Prospective Study of Kinesthesia After ACL Reconstruction

Abstract

Previous studies used a variety of methods to assess kinesthesia, thus no consensus exists regarding kinesthetic adaptation after anterior cruciate ligament (ACL) reconstruction. This study prospectively examined whether kinesthesia is adapted after ACL reconstruction, and then discussed the actual angular velocity required to properly assess kinesthesia in ACL-reconstructed patients. 31 patients were evaluated using the threshold to detect passive motion (TTDPM) test, which was applied preoperatively, and at 3, 6, and 12 months following surgery. TTDPMs were measured at 15° or 45° of knee flexion toward both extension and flexion with angular velocities of 0.1°/s or 0.2°/s. ACL-reconstructed knees showed significantly impaired TTDPMs compared to healthy knees before the operation at 15° of knee flexion toward extension and at 45° of knee flexion toward both extension and flexion at 0.2°/s (15° of knee flexion toward extension, P=0.036; 45° of knee flexion toward extension, P=0.015; 45° of knee flexion toward flexion, P=0.030). However, there were no significant differences after 3 months of follow-up. On the basis of these results, applying 0.2°/s seems appropriate to assess TTDPM for patients with an ACL reconstruction, and kinesthesia is adapted within 12 months after the operation. Sensory function and biomechanical stability are also adapted following ACL reconstruction.

Introduction

Anterior cruciate ligament (ACL) injuries are unfortunately common in people undertaking sport [10,14,21]. To return to athletic activities, ACL-deficient patients require the following: 1) reconstruction of the damaged ACL; 2) achievement of biomechanical stability; 3) restoration of muscle strength around the knee joint; and, 4) adaptation of joint proprioceptive function [5,15,22,27,29,30]. In the last 2 decades, most orthopedic surgeons focused on ACL reconstructive surgeries to restore biomechanical stability in the knee. However, the ‘best surgical technique’ has not been established based on the available evidence. Indeed, a recent comprehensive systematic review revealed that most aspects of surgical and rehabilitative management of ACL rupture remain controversial [3]. Recent research has also shifted focus to the ACL as a sensory modality, and not only as a strong band required for mechanical joint stability. Proprioception is defined as the sum of awareness of joint position (joint position sense: JPS) and awareness of joint motion (referred to as kinesthesia) [16]. Joint proprioception is believed to provide dynamic stability by achieving neuromuscular control via afferent signals from joint mechanoreceptors [22]. A previous study identified the number of mechanoreceptors in the remnant ACL and suggested that these could contribute to the knee joint proprioception [1]. Furthermore, mechanoreceptors are also important for maintaining joint stability by regulating muscle contraction whereby somatosensory, vestibular, and visual inputs are integrated in the central nervous system [19]. Several methods have been used to evaluate joint proprioception [1,2,4,5,8,9,11,13,16,18,23–26,29,30,32,33]. Many of these focus on proprioception as JPS [1,9,11,18,25,29,33], although proprioceptive function also comprises kinesthetic aspects. On the other hand, assessing kinesthesia is also deemed appropriate by many researchers for detecting proprioceptive deficit in ACL injuries [2,30], because reacting to certain joint motions is easier to monitor by reproducing certain knee joint angles, compared to the task of JPS. In addition, evaluations of kinesthesia varied
Materials and Methods

Subjects
This study was designed as a prospective study, with the following inclusion criteria: no history of orthopedic injury to other joints, no multiligamentous injuries at the initial injury, and no neurological or psychological disorders. A total of 62 ACL reconstructions met the inclusion criteria from January 1, 2008 to February 1, 2009. We excluded 10 patients who had undergone revised ACL reconstructions, 12 patients who were under treatment, and 9 patients lost to follow-up for non-medical reasons. Thus, 31 ACL-deficient patients (13 males and 18 females) participated in this study (Fig. 1). The subjects had a mean age of 22.2 years, height of 166.3 cm, weight of 61.8 kg, and body mass index of 22.1 kg/m². 18 patients had injured their right knee. The modal time course from the initial injury to the operation was 3 months (1–20 months). 2 of 31 patients did not remember the exact date they were injured, thus the time courses to surgery for those patients were not precise (Table 1). Subjects participated in recreational level of physical activities. Most injuries (30 of 31) were sports-related including from basketball, soccer, handball, volleyball, and judo. Complete ACL tears were confirmed by arthroscopy, and all patients underwent arthroscopic ACL reconstructions with the choice of semitendinosus and/or gracilis autograft. 20 patients underwent double-bundle ACL reconstructions, and 5 of these had meniscectomies or meniscal sutures. 8 patients underwent quadrupled single-bundle ACL reconstructions, of which 4 had meniscectomies and meniscal sutures. 3 subjects underwent augmentation techniques, with 1 of these having meniscal sutures (Table 2).

