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Dynamic-Position-Sense Impairment's Independence of Perceived Knee Function in Women With ACL Reconstruction

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Abstract

Context—There is conflicting evidence in the literature regarding whether women with anterior cruciate ligament reconstruction (ACLR) demonstrate impaired proprioception. This study examined dynamic-position-sense accuracy and central-nervous-system (CNS) processing time between those with and without long-term ACLR.

Objective—To compare proprioception of knee movement in women with ACLR and healthy controls.

Design—Cross-sectional.

Setting—Human neuromuscular performance laboratory.

Participants—11 women (age 22.64 ± 2.4 y) with ACLR (1.6–5.8 y postsurgery) and 20 women without (age 24.05 ± 1.4 y).

Interventions—The authors evaluated subjects using 3 methods to assess position sense. During knee flexion at pseudorandomly selected speeds (40°, 60°, 80°, 90°, and 100°/s), subjects indicated with their index finger when their knee reached a predetermined target angle (50°). Accuracy was calculated as an error score. CNS processing time was computed using the time to detect movement and the minimum time of angle indication. Passive and active joint-position sense were also determined at a slow velocity (3°/s) from various knee-joint starting angles.

Main Outcome Measurements—Absolute and constant error of target angle, indication accuracy, CNS processing time, and perceived function.

Results—Both subject groups showed similar levels of error during dynamic-position-sense testing, despite continued differences in perceived knee function. Estimated CNS processing time was 260 ms for both groups. Joint-position sense during slow active or passive movement did not differ between cohorts.

Conclusions—Control and ACLR subjects demonstrated similar dynamic, passive, and active joint-position-sense error and CNS processing speed even though ACLR subjects reported greater impairment of function. The impairment of proprioception is independent of post-ACLR perception of function.

Keywords

female; neuromuscular control; proprioception; reflex; surgery

Anterior cruciate ligament (ACL) injuries typically occur during complex movement sequences such as rapid deceleration, cutting or pivoting on a planted foot, or landing on 1 leg.¹ High-speed movements require rapid processing of sensory inputs to trigger appropriate neuromuscular-control strategies in response to external environmental forces.^{2–6} The rationale for many rehabilitative treatments is grounded in the notion that women with ACL reconstruction (ACLR) or injury suffer from a more impaired ability to accurately discern joint-angle velocity or position from various sensory inputs from the knee (proprioception), leading to a higher incidence of injury.

There is conflicting evidence in the literature regarding whether patients with ACLR demonstrate impaired proprioception. A few reports suggest that proprioception deficits persist after ACLR,^{7,8} but most support full recovery of proprioception.^{4–9} However, the proprioception tasks in many of these studies do not simulate proprioception challenges faced by patients after return to normal activities. Most previous studies have examined kinesthesia, a subcomponent of proprioception, via joint rotations at low velocity.^{7,9–13} These low velocities may not resemble those in joint rotations common during functional activities.^{14,15} There is evidence that patients with ACLR show altered reactive muscle-activation patterns during functional tasks^{4,5}; however, it is unclear whether ACL injury adversely affects central-nervous-system (CNS) processing of somatosensory inputs from the knee. Numerous factors support a role for the ACL in sensorimotor control, including the presence of mechanoreceptors in the ligament,¹⁶ reflex connections from the ACL to the hamstrings,^{17,18} and the presence of somatosensory evoked potentials in response to electrical and mechanical stimulation.¹⁹ However, the relative contribution of the ACL to proprioception, in concert with joint receptors, skin receptors, and group Ia/II-spindle afferents, is uncertain. The redundancy inherent in multimodal control of proprioception may offset any deficits in reconstructed ACL somatosensory input. The effect of ACLR on central integration of proprioceptive inputs is currently unknown.

The purpose of this study was to determine whether proprioception of knee movement is impaired in women with ACL reconstruction and whether potential impairments are associated with impairments in perceived function. Proprioception was examined by comparing subjects with intact and reconstructed ACLs with regard to dynamic-position-sense error, CNS processing time of sensory information, and joint-position-sense error during active and slow passive reproduction of a target position. We hypothesized that proprioceptive measures of impairment would be independent of perceived knee function in women with chronic ACLR.

Methods

Design

This cross-sectional study had 2 independent variables including group (ACLR and control) and proprioception-test type (dynamic, active, and passive). The dependent variables included knee-position error scores (absolute error, constant error), EMG amplitudes, and perceived impairment on patient-oriented outcome measures.

