in cerebral and cortical function associated with concussions and can assist with return-to-play decisions.³⁷ The Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) software (NeuroHealth Systems, Pittsburgh, Pa)^{35,51} has been shown to be a reliable method⁵² for examining deficits in reaction time, processing speed, working memory, and attention and concentration. Although neurocognitive changes have traditionally been related to mild traumatic brain injury, deficits in cortically driven reaction time, processing speed, and visual and verbal memory may also indicate diminished capacity for neuromuscular control and thereby predisposition to noncontact injury. To date, previous research has linked cerebral performance with motor control or related motor control strategies and injury, but no studies have investigated the relationship between neurocognitive function and NCACL injuries. By considering such an alternative application for neurocognitive tests, this inquiry may provide insight into cerebral mechanisms of neuromuscular control and injury prevention, adding to current research attempting to link neurocognitive function with cortical mechanisms controlling the motor program. Therefore, the purpose of this study was to determine if preseason (baseline) neurocognitive performance was lower in athletes who later went on to suffer an NCACL injury.

MATERIALS AND METHODS

Research Design

A case-control design was used to compare neurocognitive test scores and NCACL injuries. The independent variable was the injury status (injured or noninjured). The dependent variables were obtained during preseason baseline

TABLE 1
Frequency Distribution of NCACL-Injured
Subjects by Sport (n = 80)^a

Team	No. of Patients
Women's soccer	16
Football	12
Women's lacrosse	5
Women's basketball	9
Women's volleyball	5
Men's soccer	8
Men's basketball	6
Men's lacrosse	6
Field hockey	3
Women's gymnastics	5
Wrestling	3
Fencing	1
Softball	1

^aNCACL, noncontact anterior cruciate ligament.

TABLE 2
Matching of NCACL and Control Groups^a

Variable	NCACL, Mean ± SD	Control, Mean ± SD	P Value
Height, cm	68.82 ± 4.18	68.80 ± 4.52	.971
Weight, kg	159.93 ± 34.44	166.01 ± 37.38	.248
Collegiate experience, y	1.21 ± 1.34	1.18 ± 2.27	.508

^aNCACL, noncontact anterior cruciate ligament.

neuropsychological test scores on verbal memory, visual memory, processing speed, and reaction time.

Subjects

One hundred sixty athletes (80 NCACL, 80 control) from 18 universities participated in this study. All of the athletes selected for this study were practicing and competing in the 2001-2002, 2002-2003, and 2003-2004 academic seasons. The injured group consisted of athletes representing Division I (n = 38), Division II (n = 27), Division III (n = 7), NAIA (n = 6), and NCCAA (n = 2) institutions and competed in various sports (Table 1). All NCACL injuries were diagnosed by a team physician, and a complete ACL tear was confirmed during reconstructive surgery. Athletes who sustained a direct blow as a component of the mechanism of injury and those reporting a previous knee sprain or head injury were excluded from the study. Of the 80 NCACL-injured athletes, 45 were women (age, 20.6 ± 1.7 years; weight, 65.6 ± 9.4 kg; height, 168.8 ± 8.8 cm), and 35 were men (age, 20.8 ± 1.1 years; weight, 88.4 ± 16.1 kg; height, 182.6 ± 9.7 cm).

Potential control subjects were first sorted based on the matching criteria of height, weight, age, gender, sport, position, and years of experience at the collegiate level (Table 2) from the larger database of athletes including all 18

TABLE 3
Neuropsychological Test Score for NCACL and Control Groups (n = 160)^a

Neurocognitive Test	Mean ± SD	F Test (score)	P Value	Effect Size	95% CI	
				Cohen <i>d</i>	Lower	Upper
Verbal memory 77, 79						
NCACL	.84 ± .08	4.08	.045 ^b	-.47	.83	.86
Control	.88 ± .09				.85	.89
Visual memory 66						
NCACL	.72 ± .12	19.16	.00 ^c	-.77	.70	.76
Control	.82 ± .14				.79	.85
Processing speed 33						
NCACL	36.9 ± 6.6	12.04	.001 ^c	-.55	35.3	38.6
Control	41.0 ± 8.2				39.4	42.7
Reaction time (ms) .65						
NCACL	.57 ± .07	9.66	.002 ^c	.46	.55	.59
Control	.53 ± .10				.51	.55

^aNCACL, noncontact anterior cruciate ligament; CI, confidence interval; ms, milliseconds.

^bSignificant at the .05 level.

^cSignificant at the .01 level.

schools. A random numbers list was then used to identify a subset of 80 for comparison.