All subjects participated in similar postoperative rehabilitation programs, which did not include specific proprioceptive training. Those who underwent an ACL reconstruction without meniscal sutures commenced a range of motion exercises using a continuous passive motion device on the third day after the ACL reconstruction. One week later, these patients were allowed one-third weight-bearing exercise. The load was gradually increased by one third of the patients’ body weights each week until the patients achieved full weight bearing. Those with meniscal sutures immobilized their involved limbs for 2 weeks to ensure efficient postoperative rehabilitation. Thereafter, these patients started load-bearing exercise according to the regimen described for the other patients. All patients engaged in closed kinetic (CKC) exercises for up to 4 months after the surgery. Full-weight-bearing postoperative rehabilitation exercises included squats, forward and side lunges, and knee-bent walking. All patients wore a knee brace that limits knee flexion to a 30° angle on their reconstructed limbs until the 3-month follow-up. All patients were allowed to jog at 4 months after the surgery and run at full speed by 6 months postsurgery. The subjects returned to full sports activities at 10 months after the reconstruction on our rehabilitation protocol. All patients were satisfied with the outcome of the surgery and the rehabilitation outcomes were assessed using a Knee Lax Arthrometer (Gasto Special Products B.V, The Netherlands) on both 20N and 30N, and the Biodes system 3 version 3.2 (Biodex Medical Systems, Shirley, NY) measuring at 60°/s and 180°/s (Table 3,4).
were adjustable for the study purpose. This device could measure angular velocity, and resting time between measurements healthy volunteers with a mean age of 21.8 years on test-retest testing apparatus (Sensor Ouyou, Hiroshima, Japan; Proprioceptive function was measured using a proprioception IJSM [17].

Pivot-shift positive. The study protocol accorded with the ethics of follow-up by measuring the subjects’ threshold to detect passive motion (TTDPM). TTDPM was represented by the reaction time from the movable shaft starting movement to the point at which patients pressed the stop switch. The data were obtained from both involved and uninjured limbs at each measurement; the uninjured limbs provided the healthy control data in this study.

As preparation for the measurement, subjects were seated in a neutral angle of lumbar flexion with the popliteal fossa situated approximately 5 cm from the edge of the seat. The testing limb was put into an air splint to eliminate any cutaneous stimulation and to minimize neural input from mechanoreceptors in the foot and ankle. The testing limb was then fastened onto the footrest and the subjects were fitted with headphones emitting “white noise” and eye masks to shut out any audiovisual cues. After the preparation, the axis of rotation of the limb being tested and the axis of the movable shaft were aligned. The movable shaft was connected to a motor-driven rotational transducer interfaced with a computer to measure reaction time to the passive motion. Left limbs were measured first for each subject, regardless of the side involved. A hand-held switch enabled each subject to stop the movement when they perceived it as joint motion. During the test, the subjects were instructed via a microphone attached to the testing device.

According to the previous study [8], we set up the starting positions at 15° flexion and 45° flexion of the knee joint. The movable shaft shifted gradually by 0.1°/s toward either the flexion or extension direction at random. We conducted 8 measurements in a random sequence, thus we measured kinesthesia once for each starting position and direction of the movement. Resting times between each measurement were set randomly within 10 s to minimize patient guessing. Patients were instructed to press the switch when they felt their lower limbs moving towards either flexion or extension from either starting position. The times that patients took to press the button (reaction times) were recorded and analyzed statistically. Patients practiced twice before the initial measurement without warming up.