Participants

The study sample consisted of 31 women (20 controls, 11 ACLR patients) age 21–29 years. Inclusion criteria for the ACL group included having had complete ACLR with either patellar tendon or hamstring autograft at least 1 year previously, the ability to climb stairs without difficulty, full joint range of motion, regular physical activity, and absence of knee-joint effusion. Individuals who had undergone meniscal repair ($n = 3$) along with ACLR were also included in the study. Exclusion criteria were concomitant ligament injury, any prior knee surgery on the ipsilateral or contralateral knee, or pain during activity or rest. The mean time since surgery for the ACLR group was 3.61 years (SD 1.98, range 1.6–5.8). Young active women who had no prior knee pathology composed the control group. Each subject provided written informed consent before participation in the study in accordance with the institutional review board. All subjects were right-foot dominant, and the side of injury was countered by testing comparable sides in the control group.

Patient-Oriented Outcome Measures

Subjects completed patient-oriented outcome measures to investigate whether potential observed differences in proprioceptive function were associated with changes in functional activity, general health, or perceived impairment.

Subjects were measured for activity level by the Marx Activity Scale²⁰ and the Tegner Activity Rating Scale,²¹ quantifying subjects' general functional activity and sport-specific activity levels, respectively. Both are short, patient-reported activity assessments we included to investigate whether function in high-demand sport activity, as well as activity generalized to daily function, differed between subject groups.

The IKDC Subjective Knee Evaluation Form²² is a site-specific form designed to measure sports activity, function, and symptoms in patients with 1 or more knee conditions. Scores are represented as a single index, with higher scores representing greater function and lower knee symptoms. The KOOS Knee Survey²³ is another site-specific inventory used to evaluate short- and long-term symptoms and function in patients with knee pathology. This scale was included to measure knee-specific function across 5 separate subscales: pain, other symptoms, function in daily living, function in sport and recreation, and knee-related quality of life.

The Short Form Medical Outcome Survey (SF-36)²⁴ is a general health outcome measure we included to determine whether any perceived impairment by subjects extended beyond sport- or joint-specific function.

Experimental Procedure

The experimental task required subjects to use proprioceptive information from the lower extremity to trigger a sequential upper extremity movement (index-finger flexion). Subjects were positioned in an isokinetic dynamometer (Kin-Com 125E Plus, Chattecx Corp) that allowed passive or active flexion and extension of the knee through a 70° movement arc (10–80° knee flexion). Subjects tapped a pressure-sensitive wafer switch with the index finger when they perceived that the knee had reached a previously defined target angle. Subjects wore headphones playing white noise to remove auditory feedback and wore a blindfold to obscure vision during the task.

The experimental task was divided into 5 conditions: passive, active, dynamic practice, dynamic, and reaction time. In each condition, the examiner positioned the subject's knee at the target angle for 5 seconds to allow development of internal representation of the limb position. The order of passive, active, and dynamic conditions was counterbalanced in the ACLR and control groups. The order in which the velocities were introduced was pseudorandom. That is, the Kin-Com was preprogrammed for 6 different velocity-order patterns. The pattern to be introduced was assigned randomly.

Dynamic-Position-Sense Testing—Dynamic position sense is rarely a part of proprioception assessment in patients with orthopedic conditions but has been used extensively in the motor control literature.^{2,3,25–29} The advantage of this assessment is that the subject must interpret the velocity and make a prediction as to when the knee will reach the 50° target angle. At slow velocities, the subjects can use “position” information. However, at higher velocities, the subject must “interpret” the early velocity information to make a prediction when the knee will pass through the target angle. Because the subjects did not know what velocity was coming with each trial, they had to strive to process early information to indicate when the knee would pass through the target angle. This response is in contrast with a pure simple volitional reaction time, which would reflect a simple indication as to when the knee moves, rather than striving to process information to predict when it will pass through the target angle. The difference between the simple volitional reaction time and the more complicated processing time to interpret the target becomes the additional CNS processing time.^{2,25}

To learn the process, subjects performed 12 dynamic practice repetitions, 2 at each experimental angular velocity (40°, 60°, 80°, 90°, and 100°/s). The examiner positioned the subject's knee at the target angle (50°) for 5 seconds to allow development of internal representation of the limb position and then placed the subject's knee at a uniform starting position for all velocity trials (10° of knee flexion). As the dynamometer flexed the knee at each given velocity, the subject indicated as the knee passed through the target angle. Verbal feedback was provided after each practice repetition via one of 5 cues: very early (>10° before the target angle was reached), early (4–10°), perfect (0–3°), late (4–10°), and very late (>10°). Subjects got results via visual feedback displaying knee angle, target angle, and index-finger indication time after the second repetition of each velocity (Figure 1).