Instrumentation

ImPACT version 2.0²³ was used for the study and administered in a private office or restricted-access laboratory. The ImPACT instrument is a computer-based program used to assess neurocognitive function and concussion symptoms. The software program consists of 6 neurocognitive tests that evaluate word recognition, design memory, visual processing and memory, symbol matching (Xs and Os), color matching, and working memory/visual response speed. These 6 neurocognitive tests yield 4 "composite" scores in the areas of verbal memory, visual memory, reaction time, and processing speed.^{23,26}

The verbal memory composite score represents the average percentage correct, for example, out of 100%, for the word recognition paradigm, the symbol number match task, and the letter memory task (with an accompanying interference task). The visual memory composite score is composed of the average percentage correct, for example, out of 100%, for 2 tasks: the design memory task (which requires the discrimination of a series of abstract line drawings) and the memory task, which requires the identification of a series of illuminated Xs or Os after an intervening task (mouse clicking a number sequence from 25 to 1). The first test taps immediate and delayed memory for visual designs, and the second test measures short-term spatial memory (with an interference task). The reaction time composite score represents the average response time (in milliseconds) on a choice reaction time (go/no-go) task and the previously mentioned symbol match task (which is similar to a traditional digit symbol task). The processing speed composite represents the weighted average (in seconds) of the 3 tasks (Xs and Os, symbol match, color match) that are done as interference tasks for the memory paradigms. ImPACT employs random variation of stimuli, which affords alternate forms to reduce practice effects

traditionally seen in repeated measures administration. Each of the content areas contains practice trials that require the user to demonstrate understanding of the instructions and proficiency with the goal of the task.³⁵

Test-retest reliability for ImPACT was assessed for 8 days, across 4 administrations, yielding correlation coefficients ranging from 0.66 to 0.85 for the verbal memory index, 0.75 to 0.88 for the processing speed index, and 0.62 to 0.66 for the reaction time index.²⁷ Using reliable change indices, repeated administrations for a 2-week period revealed no practice effects.²⁴ In another study, 1-week test-retest reliability coefficients were as follows: 0.70 for verbal memory; 0.67 for visual memory; 0.79 for reaction time; and 0.86 for processing speed, with significant test-retest differences for only the processing speed composite scores³⁶ within subject comparisons. Criterion-related validity of ImPACT was demonstrated through the ability to separate injured from age-matched noninjured control subjects who suffered even mild concussions.²⁴ Concurrent validation of ImPACT revealed correlations with the Symbol-Digit Modalities Test (SDMT), which ranged from 0.37 and 0.46 for visual and verbal memory indices to 0.60 and 0.70 for reaction time and processing speed indices.⁵³

Because the SDMT is believed to measure scanning and tracking aspects of attention, as well as processing speed,²⁵ these coefficients represent good convergent and divergent validity. Correlations between ImPACT visual and verbal memory composites with the Brief Visual Spatial Memory Test-Revised (BVM-T-R) total score ($r = .50$) and the delayed recall score ($r = .85$) have been established⁴; the processing speed composite was shown to correlate with the Trailmaking Tests A ($r = -.49$) and B ($r = -.60$) and the SDMT ($r = .68$).

Testing Procedures

Institutional Review Board approval was obtained from each university, as well as permission for athlete participation from the head athletic trainer. Certified athletic

trainers completed an NCACL-injury tracking form identifying the number of athletes at their institution who sustained an NCACL injury during the past 3 years and indicating whether surgical confirmation of a complete tear was achieved. The study design was explained to all potential subjects, and each individual signed a consent form. The preseason baseline ImpACT test scores, for either the fall or spring before the NCACL injury, were then used for analysis.

Data Analysis

The ImpACT yields scores for verbal and visual memory, processing speed, and reaction time. Higher scores on processing speed and verbal and visual memory indicate a better performance. A faster score on reaction time indicates better performance.

A 1-way analysis of variance was conducted to analyze neurocognitive function between the 2 groups (NCACL and control). The level of significance was set at $P = .05$. All analyses were conducted using the Statistical Package for the Social Sciences version 11.1 (SPSS Inc, Chicago, Ill).

RESULTS

Statistical differences were found between the NCACL-injury group and the matched controls on all 4 neurocognitive subtests. The NCACL-injured athletes had slower reaction times ($F_{1,158} = 9.66, P = .002$) and slower processing speeds ($F_{1,158} = 12.04, P = .001$) and performed significantly worse on visual memory ($F_{1,158} = 19.16, P = .000$) and verbal memory ($F_{1,158} = 4.08, P = .045$) composite scores compared with controls (Table 3).