Statistical analysis
2-way analysis of variance (ANOVA) with Bonferroni post hoc test was used to detect statistically significant differences between ACL-reconstructed and intact knees throughout the time courses before and after the ACL reconstructive surgery, and kinesthetic adaptation with examining prognosis for each

### Table 3
Mean (+SD) of anterior displacement on ACL-reconstructed and intact limbs at each time point.

<table>
<thead>
<tr>
<th>Time</th>
<th>ACLR side (mm)</th>
<th>Healthy side (mm)</th>
<th>Side to side difference (mm)</th>
<th>ACLR side (mm)</th>
<th>Healthy side (mm)</th>
<th>Side to side difference (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preop</td>
<td>8.8±2.7</td>
<td>6.8±2.7</td>
<td>2.0±2.4</td>
<td>11.7±3.4</td>
<td>8.2±3.4</td>
<td>3.5±3.0</td>
</tr>
<tr>
<td>Post 3M</td>
<td>7.0±3.3</td>
<td>7.3±3.2</td>
<td>−0.3±3.4</td>
<td>8.4±4.1</td>
<td>9.1±4.2</td>
<td>−0.8±4.5</td>
</tr>
<tr>
<td>Post 6M</td>
<td>8.7±3.4</td>
<td>7.7±3.0</td>
<td>1.0±3.4</td>
<td>10.5±3.9</td>
<td>9.6±3.9</td>
<td>0.8±4.3</td>
</tr>
<tr>
<td>Post 12M</td>
<td>8.2±3.4</td>
<td>6.8±2.9</td>
<td>1.4±2.6</td>
<td>9.7±4.0</td>
<td>8.5±3.6</td>
<td>1.3±3.2</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD

### Table 4
Mean muscle strength to the intact knee (% to the intact side) on knee extension and flexion using the biodex system 3 at 6-month and 12-month follow-ups.

<table>
<thead>
<tr>
<th>Time</th>
<th>Extension 60°/s isokinetic muscle strength</th>
<th>Flexion 60°/s isokinetic muscle strength</th>
<th>Extension 180°/s isokinetic muscle strength</th>
<th>Flexion 180°/s isokinetic muscle strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post 6M</td>
<td>70.4%</td>
<td>82.3%</td>
<td>78.7%</td>
<td>86.6%</td>
</tr>
<tr>
<td>Post 12M</td>
<td>83.4%</td>
<td>78.7%</td>
<td>85.9%</td>
<td>87.2%</td>
</tr>
</tbody>
</table>

Values are presented as mean

In addition, the preoperative subjective Lysholm outcome score of 74.5±7.9 improved to 98.5±2.7 after the operation. Finally, 1 patient showed a positive Lachman test, but none were Pivot-shift positive. The study protocol accorded with the ethics review board at our institution and the ethical standards of the IJSM [17].

Proprioceptive testing apparatus and procedures
Proprioceptive function was measured using a proprioceptive testing apparatus (Sensor Ouyou, Hiroshima, Japan; ﬁg. 2), which was developed in a previous study [4]. We conﬁrmed the reliability and validity of this apparatus by pretesting on 24 healthy volunteers with a mean age of 21.8 years on test-retest methods. Testing time, starting position, directions of movement, angular velocity, and resting time between measurements were adjustable for the study purpose. This device could measure the knee joint proprioception at a minimal angular velocity of 0.1°/s controlled by a motor attached to a movable shaft and computer system.

We assessed knee joint proprioception (kinesthesia) 4 times: before the operation and at 3 months, 6 months, and 12 months of follow-up by measuring the subjects’ threshold to detect passive motion (TTDPM). TTDPM was represented by the reaction time from the movable shaft starting movement to the point at which patients pressed the stop switch. The data were obtained from both involved and uninjured limbs at each measurement; the uninjured limbs provided the healthy control data in this study.

