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The effects of proprioceptive or strength training on the neuromuscular function of the ACL reconstructed knee: a randomized clinical trial

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Objectives: **The purpose of this study was to determine the effects of a proprioceptive training program (PT) vs. a strength training (ST) program on neuromuscular function after anterior cruciate ligament (ACL) reconstruction. The second purpose was to establish the determinants of functional ability for the operated limb.** ***Methods:*** **Ten participants with unilateral ACL reconstructions were randomly assigned to one of the following 12-week training protocols: (1) isotonic ST, and (2) PT. The outcome measures were: (1) peak torque time of the hamstring muscles (PeakTT), (2) average concentric and eccentric torques of the quadriceps and hamstring muscles, (3) one-legged single hop for distance (SLHD), (4) one-legged time hop (TH), and (5) subjective scores.** ***Results:*** **There was a significant group by time interaction effect for PeakTT ($P = 0.017$). The PT group demonstrated greater percent change in isokinetic torques than the ST group at the end of the 12 weeks ($P \leq 0.05$). Participants in both groups demonstrated similar significant gains in functional ability and subjective scores ($P \leq 0.014$). Quadriceps strength is a determinant of functional ability for the operated limb ($R^2 = 0.72$).** ***Conclusions:*** **Both training protocols influenced PeakTT. The beneficial effects of ST on PeakTT appear to be load-dependent, while sufficient practice may be crucial in maintaining PeakTT improvements induced by PT. Proprioceptive training alone can induce isokinetic strength gains. Restoring and increasing quadriceps strength is essential to maximize functional ability of the operated knee joint.**

The anterior cruciate ligament (ACL) plays a major role in maintaining the normal function of the knee and although surgical reconstruction often provides good results, there remains a great deal of scope for improving function after this procedure (Ellison & Berg, 1985; Novak, Bach, Hager, 1996; Nyland, Currier, Ray, Duby, 1993; Timoney et al., 1993). Strength training (ST) has been traditionally emphasized after ACL reconstructions. However, since the discovery of mechanoreceptors that can detect changes in tension, speed, acceleration, direction of movement, and the position of the knee joint in the human ACL, it has been postulated that information from the ligament assists in dynamic stability of the knee joint (Johansson, 1991; Johansson, Sjolander, Sojka, 1991a; Johansson, Sjolander, Sojka, 1991b; Kennedy, Alexander, Hayes, 1982; Schultz, Miller, Kerr, Micheli, 1984; Schutte, Dabezies, Zimny, Happel, 1987; Zimny, Schutte, Dabezies, 1986). Thus, an ACL rupture may alter somatosensory information and impair neuromuscular control of the affected knee joint (Kennedy, Alexander, Hayes, 1982). Although proprioceptive training (PT) is currently emphasized after ACL reconstruction, no studies have compared the effectiveness of PT to ST in restoring neuromuscular control.

Thus, the primary objective of this randomized clinical trial was to examine the effectiveness of PT vs. ST in restoring neuromuscular function, as assessed by peak hamstring torque time (PeakTT), in 10 participants with unilateral ACL reconstructions. The second objective of this research study was to establish the determinants of functional ability for the operated limb. To our knowledge, there are no prospective studies comparing the effects of two exercise protocols on neuromuscular function after ACL reconstruction.

Methods

Participants

Participants were recruited by mail from two orthopaedic surgeons' operating room lists. Both surgeons (including co-author JPM) used a standardized ipsilateral semitendinosus tendon

ACL reconstruction with identical post-operative protocols that is described in JPM's paper (Gomez, McConkey, Thompson, Ratzlaff, Dean, 1990). Both surgeons consulted at one sports medicine clinic and operated at one hospital. Ten participants with unilateral ACL reconstruction who met the inclusion criteria were recruited and randomly assigned to one of the two experimental training groups. Individuals between the ages of 18–38 with an unilateral ACL reconstructed limb were eligible for the study if they had: a minimum of 6 months since the date of operation; no significant pathology in the operated limb (such as significant osteoarthritis); normal hip and ankle joint function; no neurological diseases; no vestibular or visual disturbances; no arthritic conditions involving the lower extremities; no physiotherapy sessions (within the last 6 weeks prior to entering the study); full range of motion (both active and passive) in the operated knee joint; no significant pain or obvious swelling in the operated knee with light recreational activities (such as cycling, swimming, and walking) or with normal activities of daily living. Individuals who were earlier than six months post-operation were excluded to ensure that the research intervention and testing protocol could not be considered to compromise the ACL graft in any way. Individuals were also excluded if they had any cardiovascular, respiratory, systemic, or metabolic condition limiting exercise tolerance. The non-operated (all ACL intact) limb was used as control for each participant.