For purposes of testing, subjects completed 20 dynamic-position-sense trials as described in the practice trials, 4 at each experimental angular velocity in pseudorandom order. The

investigators provided no feedback or results for the test trials. Finally, subjects performed reaction-time tests at each presented experimental velocity (4 for each velocity). Accordingly, they touched the wafer switch as soon as they detected the onset of knee flexion by the dynamometer.

Passive Trials—After positioning the subject's knee at the target angle (50° of knee flexion) for 5 seconds, the examiner placed the knee at a randomly selected starting position (20°, 30°, 40°, 60°, 70°, 80°, or 90° of knee flexion). From this starting point, the examiner passively flexed or extended the knee in the dynamometer at ~3°/s through the target angle to the end of the movement arc. Subjects were instructed to indicate by tapping the force sensor when the knee reached the target angle. The computer digitally recorded the precise angle at the time of indication. Subjects performed 2 repetitions from each starting position.

Active Trials—In the active trials, subjects actively held the knee for 5 seconds at the target angle (50°) to establish internal representation with descending neural drive. The examiner then placed the knee at a randomly selected starting position (20°, 30°, 40°, 60°, 70°, 80°, or 90° of knee flexion). Subjects actively flexed or extended the knee at a slow, self-selected angular velocity to the perceived target angle, indicating via the switch when reaching the target.

We chose only the knee-flexion motion to focus on the motion that quite often is involved with noncontact knee injuries. We opted to limit the expanse of the experiment so subjects could remain focused on this single task. Concentration is important to gaining credible data during these types of tasks. Thus, our preliminary data confirmed that subjects could maintain focus better for a shorter-duration experiment. We therefore did not include knee extension in this study.

Knee-Laxity Measurements

Stability of the ACLR and noninjured knees of the ACLR group was measured using a KT-2000. Measures were obtained after the conclusion of all dynamic-position-sense testing by a physical therapist.

EMG

EMG activity was recorded before and during knee rotation at each dynamic velocity to investigate whether anticipatory or reflex CNS activity may have influenced task performance. Bipolar silver–silver chloride surface EMG electrodes (8 mm in diameter, fixed intercontact distance of 20 mm) recorded activity in the vastus lateralis and lateral hamstring muscles. Each electrode contained an onsite preamplifier with a gain of 35. The signal was further amplified by a GCS 67 amplifier (Therapeutics Unlimited, Iowa City, IA) with adjustable gain from 500 to 10,000. The amplifier used a high-impedance circuit (>15 MΩ at 100 Hz) with a common-mode rejection ratio of 87 dB at 60 Hz and a bandwidth of 40–4000 Hz. The vastus lateralis electrode was placed at two thirds the distance from the anterosuperior iliac spine to the lateral joint line. The lateral hamstring electrode was placed at half the distance from the ischial tuberosity to the lateral knee-joint line.³⁰ All subjects performed 3 maximum voluntary contractions (MVCs) for 3 seconds at 50° of knee flexion

for both knee flexion and knee extension before the experimental tasks. Generally, the gain was fixed at 10,000 times.

Data Recordings

A 12-bit A-D converter digitally sampled all signals. Datapac 2K2 Version 3.17 (Run Technologies, Inc, Laguna Hills, CA) was used to display the integrated data from the A-D converter. The EMG data were sampled at 2000 Hz, and all other data were sampled at 200 Hz.

Data Analysis

Digitized data were plotted using Sigmaplot (Windows version 10.0, SPSS Inc). Dynamic, active, and passive position senses were examined by calculating absolute error, constant error, reaction time, and EMG amplitude. Absolute error (overall accuracy of performance) was calculated as the mean absolute value of the indication-angle error. Constant error was the mean knee angle at the time of indication. In constant-error estimates, positive and negative values are included in mean calculations and can thus cancel each other. Constant error therefore provides information regarding the overall direction of indication error. The time of indication in the dynamic-position-sense trials was calculated as the time from the onset of knee displacement until the subject tapped the wafer switch, indicating the perceived moment the knee reached the target angle. Time to target was calculated as the time interval from the onset of knee displacement to the instant the target angle was actually reached by the knee. Reaction time, measured in separate trials from the dynamic-position-sense trials, was calculated as the time interval from the onset of knee displacement until the subject touched the wafer switch to indicate the onset of movement only, without regard for joint velocity. Central processing time, reflecting the ability of the CNS to use proprioceptive information to trigger the coordinated finger-tapping response, was estimated by subtracting the lower time limit for accurate dynamic position sense from the simple reaction-time measures.

