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Lower Extremity Reaction Time in Individuals With Contact Versus Noncontact Anterior Cruciate Ligament Injuries After Reconstruction

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Context: Deficits in perceptual-motor function, like visuomotor reaction time (VMRT), are risk factors for primary and secondary anterior cruciate ligament (ACL) injury. Noncontact ACL injuries have been associated with slower reaction time, but whether this association exists for patients with contact ACL injuries is unknown. Exploring differences in VMRT among individuals with contact versus noncontact ACL injuries may provide a more comprehensive understanding of modifiable risk factors.

Objective: To compare lower extremity VMRT (LEVMRT) in individuals with contact or noncontact ACL injuries after ACL reconstruction (ACLR).

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: A total of 36 participants with primary, unilateral ACLR completed an LEVMRT assessment (contact ACL injury = 20 [56%], noncontact ACL injury = 16 [44%]).

Main Outcome Measure(s): The LEVMRT was assessed bilaterally and collected using a series of wireless light discs deactivated by individuals with their feet. The ACLR-active LEVMRT (ie, ACLR limb is deactivating lights) and ACLR-stable LEVMRT were compared using separate analyses of covariance to determine the association with contact or noncontact injury using time since surgery as a covariate.

Results: After controlling for time since surgery, a difference and large effect size between groups was found for the ACLR-stable LEVMRT ($P = .010$; $\eta^2 = 0.250$) but not for the ACLR-active ($P = .340$; $\eta^2 = 0.065$) condition. The contact group exhibited slower ACLR-stable LEVMRT (521.7 ± 59.3 milliseconds) than the noncontact group (483.4 ± 83.9 milliseconds).

Conclusions: Individuals with contact ACL injury demonstrated a slower LEVMRT while their ACLR limb was stabilizing. The group differences during the ACLR-stable LEVMRT task might indicate deficits in perceptual-motor function when the surgical limb maintains postural control during a reaction time task. After ACLR, individuals with contact injuries may need additional motor learning interventions to enhance perceptual-motor functioning.

Key Words: neurocognitive function, knee injury

Key Points

- After anterior cruciate ligament reconstruction, individuals who sustained contact injuries displayed a slower lower extremity visuomotor reaction time when the injured limb served as the primary stabilizer.
- Deficits in postural control may contribute to the observed changes in lower extremity visuomotor reaction time.

The anterior cruciate ligament (ACL) is a primary knee stabilizer commonly injured during sport participation.[1] Most ACL injuries (72%–95%) are the result of a change of direction or other dynamic task without physical contact.[2] Neuromuscular and biomechanical risk factors associated with noncontact injury have been identified, including altered central nervous system activity: specifically, changes in reaction time (RT).[3] Individuals who exhibited a slower RT were more likely to sustain a noncontact ACL injury.[3] In the absence of a collision or direct contact with a person or object, the excessive force generated by ground impact leads to an ACL injury.[2,4] Given the large percentage of noncontact ACL injuries, researchers have focused prevention efforts on this mechanism. Currently, less is known about the perceptual-motor function in individuals who sustain contact ACL injuries. Collision can be an inevitable part of sport, but individuals with worse perceptual-motor coordination and visual perception may not be able to efficiently recognize, process, and respond to environmental factors (eg, other players), which can cause additional exposure to injurious forces.[5] For example, athletes who sustained a noncontact ACL injury exhibited worse RT than those who did not sustain an injury; however, whether RT is associated with contact ACL injuries is unknown.

After ACL injury, somatosensory feedback from the knee is altered, which may result in deficits in postural and motor control.[6,7] This altered motor response could contribute to a slower RT, maladaptive neuromuscular activation, and permanent changes in the sensorimotor regions of the brain.[8] Secondary ACL injuries often occur in athletes who return to competitive levels of sport participation that require higher-level processing and perceptual-motor functioning.[9] Thus, prolonged and unaddressed neurocognitive and neuromuscular factors related to sensorimotor processing may contribute to the enhanced injury risk.[9] Lower extremity visuomotor RT (LEVMRT) has been used to assess deficits in perceptual-motor function in individuals after ACL reconstruction (ACLR) and has the unique ability to characterize unilateral limb functioning.[10]

