Acta Med. Okayama, 2012
Vol. 66, No. 3, pp. 231-237

Acta Medica
Okayama
http://escholarship.lib.okayama-u.ac.jp/amo/

Original Article

Early Rehabilitation with Weight-bearing Standing-shaking-board Exercise in Combination with Electrical Muscle Stimulation after Anterior Cruciate Ligament Reconstruction

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The objective of early rehabilitation after anterior cruciate ligament (ACL) reconstruction is to increase the muscle strength of the lower extremities. Closed kinetic chain (CKC) exercise induces co-contraction of the agonist and antagonist muscles. The purpose of this study was to compare the postoperative muscle strength/mass of subjects who performed our new CKC exercise (new rehabilitation group: group N) from week 4, and subjects who received traditional rehabilitation alone (traditional rehabilitation group: group T). The subjects stood on the device and maintained balance. Then, low-frequency stimulation waves were applied to 2 points each in the anterior and posterior region of the injured thigh 3 times a week for 3 months. Measurement of muscle strength was performed 4 times (before the start, and then once a month). Muscle mass was evaluated in CT images of the extensor and flexor muscles of 10 knees (10 subjects) in each group. The injured legs of group N showed significant improvement after one month compared to group T. The cross-sectional area of the extensor muscles of the injured legs tended to a show a greater increase at 3 months in group N. This rehabilitation method makes it possible to contract fast-twitch muscles, which may be a useful for improving extensor muscle strength after ACL reconstruction.

Key words: anterior cruciate ligament reconstruction, closed kinetic chain, electrical muscle stimulation, standing-shaking-board exercise

The objective of early rehabilitation after anterior cruciate ligament (ACL) reconstruction is to increase the muscle strength of the lower extremities while ensuring the prevention of re-rupture of the reconstructed ligament. Usually, physical exercise is divided into 2 types: open kinetic chain (OKC) exercise and closed kinetic chain (CKC) exercise. Clinically, in exercise of the lower extremity, CKC exercise is conducted in a standing position by grounding the legs, while OKC exercise is conducted with a free posture without grounding the legs. Therefore, OKC exercise involves only the quadriceps femoris muscle, pulling the tibia forward. On the other hand, CKC exercise induces co-contraction of the agonist and antagonist muscles, reducing stress on the reconstructed ligament compared to that with OKC exercise;

Received July 25, 2011; accepted December 9, 2011.
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therefore, it is considered to be a safe and useful method of rehabilitation after ACL reconstruction [1]. CKC exercise is also considered useful to reduce pain in the patellofemoral (PF) joint [2], and has recently become widely used for this purpose. However, the fact that in CKC exercise the rectus femoris muscle, one of the bi-articular muscles, is underused whereas the vastus muscle, one of the mono-articular muscles, is highly activated, may pose a problem [3]. Based on the fact that voluntary movement usually begins with the contraction of slow-twitch muscle fibers whereas contraction induced by an electric stimulus begins with fast-twitch muscle fibers, we developed a novel training method of active CKC exercise on a shaking board while an electric stimulus is applied to the muscles, and conducted it in subjects soon after ACL reconstruction. We also measured muscle strength over time and evaluated the change in muscle mass with computed tomography (CT). Although the measurement of isokinetic muscle strength using devices such as CYBEX is the mainstay of muscle measurement, measuring the maximum muscle strength soon after reconstruction may be an overload to the restored ligament because those devices employ OKC exercise. Therefore, we measured the maximum muscle strength with a muscle-strength measuring device employing CKC in evaluating the usefulness of this new rehabilitation method.

