Visual cognition associated with knee proprioception, time to stability, and sensory integration neural activity after ACL reconstruction

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Funding information
The Ohio State University College of Medicine; National Athletic Trainers’ Association Research and Education Foundation; National Strength and Conditioning Association Foundation

Abstract
Visual cognitive ability has previously been associated with anterior cruciate ligament injury and injury risk biomechanics in healthy athletes. Neuroimaging reports have identified increased neural activity in regions corresponding to visual-spatial processing, sensory integration, and visual cognition in individuals after anterior cruciate ligament reconstruction (ACLR), indicating potential neural compensatory strategies for motor control. However, it remains unclear whether there is a relationship between visual cognition, neural activity, and metrics of neuromuscular ability after ACLR. The purpose of this study was to (1) evaluate the relationship between visual cognitive function and measurements of neuromuscular control (proprioception and time to stability [TTS]), isokinetic strength, and subjective function, and (2) examine the neural correlates of visual cognition between ACLR (n = 16; time since surgery 41.4 ± 33.0 months) and demographically similar controls (n = 15). Visual cognition was assessed by the ImPACT visual motor and visual memory subscales. Outcome variables of proprioception to target knee angle 20°, landing TTS, strength, and subjective function were compared between groups, and visual cognition was correlated within groups to determine the relationship between visual cognition and outcome variables controlled for time from surgery (ACLR group). The control group had better IKDC scores and strength. Visual memory and visual motor ability were negatively associated with proprioception error (r = −0.63) and TTS (r = −0.61), respectively, in the ACLR group but not controls. Visual cognition was associated with increased neural activity in the pre-cuneus and posterior cingulate cortex in the ACLR group but not control participants. These data suggest the neural strategy in which ACLR participants maintain proprioception and stability varies, and may depend on visual cognition and sensory integration neural activity.

Keywords
ACL, knee, proprioception, visual-cognition
INTRODUCTION

Prevalence of anterior cruciate ligament (ACL) injuries continues to rise,\(^1\) with the majority occurring through noncontact mechanisms.\(^2\) The noncontact injury mechanism can be attributed to a sensorimotor prediction error that results in poor neuromuscular control and knee valgus collapse.\(^3,4\) Noncontact injuries occur shortly after foot contact with the ground during instances of deceleration, change of direction, pivoting, or landing.\(^5\) When an ACL injury occurs, an athlete’s visual attention is generally fixated on a key external environmental factor such as a sport ball or another player.\(^6\) External visual attention at the time of an ACL injury indicates that visually mediated cognition (i.e., visual cognition) may influence injury risk neuromuscular control.

The immediate post-concussion assessment and cognitive testing (ImPACT) assessment constructs evaluate visual cognition.\(^5\) Swanik et al.\(^6\) observed that athletes who sustained a noncontact ACL injury demonstrated lower baseline scores on four ImPACT composite subscales when compared with uninjured teammates. Specifically, individuals who sustained an ACL injury demonstrated the greatest deficit on the visual memory subscale of the ImPACT assessment at preseason.\(^6\) Monfort et al.\(^7\) examined how visual cognitive ability influences biomechanics in healthy individuals in a soccer ball-handling 45° run-to-cut task, reporting that poorer ImPACT visual memory scores were associated with greater peak knee valgus angle.\(^7\) Likewise, Herman et al.\(^8\) examined the concussion resolution index (CRI) across three composite indices: reaction time, complex reaction time (visual memory), and processing speed to stratify healthy individuals into high versus low neurocognitive performers. Findings indicated that lower CRI performance was associated with ACL injury landing mechanics of increased peak vertical ground reaction force (GRF), peak anterior tibial shear force, knee abduction moment, and knee abduction angle during an unanticipated landing.\(^8\) These studies indicate the potential of visual cognitive abilities to influence ACL injury risk neuromuscular control, but do not give insight into how injury may further influence the relationship between visual cognition and sensorimotor control.