Ethical approval was acquired from the Committee on Human Experimentation of the University of British Columbia and all participants provided written consent.

Training

After the participants completed the baseline measures, they began the 12-week, thrice-weekly training program. Details of each training program are available from the Correspondence (TLA). The training programs were designed based on published evidence and clinical experience (Beard, Dodd, Trundle, Simpson, 1994; Ihara & Nakayama, 1986). Increased loading was the method of progression for the ST program while the PT program was progressed by: decreasing the base of support, decreasing the stability of the surfaces, increasing the number of repetitions (and hence the rate of muscular contraction and the amplitude of perturbations), removing visual feedback, and increasing the speed and complexity of tasks. The PT program incorporated balance, agility and perturbation based exercises. All exercises for the ST program were performed bilaterally. As well, the participants were required to perform the exercises without any (knee) bracing.

To maximize consistency in the exercise sessions, all sessions for the PT group occurred on the campus of University of British Columbia and were supervised directly by a physiotherapist (TLA). Sessions for the ST group occurred at one of several prescribed weight rooms and were supervised directly either by TLA or by a second physiotherapist. The participants recorded the details of all sessions in a training log that was collected weekly. Compliance was monitored directly through supervision and indirectly through training logs.

Experimental design and descriptive data of participants

Figure 1 illustrates the experimental design used in this study. Baseline measures included routine descriptive variables. A physiotherapist also performed a standard clinical assessment of the operated knee joint. Specifically, the passive stability of the operated knee joint in the sagittal plane was assessed using the anterior drawer test at 90° of knee flexion and the Lachman test at 30° of flexion. The stability of the operated knee joints was also assessed after each training session. There were three test occasions in total over the 12-week period.

Outcome measures

Subjective scores Subjective scores were obtained using the modified Lysholm and Gillquist Knee Scoring Scale and the Tegner and Lysholm Activity Scale to detect any changes in the participants' level of activity and function before and after 12 weeks of intervention (Lysholm & Gillquist, 1982; Tegner & Lysholm, 1993).

Average isokinetic torque

Average isokinetic torques (Nm) of the hamstring and quadriceps muscles were assessed using the Kinetic Communicator (KIN-COM®.) isokinetic dynamometer (Chattex Corp., Chattangooga, TN) system at 45°/s (Farrell & Richards, 1986). To protect the ACL graft, all tests of quadriceps muscle torque were performed between 10 and 90° of knee flexion. All tests of hamstring muscle torque were performed between 0 and 90°. Gravity compensation was performed for all isokinetic testing.

