Cross-education improves quadriceps strength recovery after ACL reconstruction: a randomized controlled trial

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Abstract

Purpose The aim of this study was to investigate the effects of concentric and eccentric cross-education (CE) on quadriceps strength and knee function recoveries after anterior cruciate ligament (ACL) reconstruction.

Methods Forty-eight patients (age: 29.5 ± 6.8 years, body mass index: 26.1 ± 3.2 kg/m²) who had undergone ACL reconstruction with hamstring tendon autograft were included in the study. The patients were randomly divided into three groups when they reached four weeks post surgery: (1) concentric CE (n = 16); (2) eccentric CE (n = 16); and (3) control (n = 16). All groups followed the same post-surgical rehabilitation program for their reconstructed limb. Additionally, the two experimental groups followed eight weeks of isokinetic training for the uninjured knee at 60°/s for 3 days per week. Quadriceps maximum voluntary isometric strength (MVIC) was measured during the 4th week (pre-training), 12th week (post training), and 24th week post surgery. The single-leg hop distance and International Knee Documentary Committee (IKDC) scores were also evaluated during the 24th week post surgery. Analysis of variance was used for statistical analysis.

Results Group-by-time interaction was significant for quadriceps MVICs for reconstructed and healthy limbs (p = 0.02). Quadriceps strength of both knees was greater in concentric and eccentric CE groups compared to control group during the 12th- and 24th weeks post surgery (p < 0.05). Strength gain was 28% and 31% in concentric and eccentric CE groups, respectively, when compared with the control group. Concentric and eccentric CE had similar effects on quadriceps strength recovery (n.s.). IKDC score, and single-leg hop distances were not significantly different among groups (n.s.).

Conclusions Concentric and eccentric quadriceps strengthening of healthy limbs in early phases of ACL rehabilitation improved post-surgical quadriceps strength recovery of the reconstructed limb. CE should be integrated into ACL reconstruction rehabilitation, especially in the early rehabilitative phases to restore quadriceps strength.

Level of evidence Randomized controlled trial, Level I.

Keywords Anterior cruciate ligament · Cross-over effect · Quadriceps strength · Rehabilitation

Introduction

Anterior cruciate ligament (ACL) injuries are the most common knee injuries that mainly occur during sports that include cutting and pivoting maneuvers [1]. Individuals who suffer from ACL injuries require ACL reconstruction (ACLR) if they wish to return to pre-injury levels of sport participation [1, 5]. However, significant decreases in muscle strength, asymmetries in loading strategies, and decreased knee stability, which may possibly cause a lower rate of return to sport and a second ACL injury, have commonly been observed after ACLR [17, 27, 29].

Quadriceps strength decrement after ACLR is the primary problem that could persist for years even if advanced and
accelerated rehabilitation protocols are followed [13]. Since quadriceps strength is correlated with the functional performance, patient-reported outcomes and osteoarthritis development in long-term post-ACLR occur [34, 37]; thus, maximizing quadriceps strength following ACLR is an essential component of rehabilitation [30]. Augustsson [3] suggested that current strengthening exercises during ACLR rehabilitation may be insufficient in terms of quadriceps strength and muscle volume recovery, and this probably increases the risk of re-injury when an individual returns to sports. Because quadriceps strengthening in non-weight bearing positions (leg extension) in the early ACLR period has been thought to be detrimental for graft healing, weight-bearing exercises with limited knee ranges of motion are mostly suggested for these patients [9]. However, these type of exercises might not be enough to strengthen the quadriceps as much as the non-weight-bearing exercises do.

One cross-education (CE)-related phenomenon is strength improvement of the untrained limb after unilateral strengthening of the homologous contralateral limb [31]. CE was originally described by Scripture et al. [31], and many studies have attempted to show CE effects on both healthy and patient population [8, 10, 12, 18, 22, 23, 25, 26, 32, 35, 38]. However, the precise physiological mechanism(s) underlying CE remains unknown. One study suggested that training one limb could induce adaptation in the control system for the opposite side (spill-over) [12], and other studies explained the CE effects as the capability of the untrained limb to access neuromuscular adaptations in the trained limb [7, 11, 12]. Indeed, CE could be a promising treatment in cases in which injured limb strengthening was not possible or may actually be detrimental [23, 24]. To date, only one study has evaluated CE’s influence on quadriceps post-ACLR strength recovery [26]. The authors reported that eccentric CE was effective for minimizing quadriceps deficits 8 weeks post-ACLR and also that it could increase quadriceps isometric strength at 45° and 90° of knee flexion when compared to the control group [26]. On the other hand, strength gains in the healthy limb were not documented in conjunction with those in the reconstructed limb in the study, so it is not clear how much strength gain was actually provided by CE effect.

