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# Effects of the Use of Cross-education to the Affected Side through Various Resistive Exercises of the Sound Side and Settings of the Length of the Affected Muscles

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## ABSTRACT

The purpose of this study was to determine what kind of resistive exercise of the sound limb causes the most effective cross-education, which is defined as the muscle activity of the unexercised limb during contralateral exercise, by analyzing the force and electrical activity of the affected muscle. Six orthopedic patients with unilateral lower extremity impairment that resulted in unexercised quadriceps muscles through treatment by immobilization were the subjects of this investigation. The effect of cross-education was determined by observing the maximal torque of the unexercised quadriceps (MT) and the integrated electromyograms of the unexercised rectus femoris at the time of the maximal response of the torque (IE). A double-blind experiment was conducted with eighteen randomly applied combinations, consisting of six different exercises and three different knee angles. The various resistive exercises on the sound side consisted of proprioceptive neuromuscular facilitation (PNF) movements, PNF positions, straight movements and straight positions in the sagittal plane. Both the mean percentage of the IE and MT were above 23% in the PNF movement, while a mean above 13% was not found in any of the other exercises. PNF movement combined with hip internal rotation was found to be significantly effective for inducing cross-education.

***Key words:*** *Cross-education, PNF, Muscle atrophy, Muscle strength*

Immobilization of an extremity inevitably results in disuse muscle atrophy. In addition, Fuglsang-Frederiksen et al[6)] found a reduction of motor unit activation in the disused quadriceps muscle (following immobilization of the knee joint) during flexion of the patient's knee. Sale et al[32)] also found that immobilization for an average of five weeks in 11 healthy subjects caused a significant decrease in voluntary strength and reflex potentiation. In addition, Sale et al[32)] reported that the apparent reduction in the number of functioning motor units after immobilization suggests a temporary loss of functioning motor units rather than an anatomic loss of units. If the temporary loss of functioning motor units could be reduced, the decrease in voluntary strength and reflex potentiation might be avoided during immobilization. A method to facilitate these units of an immobilized muscle might produce such a result. However, most immobilization is done by placing the affected limb in a cast, producing a situation in which the affected limb can not be approached directly. To prevent a reduction in the number of functioning motor units and muscle atrophy, physical therapists often use cross-education effects by exercising the sound limb or other healthy parts to stimulate muscle activity in the affected limb that can not be directly approached. Cross-education is an exercise applied to one side of the body to induce muscle activity on the contralateral unexercised part or parts. Scripture et al[34)] first demonstrated this phenomenon and called it cross-education. Hellebrandt et al[9)] subsequently demonstrated that exercise of the progressive resistance type not only increases the functional capacity of the contractile tissues subjected to direct training, but has a significant effect on the strength and endurance of homologous muscle groups of the contralateral unpracticed limb.