Assessments of RT can be used to measure perceptual-motor functioning and create avenues for identifying and modifying risk factors associated with primary and secondary ACL injury.[11] Reaction time includes stimulus perception and processing and initiation of the motor response. *Visuomotor RT* (VMRT) is defined as the time between stimulus recognition and motor response and is especially important in athletic populations because of the short amount of time during which athletes must process stimuli to produce an appropriate motor response.[11] A slower VMRT is detrimental to sport performance, as delays in visual processing and motor response can place the athlete at risk for ACL injuries.[3,12] Individuals who experience delays in either aspect may demonstrate worse perceptual-motor function and differences in the constructs of perceptual-motor function, such as visual perception or perceptual-motor coordination. Poor visual perception could lead to delays in recognizing the stimulus (eg, an oncoming player) and, consequently, greater exposure to physical contact. Worse perceptual-motor coordination could lead to poor neuromuscular coordination, placing the knee in a compromised position and increasing the risk of a noncontact injury. Despite these differences, a delay in either recognition of the stimulus or coordination of dynamic movements may result in worse RT.

Dynamic movement control, which is also necessary for competitive sport participation, requires preparation or anticipation of the motor response, including faster RT and enhanced neuromuscular control.[10] Therefore, suboptimal motor programming and deficits in RT or neuromuscular control may perpetuate the risk of sustaining not only primary but also secondary ACL injuries.[13] Understanding the components of perceptual-motor function (eg, VMRT) and their relationships with contact and noncontact ACL injury mechanisms is critically needed to identify underlying risk factors for sustaining both primary and secondary ACL injuries. The exclusion of contact ACL injuries from a plethora of ACL research limits our ability to identify differences or similarities in the risk factors associated with the mechanism of injury. The VMRT is a salient and modifiable factor that may be relevant for addressing the primary ACL injury risk,[11] but after ACLR, individuals with primary or secondary ACL injuries may display differences in perceptual-motor function. Swanik et al[3] demonstrated that athletes who sustained a noncontact ACL injury had worse RT than uninjured athletes. However, we do not know whether individuals who sustain contact ACL injuries exhibit similar deficits in RT. Therefore, the purpose of our study was to compare perceptual-motor function, as assessed by LEVMRT, between individuals who sustained a contact ACL injury and individuals who sustained a noncontact ACL injury after ACLR. Given the lack of existing outcomes data after ACLR for patients with contact injuries, we opted to present support for the null hypothesis and suggest that neither group would show a difference in perceptual-motor function after ACLR. The current evidence for deficits in perceptual-motor function focuses on noncontact ACL injury or lower extremity musculoskeletal injury but does not provide much insight into potential similarities with contact ACL injuries,[12] so the support for a directional alternative hypothesis is scarce.

METHODS

Study Design

In this cross-sectional study, we examined clinical outcomes after ACLR. The independent variable was group (ie, contact or noncontact). The dependent variable was bilateral LEVMRT. The study was approved by the Michigan State University Institutional Review Board. We obtained informed consent ($\geq$18 years old) or informed assent and parental or guardian consent ($<$18 years old) before study enrollment.

Participants

A total of 36 individuals met inclusion for this study: (1) 14 to 35 years old, (2) unilateral ACL injury due to sport participation, and (3) $\geq$4 months to 5 years post-ACLR. Recruits were excluded if they had injured ligaments other than the ACL, had injury or surgery to the surgical limb within the previous 3 months, sustained a concussion within the past 3 months, or had a condition that affected the central nervous system.

Procedures

All participants completed a standard demographic questionnaire via Qualtrics, the Knee injury and Osteoarthritis Outcome Scale (KOOS) to evaluate self-reported knee function, and the Tegner Activity Scale (Tegner) to evaluate their level of activity. The KOOS is valid and reliable and consists of 42 items in 5 subscales: pain, symptoms, activities of daily living, function in sport, and knee-related quality of life.[14] Items in each subscale are scored on a 5-point Likert scale. Scores are normalized to a 0 to 100 scale, with higher scores indicating better function. The Tegner is a valid and reliable survey for individuals with a history of ACLR and consists of an 11-point Likert scale, with higher scores indicating higher levels of sport performance.[15] Participants reported age, sex, sport, limb dominance, and contact or noncontact mechanism of injury. Descriptions of the mechanisms of injury were provided in the questionnaire, and to protect against recall bias, participants had the opportunity to question the investigator if they needed clarification. If available, a chart review confirmed the self-reported mechanism of injury. Sports were dichotomized into open- or closed-skill categories based on a previous study.[16] Standing height and mass were assessed during the laboratory visit via a stadiometer and mechanical scale. Participants were dichotomized into the contact or noncontact group based on their responses to the demographic questionnaire.