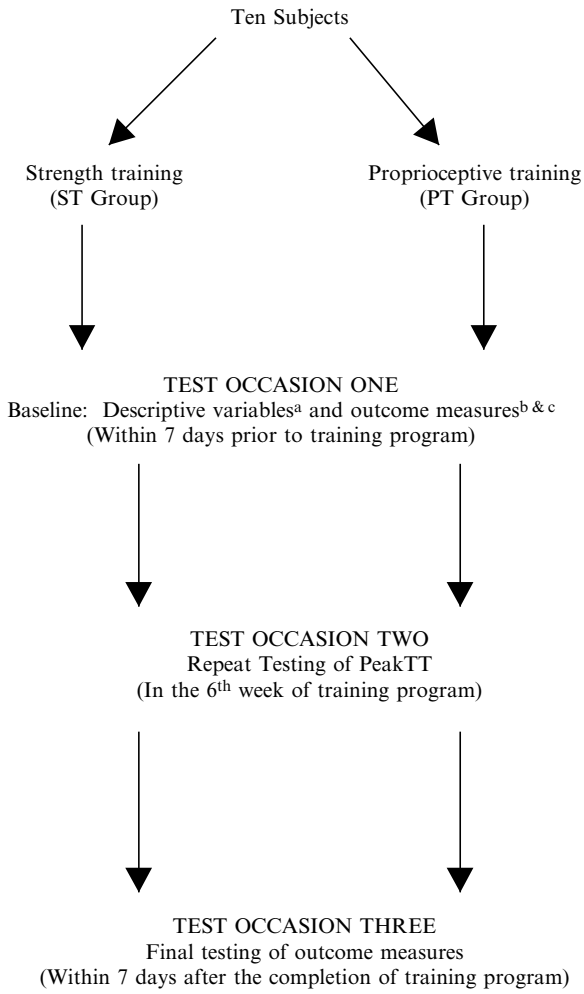

Fig. 1. Experimental design. [a]Age in years; weight in kilograms; height in centimeters; activity level prior to injury (Tegner and Lysholm Activity Scale); time interval from surgery to entering the study in months; and time interval from initial injury to surgery in months. [b]Subjective scores (Lysholm and Gillquist Knee Scoring Scale; Tegner and Lysholm Activity Scale); average isokinetic torques of the quadriceps and hamstring muscles in Nm; one-legged single hop for distance and one-legged time hop; and peak torque time of the hamstring muscles (PeakTT). [c]All outcome measures were assessed bilaterally.

A low acceleration rate was used for all tests. The non-operated limb was always tested first.

Functional hop tests

Two one-legged hop tests, one-legged single hop for distance (SLHD) and one-legged timed hop (TH), were assessed and used as indicators of lower limb function. Both of these one-legged hop tests were conducted in the manner described by Booher, Hench, Worrell, Stikeleather (1993). The non-operated limb was always tested first. The mean of two trials was calculated and used as the criterion score.

Peak torque time (PeakTT)

Peak torque time of the hamstring muscles (PeakTT) was assessed using the KIN-COM dynamometer at, 190°/s based on the method of Small, Waters, Voight (1994). Peak torque time of the hamstring muscles is the time lapse between the initial movement of the dynamometer lever arm and the generation of maximum torque by the hamstring muscles in response to the sudden forward movement of the dynamometer lever arm (Ihara & Nakayama, 1986; Beard, Kyberd, Fergusson, Dodd, 1993). The forward movement of the dynamometer level arm was set at, 190°/s. The non-operated limb was always tested first. Each PeakTT test occasion consisted of four practice trials, a one-minute rest, and six testing trials at, 190°/s. The six testing trials occurred at random intervals of 3, 5, 6, or 8 s to minimize the participants' tendency to anticipate the forward movement of the lever arm. We recorded time in 10 ms intervals. The slowest and the fastest times to hamstring peak torque were eliminated from the six trials. The mean of the remaining four trials was used as the criterion score.

The reliability of PeakTT between two test occasions was assessed in a pilot study (Liu, 1998). The intraclass correlation coefficient (ICC) for the non-dominant limb was 0.90 and 0.92 for the dominant limb. The standard error of measure (SEM) was 11 and 12 ms for the non-dominant and the dominant limb, respectively.

Power analysis

Based on a hypothesized 10–12% difference in PeakTT between the two groups, the number of participants required to achieve a power of greater than 0.85 was estimated by power analysis. The number of participants used (per group) in this study is comparable to published prospective ACL rehabilitation studies (Ihara & Nakayama, 1986; Blanpied, Carroll, Douglas, Lyons, Macalisang, Pires, 2000; Wojtys, Huston, Taylorm, Bastian, 1996).

Statistical methods

We compared baseline measures between groups using the independent samples *T*-test. Repeated-measures ANOVA was used to determine differences at the end of the 12 weeks between and within the experimental groups for the four outcome measures. For variables that were significantly different at baseline, the percentage change score was used instead for between group comparisons. Pearson product–moment correlation coefficients were calculated for isokinetic torques, PeakTT, and functional hop test scores. The variables that significantly correlated with the functional hop tests were used for subsequent linear stepwise regression analyzes. The level of significance for all statistical test were set at $P \leq 0.05$.

Results

All participants completed 12 weeks of training. Mild muscle soreness and/or mild patellofemoral joint discomfort were the most common (temporary) consequences of training.

Baseline measures

The characteristics of both groups are described in Table 1. The ST group consisted of three males and two females. The PT group consists of one male and four females. Both groups consisted of three right and two left ACL reconstructed knees. All participants were right dominant in the lower extremities.

All participants had full active and passive range of motion (at least 0° of extension and 125° of flexion) and good stability (in the sagittal plane) in the operated knee joint. As well, the passive stability of the participants' operated knee joint remained unchanged throughout the 12-week training period.

There were no significant differences between the two groups in their descriptive variables. However, there was a significant difference in average quadriceps torques of the operated limb (concentric: $P = 0.013$; eccentric: $P = 0.005$) between groups at baseline.

Compliance

Participants in the ST group completed a mean of 32 ± 3 sessions while participants in the PT group completed a mean of 31 ± 2 sessions of the total 36 sessions.

