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Restoration of sagittal and transverse plane proprioception following anatomic double-bundle ACL reconstruction

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Abstract
Purpose To investigate the restoration of knee proprioception after anatomic double-bundle ACL reconstruction.
Methods Eleven subjects who underwent anatomic double-bundle ACL reconstruction (12.5–15 months following surgery) and eleven healthy control subjects participated in the study. Sagittal and transverse plane threshold to detect passive motion (TTDPM) were assessed utilizing a customized isokinetic dynamometer by passively rotating the tibia about a fixed femur in both the sagittal plane and transverse plane at 0.25°/s until the subject signalled recognition of movement and movement direction. Based on the normality assumption, either dependent *t* test or Wilcoxon test was utilized to determine whether significant differences were present between the ACL-reconstructed and the uninjured contralateral limbs. Independent *t* test or Mann–Whitney test was utilized to compare between the ACL-reconstructed/uninjured contralateral and the external control limbs.
Results There were no significant differences in TTDPM measurement in eleven out of twelve comparisons between the ACL-reconstructed and the uninjured contralateral/external control limbs. The only statistical significant difference was found on TTDPM towards internal rotation direction from the externally rotated-test position between the ACL-reconstructed and the uninjured contralateral limbs ($p = 0.01$).
Conclusions Based on a small sample of eleven subjects, the current results indicate a restoration of both sagittal and transverse plane TTDPM following the anatomic double-bundle ACL reconstruction.
Level of evidence III.

Keywords Sagittal and transverse plane · Anatomic double-bundle ACL reconstruction · Threshold to detect passive motion · Proprioception

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Introduction

The sensorimotor system (afferent sensory information, central processing and integration, and neuromuscular control) has been recognized as essential in the maintenance of knee stability [36]. The anterior cruciate ligament (ACL) acts to mechanically stabilize the knee primarily by resisting anterior translation and secondarily by valgus/varus and internal/external rotation of the tibia on the femur [1, 2, 24], but also provides afferent information that is utilized as proprioceptive information during lower extremity loading. Histological studies have shown that Ruffini endings, Pacinian corpuscles, Golgi-like receptors, and free nerve endings are present in the intact ACL [8, 11]. Proprioceptive signals from these mechanoreceptors are integrated into the sensorimotor system and contribute to successful neuromuscular control of the lower extremity. Injury to the ACL will result in a loss of both mechanical stability and proprioceptive feedback at the knee, directly affecting functional joint stability and can lead to further deterioration of the knee joint integrity [21, 23]. The mechanical restraint and proprioceptive function of the ACL both help to provide functional joint stability of the knee during movement. Therefore, it is essential to monitor the restoration of proprioception after an ACL injury or ACL reconstruction/rehabilitation for safe and functional return to activities of daily living and sport [6, 23].

Knee proprioception deficits exist after an injury to the ACL [5, 7, 31], and these proprioceptive deficits correlate with a decrease in functional performance [5]. Additionally, proprioceptive deficits can be present in the contralateral uninjured knee following an ACL injury [30, 35]. Furthermore, reconstructive surgery to repair the ACL may or may not fully restore proprioception when ACL-reconstructed limbs are compared to uninjured contralateral and external control limbs [4, 22, 30, 35, 37]. For example, Reider et al. [35] and Ozenci et al. [30] reported no significant difference in proprioception when ACL-reconstructed limbs were compared to uninjured contralateral and external control limbs while Roberts et al. [37] and Bonfim et al. [4] reported bilateral proprioceptive deficits following ACL reconstruction compared to external control limbs. Due to differences in methodologies, subject demographics, surgical techniques, rehabilitation procedures, it is difficult to explain the mixed results. However, further investigation on proprioception following ACL reconstruction is warranted.

