

Impaired neuromuscular control up to postoperative 1 year in operated and nonoperated knees after anterior cruciate ligament reconstruction

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Abstract

The current study was performed to assess serial changes in neuromuscular control until 1 year postoperatively in nonathletic patients undergoing anterior cruciate ligament reconstruction (ACLR).

Ninety-six patients were included. Serial neuromuscular control tests were performed preoperatively, at 6 months, and 1 year postoperatively. Neuromuscular control was evaluated using acceleration time (AT) and dynamic postural stability (overall stability index, OSI). Functional activity levels were assessed using the Tegner activity-level scale.

Preoperative AT of quadriceps and hamstrings in operated knees was 78.9 ± 6.4 and 86.5 ± 6.2 ms, respectively, which significantly reduced to 56.9 ± 2.0 and 62.5 ± 2.8 ms at 1 year ($P=0.006$ and 0.002 , respectively). In nonoperated knees, preoperative AT of quadriceps and hamstrings was 47.6 ± 1.7 and 56.5 ± 1.7 ms, respectively, which was significantly prolonged to 54.3 ± 2.0 and 67.9 ± 2.7 ms at 1 year ($P=0.02$ and 0.001 , respectively). Preoperative OSI of nonoperated knees was $1.2 \pm 0.0^\circ$. It significantly increased to $1.5 \pm 0.1^\circ$ at 1 year ($P<0.001$). In operated knees, preoperative OSI was $1.8 \pm 0.1^\circ$. It significantly decreased to $1.4 \pm 0.1^\circ$ at 1 year ($P=0.001$). Tegner scale at 6 months and 1 year were significantly lower than pre-operative scale ($P<0.001$). AT and OSI on both knees showed significant negative correlation with Tegner scale at 6 months and 1 year.

Neuromuscular control in both knees was not restored to preoperative levels of the nonoperated knees until 1 year after ACLR. Therefore, clinicians and physical therapists should attempt to enhance neuromuscular control in both nonoperated and operated knees.

Abbreviations: ACL = anterior cruciate ligament, ACLR = anterior cruciate ligament reconstruction, AT = acceleration time, OSI = overall stability index.

Keywords: acceleration time, anterior cruciate ligament injury, anterior cruciate ligament reconstruction, dynamic postural stability, neuromuscular control

1. Introduction

Anterior cruciate ligament (ACL) injury is one of most common and devastating sports-related injuries of the knee joint.^[1–5] The

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goal of ACL reconstruction (ACLR) is for patients to return to their previous activity and sports level.^[6,7] Various risk factors including anatomic, genetic, hormonal, occupational, and neuromuscular abnormalities have been identified to be related to ACL injury.^[8] Among these, neuromuscular control is a modifiable factor.^[9] Therefore, many therapeutic exercises have focused on the restoration of neuromuscular control before and after ACLR.^[10,11]

ACL injuries can disrupt complex interactions within the neuromuscular system, resulting in impaired kinesthesia and proprioception, abnormal muscle activation, and dynamic knee joint stability.^[12–14] Therefore, recent evaluations of rehabilitation after ACL injury have emphasized the importance of the recovery of neuromuscular control. Neuromuscular control after ACLR injury has been examined by various methods including the proprioception test, postural stability test, and functional performance tests.^[12,14,15] However, there is still no universal test to objectively assess neuromuscular control after ACLR.^[16] Recently, the isokinetic test has been widely used to evaluate neuromuscular function in ACL injuries. In the isokinetic test, the peak torque has been considered as a gold standard.^[17] However, the strength parameters cannot represent comprehensive muscular performance.^[18] Literature data indicate that the acceleration time (AT) has been considered as a meaningful variable to provide information regarding muscle recruitment and neuromuscular readiness to produce maximal muscular contraction.^[17,19,20] In

addition, many studies have demonstrated that a torn ACL may cause compromised postural control as well as reduced knee stability.^[21,22] Thus, assessment of dynamic balance could be a good method to evaluate the function of the sensory motor system after ACL injury.^[12,23]

The present study aimed to evaluate serial change in neuromuscular control in both operated and nonoperated knees after ACLR up to 1 year postoperatively by using AT and dynamic postural stability in nonathletic patients who underwent ACLR using hamstring tendon autografts. It was hypothesized that neuromuscular control of the operated knee would not be restored to the preoperative level of the nonoperated knee until 1 year postoperatively.