Subjective scores

There was a significant improvement in subjective scores (Lysholm and Gillquist Knee Scoring Scale scores: $P = 0.01$; Tegner and Lysholm Activity Scale

Table 1. Characteristics of subjects ($n = 10$)

Characteristic	Strength training* $n = 5$	Proprioceptive training* $n = 5$
Height (cm)	175.1 (10.6); 165.7–190.8	168.1 (10.3); 158.1–179.7
Weight (kg)	76.9 (16.0); 61.5–103.0	67.1 (14.0); 52.0–90.0
Age (year)	24.7 (2.7); 22.5–29.3	25.0 (3.7); 20.4–30.5
Activity level prior to injury (Tegner & Lysholm)	8.6 (1.1); 7.0–10.0	8.8 (1.1); 7.0–10.0
Time from surgery to study (month)	12.2 (8.3); 7.0–27.0	6.7 (0.8); 6.0–8.0
Time from Injury to surgery (month)	23.8 (26.8); 2.0–55.0	29.0 (57.6); 1.0–132.0

No significant differences between the two training groups. Data presented as means (SD); range.

Scores: $P = 0.003$) within each group after the 12 weeks, but not between the groups ($P = 0.297$). Table 2 provides the baseline and change values for the subjective scores while Fig. 2 illustrates the mean change in scores.

Average isokinetic torque

The PT group had significantly greater percent change in average isokinetic torques of the operated limb compare to the ST group after 12 weeks of training (Fig. 3). Specifically, the PT group demonstrated greater percent change in average concentric quadriceps torque ($P = 0.005$) and eccentric hamstring torque ($P = 0.04$).

There were no significant differences in percent change between the two groups in average isokinetic torques of the non-operated limb ($P > 0.120$). Table 3 contains the baseline and percent change values for each group.

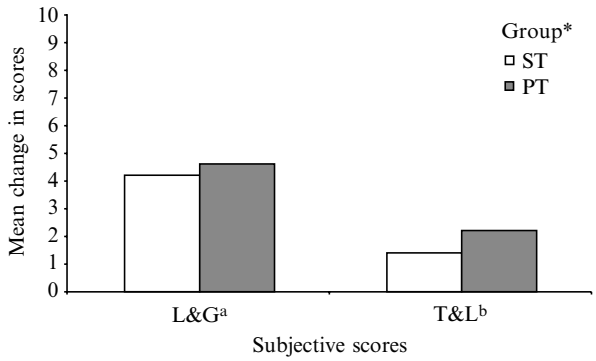

Fig. 2. Mean change in subjective scores after 12 weeks of exercise intervention. *ST = Strength training group; PT = Proprioceptive training group. [a]L&G = Lysholm and Gillquist knee scoring scale. [b]T&L = Tegner and Lysholm Activity scale.

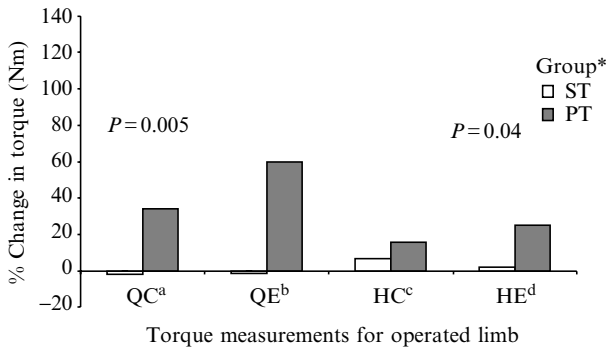

Fig. 3. Percent change in average isokinetic torques (in Nm) for operated limb. *ST = Strength training group; PT = Proprioceptive training group. [a]QC = Concentric quadriceps. [b]QE = Eccentric quadriceps. [c]HC = Concentric hamstrings. [d]HE = Eccentric hamstrings.

Table 2. Baseline and Change (Δ) values for Lysholm and Gillquist Knee Scoring Scale (L&G) and Tegner and Lysholm Activity Scale (T&G). Mean (SD) reported unless otherwise stated

	Strength training ($n = 5$)		Proprioceptive training ($n = 5$)	
	Baseline	Δ (95% CI)*	Baseline	Δ (95% CI)
L&G	92.6 (6.1)	4.2 (2.0–6.4)	87.6 (7.3)	4.6 (−2.3–11.5)
T&L	5.8 (1.8)	1.4 (−1.6E-02–2.8)	4.6 (1.1)	2.2 (0.4–4.0)

No significant differences between the two training groups. *CI = Confidence interval.