Hellebrandt et al[10] also demonstrated that repetitive contraction against progressively increasing resistance was observed to be associated from the outset with electromyographic (EMG) evidence of co-contraction of the ipsilateral antagonist. The muscle activity of the contralateral unexercised part or parts induced by exercise applied to the other side of the body is expressed in various ways, which tends to be confusing. This phenomenon has been referred to as cross-education[9,10,12,34–36], cross transfer[17], cross training[14,15,39–41], excitation overflow[26], motor overflow[43], exercise overflow[25], overflow effects[29], cross motor irradiation[30], overflow movements[37], and motor irradiation[19,38]. There has also been conflict in the literature about whether this effect actually exists or not, in spite of the fact that significant effects of cross-education have been reported. Examples for the support of this effect are as follows. Komi et al[22] did a controlled study of six monozygotic adolescent pairs of twins, who were used so that one member of each pair served as a training subject and the other as a non-exercising control. After 12 weeks of isometric strength training, four sessions a week, they found that the isometric knee extension strength improved 11% in the untrained legs, 20% in the trained limbs, and 0% in the control limbs. Kannus et al[17] found in a controlled study of 20 volunteers that after seven weeks of isometric and concentric isokinetic training three times a week, the average change in the peak torque of the quadriceps muscle was +19% in the trained limb, +11% in the untrained limb, and 0% in the untrained control limbs. In a controlled study of 16 volunteers to examine the effects of cross-training, Weir et al[41] investigated the effect of unilateral concentric knee extension weight training and cross-training of the untrained limb. They found that after eight weeks of unilateral concentric weight training, four sessions a week, isometric strength increases occurred at three joint angles of the knee (15°, 45°, and 75°) and occurred in both limbs. They suggested that this was evidence of cross-training. Housh et al[14] found in a controlled study of seventeen volunteers that after eight weeks of knee extensor muscle exercise of the nondominant limb with eccentric contractions of constant external resistance, significant increases in eccentric strength of both the trained (29%) and untrained (17%) limbs occurred. Shields et al[35] found in a controlled study of 24 volunteers that, after six weeks, the regular training group (a rhythmic right handgrip training program using 30% of a maximal isometric contraction) and low-level training group (daily training with a near-zero load) showed similar increases in cross-education. On the other hand, failures of attempted cross-education have been also reported. Weir et al[39] found in a controlled study of 17 volunteers that after six weeks of unilateral isometric knee extension training at 80% of the maximal isometric torque at four joint angles (zero, 15°, 45°, 75°, and 90°), joint angle specificity for the isometric torque was found in the training group only, with significant increases in torque at 45° and 75°. No significant increases in the torque were found in the untrained limb of the training group or in either limb of the control group. Housh et al[15] found in a controlled study of 16 volunteers that, after eight weeks of unilateral concentric contraction with constant external resistance, no change in the isokinetic peak torque for the unexercised limb was noted.

Weir et al[41] suggested that it was not known whether the contraction stimulus was sufficient to stimulate a training effect in the untrained muscles, and that further research was needed to determine the efficacy of unilateral training of the contralateral limb during rehabilitation of an injured and/or immobilized ipsilateral limb. There is little literature about the immediate effects of contraction of the sound muscles on the affected contralateral limb with orthopedic patients[36]. Despite the early observation of cross-education, most subsequent works have been with normal volunteers or patients suffering from neuromuscular disorders[9,10,12,14–17,25,26,29,30,34,35,39–41].

Clinically, there are many methods used to induce cross-education of the affected contralateral limb with orthopedic patients. The authors found through personal clinical experiences that proprioceptive neuromuscular facilitation (PNF) techniques[19,38] were more effective in inducing cross-education of the affected side than other methods. PNF, developed by Knott and Kabat, is a useful method for therapists to facilitate the contraction of muscle groups in particular synergistic patterns, which begin with placing the muscles to be facilitated under maximal stretch and end with the muscles at the maximally shortened ends of their ranges[8]. The mass movement patterns of facilitation are spiral and diagonal in character and closely resemble the movements used in sports and in work activities[38]. The spiral components of the PNF pattern most likely induce cross-education effectively. However, the effects of spiral patterns on the unexercised muscle, when used in various resistive exercises on the sound side, have not been shown objectively in the literature. In the literature, joint angle specificity for inducing cross-education has shown confusing results. The same investigators reported different findings in different studies[39,41]. Weir et al[39] found that there was joint angle specificity for isometric torque, and, in the training group, significant increases in torque were found at 45° and 75° but not at 15°. The same authors[41] also found that the effects of concentric weight training were not joint angle specific, as the isometric strength cross-education occurred at all three joint angles (15°, 45°, and 75°). It has not also yet been demonstrated which degree of knee flexion in a cast is most effective for facilitating cross-education.