Previous works have indicated that musculoskeletal injuries may accentuate visual cognitive-related deficits or dependence for maintaining neuromuscular control.\(^9\) After ACL injury, simple knee motor control tasks to engage the quadriceps,\(^10,11\) complete a supine heel slide,\(^12\) and active joint position sense (AJPS)\(^13\) require greater frontal cortex and visual-spatial brain region activity. These neural activity differences may contribute to visually mediated neurocognitive load, reducing postural stability in those with prior injury.\(^14\) Changes in neural demands and accompanying functional deficits after ACL injury are commonly attributed to a disruption in ligamentous afferents that maintain both muscular responses and joint position sense (proprioception) for joint stability.\(^15\) However, assessment of proprioception typically involves active or passive reposition to a target angle and requires patients to “memorize” their knee joint spatial location that entails working memory.\(^16\) Thus, current measurements of proprioceptive deficits might be attributed to the ligamentous afferent disruption or alterations in sensorimotor and visual cognitive control (particularly, visual memory) of joint position.

Sensorimotor prediction errors that result in ACL injury occur during the first 100 ms of foot contact with the ground.\(^17\) Alterations in visual cognition and associated neural activity may negatively influence the ability to rapidly stabilize from landing within this brief time period. A metric that can more accurately quantify motor coordination that contributes to rapid stabilization ability is time to stabilization (TTS), a technique that measures the time taken to regain postural stability after a dynamic task, such as landing from a single-leg jump.\(^18,19\) TTS is a reliable measure of lower extremity stability and has been shown to detect deficits in dynamic stability after ACL injury.\(^18,20\) Although longer TTS after injury is typically attributed to reduced muscle strength, altered muscle firing,\(^21\) and biomechanics, the nature of rapid stabilization could also depend on visual cognitive function, specifically visual motor speed.

The current study aimed to investigate the relationships between neural activity, visual cognitive ability, and sensorimotor function after ACL reconstruction (ACLR), relative to healthy controls, and address gaps in knowledge specific to the contribution of visual cognition to proprioception and dynamic stability after ACLR. Specifically, the aims of this study were to (1) evaluate the relationship between visual cognitive processing and assessments of sensorimotor control (proprioception and TTS) in ACLR individuals, relative to similar demographic controls, and (2) determine the neural correlates of visual cognitive function during knee motor control between ACLR individuals and demographically similar controls.

METHODS

2.1 Participants

This case-control study enrolled 16 individuals with a history of left unilateral primary ACLR (6 male, 21.5 ± 2.6 years, 69 ± 15.9 kg, Tegner 7.4 ± 1.1, time since surgery 41.4 ± 33.0 months, 13 hamstring, 3 bone patella-tendon bone grafts) and 15 healthy controls (6 male, 22.9 ± 3.03 years, 70.9 ± 14.9 kg, Tegner 7.5 ± 1.1) aged 18 to 35 years. ACLR participants demonstrated MRI compliance, time since surgery: 6 months to 5 years, a Tegner activity score ≥6, and they were cleared for sport participation by their surgeon. Control participants demonstrated similar demographics (age, mass, and physical activity level), reported no history of lower extremity injury, and were MRI compliant. Individuals with right extremity, bilateral ACL injury and/or revision surgery were excluded. There was no significant difference between groups or between graft types for age, mass, or activity level (p > .05). The current study was approved by The Ohio State University Biomedical Sciences Institutional Review Board and informed consent was obtained before participant enrollment.
2.2 Measurement of cognitive function

ImPACT (ImPACT Applications, Inc.) was used to assess neurocognitive function and was administered in a private office/laboratory. The ImPACT is a reliable computerized assessment that aims to evaluate neurocognitive ability on six modules: working memory, design memory, X's and O's, symbol matching, color matching, and three letters. Four subscale composite scores to quantify verbal memory, visual memory, reaction time, and visual motor speed ability are generated on the basis of the six modules. Reliability and ceiling effects have been established, with the visual memory composite score being moderately reliable \(r = .53\), a ceiling score of 100 (1.6% of scores at ceiling), and a visual motor composite score being the most reliable \(r = .69\) with a ceiling score of 52.9 (0.5% of scores at ceiling). For either visual cognitive ImPACT composite score, higher scores indicate better performance. Previous literature demonstrates increased injury risk biomechanics and ACL injury risk in healthy athletes with lower ImPACT performance, specifically on subscales related to visual cognition (visual memory and visual motor subscales). ACLR may further accentuate visual cognitive deficits and/or dependence on vision for sensorimotor integration; therefore, the visual memory and visual motor subscales were used in analyses. The visual memory construct aims to assess visual attention, scanning, and memory. The visual motor construct aims to evaluate reaction and/or anticipatory responses to visual stimuli and integrates components of decision-making, working memory, and learning.