2. Materials and methods

2.1. Patient enrolment

The study protocol of the present study was approved by the institutional review board at our institute (Korea University Anam Hospital). We retrospectively reviewed 462 patients who had undergone anatomical single-bundle ACL reconstruction with hamstring autografts at our institute between October 2010 and December 2016. The operations were performed by 2 knee arthroscopic specialists, who both had the technical knowledge and experience to carry out this procedure. All patients were diagnosed by magnetic resonance imaging and physical examinations including anterior drawer test, pivot shift test, Lachman test, and finally confirmed by arthroscopic examination at the time of operation. We excluded patients with bilateral ACL injury; concomitant injuries including meniscus tear, collateral ligament injuries requiring operation, and bony fractures; revised ACL; and athletic patients. We also excluded patients with prior experience of isokinetic and balance tests and those who could not perform the 2 tests due to limited range of motion (ROM) and pain. Among these 462 patients, 315 were excluded, and 51 were lost to follow-up; thus, 96 patients were finally enrolled in the present study (Table 1).

2.2. Assessment of the AT

The AT, defined as muscle recruitment time for attaining pre-set angular velocity (60°/s in our study) during maximal muscle contraction was measured as an index for neuromuscular control in the current study.^[20,24] AT (ms) of the hamstrings and

quadriceps was measured during flexion/extension using Biodex multi-joint system 4 (Biodex Medical Systems, Shirley, NY). Slower acceleration time is related to delay of the neuromuscular control.^[20] Each participant was seated in an upright position on the isokinetic chair, fixed across the chest with 2 straps, and flexed hips and knees 90° each. Subjects grasped the edge of the chair. The lateral femoral condyle of the knee joint was aligned with the rotational axis of the isokinetic machine. Before testing, the subjects were allowed a 5-minute warm up, and then were asked to perform 5 submaximal repetitions of flexion and extension motion at 180°/s, followed by 5 maximal contractions at 180°/s after one minute of rest period (Fig. 1A). Gravity correction for torque values was obtained in a relaxed state at 30° knee extension, and was calculated by the Biodex advantage software.

2.3. Assessment of dynamic postural stability

Dynamic postural stability was measured as another index for neuromuscular control using the Biodex Stability System (BSS; Biodex Medical Systems). The BSS can move up to 20° tilt of the foot platform surface in any direction. The dynamic single leg test was evaluated for change of the posture at each level condition, while decreasing the stability level from level 12 (most stable) to level one (most unstable). Each subject stood barefoot, and was instructed to stand with 90° flexion of the opposite knee on the platform, with their arms held at the pelvis (Fig. 1B). Initially, the uninvolved side was tested, followed by the other leg, with a rest period of 10 s between each leg. Participants performed 2 trials in 20 s for the record of the postural stability parameter. The mean and standard deviation of the 2 trials were calculated by the stability system (overall stability index, OSI). A lower stability index indicated good postural stability.^[25,26]

2.4. Assessment of the functional activity levels

The functional activity level was measured by using the Tegner activity-level scale. Test-retest reliability for the Tegner activity-level scale was good (intraclass correlation coefficient = 0.8) for ACL injury.^[27] The Tegner activity-level scale consists of activities of daily living, working, recreation sports, and competitive sports from a score of 0 (sick leave) to 10 (national elite sports). Thus, a lower Tegner activity-level scale indicates poor function of the knee joint.

2.5. Postoperative rehabilitation

ACL rehabilitation at our clinic is divided into 3 phases. Initial phase is up to 6 weeks, and goal of the treatment is to gain ROM, pain control, and normal gait. Second phase is up to 12 weeks, and the goal is to improve the muscle strength and proprioception. Final phase is after 12 weeks, and the goal is to improve the functional performance. Authors allowed unrestricted activities in sports participation for all patients 6 months postoperatively. All patients were prescribed the same rehabilitation protocol.