In this study, we aimed to investigate quadriceps strength recovery in the reconstructed limb following the 8-week isokinetic quadriceps concentric and eccentric training of the contralateral limb and again at 12 weeks post training. It was hypothesized that isokinetic quadriceps strength training of the contralateral limb would provide strength increase in the quadriceps strength of the reconstructed limb.

Materials and methods

Forty-eight individuals who had undergone ACLR with hamstring tendon autograft were included in the study. Inclusion criteria of the study included several parameters: (a) unilateral arthroscopic ACLR with hamstring tendon autograft HTG; (b) ages between 17 and 45 years; (c) non-contact injury mechanism; (d) pre-injury Tegner score ≥ 5; and (e) regular continuation of the physical therapy program (missing no more than three sessions). To only involve physically active individuals in the study, we specified a pre-injury Tegner activity level of at least 5. Exclusion criteria consisted of several parameters: (a) ACLR with patellar tendon autograft or allograft; (b) revision of ACLR; (c) ACLR with meniscus and/or cartilage repair; (d) systemic or neurological problems; and (e) lower extremity injuries in contralateral lower extremity at least 12 months. The participants were randomly allocated into one of three training groups: (a) concentric CE with ACLR rehabilitation; (b) eccentric CE with ACLR rehabilitation; and (c) ACLR rehabilitation.

The allocation to each group was done by one of the authors who was unaware of patients’ identities. The allocation was controlled for age, body mass index (BMI), and pre-injury Tegner activity level to guarantee a homogeneous distribution between groups. Patients knew that they were involved in an experimental study, but they were unaware of the other experimental groups of the study. Assessments and data analyses were blinded. The assessors were blinded with respect to patients’ allocations and were assigned a numerical code to all of the recorded tests, which were blindly processed by the other investigators.

Outcome measures

Quadriceps strength

The participants attended a baseline isometric strength assessment on the 4th week after surgery followed by an 8-week intervention, and they were then reassessed at the end of the intervention and again at 12 weeks post intervention.

To determine the isometric quadriceps maximum voluntary isometric contraction (MVIC) at assessment time points, an isokinetic dynamometer was used (IsoMed®2000 D&R GmbH, Germany) The quadriceps MVIC test was reported to have demonstrated a good test–retest reliability (ICC > 0.86) [6]. The participants were seated on an isokinetic dynamometer. Their hips were flexed at approximately 90° with stabilization straps placed across the trunk, waist, and distal femur of the limb, which
was tested to minimize compensatory movement. The axis of the dynamometer was aligned with the dynamometer’s laser axis of rotation to the lateral femoral epicondyle of both limbs. The knee was flexed at 60°, and dynamometer force arm was secured 2 cm above the lateral malleolus.

Prior to muscle strength recordings, the participants were allowed three maximal voluntary isometric quadriceps contraction practice trials to familiarize themselves with the testing procedures. During the formal testing, the participants performed three MVICs (each 5-sec duration) for the quadriceps with a 2-min-rest period between each MVIC. For consistent instruction and verbal encouragement of each participant, only one tester performed the MVIC tests. The participants were asked to push as hard as possible against the dynamometer arm. The uninvolved limb was tested first. The average of the 3-peak torques was calculated. Limb symmetry index for quadriceps strength calculated as ([reconstructed limbs’ strength/contralateral limbs’ strength] x 100).

Knee physical function

The One-Leg Hop for Distance Test (OLHDT) and the International Knee Document Committee 2000 Subjective Knee Form (IKDC) were used to assess the knee function 24 weeks post surgery.

In the OLHDT, the participants stood on one leg with toes behind a mark on the floor. They were instructed to jump as far as possible with a controlled landing. The test was performed until three successful jumps were performed with each leg. The test started with the uninvolved limb followed by the involved limb. The distance in centimeter was measured. The best of the three trials was used for analysis. The OLHDT uses the limb symmetry index for OLHDT calculated as ([reconstructed limb-hop distance/contralateral limb-hop distance] x 100). Test–retest reliability of the OLHDT was acceptable (ICC > 0.75) following ACL reconstruction [19].