The LEVMRT Task

The LEVMRT was evaluated using a novel and reliable system with light-emitting wireless sensor discs (model Trainer; FITLIGHT Corp). Participants completed the LEVMRT task as described by Brinkman et al.[17] Briefly, they used 1 foot to deactivate a series of lights illuminated in random order by quickly tapping the light with their foot (Figure 1). Light distance was

Figure 1. The lower extremity visuomotor reaction time task. The active limb is the right, and the stable limb is the left. Shank length was used to place lights. The light lateral to the limb being tested was placed at half-shank length.

normalized based on participant shank length (ie, tibial tuberosity to medial malleolus) to decrease the emphasis on balance during the task. Five lights were placed in a semicircle of 45° increments. The light lateral to the limb being tested was placed at half the distance of shank length with all other lights placed at the full distance of shank length (cm). The LEVMRT was measured while the ACLR limb was deactivating the lights (ie, ACLR active) and when the ACLR limb was stabilizing as the contralateral limb deactivated the lights (ie, ACLR stable). Participants completed three 30-second practice trials on each limb, followed by a 1-minute test trial on each limb. The average time (milliseconds) it took participants to deactivate the illuminated lights during the 1-minute trial was used to determine the LEVMRT. Limb order was counterbalanced, and participants had a 30-second rest period between trials to decrease the effects of fatigue.

Statistical Analysis

Descriptive statistics for participant demographics, KOOS subscale scores, and Tegner scores were calculated. The ACLR-active and ACLR-stable LEVMRTs are presented as the average time in milliseconds (mean ± SD) for the contact and noncontact groups. Descriptive statistics for sex by group were based on previous findings of sex differences in perceptual-motor function.[18] We examined the data to identify possible outliers. Counts and percentages were reported for sex, open or closed sport, and injury to the dominant or nondominant limb. Medians and ranges were supplied for the Tegner preinjury and current scores. Shapiro-Wilk tests were conducted for all demographic variables. Wilcoxon rank sum tests were used to examine between-groups differences in age, height, mass, time since surgery (TSS), KOOS subscale scores, and Tegner scores. A χ^2 test of independence was calculated to examine group differences in sex and sport (ie, open skill versus closed skill). We computed a Fisher exact test to measure differences in injury to the dominant or nondominant limb between groups. Separate analyses of covariance (ANCOVAs) were conducted to compare differences between the ACLR-active and ACLR-stable LEVMRT for contact versus noncontact ACL injury. Time since surgery was included as a covariate due to its effect on functional outcomes, specifically dynamic postural stability, after ACLR.[19] Brophy et al[19] found improvements in dynamic postural stability from presurgery to 12 months after ACLR, which would likely influence participants' performance during the LEVMRT task. Covariates other than TSS were not included in the initial model because of the small sample size, as overfitting the model with multiple covariates could reduce generalizability. Partial η^2 effect sizes were determined to examine clinically meaningful between-groups differences and were interpreted as *small* ($\leq$0.01), *moderate* (0.06), or *large* ($\geq$0.14).[20] The α level was set a priori at $P < .05$. All statistical analyses were performed using SPSS (version 28.0.1.0; IBM Corp).

RESULTS

Participant demographics, ACLR-active, and ACLR-stable LEVMRT are presented in Table 1. Eight participants were outliers based on their TSS (1.5× ± interquartile range) and were removed, as they were well past the return-to-activity window (35.5 ± 15.9 months) and could have experienced changes in perceptual-motor function (eg, sustaining additional injuries,[21] transitioning to a different level of play,[22] leaving their sport). Further, 24 months has been a common time point of interest for understanding successful return to activity and clinical outcomes after ACLR.[23,24] Time points within 24 months may be more salient to perceptual-motor function interventions that address the secondary ACL injury risk. One outlier in the ACLR-stable (contact ACL group n = 35 754 milliseconds) and ACLR-active LEVMRT (noncontact ACL group n = 35 716 milliseconds) was removed from the analysis. The final sample size after outliers were removed was 36 participants. Twenty participants sustained a contact ACL injury (56%), and 16 participants (44%) sustained a noncontact ACL injury. Some participants' data for Tegner preinjury scores (n = 4), Tegner current scores (n = 4), and the KOOS (n = 6) were not available. Differences were found between the contact and noncontact groups for age