2.6. Statistical analysis

Based on a previous for postural stability in patients with ACL tears,^[25] an OSI difference > 0.5 between the preoperative baseline and postoperative 1 year was regarded as clinical difference. A power analysis was performed to determine sample size, at a power of 0.8 and an α level of 0.05. A pilot study of 5

Table 1

Demographic data in enrolled patients.

Subjects characteristics	
Sample size (number)	96
Gender (male/female)	59/37
Age, years*	29.6 ± 9.2
Height, cm*	172.1 ± 7.7
Weight, kg*	71.9 ± 13.4
Injured side (right/left)	71/25
Activity when injured (n)	
Soccer	48
Baseball	14
Basketball	25
others	9

ACL = anterior cruciate ligament.

* The values expressed as mean ± standard deviation.

All data were recorded and analyzed by a physical therapist.



Figure 1. Measurement of the acceleration time (A) and dynamic postural stability (B).

knees found that the standard deviations for preoperative and postoperative 1 year for OSI were 0.4 and 0.8, respectively. The results of a pilot study involving 5 knees indicated that 92 knees were required to detect a significant difference in OSI of > 0.5 between the preoperative baseline and postoperative 1 year. The power for detecting the differences in OSI was 0.817. The 3 time points (preoperative baseline, postoperative 6 months, and 1 year) of AT and OSI were compared through repeated measures analysis of variance. If it showed significant difference, a Bonferroni post hoc test was used to determine the differences between the time points. Paired *t*-test was used to compare results between the operated and nonoperated knees, over time. Correlations between neuromuscular control index (AT and OSI) and functional activity levels (Tegner activity-level scale) were assessed by Pearson's coefficient of correlation (*r*) at each time point. Data were analyzed using the SPSS for software version 17.0 (SPSS Inc., Chicago, IL, USA). A value of $P < .05$ was considered statistically significant.

3. Results

A total of 96 patients were enrolled in this study. All patients injured their ACL during various sports activities. Mean age at the time of operation was 29.6 ± 9.2 years. Demographic data of the enrolled patients are summarized in Table 1.

3.1. Acceleration time

Preoperatively, mean AT of the quadriceps and hamstring muscles of operated knee was 78.9 ± 6.4 and 86.5 ± 6.2 ms, respectively. Mean AT was significantly reduced to 56.6 ± 2.5 and 63.5 ± 2.3 ms at 6 months and 56.9 ± 2.0 and 62.5 ± 2.8 ms at 1 year postoperatively ($P = .006$ and $.002$, respectively). In nonoperated knees, preoperative mean AT of the quadriceps and hamstring muscles was 47.6 ± 1.7 and 56.5 ± 1.7 ms, respectively. The AT was significantly prolonged to 55.4 ± 2.3 and 66.9 ± 3.4 ms at 6 months and 54.3 ± 2.0 and 67.9 ± 2.7 ms at 1 year

postoperatively ($P = .020$ and $.001$, respectively). Preoperative mean AT of the quadriceps muscles of the nonoperated knee was significantly shorter than that of both operated and nonoperated knees at 1 year postoperatively ($P = .001$ and $.037$, respectively). Preoperative mean AT of the hamstring muscles of the nonoperated knee was also significantly shorter than that of both operated and nonoperated knees at 1 year postoperatively ($P = .031$ and $.001$, respectively). That is, operated and nonoperated knees did not recover to the preoperative level of the nonoperated knees in terms of AT (Table 2).

3.2. Dynamic postural stability

Mean preoperative OSI on the nonoperated knees was 1.2° . It significantly increased by $1.5 \pm 0.1^\circ$ and $1.5 \pm 0.1^\circ$ at 6 months and 1 year postoperatively, respectively ($P = .000$). In operated knees, mean preoperative OSI was $1.8 \pm 0.1^\circ$. It significantly decreased by $1.5 \pm 0.1^\circ$ and $1.4 \pm 0.1^\circ$ at 6 months and 1 year postoperatively, respectively ($P = .001$). Preoperative mean OSIs on the nonoperated knees were significantly less than that of both operated and nonoperated knees at 1 year postoperatively ($P = .001$ and $< .001$, respectively), indicating that operated and nonoperated knees did not recover to the preoperative level of the nonoperated knees in terms of OSI (Table 2).