The purpose of this study was to determine what type of resistive exercise pattern of the sound limb causes the most effective cross-education in the affected limb, while also considering different joint angles of the knee. We postulated that the most effective condition would induce the largest contraction of the unexercised muscle. We observed the unexercised muscle activity by analyzing its force and electrical activity during exercise of the contralateral limb, which we defined as cross-education. We decided that the EMG activity in the rectus femoris is the parameter of cross-education. Kollmitzer et al[21] found that EMG activity recorded from the rectus femoris was more reliable and suitable for clinical applications if submaximal voluntary isometric contraction measurements were performed. These results were compared with EMG activity taken from the vastus lateralis and vastus medialis muscles in eighteen healthy subjects. In accordance with these findings and considering the co-action between the vasti and the rectus femoris muscles, regardless of the amount of hip flexion[33], we thereby represent the electrical activity of the rectus femoris muscle as the electrical activity of the quadriceps muscle group. Another parameter in cross-education is the strength of the quadriceps muscles of the affected side, which was measured by a dynamometer. The dynamometer can measure strength accurately with excellent reproducibility[4,24].

The effect of exercise intensity on the unexercised side is not clear. Arai et al[2] found that the minimal work load to induce cross-education for the atrophied muscle was 2% of the maximal isometric torque value of the unaffected knee extensor muscles. Considering this result, we determined that the adequate load to induce cross-education on the affected side was 10% of the maximal voluntary isometric contraction (MVC) of the sound side.

## MATERIALS AND METHODS

Orthopedic patients with unilateral lower extremity impairments that resulted in unexercised quadriceps due to treatment by immobilization were the subjects of this investigation. The subjects were in casts for a mean of 61.2 days (range: 41–82 days) because of injury or surgical intervention. All subjects were free from neuromuscular disorders. The subjects included six orthopedic patients, four males and two females. The mean age of the subjects was 42.2 years (range: 32–61). The diagnoses of the subjects were fracture of the tibia (four subjects), osteotomy of the tibia due to osteoarthritis (one subject), and tear of the posterior cruciate ligament (one subject). No subject had knowledge of which exercise patterns might be relatively effective to facilitate cross-education. Each subject learned each resistive exercise well enough that he or she could perform it alone before the experiment began. We asked all subjects to co-operate with us in collecting the data to help benefit the advancement of physical therapy. All subjects were judged to be cooperative by the therapists. An experienced therapist may have a certain bias towards a particular therapeutic method, which may influence the outcome. Therefore, a double-blind experiment was done in which the person who performed the techniques and provided the subject's settings and verbal commands was unaware of the purpose of the experiment. We selected physical therapy students who did not know the effects of cross-education to perform the experiments.

### Variables

**1) Independent variables.** The independent variables were six patterns of various resistive exercise and three different angles of the knee joint (20°, 40°, and 60°). The various resistive exercises on the sound side consisted of straight, rotatory, and diagonal (spiral) patterns and different types of muscle contractions. Various resistive exercises on the sound side with a weighted band around the ankle were performed. The various resistive exercise patterns were as follows. (1) PNF: Alternate movements of knee joint extension combined with a hip external rotation pattern and knee joint flexion combined with hip internal rotation (PNFER movement), which consisted of concentric and eccentric contractions for the quadriceps; (2) PNF: Alternate movements of knee joint extension combined with a hip internal rotation pattern and knee joint flexion combined with hip external rotation (PNFIR movement), which also consisted of concentric and eccentric contractions for the quadriceps; (3) Alternate movements of knee extension and flexion in the sagittal plane without hip rotation (ST movement), which consisted of concentric and eccentric contractions for the quadriceps; (4)Isometric knee extension contractions with the hip and ankle-foot joints in neutral positions (N position); (5) PNF: Isometric contractions with the hip in flexion, adduction, and external rotation, the knee in extension, and the ankle-foot in dorsiflexion and eversion (PNFER position); and (6) PNF: Isometric contractions with the hip in flexion, abduction, and internal rotation, the knee in extension, and the ankle-foot in dorsiflexion and inversion (PNFIR position).