The EMG signal was root-mean-square processed with a time constant of 10 milliseconds. Separate vastus lateralis and lateral hamstring EMG-amplitude root-mean-square values were calculated over the 500-millisecond time window preceding the knee displacement and the time window encompassing the entire knee-flexion displacement at each velocity. The mean increase from resting EMG was calculated and normalized to mean EMG during maximum voluntary contraction.

Statistical Analysis

Statistical analysis was performed with SAS software (v9.1, SAS, Cary, NC). Knee-function survey measures were analyzed using *t* tests to compare ACLR patients and controls. One-way ANOVA with repeated measures on velocity was used to evaluate absolute error, constant error, and EMG amplitude for the dynamic condition. Independent *t* tests evaluated constant-error and absolute-error differences between the ACLR group and the control group in the active and passive conditions. Post hoc analysis using Tukey's Studentized range was performed on significant main effects. Results of all analyses were considered significant at $P = .05$.

Results

Comparisons of the ACLR group's and control group's demographics and quality-of-life measurements are presented in Table 1. All subjects were similar in age, height, and composite SF-36 score. KT-2000 arthrometer measurements revealed a mean side-to-side difference of 3.14 mm (SD = 2.12) in the ACLR group.

Patient-Oriented Outcome Measures

Activity scores and subjective ratings of impairment are presented in Table 1. The ACLR and control groups did not differ in scores on the Marx Activity Scale or the Tegner Activity Rating Scale. Despite the similarity in activity level, the ACLR group scored lower on the physical-function subset of the SF-36 (94.5 ± 7.89) than the control group (99.5 ± 1.54 ; $P = .01$). On the KOOS scale, ACLR subjects scored lower on ratings of pain, symptoms, participation in sports and recreation, and quality of life, indicating greater perceived impairment in these areas. The ACLR group scored significantly lower on the IKDC scale (84.97 ± 6.3) than the control group (98.57 ± 4.8 ; $P < .05$).

Dynamic-Position-Sense Accuracy

A representative example of the data acquired during a single dynamic-position-sense trial is shown in Figure 1. The absolute error of finger-indication accuracy at each velocity was analyzed to determine whether the ACLR and control groups differed in the ability to use proprioceptive information to trigger a movement sequence in the upper extremity. There was no significant effect of subject group ($F_{1,145} = 3.76$, $P = .053$) or subject $\times$ velocity interaction ($F_{5,145} = 1.52$, $P = .18$), indicating that the ACLR and control groups did not differ in their ability to perform the task. A significant effect of velocity ($F_{5,145} = 10.21$, $P = .0001$) indicated that the magnitude of absolute error differed between angular-displacement velocities.

To further examine how sensory information from the knee is used to coordinate the movement sequence, the time taken by the knee to reach the target angle (time to target) and the time of finger indication on the wafer switch (time of indication) were plotted as a function of knee angular velocity (Figures 2[A] and 3[A]). In the range from 40° to $80^\circ/\text{s}$, both groups accurately scaled their time-of-indication responses to match the time at which the knee reached the target angle across the different knee velocities. A closer analysis of the time-of-indication responses at 90° and $100^\circ/\text{s}$ showed that subjects in both groups were unable to trigger their finger movement quickly enough to match the target angle (Figures 2[B] and 3[B]). On average, both ACLR subjects and controls stopped scaling responses accurately at a lower limit of 450 to 475 milliseconds after the onset of movement.

The ACLR and control groups did not differ in the average magnitude of constant error ($F_{1,145} = 0.07$, $P = .79$), nor was there any significant subject type $\times$ velocity interaction ($F_{5,145} = 0.83$, $P = .52$). A significant effect of velocity ($F_{5,145} = 50.76$, $P < .0001$) indicates that errors in performance were directionally biased similarly in both groups at specific velocities. Post hoc analysis of constant error showed that the magnitude of error at angular velocities of 40° , 60° , and $80^\circ/\text{s}$ did not differ between groups. Constant error was

significantly greater than 0 (knee flexed greater than target angle) at velocities of 90° and 100°/s ($P < .05$; Figure 4).