Table 3. Baseline and Percent Change (% Δ) values for average isokinetic torque in Nm for the quadriceps and hamstring muscles. Mean (SD) reported unless otherwise stated

	Strength training ($n = 5$)		Proprioceptive training ($n = 5$)	
Average torque (Nm)	Baseline	%Δ (95% CI)	Baseline	%Δ (95% CI)*
Concentric quads				
ACLR[†]	144.4 (31.4)	−1.8 (−14.3–10.7)[§]	80.2 (32.8)	34.2 (11.6–56.8)
ACLI[‡]	149.4 (40.3)	4.5 (−5.2–14.2)	116.8 (30.2)	14.4 (2.4–26.5)
Eccentric quads				
ACLR	161.0 (38.2)	−1.6 (−12.2–9.0)	79.6 (29.0)	60.0 (−15.3–135.5)
ACLI	172.6 (59.2)	4.0 (−20.8–28.9)	142.0 (43.1)	24.1 (−41.4–89.7)
Concentric hamstring				
ACLR	71.0 (24.6)	6.8 (−13.0–26.6)	53.2 (15.5)	16.0 (−6.0–38.0)
ACLI	80.8 (26.6)	−1.2 (−11.2–8.8)	61.0 (24.0)	8.8 (−7.2–24.8)
Eccentric hamstring				
ACLR	85.4 (28.3)	1.9 (−10.7–14.5)[¶]	58.6 (17.2)	25.1 (2.0–48.2)
ACLI	93.8 (37.6)	9.2 (−8.5–26.8)	78.0 (26.6)	11.2 (−1.8–24.3)

*CI = Confidence interval; [†]ACLR = ACL reconstructed limb; [‡]ACLI = ACL intact or normal limb. [§]Change is significantly different between the two groups ($P < 0.01$). [¶]Change is significantly different between the two groups ($P < 0.05$).

Functional hop tests

Both groups made significant improvements in their ability to perform the functional hop tests with their operated limb (TH: $P = 0.001$; SLHD: $P = 0.001$) and with their non-operated limb (TH: $P < 0.001$; SLHD: $P = 0.014$), with no significant differences between the groups ($P \geq 0.151$). Table 4 provides the mean and change values for both group while Fig. 4 illustrates the mean change in scores.

Peak torque time

There was no significant difference between ($P = 0.082$) and within ($P = 0.798$) the two groups in PeakTT for the operated limb. However, a significant group by test occasion interaction effect ($P = 0.017$) was evident. Table 5 provides the descriptive PeakTT data.

A curvilinear relationship (quadratic trend) between PeakTT and test occasion existed for both groups. As illustrated by Fig. 5, the two groups demonstrated very different trends in PeakTT over the 12-week period, such as the ST group had a slowing of PeakTT while the PT group demonstrated an improvement of PeakTT at 6 weeks.

There were no significant findings for the non-operated limb.

Regression analyzes

Average concentric quadriceps torque, average eccentric quadriceps torque, average concentric hamstring torque, and average eccentric hamstring torque were significantly correlated with SLHD (Table 6). No significant correlations were found between any of the five variables and TH.

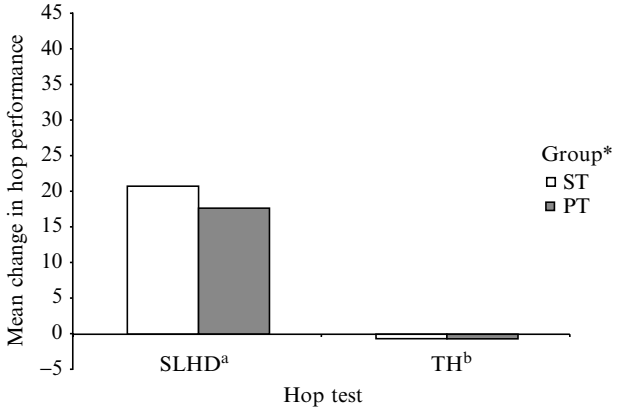

Fig. 4. Mean change in operated limb after 12 weeks of exercise intervnetion. SLHD is measured in centimeters, TH in seconds. *ST = Strength training group; PT = Proprioceptive training group. [a]SLHD = One-legged single hop for distance. [b]TH = One-legged timed hop.