2.3 Measurement of proprioception

Knee proprioception by AJPS was measured using an isokinetic dynamometer (Biodex, System 3). Participants were seated and strapped into the dynamometer with their hips and contralateral (right) knee flexed to 90° and the involved (left) knee flexed to 45°, blindfolded, and ears covered. Participants were instructed to straighten their left extremity from the starting angle of 45° to the target angle of 20° and asked to remember that knee position. The participants’ knee was then flexed back to 45° and supported by the dynamometer. Participants then actively returned to the 20° target angle and hit a button to lock the dynamometer in place when they believed to have reproduced the target angle. Proprioceptive error was determined by the absolute difference from reproduced angle from the target 20°. Each reproduction trial was preceded by the target acquisition trial for a total of four trials, with the average absolute error of the trials used for statistical analysis.

2.4 Measurement of time to stability

The maximal jump height for each participant was determined on the basis of a standing vertical jump. Participants were instructed to stand beneath a Vertec (Vertec Power Systems) on both feet and complete a maximum vertical jump touching the highest rung possible. Technique for vertical jump (countermovement, etc.) was not restricted. The peak height jumped of three successful trials was recorded and used for the following methods. After maximal jump height was established, the Vertec was adjusted to 50% of the maximal height determined by the rung that was halfway between the baseline standing reach and maximal jump height. Participants stood behind a mark on the floor 70 cm away from the center of the landing force platform recording at 1000 Hz (Model 4060 NC; Bertec Inc). They were instructed to complete a forward bipedal jump toward the platform, touch the previously set rung of the Vertec with one hand, and land on their left foot on the force platform (Figure 1). Upon landing, participants placed their hands on their hips as fast as possible and maintained balance for 10 seconds (s). If the participant missed the Vertec target height, was unable to land without stepping, or employed other measures to regain balance that required putting the other foot on the ground or stepping off the force plate, the trial was omitted. Three successful trials were completed for the left (involved) lower extremity of each participant. Participants completed at minimum two practice trials.

TTS uses the triplanar GRF to determine dynamic postural stability as the time it takes for the landing GRF to stabilize. Raw GRF data were filtered with a second-order dual low-pass 30 Hz filter. TTS is calculated using GRF from a 10 s window, starting at maximal resultant GRF. Horizontal range variation was determined as minimum rectified anterior-posterior (AP) and medial-lateral (ML) GRF from the last half of the 10 s window of interest. An unbounded
third-order polynomial was fitted to each of the AP and ML components of the GRF. TTS for each GRF component is the point at which the unbounded third-order polynomial transsects the horizontal range variation. The root of the summed squared TTS from AP and ML GRF was then calculated and used for analysis.

2.5 | MRI paradigm and data acquisition

Scans were completed on a 3.0-T MAGNETOM (Siemens AG) scanner using a 12-channel head coil. Each session consisted of a structural T1-weighted image, followed by a functional scan. Blood oxygen level-dependent functional acquisition consisted of four blocks of 30 s of knee flexion/extension (beginning at 45° of flexion to full terminal extension) interleaved with five blocks of rest periods. To normalize motor performance and minimize head motion, participants were temporally cued using an auditory metronome paced at 1.2 Hz during each movement block. Furthermore, the use of an ankle dorsiflexion splint was placed on the left ankle to assure that the only joint movement was from the knee. Each functional session included 90 whole-brain gradient echo-planar scans: TR = 3000 ms; TE = 28 ms; field of view = 220 mm; slice thickness = 2.5 mm; voxel size = 2.5 mm³ for 55 slices.

2.6 | Image processing and neuroimaging data analysis

Preprocessing fMRI data using software package functional magnetic resonance imaging of the brain software library (FSL) consisted of brain extraction, MCFLIRT motion correction, Gaussian kernel FWHM 5 mm spatial smoothing, and mean-based intensity normalization of all volumes. Independent Component Analysis-based strategy for Automatic Removal of Motion Artifacts was used to further denoise and reduce motion-induced signal. After motion artifact denoising, fMRI preprocessing included high-pass filtering at 90 Hz. All T1-weighted three-dimensional structural images and standard Montreal Neurological Institute and Hospital coordinate system 152, 2 mm space were extracted using FSL’s brain extraction tool and co-registered with functional images using nonlinear image registration. Subject level rest versus move contrasts and group-level neural correlate analysis on the demeaned visual memory and visual motor subscale scores were completed with p < .05 cluster corrected for multiple comparisons and z > 3.1 to identify regions of activation during knee motor control that were groupwise correlated to visual motor and visual memory composite subscales.