**2) Dependent variable.** The maximal effect of cross-education was determined by observing the maximal torque of the unexercised knee joint extension movement and the IEMGs of the unexercised quadriceps at the maximal response on the torque. The maximal torque value with the least maximal torque variation in a 50 msec area was

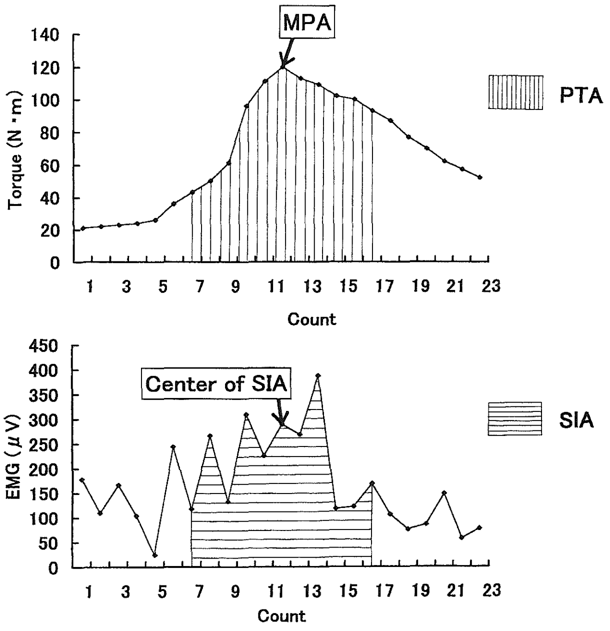


**Fig. 1.** Each peak torque area (PTA) was calculated by integrating the data of 11 counts that was centered by the MPA (1count = 10 msec). The center of the synchronized IEMG area (SIA) was not the maximal amplitude of the IEMG, but instead was dependent on the center of the MPA.

determined as the zone of the maximal peak amplitude (MPA). Each peak torque area (PTA) was calculated by integrating the data of 11 counts (110 msec interval) that was centered by the MPA. The center of the synchronized IEMG area (SIA) was not the maximal amplitude of the IEMG, but instead was dependent on the center of the MPA. Each SIA was calculated by integrating the data of 11 counts (110 msec intervals), which was synchronized (Fig. 1). To gain objective data for the cross-education parameter, the following equations were used to express the percentage of the maximal torque (PMT) and percentage of the synchronized IEMG (PSI) of the unexercised limb during each resistive exercise of the sound limb.

PMT = (PTA of the unexercised limb at the measured angle of knee flexion) / (PTA of the maximal isometric exercise of the unexercised limb at 60° of knee flexion) × 100

PSI = (SIA of the unexercised limb at the measured angle of knee flexion) / (SIA of the maximal isometric exercise of the unexercised limb at 60° of knee flexion) × 100

**Equipment**

Following the preparation of each experiment, the subjects performed a test of the affected limb on a dynamometer (Kin-Com-125AP, Chattanooga Corp., Chattanooga, Tenn., USA). During the tests, the position for resting was sitting with the back rest at 60° and the seat angle at 15° horizontal to the dynamometer seat. A seat belt was hooked tightly across the subject's hips and lower abdomen, with two crossover shoulder harnesses and a lap belt as supports. The dynamometer was attached to the affected side. The subject's affected knee joint axis was aligned with the axis of the dynamometer head by palpation of the subject's lateral knee joint space between the lateral femoral condyle and the fibular head. The length of the lever was adjusted so that the shin pad was placed just proximal to the malleoli. A strap was placed across the midportion of the subject's affected thigh and the pad of the lever arm was placed just proximal to the medial malleolus. Torque was measured by a strain gauge embedded in the ankle cuff (Fig. 2). The EMGs were recorded simultaneously with the torque. A pair of surface electrodes was placed over the rectus femoris at a distance of one-third of the length of the thigh from the patella, with a separation of 40 mm between the centers of the electrodes. To record the results of the EMG data obtained from the surface electrodes, the EMG recorder included in the dynamometry system was used. For bipolar EMG recordings, two active electrodes and one ground electrode were used. After the skin area over the rectus femoris was wiped with alcohol, Ag/AgCl electrodes (12 mm, in diameter) were applied longitudinally over the muscle belly. These devices were used as recommended by Knutsson et al[20]. The signal was filtered with a