3.3. Clinical outcomes

Tegner activity-level scales at 6 months and 1 year postoperatively were significantly lower than preoperative scores ($P < .001$) (Table 2).

3.4. Correlations between neuromuscular control index (AT and OSI) and Tegner activity-level scale

The correlation between neuromuscular control index (AT and OSI) and Tegner activity level is shown in Table 3. In operated knees, there was a significant negative correlation between

Table 2
Serial changes in acceleration time of hamstring and quadriceps, dynamic postural stability, and Tegner activity level of enrolled subjects.

All participants (n=96)	Pre-op. baseline (time 0)	Post-op. 6 Months (time 1)	Post-op. 1 year (time 2)	P-value			Mean (95% CI)		
				Time 0 × 1	Time 0 × 2	Time 1 × 2	Time 0 × 1	Time 0 × 2	Time 1 × 2
Quadriceps AT (nonoperated)	47.6 ± 1.7	55.4 ± 2.3	54.3 ± 2.0						
				.023	.037	1.0	-7.8 (-14.8 to -0.8)	-6.6 (-13.0 to -0.3)	1.1 (-0.4 to 6.3)
Quadriceps AT (operated)	78.9 ± 6.4	56.6 ± 2.5	56.9 ± 2.0		.006				
				.004	.005	1.0	22.2 (5.7 to 38.8)	21.9 (5.3 to 38.6)	-0.3 (-6.6 to 6.0)
Hamstring AT (nonoperated)	56.5 ± 1.7	66.9 ± 3.4	67.9 ± 2.7		.001				
				.015	.001	1.0	-10.4 (-19.3 to -1.6)	-11.3 (-18.5 to -4.2)	-0.9 (-9.2 to 7.4)
Hamstring AT (operated)	86.5 ± 6.2	63.5 ± 2.3	62.5 ± 2.8		.002				
				.002	.001	1.0	23.0 (7.4 to 38.7)	24.1 (8.1 to 40.0)	1.0 (-6.7 to 8.8)
OSI (nonoperated)	1.2 ± 0.0	1.5 ± 0.1	1.5 ± 0.1		<.001				
				<.001	.001	1.0	-0.3 (-0.5 to -0.1)	-0.3 (-0.5 to -0.1)	0 (-0.1 to 0.2)
OSI (operated)	1.8 ± 0.1	1.5 ± 0.1	1.4 ± 0.1		.001				
				.040	.001	.224	0.3 (0 to 0.5)	0.4 (0.1 to 0.6)	0.1 (0 to 0.3)
Tegner activity scale	7.0 (4 to 9)	3.0 (1 to 9)	4.0 (3 to 9)		< .001				
				< .001	< .001	< .001	3.5 (3.2 to 3.9)	2.2 (1.9 to 2.5)	-1.3 (-1.6 to 1.1)

Compared with preoperative nonoperated knee	Pre-op. baseline	Post-op. 6 Months	Post-op. 1 year	P-value	Mean (95% CI)		
Quadriceps AT (operated)	47.6 ± 1.7	56.6 ± 2.5	56.9 ± 2.0	.001	-9.0 (-16.0 to -2.0)	-9.4 (-15.3 to -3.4)	-0.3 (-6.6 to 6.0)
Hamstring AT (operated)	56.5 ± 1.7	63.5 ± 2.3	62.5 ± 2.8	.031	-7.0 (-13.8 to -0.2)	-5.9 (-13.4 to 1.6)	1.0 (-6.8 to 8.8)
OSI (operated)	1.2 ± 0.0	1.5 ± 0.1	1.4 ± 0.1	.001	-0.3 (-0.6 to -0.1)	-2.2 (-0.4 to -0)	0.1 (-0 to 0.3)

AT=acceleration time, CI=confidence interval, OSI=overall stability index.