Table 4. Baseline and Change (Δ) values for one-legged timed hop (TH) in seconds (s) and one-legged single hop for distance (SLHD) in centimetres (cm). Mean (SD) reported unless otherwise stated

	Strength training ($n = 5$)		Proprioceptive training ($n = 5$)	
Hop test	Baseline	Δ (95% CI)*	Baseline	Δ (95% CI)
TH (s)				
ACLR†	2.34 (0.22)	−0.6 (−1.0 to −0.3)	2.75 (0.58)	−0.7 (−1.2 to −0.2)
ACLI‡	2.27 (0.25)	−0.5 (−0.8 to −0.3)	2.21 (0.20)	−0.4 (−0.6 to −9.6E-02)
SLHD (cm)				
ACLR	160.3 (33.8)	20.7 (5.4–36.0)	133.3 (38.3)	17.6 (3.6–31.6)
ACLI	168.2 (29.9)	10.9 (−1.9–23.8)	165.6 (24.0)	5.7 (−1.8–13.3)

No significant differences in change between the two groups. *CI = Confidence interval; †ACLR = ACL reconstructed limb; ‡ACLI = ACL intact or normal limb.

Table 5. Baseline, 6th Week, and 12th Week values for peak torque time of the hamstring muscle (PeakTT) in milliseconds (ms). Mean (SD) and confidence interval reported

PeakTT (ms)	ST Group†	PT Group‡	ST Group 95% CI*	PT Group 95% CI
Baseline				
ACLR§	482.5 (24.9)	478.0 ± 20.6	457.1–516.9	445.1–504.9
ACLI¶	499.0 (32.1)	498.0 ± 34.1	474.2–527.8	473.7–527.3
6th week				
ACLR	498.5 (23.2)	456.0 ± 6.5	480.1–521.9	433.1–474.9
ACLI	487.0 (35.9)	493.5 ± 33.0	454.7–524.1	461.8–531.2
12th week				
ACLR	480.0 (19.1)	472.0 ± 11.1	464.3–496.7	454.3–486.7
ACLI	506.0 (28.6)	490.0 ± 29.8	477.3–530.7	461.8–515.2

No significant differences between and within the two groups based on RM ANOVA results. Significant interaction effect ($P = 0.017$). *CI = Confidence interval; †ST Group = Strength training group; ‡PT Group = Proprioceptive training group; §ACLR = ACL reconstructed limb; ¶ACLI = ACL intact or normal limb.

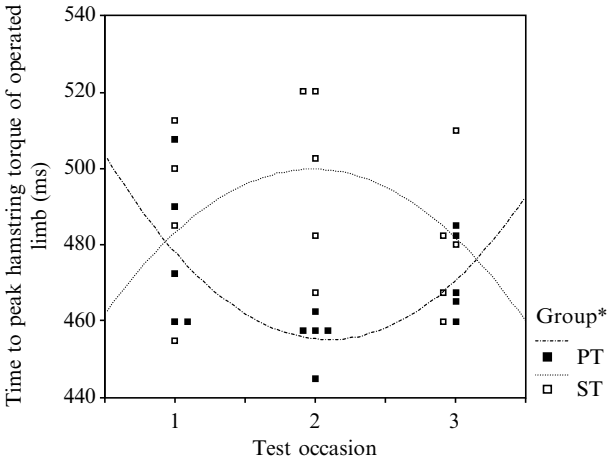

Fig. 5. Scatter plot (with fit line) of PeakTT of operated limb demonstrating a significant group by time interaction ($P = 0.017$). *ST = Strength training group; PT = Proprioceptive training group.

Table 6. Relationship between average isokinetic torques in Nm and functional ability of the operated limb as determined by the one-legged single hop for distance (SLHD) in centimetres. Pearson product–moment correlation coefficients (r) reported. Pooled sample ($n = 10$)

SLHD (cm)	Coefficient (r)	Significance
Concentric quadriceps	0.86	0.002
Eccentric quadriceps	0.78	0.008
Concentric hamstring	0.85	0.002
Eccentric hamstring	0.67	0.035

Of the four variables entered into the stepwise regression model, average concentric quadriceps torque was the single significant predictor of operated limb function ($R^2 = 0.72$). In the regression model for the non-operated limb, average concentric hamstring torque was the single significant predictor of function ($R^2 = 0.52$).

Discussion

Because ACL injuries are associated with well-documented impairment of neuromuscular function, PT forms an important component of ACL rehabilitation (Barrett, 1991; Corrigan, Cashman, Brady, 1992; Lephart, 1994). However, the effectiveness of PT after ACL surgical reconstruction has not been critically evaluated and to our knowledge, the present study is the first randomized clinical trial comparing two rehabilitation regimes in restoring neuromuscular function after ACL reconstruction.