DISCUSSION

This is the first study to examine the relationship between decreased neurocognitive performance and NCACL injuries. Athletes who suffered NCACL injuries had significantly slower reaction times and processing speeds, as well as lower visual and verbal memory scores during their preseason tests. Noncontact ACL injuries are associated with errors in coordination,^{1,10,13,14,30,33,57,58,62} and the neurocognitive differences identified in our study may predispose certain individuals to noncontact injuries.

Previous literature suggests these neurocognitive characteristics can have an important role in coordination, sports performance, and injury.²⁶ In comparison with normative values published for this age group, our observed scores ranged from low average to average.²⁶ The decreased performance by the NCACL group would be characterized as "diminished" but did not reach a level necessary to classify these subjects as having a neurocognitive "impairment."^{1,10,13} However, these deficits warrant discussion regarding their possible relationship with the loss of neuromuscular control and noncontact injury mechanisms.

Physical activity requires situational awareness of a broad attentional field to continuously monitor the surrounding environment, filter irrelevant information, and simultaneously execute complex motor programs.^{34,46,61} Increased arousal or anxiety changes an athlete's concentration, narrows their attentional field, and alters muscle activity, which has been associated with poor coordination and inferior performance.^{9,14} The amount and speed of neural processing required for a task can be measured using reaction time.³⁰ Athletes generally have better reaction times, but delays can occur when the number of response alternatives increases.^{1,14,54} Also, reaction times are slower when memory retention and fine motor tasks are performed at the same time as walking³³ or in combination with auditory stimuli.^{9,50,60,62} A common example used to demonstrate how decreased reaction time contributes to poor performance involves the slowed reactions of distracted drivers during automobile accidents.^{57,58} In an athletic population, our results agree with previous research suggesting that mental abilities and slowed reaction time may be linked with general musculoskeletal complaints.^{10,19,21,31,62} Although the reaction time deficits recorded in this study do not meet established criteria to suggest NCACL subjects were impaired, attempting to execute complex athletic maneuvers in a rapidly changing sport environment can slow reaction time or processing speed and compromise motor performance.^{59,62} Mild deficits in reaction time and processing speed could make individuals more susceptible to brief errors in judgment or loss of coordination when confronted with complex environmental cues during athletic competition. This task uncertainty or hesitation has been shown to attenuate muscle activity, which would compromise dynamic restraint and increase the risk of NCACL injury.^{2,10,13,15,33,38,43}

The decreased visual and verbal memory composite scores of NCACL subjects may also be associated with mistakes in coordination.^{2,10,13} The selection process determining which of the many stimuli in a complex environment requires immediate attention involves mechanisms for learning and memory.³⁸ The region of the visual field from which a person chooses to process information is determined by visual attention.¹³ Athletes with decreased visual attention skills may have difficulty interpreting and negotiating conflicting information when challenged with unanticipated events. Lacking the capacity to quickly redirect attention from one location to the next or distribute attention across multiple locations will decrease an individual's visual-spatial orientation.^{7,29,32,33,48,50} This state is frequently described as spatial disorientation or a loss of situational awareness.⁵⁹ The momentary disorientation can disrupt execution of routine motor programs or alter muscle activity, effectively diminishing the dynamic restraint capabilities.

Several limitations to this study should be acknowledged before considering the potential prognostic value of these results. These results show small but statistically significant differences between the NCACL and control groups on all 4 neurocognitive subtests. It is important to note that these differences were found retrospectively on

baseline preseason testing, and participants were assigned to the control group randomly from a larger pool of college athletes. Athletes' scores from both groups were consistent with nationally published normative data, suggesting that there was no systematic error attributable to our selection methods. However, athletes in the NCACL group consistently scored worse than controls. Previous knee and head injury information for subject exclusion was collected by self-report and could have caused selection bias. Furthermore, one weakness of case control studies is the selection of a comparison group. While matching variables and random selection were included to minimize this bias, the results of this study should be viewed with caution until more prospective observations can be reported.

CONCLUSION

Differences were found in all 4 neurocognitive subtests between NCACL-injured subjects and uninjured controls. Decreased reaction times, processing speed, or visual spatial disorientation may expose athletes to injurious situations by disrupting the neuromuscular control necessary for dynamic restraint. These findings should be regarded with caution because specific injury mechanisms affected by neurocognitive deficits are still unclear and require speculation until further investigations can be completed. The interaction between reflexive pathways and cortical control should be explored before deficits in higher brain center neurocognitive function can be clearly linked to dynamic restraint mechanisms and outcome performance on athletic maneuvers. This is the first study to link neurocognitive function to NCACL injury and may present an alternative application for neurocognitive testing in the area of injury prevention.

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