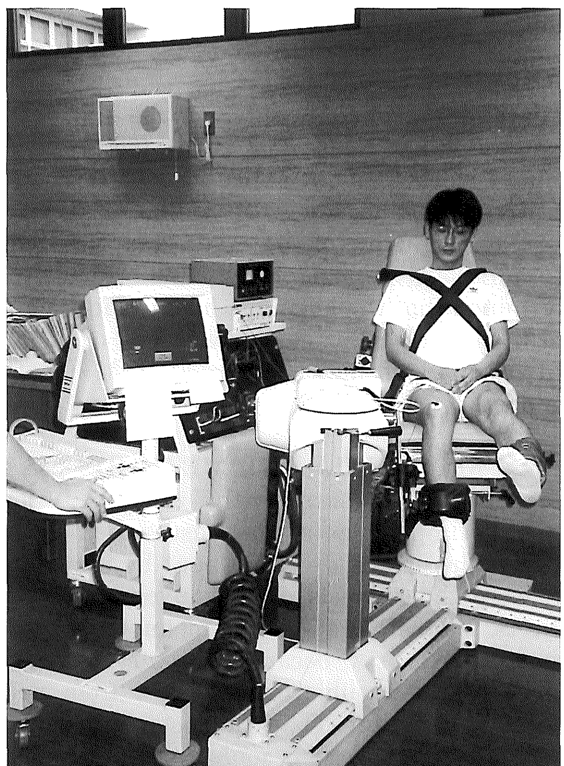

**Fig. 2.** The position of the subject on the Kin-Com dynamometer during the experiments; PNFIR movement pattern.

bandpass of 58 Hz to 480 Hz. This frequency tailored signal was then amplified by a variable gain stage, which allows the operator to set the gain of the system to suit the particular needs of the experiment. The signal from this amplifier is available as an output from the system, and it is also further processed by a circuit which computes the absolute value of the magnitude of the EMG signal and the average of the signal over a 10 msec period. We determined the magnitude of the EMG within ± 20 $\mu$V before calibration. This averaged output was displayed on a monitor of the dynamometer system.

**Procedure of the various resistive exercises**

The order of experiments was as follows.

1) To determine the amount of resistance of the sound side, the MVC of the sound knee extensors at 60° of knee flexion was performed on the dynamometer for four seconds. The amount of resistance was 10 % of the MVC of the sound side.

2) The MVC of the affected knee extensors at 60° of knee flexion was likewise done on the dynamometer for four seconds.

3) To obtain the values of the maximal MPA and SIA of the affected limb, the dynamometer was kept attached to the affected limb during the performance of the MVC of the sound limb.

4) To obtain the values of the MPA and SIA of the affected limb, the dynamometer was kept attached to the affected limb to measure the force of the affected quadriceps during the performance of various exercises on the sound side. The various resistive exercises on the sound side with a weighted band around the ankle were done. The various resistive exercise patterns were the PNFER movement, PNFIR movement pattern, ST movement, N position, PNFER position, and PNFIR position. Following a warm-up, consisting of five minutes of unloaded exercises, each resistive exercise pattern was performed for four seconds. The rest between each exercise was one minute.

**Data Collection**

The design of the experiments was done with the random ordering of knee angle and type of resistive exercise. The Kin-Com dynamometer was externally calibrated with weights before testing and electronically calibrated before each test session. During the various resistive exercises of the sound side, the torques and IEMGs of the affected side were recorded simultaneously in the form of digital data. The synchronized digital torque and IEMGs data were calculated from each of the 400 points sampled for four seconds and stored by a 386 IBM-compatible microcomputer interfaced with the Kin-Com dynamometer.