Time 0 × 1, P value between time 0 and 1; Time 0 × 2, P value between time 0 and 2; Time 1 × 2, P value between time 1 and 2.

The values expressed as mean ± standard deviation, measurement unit of the acceleration time was millisecond (ms), measurement unit of the postural stability was degree (°)

Tegner activity level and AT of the quadriceps muscles in every time point ($r = -0.318, P = .002$; $r = -0.254, P = .012$; $r = -0.345, P = .001$, respectively). AT of the hamstring muscles showed significant negative correlation with Tegner activity level at 6 months and 1 year postoperatively ($r = -0.258, P = .011$; $r = -0.273, P = .007$, respectively). Significant correlations between ATs of quadriceps and hamstring muscles, and Tegner activity level were also identified in nonoperated knees at 6 months and 1 year postoperatively ($r = -0.439, P < .001$; $r = -0.445, P < .001$, respectively in quadriceps muscles / $r = -0.245, P = .016$; $r = -0.378, P < .001$, respectively in hamstring muscles). Tegner activity level also significantly correlated with

OSI at 6 months and 1 year postoperatively in both knees ($r = -0.211, P = .039$; $r = -0.409, P < .001$, respectively in operated knees / $r = -0.399, P < .001$; $r = -0.272, P = .007$, respectively in nonoperated knees).

4. Discussion

The present study evaluated neuromuscular control of nonathletic patients who had undergone ACLR with hamstring tendon autografts using AT and dynamic postural stability (OSI). Neuromuscular control of the operated knee gradually improved up to 1 year postoperatively; however, it did not recover to the

Table 3
Correlations between neuromuscular control index (AT and OSI) and Tegner activity-level scale.

Parameters	Operated knees			Nonoperated knees		
	Pre-op. baseline	Post-op. 6 months	Post-op. 1 year	Pre-op. baseline	Post-op. 6 months	Post-op. 1 year
Quadriceps AT & Tegner activity-level scale						
PCC (r)	-0.318	-0.254	-0.345	-0.009	-0.439	-0.445
p-value	0.002*	0.012*	0.001*	0.928	< 0.001*	< 0.001*
Hamstring AT & Tegner activity-level scale						
PCC (r)	-0.063	-0.258	-0.273	-0.004	-0.245	-0.378
p-value	0.543	0.011*	0.007*	0.966	0.016*	< 0.001*
OSI & Tegner activity-level scale						
PCC (r)	0.018	-0.211	-0.409	0.091	-0.399	-0.272
p-value	0.864	0.039*	< 0.001*	0.380	< 0.001*	0.007*

ACL=anterior cruciate ligament, AT=acceleration time, OSI=overall stability index, PCC=Pearson correlation coefficient.

* Statistically significant.

preoperative level of the nonoperated knees, even at 1 year postoperatively. In addition, neuromuscular control on the nonoperated knees was shown to be significantly decreased at both 6 months and 1 year postoperatively compared with that at the preoperative level. The neuromuscular control indices (AT and OSI) showed statistically significant correlations with Tegner activity level.

Neuromuscular control is defined as the afferent sensory recognition of joint position and motion and the following efferent response to that awareness.^[28] Impaired neuromuscular function around the knee is considered to be responsible for persisting functional deficits such as decreased maximal strength, limited postural control, or prolonged muscle reaction time.^[29] As impaired neuromuscular control is a significant contributor to injuries, improving and optimizing neuromuscular control represents a fundamental purpose of rehabilitation after surgical or non-surgical treatment of various knee injuries.^[30,31] Previous studies have demonstrated that injured ACL could disrupt complex interactions within the neuromuscular system, resulting in impaired kinesthesia and proprioception, abnormal muscle activation, and dynamic knee joint stability.^[12,14,29]

Isokinetic test has been recently widely used to assess neuromuscular control after ACL injury. Although the peak torque measure has been considered as a gold standard in isokinetic test, muscle balance considerations should also be assessed to understand patients' neuromuscular control status more comprehensively.^[17,18] The AT has been defined as the time to accelerate to a preset dynamometer speed. It is established as a muscle recruitment variable, which provides important information regarding neuromuscular control ability to produce maximal muscular action.^[19,20] However, there is a lack of studies regarding AT after ACL injury in literature.