Triggered Responses Versus Reaction Time

Reaction times during the dynamic-position-sense task were calculated from 80° to 100°/s to examine whether subjects were triggering the higher-velocity responses based on interpreting sensory information (which takes processing time) or simply reacting to dynamometer movement irrespective of angular velocity. Average reaction time across the 80° to 100°/s velocities was 212.81 ± 54.0 milliseconds for the ACLR group and 209.13 ± 42.5 milliseconds for the control group. The pooled reaction times did not vary between groups ($P = .71$), nor did reaction time vary between groups at the individual velocities of 80°, 90°, or 100°/s. Based on the time of indication at each velocity from 80° to 100° the average time necessary for the CNS to process the proprioceptive information (mean time of indication [450–475 ms]) – mean reaction time [213–209 ms]) was 255 milliseconds for ACLR subjects and 263 milliseconds for the control group.

Active-Position-Sense Accuracy

Mean absolute error did not differ between the ACLR and control groups ($P = .09$) when subjects were asked to actively move the knee from a pseudorandom starting position to the previously demonstrated target angle. The overall magnitudes of absolute error in the active task were $7.65^\circ \pm 5.27^\circ$ and $6.96^\circ \pm 5.58^\circ$ for the ACLR and control groups, respectively. The ACLR group exhibited significantly greater constant error in the active task, with a mean deviation of $-6.64^\circ \pm 6.5^\circ$ compared with $-4.69^\circ \pm 7.60^\circ$ for the control group ($P = .0001$; Figure 5[B]).

Passive-Position-Sense Accuracy

The ACLR and control groups did not differ in absolute-error magnitude during passive-joint-position-sense testing at 3°/s ($P = .21$). ACLR subjects displayed a mean error of $10.18^\circ \pm 6.85^\circ$ compared with $9.64^\circ \pm 6.96^\circ$ for healthy controls (Figure 5A). The constant-error means for the ACLR and control groups were $-9.21^\circ \pm 8.12^\circ$ and $-7.71^\circ \pm 9.06^\circ$, respectively ($P = .003$). The negative constant-error mean values indicate that both groups, on average, undershot the target angle, with the knee in greater extension than the target angle.

EMG

During the dynamic and passive tasks, the mean EMG amplitude remained less than 0.56% of MVC. ACLR subjects showed greater mean vastus lateralis activity before knee displacement (0.52% MVC) than controls (0.09% MVC; $F_{1,145} = 20.29$, $P < .0001$). Vastus lateralis activity was likewise higher for ACLR subjects during dynamic knee rotation, 0.56% and 0.25% for the ACLR and control groups, respectively ($F_{1,145} = 28.14$, $P < .0001$). Lateral hamstring activity did not differ between groups during the displacement ($P = .47$), although ACLR subjects showed greater activity before displacement, with 0.13% compared with 0.08% for controls ($P = .013$).

Discussion

In this study, we used a novel method to estimate the temporal processing of the CNS for proprioceptive information in those with ACLR. We determined the effect of ACLR on proprioception of knee movement, as illustrated by dynamic-position-sense error at high velocities, CNS processing time, and joint-position-sense error during active and slow passive reproduction of a target position. Subjects with ACLR did not differ from healthy controls in magnitude of joint-position-sense error during high-velocity dynamic, active, or passive movements through a predetermined target angle (50°). ACLR subjects and controls exhibited similar CNS processing time for a triggered upper extremity movement sequence. However, despite similar performance on proprioception tasks, ACLR subjects differed from controls in subjective knee-function ratings.

Dynamic Position Sense

The dynamic-position-sense task, used previously in the ankle,^{25–27} required the CNS to account for position and velocity during joint rotation at various angular velocities. By offering many velocities, this method enables investigation of the limits at which the CNS can accurately scale responses based on existing inputs. If reflex loops mediated by the ACL are lost or negatively altered by ligament reconstruction, the amount or quality of afferent information may not be adequate for accurate task performance. Declines may be reflected in task precision (magnitude of error) or timing (CNS processing time).