**Test-retest reliability**

Three subjects were examined with five repetitions of the MVC of the sound limb within two hours for determining simple replication reliability. The experiments of reproducibility were examined by the same physical therapist. The effects of the MVC of the sound knee extension on the affected quadriceps, represented by PMT and PSI, were determined on the dynamometer with five repetitions for four seconds with the affected knee flexed to 60° Intraclass correlation coefficients were determined on each parameter[1]. Intraclass reliability coefficients were 0.98 for the PMT and 0.98 for the PSI. Simple replication reliability was determined for PMT and PSI.

**Data Analysis**

We examined eighteen combinations, consisting of six various exercises and three muscle lengths. A two-way analysis of variance (ANOVA) for repeated measures was used to test the differences between the types of resistive exercise and degrees of knee flexion. Scheffé's post hoc test was performed to search for significant differences between all pairs of means if the overall F test was statistically significant. We set the level of significance at $p < 0.05$ for all statistical tests.

## RESULTS

%MVC ((MVC of affected side) / (MVC of sound side) × 100) in each torque and IEMG are shown in Table 1. The means (± standard error) of the PMT were 20.0 (± 3.2) % at 20°, 17.0 (± 2.7) % at 40°, and 15.9 (± 3.0) % at 60°. The means (± standard error) of the PMT were 23.9(± 3.7) % in the PNFER movement, 31.9 (± 5.6) % in the PNFIR movement, 16.9 (± 2.5) % in the ST movement, 11.6 (± 3.7) % in the N position, 12.6 (± 3.8) % in the PNFER position, and 9.1 (± 2.8) % in the PNFIR position. There was no significant interac-

**Table 1.** Period of immobilization, period from mobilization to the day of experiments and %MVC

| | age (years) | diagnosis | POI | PME | %MVC (torque) | %MVC (IEMG) |
|---|---|---|---|---|---|---|
| Case 1 | 33 | tibia fracture | 82 | 11 | 20.7 | 27.6 |
| Case 2 | 61 | tibia osteotomy | 41 | 25 | 27.1 | 15.6 |
| Case 3 | 36 | tibia fracture | 75 | 15 | 20.7 | 22.3 |
| Case 4 | 43 | Tear of PCL | 61 | 7 | 21.8 | 50.5 |
| Case 5 | 48 | tibia fracture | 56 | 7 | 58.1 | 62.5 |
| Case 6 | 32 | tibia fracture | 52 | 5 | 22.8 | 19.1 |

POI=period of immmobilization (days)
PME=period from mobilization to the day of experiment (days)
%MVC= (MVC of affected limb)/(MVC of sound limb) × 100

tion between the type of resistive exercise and joint angle for the PMT. The two-way ANOVA for the PMT revealed a significant effect for the type of resistive exercises but not for the degree of knee flexion (Table 2). The post hoc analysis for the PMT indicated that significant differences obtained between the PNFIR movement and PNFER movement, between the PNFIR movement and ST movement, between the PNFIR movement and N position, between the PNFIR movement and PNFER position, between the PNFIR movement and PNFIR position, between the PNFER movement and N position, between the PNFER movement and PNFER position, and between the PNFER movement and PNFIR position (Fig. 3).

The means (± standard error) for the PSI were 11.9 (± 3.7) % at 20°, 23.5 (± 13.2) % at 40°, and 17.4 (± 6.6) % at 60°. The means (± standard error) for the PSI were 25.7 (± 9.3) % in the PNFER movement, 63.3 (± 26.6) % in the PNFIR movement, 6.2 (± 1.1) % in the ST movement, 2.7 (± 0.3) % in the N position, 2.9 (± 0.3) % in the PNFER position, and 4.7 (± 1.5) % in the PNFIR position. There was no significant interaction between the type of resistive exercise and joint angle for the PSI. The two-way ANOVA for the factor of various resistive exercises for the PSI revealed significant

**Table 2.** Two-way analysis of variance for repeated measures of PMT for the angles of knee flexion and various resistive exercises

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| Angle | 2 | 326 | 163 | 1.5 | NS |
| Exercise | 5 | 6820.9 | 1364.2 | 12.2 | <0.05 |
| Angle × Exercise | 10 | 555.7 | 55.6 | 0.5 | NS |
| Error | 90 | 10064.7 | 111.83 | | |
| Total | 107 | 17767.3 | | | |

NS: Not significant.