Materials and Methods

In our institution, the bone-tendon-bone (BTB) method is usually used for ACL reconstruction. Both bone tunnels on the femoral and tibial sides of the ligament to be restored are made to match their anatomical sites, the implanted tendon is twisted on the tibial side and the piece of the bone is fixed with an interference screw. Traditionally, postoperative rehabilitation starts on the day after surgery, with range-of-motion training of the knee. From day 10 after surgery, partial weight-bearing gait exercise with a brace with up to −20 degrees of extension is allowed, and simultaneous contraction exercise of extensor and flexor muscles at 20 degrees of flexion starts. Quadriceps-femoris muscle exercise starts with the OKC method from 60 to 90 degrees of flexion, with suppression of the tibia being pulled forward by placing a rubber band on the distal leg, and exercise for neuromuscular coordination also starts. Leg curl starts at week 3, full weight-bearing gait exercise at week 4, along with half-squat exercise from 20 to 90 degrees of flexion. Our new rehabilitation method was added from week 4 when independent gait and the range of motion of subjects had stabilized. Subsequently, based on voluntary exercise, the brace was set at −10 degrees on week 6, activities of daily living without a brace were allowed at home on week 8, jogging without a brace from week 12, and a return to sports at 6 months. In this study, we measured and compared the postoperative muscle strength/mass of subjects for whom the traditional rehabilitation method was supplemented by our new CKC exercise (new rehabilitation group: group N) and subjects who received the traditional rehabilitation method alone (traditional rehabilitation group:group T). Voluntary exercise was allowed in both groups.

Ten knees of 10 subjects (4 male and 6 female) in group N and 10 knees of 10 subjects (5 male and 5 female) in group T were examined. The subjects were randomly allocated to either group by specifying that the first 10 subjects to undergo surgery after the start of this study were group N, and the next 10 subjects who underwent surgery were group T. The mean age of subjects was 26.0 (range: 14-44) years in group N and 26.8 (range: 15-47) years in group T. The mean body weight was 64.9 kg (range: 46-90 kg) in group N, and 66.6 kg (range: 50-80 kg) in group T. The mean number of days from surgery to the start of rehabilitation was 50.9 (range: 36-62) days in group N and 46.2 (range: 40-56) days in group T. There was no significant difference in any of these parameters between the 2 groups.

In group N, one subject had medial meniscus (MM) injury alone (untreated), 6 subjects had lateral meniscus (LM) injury alone (partial resection, 3; rasping, 1; untreated, 1), and 2 subjects had both MM and LL injuries (partial resection, 2). In group T, one subject had MM injury alone (untreated), 7 subjects had LM injury alone (partial resection, 1; rasping, 2; untreated, 4), and one subject had both MM and LM injuries (partial resection). Since no subject required meniscus suture, all received the same traditional rehabilitation after surgery. Moreover, no subject had to discontinue rehabilitation or had problems interfering with measurement of muscle strength/mass due to symptoms caused by meniscus injury.

We added the therapy using a shaking board device (Shaking Board, OG Giken Co. Ltd., Okayama, Japan) and electrical stimulation for group N. The subjects stood on the device with their feet shoulder-width apart in a weight-bearing stance, and slightly bent their knees to maintain their balance. During the exercise, low-frequency stimulation waves were applied with a low-frequency stimulator to 2 points in the anterior region of the injured thigh when the thigh had maximum anterior breadth (anterior turning point) and to 2 points in the posterior region of the injured thigh when they had maximum posterior breath (posterior turning point) (Fig. 1). The device had an anterior-posterior amplitude of 80 mm and operated at frequencies of 0.5 to 3.0 Hz. Five consecutive electrical stimulations of 50 μ sec were counted as one set, and the subjects' maximum tolerable stimulation was considered the maximum stimulation voltage. Electrical stimulation was given for 20 min per session, 3 times a week for 3 months. An Isoforce GT-330 (OG Giken) was used to measure the muscle strength of both legs in both groups, using a CKC exercise that contracts the extensor and flexor muscles at the same time (Fig. 2). Measurement was performed four times (before the start, and every month after the start of rehabilitation). To evaluate muscle mass objectively, cross-sectional areas in a horizontal CT image approximately 10 cm above the superior border of the patella were computationally analyzed using Ziostation software (Ziosoft, Inc., Tokyo, Japan) (Fig. 3), and the cross-sectional areas of the extensor and flexor muscles were measured at the start and end of rehabilitation.

The protocol of this study was approved by the institutional review board of Okayama Saiseikai General Hospital, and informed consent was obtained from all subjects prior to the study. Statistical analysis was conducted by paired t-test.

Results

The muscle strength (weight ratio) of the injured

Fig. 1 Exercise of active movement for posture control in combination with electrical stimulus using weight-bearing shaking board and low-frequency electrical stimulator synchronized with oscillation.