Traditionally, ACL reconstruction has focused on the restoration of tibial anterior translation on the femur with a single-bundle technique. Tashman et al. [39, 40] reported tibial anterior translation was restored following single-bundle ACL reconstruction; however, abnormally greater external rotation and varus angles were observed. More recently, anatomic double-bundle ACL reconstruction has gained much attention because it attempts to reconstruct the ACL's native dimensions, collagen orientation, and insertion sites [42, 43] and has been shown to restore mechanical stability (Lachman's test, pivot-shift translation, and pivot rotation of the tibia) when compared to nonanatomic single-bundle ACL reconstruction [19, 26]. One of the primary goals of anatomic double-bundle ACL reconstruction is the restoration of normal kinematics in both the sagittal and transverse planes, and reviews of biomechanical studies show favourable results following anatomic double-bundle ACL reconstruction [18, 44]. Prospective studies were conducted to investigate long-term outcomes from different ACL reconstruction techniques (conventional/anatomic single-bundle and anatomic double-bundle) and reported that the anatomic double-bundle ACL reconstruction technique was better restoring rotational stability [15, 20].

Despite more and more orthopaedic surgeons perform anatomic double-bundle ACL reconstructions, in part thanks to advances in surgical technique and navigation technology [16, 41], the effects of anatomic double-bundle ACL reconstruction on proprioception have not been investigated. Furthermore, it is essential to measure proprioception in both the sagittal and transverse planes to correspond with the primary goals of anatomic double-bundle ACL reconstruction. We are aware of one study that has included proprioception tests in the transverse plane and indicated the restoration of the proprioception after single-bundle ACL reconstruction [25]. Evaluating proprioception in both planes would be clinically significant for researchers and clinicians and an important step to further understand the restoration of the knee joint integrity after anatomic double-bundle ACL reconstruction. Therefore, the purpose of this study was to evaluate the sagittal and transverse threshold to detect passive motion (TTDPM) following anatomic double-bundle ACL reconstruction and compare among ACL-reconstructed, uninjured contralateral, and external control limbs. It was hypothesized that subjects who underwent anatomic double-bundle ACL reconstruction would not show any deficits in TTDPM in the sagittal or transverse planes of the ACL-reconstructed limbs compared to the uninjured contralateral and external control limbs.

Materials and methods

A total of twenty-two subjects (eleven subjects with ACL reconstruction and eleven controls) participated in this study. Eleven subjects (seven males and four females) underwent anatomic double-bundle ACL reconstruction (12.5–15 months post-operation). All subjects with ACL reconstruction were free from other cartilage, meniscus, or ligamentous injuries. Eleven healthy subjects (seven males and four females) were matched based on gender, age, height, and weight to serve as external controls (age 23.1 ± 4.8 and 22.5 ± 3.2 years, height 175.5 ± 6.8 and 178.0 ± 10.6 cm, weight 78.0 ± 13.3 and 76.4 ± 12.7 kg for the ACL-constructed and control group, respectively). All subjects were physically active, defined as participating in physical activity at least thirty minutes a day for three times per week. Potential control subjects were excluded from participating in this study if they had any history of major lower extremity injuries that required surgery. All subjects provided informed consent prior to any testing in accordance with the University Institutional Review Board.

Double-bundle ACL reconstruction and rehabilitation

All double-bundle anatomic ACL reconstructions were performed by the same orthopaedic surgeon (F.H.F.). Allograft was used. Each subject with the double-bundle anatomic ACL reconstruction followed the same post-surgical progression guidelines during the rehabilitation process. Rehabilitation guidelines were standardized by the orthopaedic surgeon with a five-phase programme listing precautions, goals for range of motion, performance, and exercise, along with criteria for the advancement to each phase. Phases one through three began immediately and lasted to about 6 months post-operation. Phase one consisted of being locked in full extension until achieving the full knee extension, passive active range of motion (ROM) and isometric quad and hamstring exercises, and the control of pain, swelling, and inflammation. Weight-bearing status was as tolerated with two crutches during weeks zero to two, and the discontinuation for crutch use began once patient had full extension ROM and could complete a straight leg raise (SLR) without extension lag. Phase two began once the subject completed SLR without extension lag, achieved knee flexion ROM to at least 90°, and had no signs of active inflammation (about 6 weeks post-operation). Closed kinetic chain exercises, progressed ROM exercises, and the discontinuation of crutch and brace were initiated at this point. Phase three began once full ROM was reached (about 8 weeks post-operation) continued the progress of strengthening and flexibility exercises with the implementation of a walk/jog progression on a treadmill. Phase four began once subject had full, pain-free ROM and strength on approximately 70 % of uninvolved knee (about 6 months post-operation). Phase five consisted of the initiation of cutting and jumping activities and the final functional progression towards return to sport or activity. All subjects with ACL reconstruction in the current investigation were cleared for sports participation and given at least 12 months post-operation in order to participate in the study.