IKDC, a valid and reliable measure for ACL injury and ACLR (ICC = 0.91), contains ten items related to knee symptoms in addition to daily and sports activities. Scores range from 0 to 100 with higher scores indicating less disability [16].

Training programs

ACLR rehabilitation

The participants in each group attended the same ACLR rehabilitation program (Online Appendix). The ACLR rehabilitation program started during the first post-surgical week, and the patients were instructed to visit physical therapy for 3 days per week until post-ACLR week 12. The early rehabilitation program (0–4 weeks) emphasized limiting hemarthrosis and edema, obtaining full knee range of motion, achieving good quadriceps muscle control, and normalization of walking. The rehabilitation program (4–12 weeks) included progressive neuromuscular training, including core balance and strengthening exercises mostly performed in weight-bearing positions. The rehabilitation program lasted for until 12 weeks post surgery and did not include any open kinetic chain quadriceps exercises for the reconstructed and the healthy limbs.

From the 12th to 24th weeks, all participants in the groups were instructed to perform the same home-exercise program. This program included resistive hip and knee strengthening, plyometric, running, and balance exercises for both limbs 3 days per week during this period.

Cross-education

The participants assigned to the CE groups attended isokinetic concentric or eccentric contralateral limb training three times per week in addition to ACLR rehabilitation during the 8-week period between the 4th and 12th post-surgery weeks. Each isokinetic training session consisted of three sets of 12 repetitions at 60°/s ranging from 10° to 90° flexion. Between each set of repetitions, the participants were allowed 2 min of rest. As it was in muscle strength testing, the participants were instructed to perform maximal contractions during the trainings. Special attention was given to ensure that each subject kept the untrained leg as relaxed as possible during the training.

Informed consent was obtained from all individual participants included in the study, and the protocol for the study was approved by the Hacettepe University Institutional Review Board (KA-17,157). The study was registered at ClinicalTrials.gov.

Statistical analysis

Sample size calculation

Sample size was a priori calculated with a significance level of α = 0.05 and a power of 80% based on our pilot study. A sample size of 30 participants (10 participants in each group) was established for this study (effect size: 0.5, correlation among repeated measures: 0.5) to see quadriceps isometric strength difference among the groups over time.

Data analysis

IBM SPSS 21.0 was conducted for statistical analysis. The normality of the distribution was analyzed with the Shapiro–Wilk test. To ensure the group randomization was successful, demographics (age, height, body mass, BMI), time...
from injury to surgery and pre-injury activity levels of the groups were compared using a one-way analysis of variance (ANOVA).

Two-factor repeated measures of ANOVA with one within-group and one between-groups (time at the 4th, 12th, and 24th week groups and concentric and eccentric CEs and control groups, respectively) were used to determine whether quadriceps isometric strength recovery of limbs differed among groups over time. The Kruskal Wallis test was also used to analyze group difference in terms of OLHDT and IKDC scores at 24 weeks post surgery. The significant interactions and/or main effects were analyzed with the Bonferroni post hoc test. A change in score was reported with confidence interval (CI 95%) and effect size. Significance level was set at \( p < 0.05 \).

**Results**

No significant differences were found among groups in terms of demographic characteristics, pre-injury activity levels, and time from the injury to surgery (Table 1).

At the 4th week after surgery, quadriceps MVICs were similar among groups (\( p > 0.05 \)). Then, a significant time by group interaction was found for quadriceps isometric strength recovery of the reconstructed limb (\( p = 0.01 \)). Compared to the control group, quadriceps MVICs were greater in the concentric and eccentric CE groups (\( p = 0.04 \) and 0.03, respectively) at the 12th week post surgery (after intervention). At the 24th week post surgery, quadriceps strength was greater in concentric and eccentric CE groups (\( p = 0.01 \) and < 0.001, respectively) compared to the control group. There were no significant differences between concentric and eccentric CE groups with respect to quadriceps MVICs at these time points (n.s.) (Table 2).

During the 4th week post surgery, quadriceps MVICs were similar between groups (n.s.) A time-by-group interaction was found for quadriceps strength recovery of the contralateral limb (\( p = 0.01 \)). When compared to the control group, the quadriceps strength was greater in concentric and eccentric CE groups during the 12th week post surgery (\( p < 0.001 \), and there were no differences between the concentric and eccentric CE groups (n.s.). At the 24th week, only the eccentric CE groups’ quadriceps strength was found to be greater than the control group (\( p = 0.01 \)). (Table 3).