2.7 | Self-report function

The International Knee Documentation Committee (IKDC) was completed. The IKDC is a reliable self-reported functional scale after ACL injury and is scored from 0 to 100 points (higher score indicated greater self-perceived function).

2.8 | Isokinetic strength assessment

Isokinetic knee extension strength was measured with participants seated on the dynamometer, straps crossing the chest and upper thighs, and hips and knees flexed to 90°. Participants performed a standardized warm-up consisting of five isokinetic contractions at 60°/second. Limb symmetry index (LSI) was calculated ((Involved Limb/Uninvolved Limb) x100) for strength. For control participants, the involved extremity was the left lower extremity to mimic the ACLR group.

2.9 | Statistical analysis

Six independent samples t test was used to compare means of all dependent variables (IKDC, strength, ImPACT subscales, AJPS, and TTS) between groups (ACLR vs. control). For controls, Pearson’s correlation (r) was used to determine the relationship between visual memory composite scores with AJPS, IKDC, and strength. Also, visual motor composite scores were correlated with TTS, IKDC, and strength for control participants. Partial correlations controlling for time since surgery were used to examine the relationship for the same ImPACT visual-cognitive subscales with AJPS, TTS, IKDC, and strength for ACLR participants. Alpha was at 0.05 for all analyses with no correction, as these results are exploratory in nature. Correlations were interpreted as low (0.1–0.40), moderate (0.41–0.6), and strong (0.61–1.0) associations.

3 | RESULTS

One control participant did not complete the IKDC questionnaire and two did not complete the AJPS or isokinetic strength assessments due to equipment malfunction or missed data collection. As a result, correlations for these variables were completed with 14 and 13 individuals, respectively. One ACLR participant did not complete the strength assessment; therefore, 15 ACLR participants were included in strength analyses.

3.1 | ACLR versus controls comparisons

When comparing between groups, the control participants demonstrated better IKDC scores (p < .001) and isokinetic strength LSI (p = .021), with no difference in visual motor composite score, visual memory composite score, AJPS, or TTS (p > .05) (Table 1).

3.2 | ACLR and control correlations

For the ACLR participants, partial correlations indicate that higher performance on visual memory composite scores was strongly associated (r = −0.63, p = .02) with lower absolute AJPS error (better
proprioception) (Table 2, Figure S1). In addition, higher performance on the visual motor composite score was strongly associated ($r = -0.61, p = .03$) with better TTS performance (decreased time to stabilize) (Table 3, Figure S2). There were no significant correlations in controls between any outcome variables ($p > .05$, Figures S3 and S4). Visual memory and visual motor scores were not associated with IKDC or isokinetic strength LSI for either group ($p > .05$, Tables 2 and 3).

### 3.3 | Neural activity associated with visual cognitive function

In ACLR participants, brain regions correlated with visual memory function were the right precuneus and posterior cingulate gyrus (PPC) ($p < .001$), and visual motor function was correlated with right precuneus activity ($p = .022$). There were no neural correlates with either measure of visual cognitive function in control participants (Table 4, Figure 2). As this was a neural correlate identification analysis, the effect size ($r$ value) between neural activity and visual cognitive function is not reported to avoid circularity (effect size and voxel selection are not independent). A follow-up validation study is required to estimate effect size with identified regions.37

### 4 | DISCUSSION

The current study aimed to evaluate the relationship between visual cognitive processing and assessments of sensorimotor control in individuals with a history of ACLR and demographically similar controls. Despite no between-group differences for visual cognition, higher visual motor and visual memory composite scores were associated with decreased time to stabilize and less proprioceptive error, respectively, in the ACLR cohort only. No such relationship was present in the control group. In addition, there was no relationship between either visual motor or visual memory ability and isokinetic strength or IKDC in either group. Neural correlates of visual cognitive function were examined during an involved (left) knee motor task in each cohort to determine if a neural mechanism may afford visual cognition to functionally compensate for the afferent deficits of ACL reconstruction. Visual memory and visual motor composite scores were associated with neural activity within the precuneus and posterior cingulate cortex in the ACLR group, but there were no neural correlates for the controls. These data indicate that ACLR may induce unique neuroplasticity that results in visual cognition contributing to proprioception and dynamic stability to a degree that healthy controls do not require.