Threshold to detect passive motion test

Conscious proprioception is commonly evaluated by either joint position sense (JPS) or threshold to detect passive motion (TTDPM). Previous studies have indicated that TTDPM is more reliable than JPS [3, 29]. Additionally, previous studies have supported the construct validity of TTDPM as it could detect proprioceptive deficits in ACL-deficient or ACL-reconstructed limbs compare to uninjured contralateral and control limbs while JPS did not detect deficits in the same subjects [35, 37]. Our laboratory has conducted pilot studies to ensure intrasession and intersession intraclass correlation coefficients (ICC) and standard error of measurements (SEM) and found good reliability and precision using TTDPM (sagittal plane TTDPM: ICC = 0.879–0.917; SEM = 0.19°–0.22° and transverse plane TTDPM: ICC = 0.72–0.86; SEM = 0.22–0.37) [28, 29]. Therefore, TTDPM was used in the current investigation.

All TTDPM data were collected with the Biodex System 3 Multi-Joint Testing and Rehabilitation System utilizing the Research Toolkit software application (Biodex Medical Inc., Shirley, NY, USA). The Research Toolkit software allows position information in one decimal. The accuracy of Biodex position measurements has been previously validated with a digital inclinometer (mean difference = 0.04°–0.68°, method error = 0.26°–0.31°, and coefficient of variation of method error = 0 %). The trial-to-trial reliability of Biodex position was near perfect agreement (ICC = 0.99–1.00) and precise (SEM = 0.00°–0.60°) when reading values from a digital inclinometer and screen output [10]. Both ACL-reconstructed and uninjured contralateral limbs for the ACL-reconstructed subjects were tested as an internal control and used for a between-limb comparison. For external control subjects, only dominant leg was tested and used for comparing with the ACL-reconstructed and uninjured contralateral limbs. The dominant leg was operationally defined as the preferred leg to kick a ball.

The sagittal plane TTDPM procedures were similar to that used by Lephart et al. [22]. First, subjects were seated in the Biodex chair while wearing a blindfold and headphones playing white noise to eliminate visual and auditory cues. An inflated pneumatic sleeve [Pressino Gradient Sequential Compression Unit (Chattanooga group, Hixson, TN, USA)] was placed around the lower leg to minimize any tactile feedback there may be between the dynamometer and the limb (Fig. 1a) [14]. Previous studies have indicated that TTDPM is more sensitive near the end-range of motion [5, 22]. Therefore, each test was initiated with the knee positioned at 15° of knee flexion and either moved into flexion (Towards Flex) or extension direction (Towards Ext) for five trials each direction [5, 22].

The transverse plane TTDPM testing was performed while subjects were seated in the dynamometer chair with their feet and hip positioned at 90° of flexion (Fig. 1b). A padded strap was used to stabilize the leg while the dynamometer passively rotated the lower leg in the transverse plane. Again, a blindfold and headphones with white noise were used to eliminate visual and auditory cues during the test. An air pneumatic boot (FP walker boot, Aircast, Summit, NJ, USA) was applied to the dominant leg with the ankle positioned at 0° of plantar flexion and inflated to minimize tactical sensation during testing [14]. The plantar surface of the boot was mounted to the dynamometer head, allowing for rotation of the tibia in the transverse plane. Once subjects were properly positioned, their range of motion limits and reference positions were set. The following three reference positions for the rotational test were determined: (1) neutral position in which the boot is positioned vertical and aligned with the twelve o'clock position of the dynamometer; (2) internal rotation