Previous studies have reported that many patients with ACLR have sustained deficit in neuromuscular control 6 months and even 1 year postoperatively.^[32–36] The result of the present study is consistent with these findings. The neuromuscular control of the operated knees gradually improved after ACLR, but did not recover at 6 months and 1 year postoperatively to the preoperative level of the nonoperated knees. A possible explanation for this impaired neuromuscular control may be the insufficient recovery of the mechanoreceptors. Mechanoreceptors are sensory neurons that provide afferent sensory input to the central nervous system, which are present in the ACL including Pacinian corpuscles as rapidly adapting mechanoreceptors, and Ruffini endings, muscle spindles, and Golgi tendon organs as slow adapting mechanoreceptors.^[37] Goertzen et al^[38] reported that the reformation of the mechanoreceptors improved at least 1 year postoperatively after ACLR. Therefore, loss of these mechanoreceptors may have affected the recovery of neuromuscular control in the operated knees, thus leading to an impairment of functional performance. Another possible reason for impaired neuromuscular control may be the insufficient ligamentization in the operated knees. In a previous experimental study for graft biopsy, authors reported that successfully ligamentization can occur 1 year after ACLR.^[39]

Several previous studies have demonstrated that neuromuscular control could also be decreased in the nonoperated knees of patients with ACL injury.^[40–42] In addition, Keays et al^[43] reported that 10% of patients who underwent ACLR using hamstring tendon had contralateral ACL injury. Neuromuscular control in the nonoperated knees in the present study also showed results similar to previous studies. On the nonoperated knees, neither AT nor OSI recovered to the preoperative level even 1

year after ACLR. A possible reason for decreased neuromuscular control on the noninjured side is impaired afferent nerves after ACL injury.^[40] Roberts et al^[42] demonstrated that the altered afferent signals from the injured limb affected the muscular function in the uninjured limb, finally altering the sense of stability of the uninjured limb. Therefore, neuromuscular training after ACLR should be emphasized in the nonoperated knees as well as operated knees.

In the present study, the neuromuscular control indices (AT and OSI) showed statistically significant correlations with Tegner activity level in both operated and nonoperated knee joints. However, all absolute values of r (coefficient of correlation) were below 0.5. Although the reasons for this result are unclear, one possible reason may be complex factors affecting activity level after ACLR. Previous researches have demonstrated that psychological and environmental factors as well as physical factors are related to activity levels after ACL injury.^[44–46] The neuromuscular control index is only one component of various physical factors. Therefore, as a variety of factors could affect activity level after ACLR, correlations between the neuromuscular control indices and Tegner activity level might be weaker than expected.

4.1. Limitations

There are some limitations in the present study. First, this study has a retrospective design. Further prospective study is necessary to elucidate the results of the present study more clearly. Second, this study was performed only on patients who underwent ACLR. It is difficult to select normal control subjects with similar sports activity or morphological condition as patients with ACL injuries. Nevertheless, further studies that compare the difference in neuromuscular control between patients with ACLR and normal control subjects are needed to confirm the results of this study more definitely. Third, this study enrolled only the patients with isolated ACL injury to reduce selection bias. However, many ACL injured patients have concomitant meniscal or structural injuries. Further studies that will consider patients with other concomitant injuries would provide additional information. Lastly, the operations were performed by 2 different surgeons. However, the 2 surgeons were knee arthroscopic specialists with technical knowledge and experience for conducting ACL reconstruction. They performed all operations using the same technique (anatomical single-bundle ACL reconstruction) and all patients were prescribed the same postoperative rehabilitation protocol.

5. Conclusions

The neuromuscular control in both knees was not restored to the preoperative level of the nonoperated knees until 1 year after ACLR using hamstring tendon autografts in nonathletic patients. Clinicians and physical therapists should consider the results of the present study and attempt to enhance neuromuscular control in the nonoperated knees as well as the operated knees.

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