### TABLE 1 | Mean ± standard deviations for major outcomes

<table>
<thead>
<tr>
<th>Outcome</th>
<th>ACLR (mean ± SD)</th>
<th>Control (mean ± SD)</th>
<th>$p$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKDC</td>
<td>86.3 ± 11.02 (n = 16)</td>
<td>98.7 ± 2.00 (n = 14)</td>
<td>$p &lt; .001$</td>
</tr>
<tr>
<td>Isokinetic quadriceps symmetry (LSI)</td>
<td>83.01 ± 17.2 (n = 14)</td>
<td>95.8 ± 7.41 (n = 13)</td>
<td>$p = .021$</td>
</tr>
<tr>
<td>Visual motor composite score</td>
<td>41.5 ± 5.8 (n = 16)</td>
<td>43.1 ± 4.78 (n = 15)</td>
<td>$p = .347$</td>
</tr>
<tr>
<td>Visual memory composite score</td>
<td>72.8 ± 18.5 (n = 16)</td>
<td>75.67 ± 12.13 (n = 15)</td>
<td>$p = .141$</td>
</tr>
<tr>
<td>AJPS (degrees error)</td>
<td>3.8 ± 1.63 (n = 16)</td>
<td>4.3 ± 1.17 (n = 13)</td>
<td>$p = .117$</td>
</tr>
<tr>
<td>TTS (seconds)</td>
<td>3.0 ± 0.58 (n = 16)</td>
<td>3.0 ± 0.45 (n = 15)</td>
<td>$p = .713$</td>
</tr>
</tbody>
</table>

Note: Bold text represents statistically significant differences.
Abbreviations: ACLR, anterior cruciate ligament reconstruction; AJPS, active joint position sense; IKDC, International Knee Documentation Committee Subjective Knee Evaluation Form; LSI, limb symmetry index; TTS, time to stability.

### TABLE 2 | Visual memory composite score correlates

<table>
<thead>
<tr>
<th></th>
<th>AJPS</th>
<th>IKDC</th>
<th>Isokinetic strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLR</td>
<td>$r = -0.633$</td>
<td>$r = -0.28$</td>
<td>$r = -0.112$</td>
</tr>
<tr>
<td></td>
<td>$p = .02$</td>
<td>$p = .929$</td>
<td>$p = .716$</td>
</tr>
<tr>
<td></td>
<td>$n = 16$</td>
<td>$n = 16$</td>
<td>$n = 14$</td>
</tr>
<tr>
<td>Controls</td>
<td>$r = 0.34$</td>
<td>$r = 0.247$</td>
<td>$r = -0.233$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.256$</td>
<td>$p = 0.394$</td>
<td>$p = 0.445$</td>
</tr>
<tr>
<td></td>
<td>$n = 13$</td>
<td>$n = 14$</td>
<td>$n = 13$</td>
</tr>
</tbody>
</table>

Note: $r$, bivariate (Pearson) correlation for controls. Partial correlations controlling for time since ACLR surgery. Bold text represents statistically significant findings.
Abbreviations: ACLR, anterior cruciate ligament reconstruction; AJPS, active joint position sense; IKDC, International Knee Documentation Committee Subjective Knee Evaluation Form.

### TABLE 3 | Visual motor composite score correlates

<table>
<thead>
<tr>
<th></th>
<th>TTS</th>
<th>IKDC</th>
<th>Isokinetic strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLR</td>
<td>$r = -0.610$</td>
<td>$r = -0.242$</td>
<td>$r = -0.086$</td>
</tr>
<tr>
<td></td>
<td>$p = .027$</td>
<td>$p = .426$</td>
<td>$p = .781$</td>
</tr>
<tr>
<td></td>
<td>$n = 16$</td>
<td>$n = 16$</td>
<td>$n = 14$</td>
</tr>
<tr>
<td>Controls</td>
<td>$r = -0.042$</td>
<td>$r = 0.219$</td>
<td>$r = 0.277$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.881$</td>
<td>$p = 0.451$</td>
<td>$p = 0.359$</td>
</tr>
<tr>
<td></td>
<td>$n = 15$</td>
<td>$n = 14$</td>
<td>$n = 13$</td>
</tr>
</tbody>
</table>