Table 1. Participant Demographics

Characteristic	Anterior Cruciate Ligament Injury[a] Contact (n = 20, 56%)	Noncontact (n = 16, 44%)	Total (N = 36)	P Value
Sex				.279
Female	13 (50%)	13 (50%)	26	
Male	7 (70%)	3 (30%)	10	
Age, y	18.0 ± 2.9	21.2 ± 5.0	19.4 ± 4.2	.012[b]
Height, cm	172.1 ± 8.3	168.7 ± 7.6	170.6 ± 8.0	.272
Weight, kg	74.1 ± 14.3	68.7 ± 10.0	71.7 ± 12.7	.381
Limb				.004[b]
Dominant	12 (86%)	2 (14%)	14	
Nondominant	8 (36%)	14 (64%)	22	
Time since surgery, mo	6.6 ± 3.0	8.2 ± 4.7	7.3 ± 3.9	.220
Knee injury and Osteoarthritis Outcome Score				
Symptoms	65.6 ± 11.2	67.0 ± 15.8	66.3 ± 13.6	.818
Pain	94.8 ± 3.9	91.1 ± 9.3	66.3 ± 13.6	.642
Activities of daily living	98.4 ± 2.5	96.4 ± 5.5	92.9 ± 7.4	.289
Sport	85.4 ± 12.8	87.2 ± 13.7	86.3 ± 13.1	.582
Quality of life	65.2 ± 23.	65.0 ± 17.2	65.1 ± 20.0	.948
Tegner Activity Scale score				
Preinjury	9.5 [7–10]	8.5 [4–10]	9 [4–10]	.043[b]
Tegner Current	6.5 [3–9]	6 [3–9]	6 [3–9]	.970
Sport				.681
Open skill[c]	19 (58%)	14 (42%)	33	
Closed skill[d]	1 (50%)	1 (50%)	2	
Anterior cruciate ligament-reconstructed limb lower extremity visuomotor reaction time, ms				
ACLR-Active	501.8 ± 58.9	489.4 ± 92.1	496.5 ± 74.0	
Females	502.8 ± 57.3	481.7 ± 83.7	492.7 ± 70.5	
Males	499.7 ± 66.3	520.3 ± 138.4	505.9 ± 85.3	
ACLR-Stable	521.7 ± 59.3	483.4 ± 83.9	504.2 ± 73.1	
Females	526.6 ± 68.3	486.8 ± 79.2	506.7 ± 75.3	
Males	511.2 ± 35.4	469.0 ± 121.4	497.1 ± 70.1	

Abbreviation: ACLR, anterior cruciate ligament reconstruction.
[a] Descriptive statistics presented as mean ± SD for continuous variables or No. (%) for categorical variables. Tegner Activity Scale scores are presented as median [range].
[b] Denotes statistical significance.
[c] Open skill sports in the sample include basketball, football, skateboarding, soccer, ice hockey, skiing, and wrestling.
[d] Closed skill sports in this sample include running, weightlifting, or cross fit.

($P = .012$), Tegner preinjury score ($P = .043$), and injury to the dominant or nondominant limb ($P = .004$). The contact group had a lower age, higher Tegner preinjury score, and more injuries to the dominant limb. The ACLR-active ($P = .124$) and ACLR-stable ($P = .364$) LEVMRTs were normally distributed. After TSS was controlled, the overall model for ACLR-stable LEVMRT was significant with a large effect size ($P = .010$, $\eta^2 = 0.250$) between groups with the contact ACL injury group being slower (Table 2). Time since surgery was significant in the ACLR-stable ANCOVA ($P = .009$) but not the ACLR-active model ($P = .168$), though it was retained in both. However, no difference and a moderate effect size ($P = .340$, $\eta^2 = 0.065$) were noted between groups for the ACLR-active LEVMRT. To address possible limitations in our ability to interpret the significant results using TSS as a covariate, we conducted additional separate ANCOVAs with the variables that were different between contact and noncontact groups (see Supplemental Tables 1 through 3, available online at https://dx.doi.org/10.4085/1062-6050-0428.22.S1). None of the overall models for the ACLR-stable or ACLR-active groups were significant using these individual covariates and mechanism of injury (ie, age, Tegner preinjury score, and injury to the dominant or nondominant limb). These covariates were important differences between groups but may not have affected perceptual-motor function as much as the TSS. Further, changing the covariates

Table 2. Analysis of Covariance Comparing the Mechanism of Injury and Lower Extremity Visuomotor Reaction Time After Anterior Cruciate Ligament Reconstruction (ACLR)

Variable	Value df	F	η^2	P
ACLR-Active				
Overall model	2	1.12	0.065	.340
Time since surgery	1	1.99	0.059	.168
Contact versus noncontact	1	0.41	0.013	.524
Total	34			
ACLR-Stable				
Overall model	2	5.34	0.250	.010[a]
Time since surgery	1	7.68	0.194	.009[a]
Contact versus noncontact	1	5.10	0.138	.031[a]
Total	34			

[a] Denotes statistical significance.