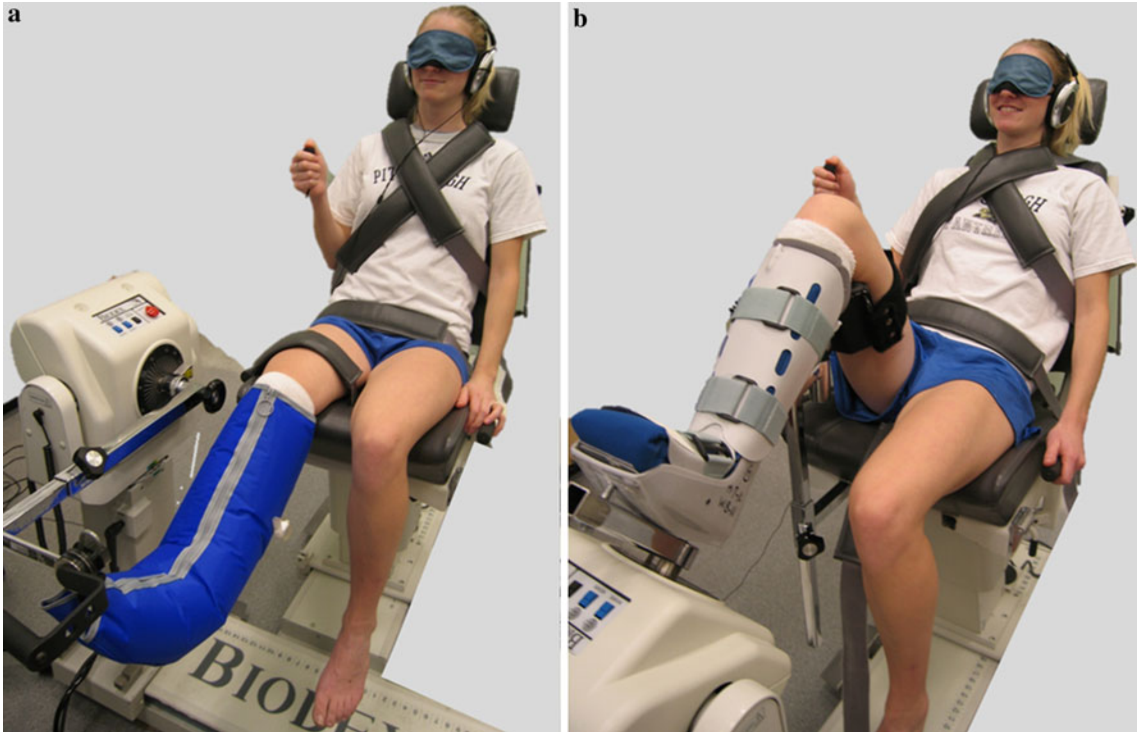

Fig. 1 TTDPM subject setting: **a** sagittal plane TTDPM, **b** transverse plane TTDPM

(IR)—test position, defined as 10° less than the maximum IR end-range position; and (3) external rotation (ER)—test position, defined as 10° less than the maximum ER end-range position. The IR- and ER-test positions were used as starting positions for the transverse plane TTDPM tests. During each test the dynamometer moves into either internal rotation (Towards IR) or external rotation (Towards ER) for five trials each direction at each starting position.

Both TTDPM procedures proceeded with the subject instructed to press a stop-button as soon as they perceived motion at the knee and could identify the direction the limb was moving. As previous studies have suggested, the identification of direction in addition to the sense of movement was used to minimize false responses [9, 34]. At an unannounced time (0–30 s after instruction), the knee was passively moved at a rate of 0.25°/s. Threshold to detect passive motion is shown to be velocity-dependent, and subjects have higher threshold (more difficult to detect) at slower velocity [33]. Therefore, we select the slowest velocity (0.25°/s) available in the dynamometer hardware. Practice trials were provided for subjects to become familiar with the testing procedures. Five repetitions towards each direction and at each staring position were randomly performed. If a subject indicated the wrong direction, the trial was discarded and repeated. The order of TTDPM tests was randomized based on the planes (sagittal or transverse plane) initially and the position and directions secondarily.

Statistical analysis

Means and standard deviations for all TTDPM variables were calculated for all subjects. Threshold to detect passive motion was calculated as the difference between the mean reference value and the mean value at the detection of movement and movement direction. There were six dependent variables (two sagittal plane and four transverse plane TTDPM). Due to the positive skewness of TTDPM data, the assumption of normality was evaluated with Shapiro–Wilk tests for each dependent variable in all groups. If the assumption of normality was violated, non-parametric tests were used.