Note: $r$, bivariate (Pearson) correlation for controls. Partial correlations controlling for time since ACLR surgery. Bold text represents statistically significant findings.
Abbreviations: ACLR, anterior cruciate ligament reconstruction; AJPS, active joint position sense; IKDC, International Knee Documentation Committee Subjective Knee Evaluation Form; TTS, time to stability.
Visual cognition as a compensatory mechanism to preserve proprioception after ACLR

Propriconception is the unconscious ability of the nervous system to integrate afferent signals to detect location of a joint in space. Previous literature suggests that ACL rupture results in proprioceptive deficits incompletely recovered with reconstructive surgery and subsequently results in greater error when assessed clinically as compared with healthy controls. Assessments of proprioception, such as AJPS, require cognitive attention and memory concentrated to the joint position, limiting isolation of somatosensory contributions to proprioception, which is the intended goal of the assessments. Our data demonstrate no statistical difference in proprioception between ACLR and control participants, contradicting a previous meta-analysis that found control participants on average have 0.35° less error (better joint position sense) than those with ACLR. Another meta-analysis evaluated proprioceptive ability between ACLR and uninjured limbs and found greater error (0.23°) in reconstructed than in contralateral knees. Regardless of the graft type, proprioceptive ability as detected by active, passive, or detection of passive movement appears to recover by 6 months after surgery as compared with the uninjured extremity. However, in these meta-analyses, the average proprioceptive error difference between groups or limbs does not exceed the standard error of the measurement (1.2°−1.7°), indicating lack of clinical significance. The lack of group differences in our study, relative to the meta-analyses, is likely attributed to the longer time since surgery (41.4 ± 33.0 months), as proprioceptive deficits are most evident 6 months or sooner after ACLR.

Our data indicate that visual memory ability may provide a means to normalize proprioception as assessed by AJPS in those with

**TABLE 4** Brain activity associated with visual memory and visual motor ImPACT subscales in ACLR group

<table>
<thead>
<tr>
<th>Cluster index</th>
<th>Brain regions</th>
<th>Voxel</th>
<th>p Value</th>
<th>Peak MNI Voxel</th>
<th>Z stat-max</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Knee motor control neural activity with visual motor composite score</td>
<td>244</td>
<td>.00153</td>
<td>8, -56, 22</td>
<td>5.48</td>
</tr>
<tr>
<td>1</td>
<td>Precuneus, posterior cingulate gyrus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Precuneus</td>
<td>525</td>
<td>.0223</td>
<td>20, -52, 22</td>
<td>3.83</td>
</tr>
</tbody>
</table>

Note: Regions of brain activity are reported that were identified in FSLeyes with the Harvard-Oxford Cortical & Subcortical Structural atlas and/or the Cerebellar Atlas in MNI152 space after normalization with FNIRT and with FSL tool atlasquery.

Abbreviations: ACLR, anterior cruciate ligament reconstruction; FMRIB, Functional Magnetic Resonance Imaging of the Brain; FNIRT, FMRIB’s nonlinear image registration tool; FSL, FMRIB Software Library; MNI, Montreal Neurological Institute and Hospital coordinate system.

**FIGURE 2** ACLR task-based neural activity associated with visual memory and visual motor ImPACT composite scores. Color bars correspond to z values for raw data. Blue shade represents neural activity associated with visual memory ability (precuneus and posterior cingulate gyrus) and red orange represents neural activity associated with visual motor ability (precuneus). A, anterior; ACLR, anterior cruciate ligament reconstruction; L, left; P, posterior; R, right [Color figure can be viewed at wileyonlinelibrary.com]
ACLR. Those with a history of ACLR and better visual memory ability may allow for enhanced internal visualization (i.e., memorization) of joint position, thus aiding in target angle reproduction. This corresponds to the methodology of assessing AJPS as well as the aim of the visual memory ImPACT score, which requires conscious cognitive attention to establish spatial position. This finding highlights the ongoing limitations with isolating proprioception with a clinical test and the inability to ascribe purely the afferent neural pathway to AJPS acuity. The afferent disruption from the ACL injury may cause patients to utilize visual cognition to assist with knee-related sensorimotor function, as a significant correlation was present for only the ACLR group. The lack of prior studies not controlling for visual cognitive abilities as a means to compensate for ACLR disrupted afferents to maintain proprioception may explain the mixed results and small effect sizes of prior joint position sense studies.41