Fig. 2 Isoforce GT-330 (OG Giken) was used to measure maximum muscle strength of both legs during CKC exercise.

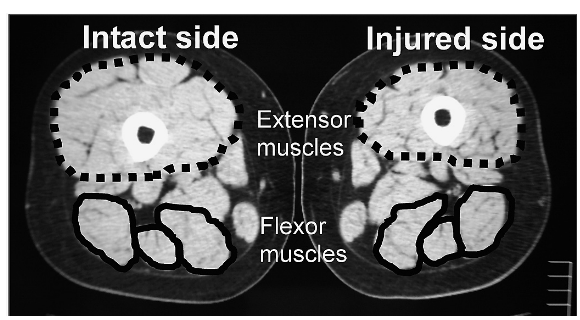

Fig. 3 Cross-sectional areas of extensor and flexor muscles of injured and intact leg were measured in horizontal CT image.

legs was significantly weaker than that of the intact legs in both groups at the start of measurement and 3 months later ($p<0.05$). However, in group N, the mean muscle strength significantly improved from 9.3 N/kg (range: 4.7–14.6 N/kg) to 16.3 N/kg (range: 7.7–22.63 N/kg) in the injured legs, and from 19.5 N/kg (range: 12.5–27.5 N/kg) to 24.8 N/kg (range: 15.5–33.7 N/kg) in the intact legs ($p<0.01$). In group T, the mean muscle strength also improved significantly from 6.2 N/kg (range: 2.4–10.4 N/kg) to 13.8 N/kg (range: 5.5–25.4 N/kg) in the injured legs and from 16.2 N/kg (range: 7.2–16.2 N/kg) to 19.8 N/kg (range: 14.5–19.84 N/kg) in the intact legs ($p<0.05$). Especially in terms of short-term improvement, the muscle strength of the injured legs in group N showed a significant improvement 1 month after the start of rehabilitation ($p<0.01$) compared to group T, suggesting also the short-term effectiveness of this new rehabilitation method (Fig. 4). The cross-sectional areas (weight ratio) of both extensor and flexor muscles measured using CT images were significantly smaller in the injured legs ($p<0.01$) than in the intact legs, suggesting muscle atrophy in both extensor and flexor muscles of the injured legs at the start of measurement (Figs. 5 and 6). However, 3 months later, whereas the cross-sectional area of the flexor muscles of the intact legs showed no significant increase in both groups ($p=0.26$ for group N, $p=0.19$ for group T) as compared to that at the start of rehabilitation, the cross-sectional area of the injured legs had significantly increased ($p<0.01$) in both groups, no longer showing a significant difference from that of the intact legs ($p=0.08$ for group N, $p=0.07$ for group T) (Fig. 5). On the other hand, the cross-sectional area of the extensor muscles of the injured legs showed a significantly lower value than that of the intact legs ($p<0.01$) 3 months after rehabilitation began, suggesting some muscle atrophy of the extensor muscles after ACL reconstruction with the BTB method. Nonetheless, at that point, the cross-sectional area of the extensor muscles of the injured legs in group T had significantly increased as compared to that at the start of rehabilitation, while there was no significant increase in the intact legs ($p=0.13$). On the other hand, the extensor muscles of group N demonstrated a significant improvement in both the injured ($p<0.05$) and intact legs ($p<0.01$) as compared to those at the start of rehabilitation, and, especially, the cross-sectional area of the extensor muscles in group N tended to show a greater increase, though not to a significant extent, compared to that in other groups.

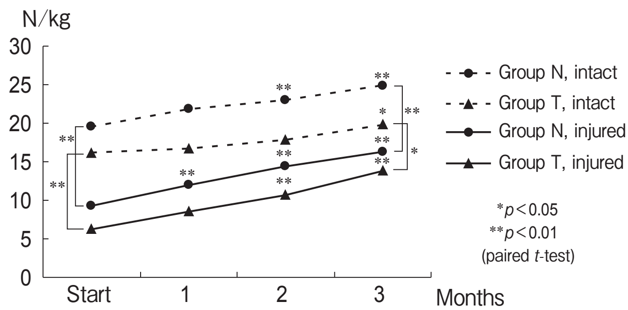

Fig. 4 Muscle strength measurement (weight ratio). Muscle strength of the injured legs in the new rehabilitation group showed significant improvement after 1 month ($p<0.01$).