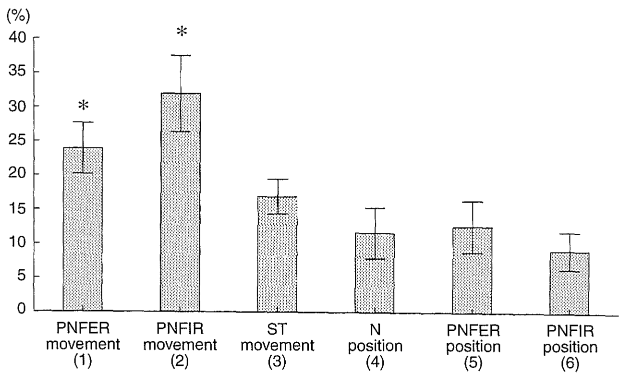


**Fig. 3.** Mean ± Standard Error of PMT
Scheffé's post hoc analysis of ANOVA for the PMT indicated that there were significant differences between (1) and (2), between (2) and (3), between (2) and (4), between (2) and (5), between (2) and (6), between (1) and (4), between (1) and (5), and between (1) and (6).
*p < 0.05

**Table 3.** Two-way analysis of variance for repeated measures of PSI for the angles of knee flexion and various resistive exercises

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| Angle | 2 | 2419.2 | 1209.6 | 0.6 | NS |
| Exercise | 5 | 51982.6 | 10396.5 | 4.7 | <0.05 |
| Angle × Exercise | 10 | 15463.4 | 1546.3 | 0.7 | NS |
| Error | 90 | 197910 | 2199 | | |
| Total | 107 | 267775.2 | | | |

NS: Not significant.

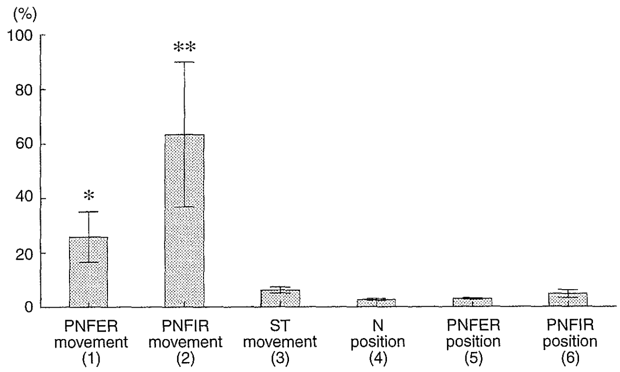


**Fig. 4.** Mean ± Standard Error of PSI
Scheffé's post hoc analysis of ANOVA for the PSI indicated that there were significant differences between (2) and (1), between (2) and (3), between (2) and (4), between (2) and (5), and between (2) and (6).
*p < 0.05, **p < 0.01

differences but not for the different degrees of knee flexion (Table 3). The post hoc analysis for the PSI indicated that there were significant differences between the PNFIR movement and PNFER movement, between the PNFIR movement and ST movement, between the PNFIR movement and N position, between the PNFIR movement and PNFER position, and between the PNFIR movement and PNFIR position (Fig. 4).

In the IEMG values, the mean of the PSI was approximately 26% in the PNFER movement and 63% in the PNFIR movement, while a mean above 7% was not found in any of the other exercises. In the torque values, the mean of the PMT was approximately 23% in the PNFER movement and 32% in the PNFIR movement, while a mean above 13% was not found in the other exercises.

The results of the post hoc analysis for the mean values of the PSI and PMT showed that the most effective pattern for inducing cross-education was the PNFIR movement. We were the first to demonstrate this significant effect of the PNFIR movement.