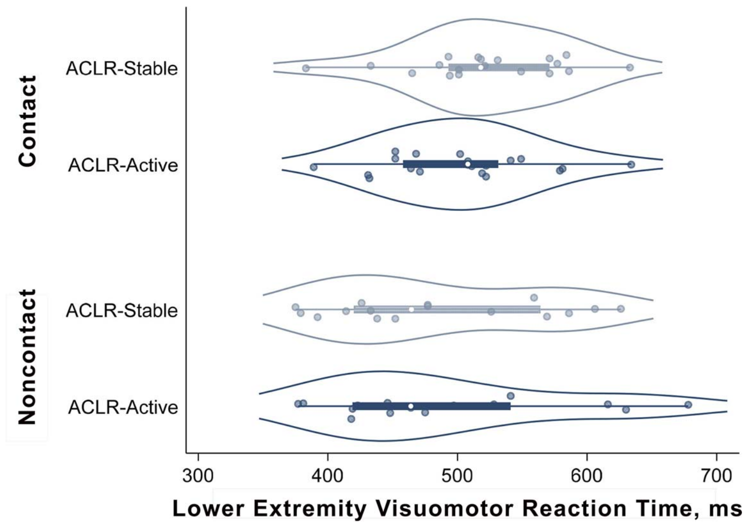

Figure 2. Violin plot of lower extremity visuomotor reaction time task by group. A higher value indicates worse performance. Abbreviations: ACLR-Active, the surgical limb is deactivating the lights; ACLR-Stable, the contralateral limb is deactivating the lights and the surgical limb is stabilizing.

in the model adjusted the significance level, but this may reflect a type II error and underpowered models.

DISCUSSION

The purpose of our study was to expand on the current knowledge of perceptual-motor function for contact and noncontact ACL injuries after ACLR. Overall, individuals who sustained a contact ACL injury exhibited a slower LEVMRT than those with noncontact ACL injuries (Figure 2). Evidence suggests a relationship between the mechanism of injury and perceptual-motor function. A difference was present between groups in ACLR-stable LEVMRT: those who sustained a contact injury exhibited a slower LEVMRT. The contact group had a worse LEVMRT when the surgical limb was stabilizing. No between-groups differences were observed when the contralateral limb was stabilizing and the ACLR limb was deactivating the lights. These results support a difference in perceptual-motor function, as assessed by the LEVMRT, between individuals with contact and noncontact ACL injuries, perhaps due to lingering deficits in postural control among those who sustained contact ACL injuries.

Perceptual-motor function assessments, which include visual perception, perceptual-motor coordination, and visuoconstructional reasoning,[25] provide a window into how individuals integrate information between the central nervous system and peripheral nervous system to produce a specific motor output.[11,12] Authors of several studies have noted central nervous system changes like increased activity in motor planning, sensory, and visuomotor areas of the brain after ACLR[26,27] and impaired postural control in single-legged dynamic and static conditions compared with healthy individuals.[6,10] Dynamic stability of the knee relies heavily on these neurocognitive processes, which may explain the increased risk of secondary noncontact ACL injury. Our data demonstrated significant and clinically meaningful changes in 1 limb during the LEVMRT task. A bilateral deficit may exist but was not captured in this task. The postural control impairments seem to persist and worsen with additional cognitive demands or the higher cognitive loads that occur in sports.[27,28]

Decreased motor performance and increased attentional demands to maintain dynamic movement control may explain the observed difference in LEVMRT when the ACLR limb was responsible for postural control.[29] The LEVMRT task involves a standardized distance for the lights to reduce the demand of maintaining balance during the task, but control is still necessary to maintain the center of mass and an upright position as the limb deactivating the lights moves. The dynamic movement of the limb deactivating the lights may cause anticipatory and compensatory adjustments by the central nervous system based on sensorimotor input (ie, illuminated light, sensation of the foot everting) and output (ie, muscles activated to deactivate the light in front or on the side). Those who sustained a contact ACL injury may use different motor control strategies or exhibit different perceptual-motor function deficits than those who sustained a noncontact injury.