As preparation for the measurement, subjects were seated in a neutral angle of lumbar flexion with the popliteal fossa situated approximately 5 cm from the edge of the seat. The testing limb was put into an air splint to eliminate any cutaneous stimulation and to minimize neural input from mechanoreceptors in the foot and ankle. The testing limb was then fastened onto the footrest and the subjects were fitted with headphones emitting “white noise” and eye masks to shut out any audiovisual cues. After the preparation, the axis of rotation of the limb being tested and the axis of the movable shaft were aligned. The movable shaft was connected to a motor-driven rotational transducer interfaced with a computer to measure reaction time to the passive motion. Left limbs were measured first for each subject, regardless of the side involved. A hand-held switch enabled each subject to stop the movement when they perceived it as joint motion. During the test, the subjects were instructed via a microphone attached to the testing device.

According to the previous study [8], we set up the starting positions at 15° flexion and 45° flexion of the knee joint. The movable shaft shifted gradually by 0.1° or 0.2°/s toward either the flexion or extension direction at random. We conducted 8 measurements in a random sequence, thus we measured kinesthesia once for each starting position and direction of the movement. Resting times between each measurement were set randomly within 10 s to minimize patient guessing. Patients were instructed to press the switch when they felt their lower limbs moving towards either flexion or extension from either starting position. The times that patients took to press the button (reaction times) were recorded and analyzed statistically. Patients practiced twice before the initial measurement without warming up.

Statistical analysis
2-way analysis of variance (ANOVA) with Bonferroni post hoc test was used to detect statistically significant differences between ACL-reconstructed and intact knees throughout the time courses before and after the ACL reconstructive surgery, and kinesthetic adaptation with examining prognosis for each
knee over the total time course. A simple linear regression analysis was also used to assess the effect of the measured angular velocities on reaction times. A dependent value was reaction time at each measurement condition and an explanatory value was angular velocity. The statistical significance level was set at \( P<0.05 \). All values are presented as mean ± standard error of the measurement; SEM.

Results

The TTDPMs were significantly impaired on ACL-reconstructed knees vs. healthy knees prior to the operation at 15° of knee flexion moving toward extension and at 45° of knee flexion toward both extension and flexion with an angular velocity of 0.2°/s (15° of knee flexion moving toward extension, 4.2±1.1 vs. 2.4±0.4, \( P=0.036 \) [mean difference −1.8 (95% confident interval: 95%CI −4.3–0.7)]; 45° of knee flexion toward extension, 7.5±1.3 vs. 5.0±0.7, \( P=0.015 \) [−2.5 (95%CI −5.4–0.4)]; 45° of knee flexion toward flexion, 5.4±1.3 vs. 3.3±0.8, \( P=0.030 \) [−2.2 (95%CI −5.1–0.8)]). However, the significant differences disappeared after 3 months of follow-up. There were also significantly improved TTDPMs on the ACL-reconstructed knees with 45° of knee flexion moving into both extension and flexion when measured at 0.2°/s (45° of knee flexion moving into extension, 7.5±1.3 vs. 5.2±0.8, \( P=0.040 \) [−2.3 (95%CI −5.3–0.7)] [at the 3-month follow-up], 7.5±1.3 vs. 5.1±0.8, \( P=0.034 \) [−2.4 (95%CI −5.3–0.5)] [at the 12-month follow-up]; 45° of knee flexion moving into flexion, 5.4±1.3 vs. 3.0±1.0, \( P=0.014 \) [−2.5 (95%CI −5.6–0.6)] [at the 6-month follow-up], 5.4±1.3 vs. 2.5±0.6, \( P=0.0033 \) [−3.0 (95%CI −5.8–0.2)] [at the 12-month follow-up]). There were also significantly impaired TTDPMs at 45° of knee flexion moving into extension with 0.1°/s at the 3-month follow-up [reconstructed knees vs. healthy knees, 10.4±1.6 vs. 7.4±1.2, \( P=0.042 \) [−3.0 (95%CI −6.3–0.5)]]. However, there were no significant differences after 6 months of follow-up. In addition, there were significantly improved TTDPMs at 15° of knee flexion moving into flexion with 0.1°/s at the 6-month follow-up [reconstructed knees vs. healthy knees, 5.9±1.1 vs. 7.8±1.0, \( P=0.039 \) [1.9 (95%CI 1.0–4.9)]], although the data showed a similar reaction time to those obtained preoperatively on ACL-reconstructed knees at the 12-month follow-up. There were no significant differences with 0.2°/s at 15° of knee flexion moving into flexion (Fig. 3–6).