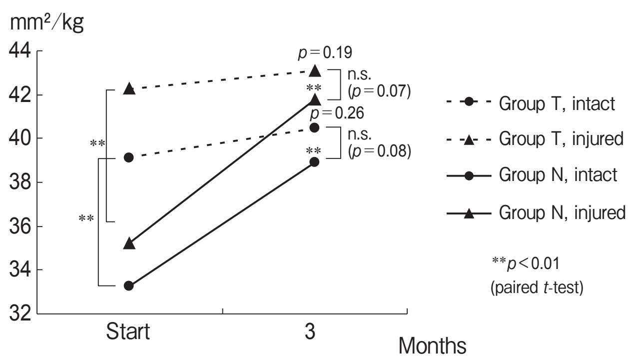

Fig. 5 Cross-sectional area of flexor muscles (weight ratio). The cross-sectional area of the flexor muscles of the injured legs significantly increased in both groups ($p<0.01$).

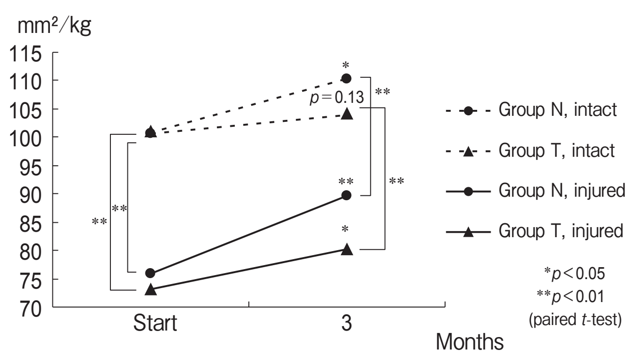

Fig. 6 Cross-sectional area of extensor muscles (weight ratio). The cross-sectional area of the extensor muscles of the injured legs in the new rehabilitation group showed a marked increase.

Our new rehabilitation method thus seemed to have a beneficial effect on muscle atrophy of extensor muscles after ACL reconstruction with the BTB method (Fig. 6).

No subject in either group developed re-rupture of the reconstructed ACL or arthralgia of the knee. All subjects were able to continue exercise safely and undergo measurement of muscle strength under full weight-bearing.

Discussion

Tomoyori *et al.* investigated factors in the recovery of muscle strength after injury, through evaluation of the extensor muscles of the knees of 227 patients who had undergone ACL reconstruction by the BTB method 12 months before, and found that the ratio of values of injured and intact legs was significantly correlated with the extensor muscle strength of the knee of patients 3 months after surgery, suggesting the importance of improvement of extensor muscle strength, starting at an earlier date after surgery [4].

There are a number of reports regarding the use of electrical muscle stimulation after ACL reconstruction. Although some have reported a lack of effectiveness [5, 6], most have reported its usefulness [7, 8]. However, in those studies, electrical muscle stimulation was conducted alone after physical therapy, or conducted independently from physical therapy; therefore, it only strengthened the stimulated muscles.

On the other hand, Maeda *et al.* developed and reported a "hybrid exercise" (HYB) technique that utilized muscle contraction generated by an electrically stimulated antagonist muscle to provide resistance to agonist muscles [9].

Iwasa *et al.* used the HYB technique, attached electrodes to the extensor and flexor muscles, and applied isokinetic concentric and eccentric contractions with knee range of motion from 10 to 100 degrees, with a stimulus frequency of 20 Hz and the maximum tolerable electrical stimulation voltage, three times a week for 6 weeks. As a result, the muscle force after 3 weeks did not increase in the flexor muscles, but did increase significantly in the extensor muscles, and especially eccentric contraction showed 30–50% higher values than concentric contractions [10].