Different trends observed in PeakTT

We found that both types of training influenced PeakTT. Statistically, this influence was due to an interaction between the type of training and the duration of training.

PeakTT measures volitional hamstring activity and is likely to be controlled by some or all of the following factors: the sensitivity of the muscle spindles; kinesthetic awareness; the ability to recruit motor units rapidly; the coordination of the limb to the specified task; and the participant's motivation and concentration level. PeakTT is of special interest in ACL research and has been used in several published studies (Beard et al., 1994; Ihara & Nakayama, 1986; Wojtys & Huston, 1994).

The PeakTT results are novel and we found no other published data with which to compare them. A curvilinear relationship between PeakTT and test occasion was observed for both experimental groups. We propose that the trend for a shorter PeakTT in the PT group at six weeks was due to improved coordination and neural activation of the operated limb. The longer PeakTT in the ST group at six weeks may have been due to either or both of the following mechanisms. First, differences between the training mode and the outcome measure tested. The ST program emphasized on slow and maximum muscular contractions rather than on quick muscular reactions to external perturbations. However, the testing of PeakTT relies on one's ability to maximally recruit their hamstring muscle in the shortest amount of time possible. Second, decreases in muscle spindle sensitivity may occur with ST (Hakkinen & Komi, 1983). A decrease in muscle spindle sensitivity of the hamstring muscle may ultimately affect one's ability to detect forward movement of the KIN-COM dynamometer lever arm.

Three prospective studies lend support to our PeakTT findings at six weeks (Ihara & Nakayama, 1986; Wojtys et al., 1996; Jerosch, Pfaff, Thorwesten, Schoppe, 1998). Using four participants with a history of knee instability, Ihara and Nakayama (1986) demonstrated significant improvements in peak hamstring torque time after 8 weeks of perturbation training. In their 6-week study using eight participants (with normal knees) per group, Wojtys et al. (1996) found PeakTT improved by the largest margin (38 ms) in the agility trained group compared to the isotonic or isokinetic trained group. It was also observed that PeakTT slowed (31 ms) in the isotonic trained group. In contrast, Hakkinen & Komi (1983) observed an improvement in the time to peak muscle torque of the quadriceps muscle during and after 16 weeks of heavy resistance ST in normal males. The investigators attributed this improvement to an increase in the fast twitch/slow twitch (FT/ST) muscle area ratio.

The regression of the PT group to baseline values at 12 weeks may be secondary to the nature of the training protocol. The training protocol was designed to become increasingly more difficult over the 12-week period by integrating speed and complex balance and agility tasks. However, an emphasis on sufficient practice of basic motor tasks at slow speeds may be more

important for regaining normal neuromuscular control after injury (Collins, Cameron, Gillard, Prochazka, 1998; Kottke, 1980). To achieve the coordination of appropriate muscle firing patterns during functional activities without the conscious awareness of the individual, adequate practice is essential (Kottke, 1980; Kottke, Halpern, Easton, Ozel, Burrill, 1978). Inadequate practice results in errors in performance due to the lack of inhibition of muscles in motor patterns. Thus, the deterioration of PeakTT may reflect the inappropriate motor patterns created secondary to the lack of adequate practice. It should be noted that Ihara & Nakayama (1986) used the same basic five exercises and Beard et al. (1994) used the same eight exercises throughout their intervention period. In contrast, a number of exercises were introduced or modified throughout our 12-week training protocol.

An increase in FT/ST area ratio may account for the positive trend in PeakTT demonstrated by the ST group at the end of the 12 weeks (Hakkinen & Komi, 1983). It is probable that the participants in this group were unable to advance to loads similar to those used in the study by Hakkinen & Komi (1983) until the latter half of the training program. Thus, any increases in FT/ST ratio would not have occurred until such time.

Proprioceptive training can increase muscle strength after ACL reconstruction

To our knowledge, the effects of PT on quadriceps and hamstring strength after ACL surgery have not been previously examined. We used percentage change scores to compare isokinetic torques between the two groups because of the significant baseline differences in quadriceps strength. This difference may be secondary to the greater number of males and the greater longer (but not significantly different) time from surgery to entering the study in the ST group compared to the PT group. However, it should be noted that nine out of the ten participants were 6–10 months post-operation upon entering the study. Thus, the longer mean time from surgery to entering the study for the ST group may largely be attributed to one individual's time value of 27 months post-operation.