Simple regression analyses identified whether the angular velocity was influential for detecting kinesthesia. The value of R-squared at the position of 15° of knee flexion moving into extension was 0.27 (F(1.61) =22.5, \( P<0.001 \)). The value did not suggest good fitness for a regression line with 15° of knee flexion moving into extension. Although the standardized coefficients might be approximately referable to predict the kinesthetic value on 15° of knee flexion moving into extension, the values of R-squared at rest conditions could not show fine fitness with the regression lines calculated for representing distribution (Table 5).

Discussion

To our knowledge, this is the first study to characterize kinesthetic transition with extremely slow angular velocities on patients with ACL reconstruction. First, we optimized the angular velocity to use in the kinesthetic measurement of ACL-reconstructed patients. Based on the results, an angular velocity of 0.2°/s reflected significant adaptation of the reconstructed limbs except at 15° of knee flexion moving into flexion. Angular velocities of 0.5–2.5°/s were used previously in the belief that they would maximally stimulate joint mechanoreceptors, despite no experimental verification [12]. A recent study [24] then sug-

![Knee joint 15° flexed toward ext.](image)

**Fig. 3** The temporal changes in mean (± standard error of the mean; SEM) threshold to detect passive motion (TTDPM) for the ACL-reconstructed and intact limbs moving into extension at 15°. \( \dagger P<0.05 \).

![Knee joint 45° flexed toward ext.](image)

**Fig. 4** The temporal changes in mean (± SEM) TTDPM for the ACL-reconstructed and intact limbs moving into extension at 45°. \( \dagger \dagger P<0.05 \).
suggested that kinesthesia was assessable using angular velocities of 0.1–0.5°/s on healthy volunteers and that there were significantly elongated reaction times at 0.1°/s. In their study, some of the subjects could not appreciate the motion at 0.1°/s, suggesting that this angular velocity is too slow for such testing. The authors also emphasized that there were no significant differences at 0.2–0.5°/s for those sensitivities in TTDPM reaction times and values at slower angular velocities were more sensitive [24]. Our study has corroborated this previous study [24], and further indicated that angular velocity influences, at least in part, kinesthetic measurement with the described proprioception testing apparatus. Subjects had difficulty in perceiving joint motion at an angular velocity of 0.1°/s, and 0.2°/s might be the critical value for properly perceiving the response of joint mechanoreceptors to the stimulation as joint motion while at the same time minimizing neural inputs from mechanoreceptors in muscles and tendons around the knee joint. We therefore recommend 0.2°/s as the most appropriate angular velocity for assessing kinesthesia in patients with ACL reconstructions using the hamstring tendon, because this angular velocity might reflect afferent input from joint mechanoreceptors. It might also represent regeneration of mechanoreceptors in reconstructed ACLs.

A previous study on the number of mechanoreceptors in the remnant ACL suggested a correlation between this number and the mechanoreceptor contribution to proprioceptive function, and that more observed mechanoreceptors might translate to better proprioceptive function [1]. Additionally, the study of [28] confirmed the regeneration of mechanoreceptors or nerve fiber endings based on somatosensory evoked potential (SEP) after ACL reconstruction. However, a conflicting study [7] suggested that sensory deficit could remain after ACL reconstruction, and other investigators reported morphologically normal mechanoreceptors at 3 months after injury, and only a few free nerve endings by 9 months after injury [30]. It should be noted however, that the average time from injury to surgery in the former study [7] was 7 months, thus degeneration of mechanoreceptors in the injured ACL might result in poor sensory recovery. Most of our patients underwent ACL reconstruction within 3 months after the initial injury, though time elapsed after injury varied from a month to 20 months. Undergoing reconstruction within 3 months seemed to produce improved kinesthesia in the present study. A longitudinal study of proprioceptive function based on JPS [18], and using a similar testing apparatus to that used in the current study, indicated that at least 18 months is needed for ACL-reconstructed patients to recover. However, we observed temporal changes in kinesthesia across the course of follow-up in our ACL-reconstructed patients, suggesting that kinesthetic adaptation starts from an earlier time point following the reconstruction than JPS-based adaptation.