No previous studies have examined dynamic position sense of ACLR knees at the high velocities used in this report. Although knee angular-rotation velocities are higher still in volitional activities,^{14,15} we observed that at 90° and 100°/s, the time of indication ceased to scale appropriately for both subject groups. Introducing velocities greater than 100°/s in this protocol would not have been fruitful because of the limitations imposed by the CNS processing time to indicate knee-joint position.

For velocities below 90°/s, dynamic-position-sense error did not differ for control and ACLR subjects, suggesting that this submode of proprioception was not impaired for the ACLR group. At 90° and 100°/s, when subjects ceased to correctly scale the time of indication, constant-error values indicate that they triggered the wafer switch when the knee passed beyond the target angle, an “overshoot” error. This finding suggested that at the fastest velocities, there was insufficient time for detection of movement and processing and initiation of the upper extremity motor sequence. To explore this possibility further, we examined CNS processing time for this task.

CNS Processing Times

Both groups ceased to scale the indication responses beyond a lower time limit of 450 milliseconds. However, subjects did not rely on simple reaction to movement; mean reaction time in both groups ranged from 190 to 230 milliseconds across all velocities. This finding indicates that subjects attempted to use the initial velocity to predict the time at which the knee would reach the target angle. This strategy would depend heavily on input from fast-adapting, velocity-sensing Ia afferent fibers. At slower joint-rotation velocities, afferent

bursts from Ia fibers are minimal,³¹ suggesting that input from slower-adapting, length-dependent group II fibers may be more useful during the slowest test conditions.

By subtracting simple reaction time from the limits-of-response scaling, we estimated the CNS processing time at approximately 260 milliseconds. This estimate is noticeably longer than processing-time estimates for the ankle (85 milliseconds) during a similar task.^{25,26} The longer processing time at the knee, despite a seemingly shorter reflex arc than in the ankle, may reflect the starting position of the task. Estimates in the ankle were made from movement starting in the joint midrange (0° plantar flexion), whereas our estimates were derived from movement starting in a shortened muscle position (10° knee flexion) where muscle-spindle sensitivity is low. Determination of initial movement velocity by Ia afferents may have been undermined by the “slack” quadriceps starting position, prolonging the central processing phase for the upper extremity motor sequence. The low level of background EMG activity before movement (0.09–0.5% MVC for the 2 groups) indicates that subjects did not volitionally contract the quadriceps to increase stiffness (and therefore Ia afferent sensitivity) at the start of joint rotation.

Active and Passive Position Sense

To test active and passive angle reproduction, we flexed or extended the knee to a predetermined starting angle within a possible range of 10° to 80°. This method differs from previous reports^{32,33} in that movement began from randomized starting positions; subjects could therefore not use the timing of movement onset as an external cue to aid performance. The ACLR and control groups did not differ in the magnitude of absolute error. The major finding from these tasks is that both groups showed approximately 10° of error with passive and 7° with active angle reproduction. Reider et al³² documented similar active position-reproduction errors in ACLR (5.6–7.3°). Unlike the current study, those authors randomized target angles, rather than starting angles, to reduce subjects’ ability to use movement timing to cue performance. Other reports have shown higher error estimates for passive angle reproduction than we observed.^{7,11} Although direct comparison between methods is difficult, we believe that testing a variety of starting angles offers a more accurate reflection of sensorimotor performance than single-angle designs.

Patient-Oriented Outcome Measures

Despite similarities in performance on proprioceptive tasks, ACLR subjects rated their physical function as significantly worse than controls. This result is consistent with MacDonald et al,¹² who found no correlation between patient satisfaction scores and average deficits in joint-position sense in ACLR patients. This finding suggests that variables other than proprioception affect the perception of knee function in ACLR subjects.

We chose to study women in this study because they have a 4 to 6 times higher incidence of ACL rupture than men participating in the same landing and pivoting sports,³⁴ potentially because of anatomic risk factors (femoral anteversion, increased Q angle, narrower intercondylar notch)³⁵ or hormonal differences.³⁶ At the expense of generalizability to men, we elected to restrict our investigation to the population at greatest risk for ACL injury and to minimize heterogeneity of the sample groups.

This study cannot address the effects of closed kinetic chain movement on the processing of proprioceptive information. Weight bearing adds additional sensory feedback that may influence joint-position sense, particularly as movement complexity increases. However, we recently demonstrated that proprioception in weight bearing may be unimpaired after ACLR,³⁷ similar to the open kinetic chain results of the current study.