Paired-sample *t* tests (parametric test) or Wilcoxon signed-ranks test (nonparametric test) were used to determine if any statistically significant differences were present between the ACL-reconstructed and the uninjured contralateral limbs. Independent *t* tests (parametric test) or Mann–Whitney *U* test (nonparametric test) were used to determine whether any significant differences were present between the ACL-reconstructed and the external control limbs and between the uninjured contralateral and the external control limbs. For all statistical tests an alpha level of 0.05 was set a priori. Effect size (Cohen's d) and power $(1-\beta)$ were calculated on each comparison.

Results

Means and standard deviations for all variables are shown in Tables 1, 2, 3 and Fig. 2. For the sagittal plane TTDPM between-limb comparison, there were no statistically significant differences in either direction (towards flexion and extension) between the ACL-reconstructed and the uninjured contralateral limbs. For the transverse plane TTDPM between-limb comparison, the ACL-reconstructed limbs had significantly worse TTDPM towards IR at ER-test position than the uninjured contralateral limbs ($p = 0.01$). There were no statistically significant differences between the ACL-reconstructed and the uninjured contralateral limbs in other positions and directions.

For the sagittal plane TTDPM between-group comparison, there were no statistically significant differences in both directions between the ACL-reconstructed and the external control limbs and between the uninjured contralateral and the external control limbs. For the transverse plane TTDPM between-group comparison, there were no statistically significant differences in any positions and directions between the ACL-reconstructed and the external control limbs and between the uninjured contralateral knees and the external control limbs.

Discussion

The current investigation aimed to examine the effect of anatomic double-bundle ACL reconstruction on sagittal and transverse plane proprioception by examining threshold to detect passive motion. It was hypothesized that TTDPM on the ACL-reconstructed limbs would be restored compared to TTDPM on the uninjured contralateral and external control limbs. These hypotheses were largely supported as there were no statistically significant differences in eleven out of twelve comparisons between both the ACL-reconstructed and uninjured contralateral limbs in subjects with the ACL reconstruction and the external control limbs in both the sagittal and transverse plane TTDPM. Based on the results of this study there appears to be a restoration of both sagittal and transverse plane TTDPM after anatomic double-bundle ACL reconstruction.

Sagittal plane TTDPM

For sagittal plane TTDPM, there were no significant differences between the ACL-reconstructed, the uninjured contralateral, or the external control limbs. The current results are in agreement with previous studies [30, 35]. One advantage of anatomic double-bundle ACL reconstruction is the presence of two anatomically placed bundles. The posterolateral-bundle of the ACL is constantly taut near sagittal plane end-range while the anteromedial-bundle of the ACL is moderately taut at mid-range, resembling the biomechanical properties of the native ACL [38]. When evaluating human conscious proprioception, sensory information to detect movement and movement direction in TTDPM testing must be resulting from mechanical tension/stretches of mechanoreceptors [17]. The current results support benefits of having two bundles as sagittal plane TTDPM in the ACL-reconstructed limbs was fully restored compared to that of the external control limbs. In fact, the sagittal plane TTDPM values in the ACL-reconstructed limbs are similar or slightly better than the TTDPM in the external control limbs.

Table 1 Between-limb comparison between the ACL-reconstructed limbs and the uninjured contralateral limbs

Direction	Reconstructed limbs Mean ± SD	Contralateral limbs Mean ± SD	p value	Cohen's d	$1-\beta$
Sagittal plane TTDPM (in degrees)					
Towards FLEX	0.9 ± 0.5	1.0 ± 0.6	(n.s.)	−0.15	0.12
Towards EXT	1.1 ± 0.8	1.1 ± 0.9	(n.s.)	0.04	0.07
Transverse plane TTDPM at IR-test position (in degrees)					
Towards IR	1.0 ± 0.4	1.1 ± 0.6	(n.s.)	−0.17	0.17
Towards ER	1.7 ± 1.0	1.8 ± 1.6	(n.s.)	−0.07	0.08
Transverse plane TTDPM at ER-test position (in degrees)					
Towards IR*	1.9 ± 1.1	1.2 ± 0.8	0.01	0.74	0.74
Towards ER	1.1 ± 0.6	0.8 ± 0.3	(n.s.)	0.61	0.59