Our results showed poor reaction times (higher thresholds) at 15° of knee flexion moving into flexion at both 0.1 and 0.2°/s angular velocities. Proprioceptive evaluation conducted previously on individuals with chronic anterior instabilities after surgery indicated no improvement in the mid-range of motion at the 6-month follow-up [11]. Therefore, even with regeneration of mechanoreceptors or nerve fibers, proprioceptive function

**Table 5** Results of simple linear regression analyses on each condition. *P<0.05. **P<0.01. 15°E, 45°E, 15°F, and 45°F presented 15° knee flexion moving into extension, 45° knee flexion moving into extension, 15° knee flexion moving into flexion, and 45° knee flexion moving into flexion, respectively.

<table>
<thead>
<tr>
<th></th>
<th>15°E</th>
<th>45°E</th>
<th>15°F</th>
<th>45°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>0.52</td>
<td>0.27</td>
<td>0.46</td>
<td>0.25</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.27</td>
<td>0.08</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td>F(1.60)value</td>
<td>22.5**</td>
<td>4.90*</td>
<td>16.0**</td>
<td>3.89</td>
</tr>
<tr>
<td>standardized coefficients</td>
<td>-0.52</td>
<td>-0.29</td>
<td>-0.46</td>
<td>-0.25</td>
</tr>
</tbody>
</table>

**Fig. 5** The temporal changes of mean (±SEM) TTDPM for the ACL-reconstructed and intact limbs moving into flexion at 15°. †P<0.05.

**Fig. 6** The temporal changes of mean (±SEM) TTDPM for the ACL-reconstructed and intact limbs moving into flexion at 45°. *P<0.05. **P<0.01.
might be still impaired for certain positions or directions of knee movement. Impairment of neuromuscular control might also exist even 2 years after the ACL surgery [31]; however, our study subjects showed improved anterior displacement and muscular strength in the clinical examinations. Our rehabilitation protocol required the patients to wear a knee brace, which limits knee extension to 30° of the full range of motion, for up to 3 months of follow-up and it is possible that such a protocol could have influenced the poor TTDPMs observed at 15° of knee flexion moving into flexion. Further studies are therefore needed to clarify the effects of these subtleties on athletic performance following ACL reconstruction.

This study had some limitations. First, there were no external controls, and previous work demonstrated that unilateral ACL injury could affect joint proprioception on the intact limbs [30]. Thus, it might be inappropriate to use intact limbs as healthy controls. Second, the subjects in this study varied widely in age, which might affect knee joint proprioception according to a previous study that showed JPS declining with age [33]. The same might also be true for kinesthesia, although the direct correlation between aging and kinesthesia remains unclear. Third, subjects underwent different surgical techniques according to their differing articular states, and one third of patients had partial meniscectomies or meniscal sutures. The double-bundle surgical technique more consistently reproduces the biomechanical profile of the ACL compared to single-bundle techniques. However, there are no evidence-based data regarding effect of surgical technique on proprioception [6]. Specific mechanoreceptors exist in menisci [20, 32], thus the procedure undertaken in some patients could potentially have affected our results. Lastly, we represented kinesthetic data as reaction time in seconds instead of as absolute error from the predetermined angles in degrees [2, 4, 5, 7, 8, 13, 16, 23, 24, 26, 30, 32]. Thus, although reaction time more accurately represents kinesthesia on the apparatus used in the current study, this factor is a possible limitation of the present study.

Conclusions

On the basis of these results, applying 0.2°/s seems appropriate for assessing TTDPM in ACL-reconstructed patients with hamstring tendon. Kinesthesia is adapted within 12 months after the operation, except at 15° of knee flexion toward flexion. Sensory function is adapted following ACL reconstruction in addition to biomechanical stability.

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References