4.2 Visual cognition as a compensatory mechanism to preserve stability after ACLR

TTS is a measure of dynamic postural stability and it evaluates the ability of an individual to quickly gain control after a dynamic movement. A previous study in Division I female athletes20 found that ACLR participants took 0.11 s longer (2.01 ± 0.15 s) to stabilize than controls (1.90 ± 0.07 s) and concluded that dynamic postural control deficits existed despite all participants having returned to full sport participation (average 2.5 years post-surgery).21 We found no difference between groups for TTS; however, both of our cohorts took longer to stabilize (Table 1) than those in Webster and Gribble,20 potentially because our cohort ranged from competitive collegiate to high-level reactional athletes rather than all elite-level college athletes. The longer TTS in our cohort could also be secondary to the calculation. Webster employed an average ± 3 standard deviations body weight across all trials to establish the HRVL (threshold to determine when stability was achieved), whereas we calculated the HRVL within each trial as originally described by Ross et al.,19 as we did not complete as many trials (3 vs. 10)20 to take an average from. Thus, our stability threshold may have been lower requiring a longer TTS.

Although no group differences in TTS were present, visual cognition (visual motor composite score) was only correlated to TTS in the ACLR group. This suggests that although functional performance was similar between groups, the mechanisms for rapid stabilization potentially differ between ACLR and healthy athletes, with visual motor processing contributing to stabilization ability only in those with ACLR history. Afferent receptors within the knee joint and adjacent musculature detect joint position through both rapid and slow mechanisms.15 When performing the TTS task, the single-leg landing requires rapid afferent transmission for detection of joint position to stabilize after landing. The emphasis during visual motor ImPACT testing is speed of motor response to a sensory stimulus. Therefore, the overall goal of quick sensory integration to produce a motor action is representative in both the visual motor score as well as the TTS assessment. Potentially secondary to the disrupted afferent signals from the ACLR knee, more reliance on rapid visual motor processing is required to achieve TTS to the level of healthy controls. This may result in participants with an ACLR to engage in a different neural control strategy compensating with visual cognition to maintain dynamic postural control.62 Our findings coincide with a previous investigation that patients with ACLR engage different components of cognition for gait adaptation as compared with controls, allowing them to preserve or even enhance function potentially via altered cognition or other compensations for motor control.62

4.3 Neural activity associated with visual cognition

The neural correlate analysis demonstrated that those with ACLR had higher activity in the PCC when engaged in knee motor control that was associated with visual memory and visual motor scores, respectively. The precuneus is the medial aspect of the parietal lobe and is a multi-modal region for sensory processing, cognition, and motor control,43 and it demonstrates increased activity during attention-demanding tasks requiring visual-somatosensory integration. Traditionally, the precuneus has been divided on the basis of functional connectivity into anterior, middle, and posterior regions. Anterior precuneus is connected to the motor cortex, insula, and superior parietal lobule (somatosensory–motor integration), middle precuneus to the prefrontal and inferior parietal lobes (cognitive), and the posterior portion, predominantly the location of the visual cognitive neural correlate, is functionally connected to visual regions.44 Thus, the specific location of the increased precuneus activity associated with visual cognition in this study could be specific to ACL deafferentation reweighting sensory processing toward increased parietal-visual processing regions.

After ACLR, increased precuneus neural activity associated with visual cognition (both included ImPACT subscales) may indicate sensory integration inefficiency (more neural activity to complete same task), relative to control participants, which promotes reliance on visual cognition. During goal-oriented tasks, precuneus activity increases with relative complexity, because more sensory information is needed for task completion.44 Therefore, PCC and precuneus activity associated with visual cognition when engaging in a relatively simple knee movement could provide a neural compensatory pathway for visual cognition to maintain proprioception and dynamic stability.45

An alternative hypothesis for heightened precuneus and PCC activity after ACLR stems from repeated co-activation between frontal cortex (cognition) and with knee motor regions, mimicking standard rehabilitation. The precuneus and PCC are “core hubs” of the default-mode network responsible for strong connectivity to the frontal cortex.44,46 Functional connectivity of the PCC and precuneus with the medial prefrontal cortex provides motor planning regions with bodily representation and sensory information.43,47 Thus, the visually cognitive focus on knee motor function during
rehabilitation could depend on internal body representation and cognitive resources, increasing associated precuneus and PCC activity to maintain motor function after ACLR.