There were no significant interactions for quadriceps limb symmetry index (n.s.). It increased gradually from 49.0 to 80.8% at 12th week and to 86.7% at 24th week post surgery (Fig. 1).

There were no significant differences among groups in terms of OLHDT and IKDC scores (n.s.) (Table 4).

**Discussion**

Isokinetic quadriceps concentric and eccentric strengthening of the contralateral limb improved the isometric quadriceps strength recovery of the untrained reconstructed limb in early period of the ACLR rehabilitation; this finding was the most important one in the study. In addition, the concentric and eccentric CE effects on reconstructed limbs were found to be similar, and 12 weeks post CE, greater quadriceps strength changes were observed in the experimental groups when compared with the control group. However,

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### Table 1 Demographic characteristics of the participants

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Body height (cm)</th>
<th>Body mass (kg)</th>
<th>BMI (kg/m²)</th>
<th>Time from injury to surgery (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentric CE (n = 16)</td>
<td>29.7 ± 6.9</td>
<td>176.4 ± 5.7</td>
<td>80.3 ± 13.6</td>
<td>7.9 ± 14.3</td>
</tr>
<tr>
<td>Eccentric CE (n = 16)</td>
<td>30.4 ± 7.5</td>
<td>174.6 ± 5.3</td>
<td>80.6 ± 12.4</td>
<td>13.6 ± 18.4</td>
</tr>
<tr>
<td>Control (n = 16)</td>
<td>28.1 ± 6.1</td>
<td>179.1 ± 3.9</td>
<td>81.7 ± 7.9</td>
<td>28.1 ± 11.0</td>
</tr>
</tbody>
</table>

**Table 2** Quadriceps maximum voluntary isometric contractions of the reconstructed limb before (at the 4th week post surgery) and following cross-education (at the 12th week post surgery) and at 12 weeks post training (at the 24th week post surgery)

<table>
<thead>
<tr>
<th>Quadriceps strength (Nm/kg)</th>
<th>4 weeks</th>
<th>12 weeks</th>
<th>Difference (CI 95%)</th>
<th>Effect size</th>
<th>12 weeks</th>
<th>24 weeks</th>
<th>Difference (CI 95%)</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentric CE (n = 16)</td>
<td>1.2 ± 0.5</td>
<td>2.5 ± 0.5 a</td>
<td>1.2 (− 1.5, − 1.0)</td>
<td>2.5</td>
<td>2.5 ± 0.5</td>
<td>2.9 ± 0.4 a</td>
<td>0.4 (− 0.7, 0.1)</td>
<td>0.6</td>
</tr>
<tr>
<td>Eccentric CE (n = 16)</td>
<td>1.2 ± 0.3</td>
<td>2.5 ± 0.4 b</td>
<td>1.3 (− 1.5, − 1.1)</td>
<td>3.6</td>
<td>2.5 ± 0.4</td>
<td>3.0 ± 0.5 b</td>
<td>0.5 (− 0.7, − 0.3)</td>
<td>1.1</td>
</tr>
<tr>
<td>Control (n = 16)</td>
<td>1.2 ± 0.4</td>
<td>2.1 ± 0.5 ab</td>
<td>0.9 (− 1.2, − 0.7)</td>
<td>2.3</td>
<td>2.2 ± 0.5</td>
<td>2.4 ± 0.3 ab</td>
<td>0.3 (− 0.4, − 0.1)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

a Quadriceps strength was greater in concentric CE than the control group at 12th weeks and 24th weeks after ACL reconstruction

b Quadriceps strength was greater in eccentric CE than the control group at 12th week and 24th week after ACL reconstruction
IKDC scores and one-leg hop for distance were similar among groups.

A recent meta-analysis showed that CE effects induced moderate to large strength gains in untrained limbs in healthy individuals depending on the contraction type and body region [23]. In the present study, strength gains in the reconstructed limb were greater than in the trained healthy limb. First, CE may decrease the central inhibitory impulses [20] and enhance the neuromuscular facilitation and voluntary activation [21] in the reconstructed limb, so that the strength changes may be more obvious in the reconstructed limb when compared to the trained limb. Second, although the participants were warned to relax their reconstructed limb during isokinetic training of the contralateral limb, undetectable isometric contractions might have occurred in the reconstructed limb, which could possibly have helped to improve quadriceps strength. Zoue et al. [38] explained this finding via a postural hypothesis that describes cases in which a contraction occurs in one limb, other muscles in the contralateral limb will contract to maintain postural stability.