Noncontact ACL injuries occur when the person generates greater forces at the knee that excessively load the ACL as a result of higher ground reaction forces, which lead to increases in the knee-abduction angle.[2,4] Noncontact ACL injuries are often the consequence of an unanticipated or insufficient neuromuscular response to joint load during high-speed or complex movements.[2] In uninjured populations, poor perceptual-motor function has been associated with increased ground-reaction force, knee-abduction moments, and other predictors of ACL injury.[30] Slow RTs prospectively identified individuals who sustained a noncontact ACL injury.[3] In our sample, the noncontact group demonstrated a better LEVMRT than the contact group. Joint-stiffening strategies may have been used by the noncontact group to artificially reduce knee movement during the task. Other perceptual-motor function impairments may have been present but not captured in this assessment because our task had a relatively small visual field with 5 stationary targets. However, the authors[26,28] of other studies have found increased activation of motor, visual, and sensory areas of the brain and increased cognitive demand during postural control. This partially supports the idea that altered postural control strategies may compensate for processing demands but likely degrade when attentional demands exceed cognitive ability.[26,31]

A paucity of research exists on those who sustain contact ACL injuries. Deficits in RT or poor spatial awareness may explain some contact ACL injuries. Generally, contact ACL injuries have been a smaller focus of injury-reduction programs given the lower percentage of injuries and the fact that collision in some sports is expected or unavoidable. In our sample, the contact group had a slower LEVMRT than the noncontact group when the surgical limb was stabilizing. The ability to anticipate or facilitate a quick motor response while the surgical limb is stationary suggests less efficient postural control.[28,29] Deficits in RT and processing speed could create task uncertainty, an inability to avoid a collision with another player or object, delayed recognition of stimuli, or the selection of an inappropriate motor response.[3,12,32] These factors have typically been linked with noncontact ACL mechanisms but seem to also be present and worse in contact mechanisms. Integrating motor learning and control principles with traditional rehabilitation approaches can help to address these detrimental perceptual-motor function changes. Slight changes in instruction to promote external focus of attention,[27] differential learning,[27] and visual-motor training[6] can be implemented during rehabilitation sessions to improve sensorimotor adaptions that translate to the demands seen during sport.[7,33] Our data do not inform the type of interventions that might be more effective for either group after ACLR, yet mechanism-specific changes in perceptual-motor function need to be addressed.

This study was not without limitations. Lower extremity VMRT was not collected before injury but at varying time points (ie, 4 months to 5 years) after ACLR. Therefore, it is challenging to translate these findings to address the primary and secondary ACL injury risks without support from the existing literature. Lower extremity VMRT is a proxy assessment of perceptual-motor function that includes components of visual perception and perceptual-motor coordination, so it is not possible to determine the specific factor(s) of perceptual-motor function that may influence the differences in RT between contact and noncontact ACL injury. Our sample size was small ($n = 36$), and a type-II error could have occurred for ACLR-active. Chart review was not available for all participants; as a result, the self-reported contact or noncontact mechanism of injury information may not be precise despite our efforts to reduce recall bias. Finally, because sex, mass, and age influence VMRT, these may be important variables to control in future analyses. Descriptive statistics for bilateral LEVMRT by sex are reported in Table 1, but no statistical analysis was performed. However, due to the limited sample size, we opted not to include these variables in our current models. Future researchers should aim for groups with similar distributions of males and females and larger sample sizes for greater inclusion of multiple covariates in the statistical models (eg, controlling for sex, limb dominance, Tegner score, and sport type).

CONCLUSIONS

Individuals with contact ACL injuries demonstrated worse perceptual-motor function (ie, LEVMRT) than those with a noncontact ACL injury. Differences between the mechanisms of injury were present in LEVMRT when the ACLR limb served as the stabilizer for the task. Lingering postural control deficits in individuals with contact ACL injuries may explain these group differences. Incorporation of motor learning interventions to enhance perceptual-motor functioning may be beneficial for all individuals after ACLR, regardless of the injury mechanism.

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SUPPLEMENTAL MATERIAL

Supplemental Table 1. ANCOVA Comparing Mechanism of Injury, Age, and LEVMRT
Supplemental Table 2. ANCOVA Comparing Mechanism of Injury, Injured Dominant or Nondominant Limb, and LEVMRT
Supplemental Table 3. ANCOVA Comparing Mechanism of Injury, Tegner Preinjury, and LEVMRT

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