5 | IMPLICATIONS

Although the ACLR participants appeared to be similar to controls on measures of proprioception and TTS, their neural strategy to maintain performance was altered. The association of visual cognitive processing to proprioception and dynamic stability may not only be secondary to the afferent disruption after ACL injury, but due in part to how rehabilitation is typically prescribed. Direct visual cognitive attention and visual memory is consistently used throughout rehabilitation whereby patients are taught movement strategies like squatting and cutting using internal visual representations of their knee. Commonly used verbal and visual cues direct attention toward the injured knee joint, altering how knee motor control typically functions (with minimal direct visual attention) and potentially compromising the role of visual cognition when returned to sport, where visual attention is directed to the environment and not the knee.48,49 Therefore, the transfer of a movement strategy (such as jump landing stability) from the controlled clinic to chaotic sport environment can be limited50 in those with ACLR by the level of visual cognition they are able to dedicate to the movement, as rehabilitation encourages visual cognition to be employed to engage in movement execution to maintain knee motor control instead of movement planning based on environmental constraints. Clinicians may consider integrating various aspects of motor learning or attention manipulation to alter the course of typically allowed compensations after ACLR.48

6 | LIMITATIONS

The small sample size is a limiting factor for broad generalization of these findings. However, the ACLR and control group were matched on age, sex, activity level, and education status to limit confounds. The current findings were a part of a secondary analysis from a study with the primary purpose of investigating neural activity differences between healthy controls and individuals post ACLR; therefore, an a priori power analysis was not conducted and the risk of committing a type 2 statistical error (failure to find a significant difference when one exists) is possible for the between-group comparisons. However, the main findings from our study pertain to the significant within-group relationships of visual cognition with proprioceptive acuity and dynamic stability, to better understand how history of ACLR may result in differential contributions of visual cognition to sensorimotor control. Another limitation is that we only assessed AJPS at one target angle and with active reposition. Assessing AJPS or passive detection of motion at multiple joint angles might result in different findings.24,39 Furthermore, despite long time duration since surgery, our cohort was highly active and still engaged in competitive athletes, which possibly contributed to no group differences. However, despite a high activity level, the ACLR cohort had lower strength LSI and IKDC scores, relative to controls.

Future research should consider visual cognitive elements in movement testing, such as eye tracking or other measures of attention, movement complexity, or dual tasking to better isolate visual cognitive contributions to sensorimotor control after injury. In addition, although our metrics were primarily quadriceps-dominant, future work should consider integrating hamstring strength and quadriceps-to-hamstring ratio, as alterations in hamstring function may contribute to neural control changes after injury.51,52 Longitudinal investigations are needed to understand the contributions of visual cognition to postural stability throughout rehabilitation to return to sport to determine ideal windows for potential adjunctive interventions to reduce dependence on visual cognition for dynamic stability. Considering that visual cognitive differences may be present before injury or influenced by rehabilitation strategies, future research should consider evaluating neural activity associated with cognitively demanding motor control processes before and after musculoskeletal injury.

7 | CONCLUSION

The findings of this preliminary investigation implicate visual cognition as a compensatory mechanism to sustain knee proprioception and dynamic stability after ACLR, potentially through increased sensory integration neural activity.

ACKNOWLEDGMENTS

The contributing authors have no conflicts of interests corresponding with this manuscript. This study was funded in part by the National Athletic Trainers’ Association Research and Education Foundation, National Strength and Conditioning Association Foundation, and The Ohio State University College of Medicine. Dr. Grooms has current and ongoing funding support from the National Institutes of Health/National Center for Complementary and Integrative Health (R21 AT009339-02), National Institute of Arthritis and Musculoskeletal and Skin Diseases (R01 AR076153-01A1), and the Department of Defense Peer Reviewed Orthopedic Research Program (OR170266). Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the Department of Defense.

AUTHOR CONTRIBUTIONS

Meredith Chaput and Janet E. Simon contributed to the analysis and interpretation of data, writing, and revisions of the manuscript. James A. Onate contributed to manuscript revisions. Cody R. Criss contributed to the analysis, interpretation of data, and writing. Steve Jamison contributed to data collection, analysis, and methodology. Michael McNally made contributions to experimental design, data collection, and revisions. Dustin R. Grooms contributed to experimental design, conceptualization, analysis, data interpretation,
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