Iwasaki *et al.* compared a group that used the HYB technique to a group with resistance exercise of the knee joint using a quadriceps-femoris muscle exerciser, and reported that the extensor muscle strength of subjects in both groups increased, and both methods had a similar muscle strengthening effect [11]. While these reports targeted healthy subjects, Maeda *et al.* stated that they intended to use the HYB technique clinically in patients with ACL injury [12]. Kawato *et al.* applied low-frequency electrical stimulation to the extensor muscles of healthy subjects, and induced eccentric contraction of extensor muscles from knee flexion movement for 20 min every session, 3 times a week for 4 weeks, and reported that the maximum muscle strength increased by 22.9% two weeks later, and by 44.3% four weeks later [13]. In these reports, the HYB technique was used only in healthy subjects, but the efficacy of active movement in combination with electrical stimulation was fully demonstrated, and its application to patients with ACL injury is anticipated. However, although the HYB technique may reduce the burden on the reconstructed ACL by stabilizing the knee joint through simultaneous contraction of both extensor and flexor muscles, it is used as an OKC exercise conducted without grounding the legs. There is, therefore, still much uncertainty regarding its safety if it is to be used for rehabilitation of patients with ACL injury. We therefore performed our post-ACL-reconstruction rehabilitation program by giving first priority to its safety.

Kawamura, a co-researcher and the inventor of this rehabilitation technique, previously published a report in which he and his colleagues assigned 18 healthy subjects to a shaking board group (group A), shaking board plus electrical stimulation group (group B) or control group (group C), and conducted the same rehabilitation program as in our study. Twelve weeks later, isokinetic knee extension and flexion muscle strength (60°/s) had not increased in group C, whereas they had significantly increased by 13% and 17%, respectively in group A and 38% and 44%, respectively in group B. Balancing ability increased in group B, indicating the effectiveness of concomitant use of a shaking board plus electrical stimulation in improving muscle strength [14].

This time, we started the rehabilitation method sooner after ACL reconstruction. The advantages of using CKC exercise are: 1) since CKC exercise involves co-contraction of extensor and flexor muscles, anterior-posterior stability increases, and the risk of re-rupture due to shear force to the restored ACL is lower than with OKC [3]; 2) although a stronger force is exerted on the entire joint surface than with OKC, the load is balanced [3], making CKC advantageous in patients complicated with meniscus injury; 3) CKC is advantageous after BTB reconstruction because it causes less pain in the PF joint than OKC [2]; and 4) subjects can exert force without hesitation, making maximum muscle strength measurement possible. There are three advantages of exercise using a shaking board in combination with electrical stimulation used in our program. The first is related to the fact that normal muscle contraction of voluntary movement begins with slow-twitch muscle fibers controlled by small-diameter neuron fibers according to the cell-size principle of muscle fibers [15], whereas electrical stimulation activates large-diameter neuron fibers so that fast-twitch muscle fibers begin to contract first [16]. Kawamura's technique, in which electrical stimulation is applied to patients while they use the shaking board, theoretically makes it possible for slow- and fast-twitch muscle fibers to be contracted at the same time. Second, an electrical stimulus is simultaneously applied at the anterior turning point when extensor muscles are working and at the posterior turning point when flexor muscles are working. Therefore, eccentric contraction matches the oscillation, making the application of a stronger electrical stimulus to the muscles possible. Third and last, since this exercise requires subjects to maintain their balance on the shaking board, the subjects conduct neuromuscular coordination movement so that an improvement of position sense is expected.

Rehabilitation after ACL reconstruction using BTB is difficult, especially regarding improving the extensor muscles. Electrical stimulation on the shaking board device strengthened extensor muscles safely and effectively in patients of a wide range of ages and can be considered a useful rehabilitation method after ACL reconstruction.

In conclusion, we conducted a novel muscle-strength training method that combines use of a shaking board device and simultaneous electrical stimulation in the relatively early period after ACL reconstruction. Based on measurements of muscle strength employing CKC exercise, and comparisons of muscle mass with that of control subjects by CT imaging, we concluded that our exercise strengthened muscle safely and effectively. Especially, the muscle strength of the injured legs in group N showed a significant improvement at one month, and the cross-sectional area of the extensor muscles in group N tended to show a greater increase at 3 months compared to that in other groups.

Acknowledgments. This work was supported by a Grant-in-Aid for Scientific Research (B) No. 18300187 from the Japan Society for the Promotion of Science, 2006–2008.

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