## DISCUSSION

Every resistive exercise we performed on the sound side with loads of 10 % of the MVC induced muscle activity in the contralateral unexercised muscle. Our study strongly supported the theory of the immediate effects of cross-education. Furthermore, a new finding we support is that the immediate effects of cross-education are significantly dependent on the type of movement pattern used in the exercising limb, which is an important factor clinically.

In general, after immobilization, there is a loss of voluntary strength. In addition, Sale et al[32] suggest a temporary loss of functioning motor units. During the MVC of muscles that had been immobilized for 5 weeks, a reduction in reflex potentiation (expressed by the amplitude of an F wave compared with an M wave) was found, which suggests an impairment in the ability to activate motor units[32]. Because of the subject's complaints of an inability to contract the muscles strongly without discomfort, Sale et al[32] concluded that the decrease in reflex potentiation after immobilization reflected a neural adaptation, which counted in part for the loss of voluntary strength.

In 23 normal human subjects, Newham et al[28] found that the extent of voluntary activation in fatigued quadriceps muscles during isometric and isokinetic voluntary contractions at 20 and 150 degrees showed some activation failure in all subjects, as compared with fresh quadriceps muscles in the parameter of the voluntary activation determined by the superimposition of tetanic electrical stimulation. Koutedakis et al[23] also found that the isometric MVC of the quadriceps at 10° of knee flexion in 10 overtrained athletes was significantly lower when compared with 10 controls matched for sex, age, sport, and performance level. But the addition of the electrical stimulation to the isometric MVC at a knee angle of 10° produced a significant increase in torque levels.

These findings suggest that not only atrophied muscles but also overused and fatigued muscles have some difficulty in voluntarily activating maximal ability. For three of our subjects, the IEMG results on the affected side during cross-education with the PNFIR movement were larger than the MVC results of the same muscle. The affected movement induced by cross-education in this study was involuntary concentric contraction of the unexercised quadriceps. This involuntary concentric contraction occurred reflexively. This effect may facilitate the activity of motor activation. This new finding may indicate that indirect activation of the motor units using cross-education with PNFIR movement may have facilitated the neural system efficiently.

The movement patterns for PNF are spiral and diagonal in character[38], which probably help to facilitate the central nervous system and to produce behavioral and arousal effects[7,13,27,42]. The neurophysiological mechanism of cross-education is postulated as the diffusion of the central drive through the ipsilateral uncrossed corticospinal tract[9,18,31,41]. According to this postulation, the amount of cross-education should increase if the central drive is facilitated efficiently. The significant cross-education effects of the PNFIR movement on the unexercised rectus femoris, as compared with other resistive exercises, might be the result of an efficient facilitation of the central drive. The immediate effect of cross-education from the PNFIR movement might be that it produces a change in the state of neural adaptation after immobilization, which may be why there was a larger increase in the PSI than in the corresponding PMT.

When resistive exercise is used to induce cross-education in atrophied quadriceps muscles, we have to consider the force-length relations of the atrophied quadriceps[11]. Considering functional activity, such as, rising from a chair, climbing stairs, strengthening the quadriceps at longer muscle lengths is thus important for the atrophied muscle[5]. As for the strengthening of the quadriceps, Bandy et al[3] also found in a study with 117 female subjects between the ages of 20 and 36 with no previous history of knee pathology that an efficient method for increasing isometric knee extension torque and EMG activity was to exercise with the quadriceps in the lengthened position.

Significant effects of cross-education at 60° of knee flexion suggested that the quadriceps can be strengthened through cross-education with the affected muscle positioned in elongated lengths. However, we were not able to investigate longer lengths of the quadriceps muscles in these experiments because of the limitations of knee joint range of motion in the participating patients. Nevertheless, in this study, we found a striking effect of cross-education. It is suggested that the effects of cross-education on more lengthened quadriceps muscles should be investigated in future.

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