The time since surgery for ACLR subjects in the current report may have influenced error scores during passive-position-sense testing. Fremerey et al³⁸ demonstrated that knee midrange proprioception deficits in ACLR limbs 6 months postsurgery improved at 3.7 years postsurgery. The uniform performance during passive motion testing between cohorts in the current report may reflect the ACLR cohort's time postsurgery (3.6 y). However, the presence of significant differences in perceived function between groups suggests that these differences cannot be explained by impaired proprioception.

Conclusion

Individuals with ACLR demonstrate similar joint-position-sense error and CNS processing speed as control subjects with similar activity levels, but impaired perception of function. Proprioception submodes other than joint-position sense may continue to be implicated in post-ACLR neuromuscular control. Understanding the impact of ACLR on sensory-system processing during dynamic tasks will be integral to establish the scientific basis for rehabilitation programs that purport to train proprioception after ACLR.

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Figure 1.

Representative example of dynamic-position-sense trial. The top 2 traces show the EMG recordings from the vastus lateralis and lateral hamstring muscles. The angled line depicts the change in knee displacement from 10° to 80° of knee flexion imposed by the isokinetic dynamometer (40°/s shown). The center horizontal trace represents the target angle of 50°. The bottom trace represents triggering of the wafer switch with the index finger. In this particular trial, the subject accurately tapped the wafer switch as the knee reached the target angle.

Figure 2.

The time to target (filled circles), time of indication (open circles), and reaction time (filled triangles) shown as a function of velocity in the dynamic-position-sense trials for anterior cruciate ligament–reconstructed subjects. (A) All 5 velocities. (B) Only the 3 fastest velocities (note difference in scale). Note in (B) that responses stop scaling at 90° and 100°/s. Reaction-time trials and triggered responses (time of indication) were significantly different ($P < .05$). Data points are mean $\pm$ SE of 11 subjects.

Figure 3.

The time to target (filled circles), time of indication (open circles), and reaction time (filled triangles) shown as a function of velocity in the dynamic-position-sense trials for control subjects. (A) All 5 velocities. (B) Only the 3 fastest velocities (note difference in scale). Control subjects stopped scaling at 90° and 100°/s, similar to anterior cruciate ligament–reconstructed subjects. Reaction-time trials and triggered responses were significantly different ($P < .05$). Data points are mean $\pm$ SE of 20 subjects.

Figure 4.

Constant error of knee angle during the dynamic-position-sense trials plotted as a function of angular velocity for anterior cruciate ligament–reconstructed (ACL) subjects and healthy controls. ACL subjects and controls showed similar levels of error at all angular velocities, including 40°/s ($P = .13$). Negative values represent knee flexion less than the target angle of 50°. Data values are mean $\pm$ SE.

Figure 5.

Mean absolute and constant error during (A) passively reproduced knee flexion at $3^\circ/\text{s}$ and (B) actively reproduced knee flexion for anterior cruciate ligament–reconstructed (ACL) subjects and healthy controls. Negative constant-error values indicate that the knee was flexed less than the 50° target angle at time of indication. Error bars are $\pm$ SE.

Table 1Knee-Function Measures, Mean $\pm$ SD

Measure	Controls	ACLR	P
SF-36			
physical function	99.5 (1.5)	94.5 (7.9)	.01
role physical	100.0 (0.0)	97.7 (7.5)	NS
bodily pain	88.1 (11.4)	86.1 (15.5)	NS
general health	86.4 (8.9)	83.5 (10.5)	NS
vitality	65.0 (18.7)	61.4 (19.3)	NS
social functioning	96.3 (16.8)	95.5 (11.6)	NS
role emotional	93.4 (23.2)	87.9 (27.0)	NS
mental health	79.4 (17.8)	74.2 (17.0)	NS
KOOS			
pain	98.33 (3.4)	92.93 (5.1)	.006
symptom	98.04 (2.8)	83.77 (6.1)	<.0001
activities of daily living	99.85 (6.1)	98.53 (6.5)	NS
sport/recreation	99.00 (5.5)	82.27 (7.2)	.002
quality of life	96.88 (3.2)	71.59 (6.4)	<.0001
IKDC	98.57 (4.8)	84.97 (6.3)	<.0001
Marx	8.50 (7.2)	9.911 (9.4)	NS
Tegner	7.11 (3.5)	6.555 (4.2)	NS

ACLR, anterior cruciate ligament–reconstructed subjects.