Previous studies have failed to demonstrate an increase in quadriceps muscle activation or hypertrophy in untrained limbs with contralateral training in healthy individuals [4, 10]. As quadriceps muscle activation or muscle thickness was not measured in the present study, it could not be indicated whether CE had any beneficial effects on muscle hypertrophy and activation after ACLR. The quadriceps weakness has commonly been observed in patients with ACLR due to arthrogenic muscle inhibition and muscle atrophy [14, 33]. If CE enhanced neuromuscular facilitation of the quadriceps in the reconstructed limb, it may have also contributed to hypertrophic quadriceps changes. Therefore, future studies are needed to investigate CE’s effects on quadriceps morphology and activation failure of the reconstructed limb after surgery.

Papandreou et al. [26] investigated the effects of 8-week eccentric CE on quadriceps strength deficits post ACLR. They measured pre-operative quadriceps strength and again at 8 weeks post-operatively. After the 8-week CE, the quadriceps strength decrement of the reconstructed ranged from 6 to 16%, but it was 37% in the control group. Thus, they suggested that eccentric CE could improve quadriceps strength in the early stages of ACLR and decrease the quadriceps strength deficits when compared to the control group. It was hard to compare our findings with the findings

| Table 3 | Quadriceps maximum voluntary isometric contractions of the contralateral limb before (at the 4th week post surgery) and following cross-education (at the 12th week post surgery) and at 12 weeks post training (at the 24th week post surgery) |
| Quadriceps strength (Healthy) | 4 weeks | 12 weeks | Difference (CI 95%) | Effect size | 12 weeks | 24 weeks | Difference (CI 95%) | Effect size |
| Concentric CE (n = 16) | 2.6 ± 0.6 | 3.1 ± 0.4 | 0.6 (−0.9, −0.3) | 1.2 | 3.1 ± 0.4 | 3.2 ± 0.6 | 0.1 (−0.4, 0.1) | 0.2 |
| Eccentric CE (n = 16) | 2.5 ± 0.5 | 3.2 ± 0.3 | 0.7 (−1.1, −0.4) | 1.6 | 3.2 ± 0.3 | 3.5 ± 0.5 | 0.3 (−0.4, −0.1) | 0.6 |
| Control (n = 16) | 2.5 ± 0.5 | 2.6 ± 0.4 | 0.1 (−0.3, −0.1) | 0.2 | 2.6 ± 0.4 | 3.0 ± 0.4 | 0.4 (−0.5, −0.3) | 1.0 |

*aQuadriceps strength was greater in concentric CE than the control group at the 12th week after ACL reconstruction
bQuadriceps strength was greater in eccentric CE than the control group at the 12th week and 24th week after ACL reconstruction

Fig. 1 Quadriceps strength limb symmetry index changes over time for each group

IKDC scores and OLHDT limb symmetry index at the 24th week after ACLR for each group

| Table 4 | IKDC score and OLHDT limb symmetry index at the 24th week after ACLR for each group |
| Knee function | Concentric CE (n = 16) | Eccentric CE (n = 16) | Control (n = 16) | p value |
| IKDC score | 82.1 ± 9.6 | 84.1 ± 9.4 | 79.4 ± 9.3 | n.s |
| OLHDT LSI | 88.9 ± 10.5 | 91.8 ± 13 | 91.9 ± 9.1 | n.s |

IKDC International knee documentation committee, OLHDT One-Leg Hop for Distance Test, LSI limb symmetry index
of Papandreu et al. [26] because the CE training type and the time period for strength measurements were different between the two studies. They used a leg press machine for eccentric contralateral limb training, and they started CE during the first post-ACLR week. However, in the current study, contralateral limb training was performed with isokinetic devices, and the training was started during the fourth post-surgical week. Isokinetic exercises maximally load the muscle through the selected range of motion compared to isometric exercises [28], so isokinetic exercises may lead to greater strength improvements than isometric exercises.