Asterisk (*) indicates significant difference between the ACL-reconstructed limbs and the uninjured contralateral limbs. p value (n.s.) indicates not significant

Table 2 Between-group comparison between the ACL-reconstructed limbs and the external control limbs

Direction	Reconstructed limbs Mean ± SD	External control limbs Mean ± SD	*p* value	Cohen's *d*	$1 - \beta$
Sagittal plane TTDPM (in degrees)					
Towards FLEX	0.9 ± 0.5	1.3 ± 0.8	(n.s.)	−0.70	0.47
Towards EXT	1.1 ± 0.8	1.2 ± 1.1	(n.s.)	−0.04	0.06
Transverse plane TTDPM at IR-test position (in degrees)					
Towards IR	1.0 ± 0.4	0.9 ± 0.4	(n.s.)	0.18	0.11
Towards ER	1.7 ± 1.0	1.3 ± 0.6	(n.s.)	0.43	0.25
Transverse plane TTDPM at ER-test position (in degrees)					
Towards IR	1.9 ± 1.1	1.5 ± 0.5	(n.s.)	0.54	0.34
Towards ER	1.1 ± 0.6	1.0 ± 0.8	(n.s.)	0.10	0.08

p value (n.s.) indicates not significant

Table 3 Between-group comparison between the uninjured contralateral limbs and the external control limbs

Direction	Contralateral limbs Mean ± SD	External control limbs Mean ± SD	*p* value	Cohen's *d*	$1 - \beta$
Sagittal plane TTDPM (in degrees)					
Towards FLEX	1.0 ± 0.6	1.3 ± 0.8	(n.s.)	−0.52	0.32
Towards EXT	1.1 ± 0.9	1.2 ± 1.1	(n.s.)	−0.08	0.07
Transverse plane TTDPM at IR-test position (in degrees)					
Towards IR	1.1 ± 0.6	0.9 ± 0.4	(n.s.)	0.32	0.18
Towards ER	1.8 ± 1.6	1.3 ± 0.6	(n.s.)	0.37	0.21
Transverse plane TTDPM at ER-test position (in degrees)					
Towards IR	1.2 ± 0.8	1.5 ± 0.5	(n.s.)	−0.38	0.21
Towards ER	0.8 ± 0.3	1.0 ± 0.8	(n.s.)	−0.69	0.20

p value (n.s.) indicates not significant

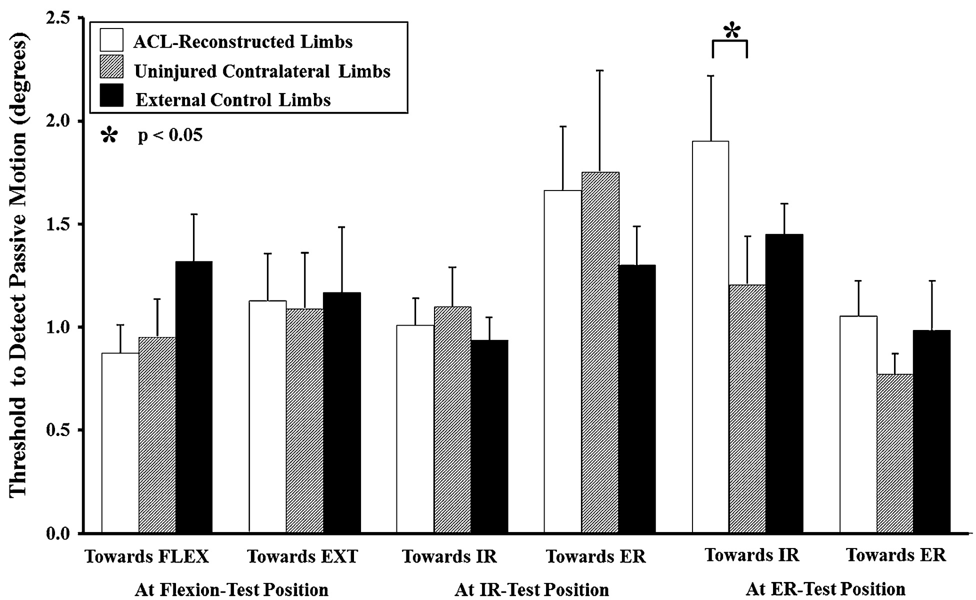

Fig. 2 Mean TTDPM for the ACL-reconstructed limbs, the uninjured contralateral limbs, and the external control limbs from 3 test positions and moving into each direction (±SE, $*p < 0.05$)