In the present study, since the isokinetic measurements are contraindicated in early ACLR phases, only the quadriceps MVICs could be measured in the participants. Although strength gains after training are contraction modesspecific in which eccentric training leads to increases more in eccentric strength, concentric strength training induces more increases in concentric strength [2]. However, both isotonic/isokinetic strength training has been shown to increase muscles’ isometric strength [15, 26, 36]. Many CE studies have demonstrated greater changes in the untrained limb’s isometric strength following eccentric training when compared with concentric training [15, 18, 22]. Hortobagyi et al. [15] demonstrated that greater mode-specific CE training benefits occur more with eccentric than concentric exercises in sedentary healthy individuals. They reported isometric quadriceps strength gains as high as 39% with eccentric CE versus 22% with concentric CE at 60°/s when compared with the control group. However, similar quadriceps strength gains were found following concentric and eccentric CE in the present study. The isokinetic quadriceps strength training was performed at the same velocity that was used in a study by Hortobahyi et al. [15], but our training period was shorter (eighth week) than it was in their study (12th week). Besides, they examined the CE effects on healthy individuals, but we examined its effect on individuals who had undergone ACLR. Therefore, the different training period and participants’ characteristics may have produced different findings between the studies.

To investigate the quadriceps strength changes of the trained and untrained limbs post CE (from 12 to 24 weeks post-surgery) was the another purpose of the present study. There is evidence that strength gains with CE were not lost after six or eight weeks of detraining [32, 35]. In the current study, it was not possible to examine CE’s detraining effects to determine whether its beneficial effects on untrained limbs were retained because the quadriceps strengthening could not be suspended during this time period in individuals with ACLR. Therefore, the same 12-week home-exercise program was recommended to the participants, and the program was renewed each month when the participants visited our clinic. Thus, it was aimed to observe whether or not quadriceps strength gains were higher in the experimental groups when compared with the controls even though all groups performed the same training program in the current study. Although the strength changes in healthy limbs were greater in control group, the strength changes of the reconstructed limbs were higher in the experimental groups. During this time period, due to training of the contralateral limb with home-exercise program in all groups, CE effects on quadriceps strength in reconstructed limbs could also be observed in the control group; however, greater quadriceps strength changes in the reconstructed limbs in the experimental groups with even greater strength changes in contralateral limb in the control group may demonstrate that the beneficial effects of isokinetic contralateral limb training may be persistent. This finding has important clinical implications in that contralateral limb strengthening in early ACLR-rehabilitative phases could positively affect quadriceps strength improvement in the subsequent rehabilitative phases.

Although apparent quadriceps strength gain was observed immediately following and 12 weeks post CE, this strength gain did not lead to significant improvement in IKDC scores and single-leg hop performances. Manca et al. [23] suggested that strength increases in untrained limbs via CE may not be linked to functional gains. Despite greater quadriceps strength observed in experimental groups at 24th week post surgery, it may not strongly be related to knee function, which we measured using IKDC scores and OLHDT [37].

This study has some limitations. First, muscle morphology was not evaluated in this study, so it is unknown if strength improvements in quadriceps strength were related to changes in muscle mass. The previous studies have suggested that muscle strength increases without hypertrophic changes post CE in healthy individuals, but it is unclear whether CE could cause a change in muscle mass of the untrained injured limb. Second, all participants in the CE groups were warned to relax the reconstructed limb during training of the contralateral limb; however, involuntary undetectable isometric contractions may have occurred and induced strength gains in reconstructed limbs. Third, apparent quadriceps strength gains in the CE groups could be attributed to familiarity with testing procedures [7]. Further, familiarity with the testing procedure may help to overcome kinesiophobia, which is a common problem seen in individuals who had undergone ACLR and thus the experimental groups may be more confident in exerting their maximal isometric strength during testing.

**Conclusion**

The results of the present study evidence that the concentric and eccentric isokinetic training program improved quadriceps MVICs of the trained leg in addition to the reconstructed limb in individuals who had undergone ACLR.
However, greater strength gains in reconstructed versus trained limbs that suggest mechanisms of the CE effects on quadriceps strength recovery of the reconstructed limb should be investigated in more detail. Eccentric and concentric CE effects on the improvements in quadriceps strength was found similar. CE should be integrated into ACLR rehabilitation, especially in the early phases of the rehabilitation to maximize the quadriceps strength.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was approved by Hacettepe University Institutional Review Board (KA/17157).

Informed consent Informed consent was obtained from all individual participants included in the study.

References