Transverse plane TTDPM

For transverse plane TTDPM, there were no significant differences between the ACL-reconstructed and the external control limbs. One of the primary goals of anatomic double-bundle ACL reconstruction is the restoration of normal function in both the sagittal and transverse planes, yet there are few studies that have investigated the effects of ACL reconstruction on proprioception in the transverse plane. Muaidi et al. [25] evaluated knee IR/ER proprioception using an absolute judgment task (in which participants actively rotate IR/ER, while a tester changes an end-range of IR/ER motion, and try to judge the magnitude of changes in the end-range) and reported significantly better proprioception after single-bundle ACL reconstruction. Due to differences in methodologies, it is difficult to compare the previous results with the current results; however, their investigation has demonstrated the importance of the transverse plane proprioception.

In the current investigation, initial positions were end-range for both internal and external range of motion. The anatomic double-bundle ACL was effective in restoring TTDPM at both end-ranges. As mechanical tension/stretches of mechanoreceptors would result in enhanced sensory feedback [17], we can speculate that the anatomic double-bundle ACL reconstruction may play a role in restoring proprioception in both internal and external rotation end-range. There are mixed results on the role of the double-bundle ACL reconstruction on restoring external rotation. Cadaveric studies have indicated that both the AM and PL bundles are important in restoring internal rotation while the ACL has less influence on restoring external rotation [13, 19]. A recent in vivo study, measuring internal and external rotation by an intraoperative computer navigation device, has indicated that the double-bundle ACL reconstruction reduces both internal and external rotation [32]. More research is needed to confirm the role of the double-bundle ACL reconstruction on restoring external rotation. The current results support that subjects had enhanced TTDPM towards both end-range (towards IR at IR-test position and towards ER at ER-test position), compared to TTDPM towards mid-range.

The only significant difference between the ACL-reconstructed and the uninjured contralateral limbs was found in one of TTDPM towards mid-range. It is not clear why there was the significant difference in TTDPM towards IR direction at the ER-test position, but not in TTDPM towards ER direction at the IR-test position. We have observed larger standard deviation in TTDPM towards mid-range (IR direction at the ER-test position and ER direction at the IR-test position) in the ACL-reconstructed subjects compared to the external control subjects and the healthy subjects from our previous investigation [27]. More subjects will likely help to stabilize the means and standard deviations, resulting in less variation.

This current investigation does have limitations. The study was designed as a cross-sectional design to compare between the ACL-reconstructed and uninjured contralateral limbs and between the ACL-reconstructed group and external control group. This study design provides a "snapshot" of 12–15 months post-operation for the ACL-reconstructed group. As such, it is not possible to determine at what time point the recovery in proprioception takes place or if there would be further restoration in later years as all individuals get back to their sports. Previous longitudinal studies have indicated the restoration of proprioception would take place within 3 months [12, 25, 35]. Therefore, it would be less likely to see further changes.

Another limitation is that we did not examine functional or clinical tests and compare with TTDPM. In addition to proprioceptive testing, pivot-shift test, subjective satisfaction level survey, activity scale survey, a single-leg hop test, knee strength assessment, and kinematic analyses would provide a comprehensive picture of how subjects are recovering following ACL reconstruction.

Lastly, a small sample size should be noted. A wide range of effect size (0.04–0.74) and power (0.06–0.74) were observed in the current investigation. A larger sample size would reduce a chance of Type I error. Therefore, the results from the current investigation should be interpreted with caution.

Conclusion

In conclusion, based on a small sample of eleven subjects, the sagittal and transverse plane TTDPM in the ACL-reconstructed limbs are similar to the uninjured contralateral (except one direction) and external control limbs, suggesting that an anatomic double-bundle ACL reconstruction is successful in the restoration of knee proprioception across both planes.

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