The greater percent change demonstrated by the PT group compared to the ST group (Figs. 3 and 4) are proposed to be due to improved coordination and neural activation secondary to the prescribed intervention. Isokinetic testing relies partially on the coordination of the tested limb. Thus, the greater gains demonstrated by the PT group may be due to better performance of the desired motor pattern compared to the ST group. We also contend that the PT program contributed significantly to neural activation involved in the early stages of strength gain. The role neural mechanism plays in strength increase before muscle hypertrophy can be quite extensive (Moritani & DeVries, 1979; Yue & Cole, 1992).

A review of the exercise log sheets handed in by the ST group indicated that progressively heavier weights were being used over the 12-week period. However, these improvements were definitely not reflected in the results of isokinetic strength testing at the end of the 12 weeks. The minimal change from baseline isokinetic torque values demonstrated by the ST group at 12 weeks may be a reflection of the specificity of training and testing modes. Rasch & Morehouse (1957) demonstrated strength gains from a 6-week training protocol in tests when muscles were employed in a familiar way, but little or no gain in strength was observed when unfamiliar test procedures were employed.

Both types of training improves hop performance and subjective scores

In keeping with previous findings (Carter, Jenkinson, Wilson, Jones, Torode, 1997; Fitzgerald, Axe, Snyder-Mackler, 2000), we observed that both ST and PT had significant beneficial effects on functional ability and subjective scores.

Determinants of functional ability

Because the true-end point of ACL rehabilitation is returning individuals to pre-injury function, it is important to ascertain the determinants of functional ability in those with ACL reconstructions in order for clinicians to design effective ACL rehabilitation programs.

Quadriceps muscle strength was a significant determinant of functional ability for the operated knee joint. It accounted for an impressive 72% of the variance in SLHD. This implies that ACL rehabilitation programs should place an emphasis on recovering quadriceps strength to maximize functional ability of the operated knee joint. This is well supported in the literature (Delitto, Irrgang, Harner, Fu, Nessi, 1993; Govett, 1995; Pincivero, Lephart, Karunakara, 1997; Wilk, Romaniello, Soscia, Arrigo, Andrews, 1994). Despite the important role that proprioception is thought to play in functional ability, we found no relationship between PeakTT and the one-leg hop tests. The literature substantiates our result (Carter et al., 1997; Govett, 1995). Govett (1995) also found a lack of relationship between proprioception and functional ability (SLHD). This lack of relationship likely reflects the complexity of human neuromuscular control.

Limitations

This study had several limitations. First, the sample size is small in this study and was based on a hypothesized

10–12% difference in PeakTT between the two groups. Thus, there is the likelihood that this study was underpowered to demonstrate differences between the two groups in the secondary outcome measures. However, other published ACL rehabilitation studies have used similar number of participants per group (Ihara & Nakayama, 1986; Blanpied et al., 2000; Wojtys et al., 1996). Also, despite the small sample size used, this study revealed a significant interaction effect between the type and the duration of training on neuromuscular function. Interaction effects must be interpreted before conclusions can be made for main effects. (Portney & Watkins, 1993) As well, this interaction effect has not been described previously in the literature.

Second, although there were no statistical significant differences between the two groups on the descriptive variables, the difference in the time from surgery to entering the study between the two groups (12 months vs. 7 months) may have clinical significance. The greater mean time from surgery to entering the study for the ST group arose because one participant entered 27 months post-operation. All remaining nine participants were between 6 and 10 months post-operation upon entering the study. A more strict time interval (time from surgery to entering the study) in the inclusion criteria would have been more prudent.

Third, the two groups were quite uneven in the distribution of males and females. To the best of our knowledge, it is not known whether training effects are different between males and females. However, if our sample size was larger, we could have stratified according to sex and reduced a potential confound.

Conclusion

It is clear that both ST and PT are important in ACL rehabilitation. However, it is not obvious if one is significantly more effective in restoring neuromuscular control. Part of the difficulty in establishing an answer to the question is the lack of a gold standard for measuring neuromuscular control.

We conclude that both types of training influence PeakTT but that they must operate via independent neuromuscular mechanisms as they can change in opposite directions. Both ST and PT are beneficial for restoring functional ability and improving subjective scores. Restoring and increasing quadriceps strength of the operated limb is essential to maximize the functional ability of the affected knee joint. Also, PT alone can induce strength gains in the operated limb. However, future studies using larger sample sizes are needed to clarify these observations.

Perspectives

We tested the effect of a progressively more challenging 12-week PT protocol, similar to those used in the clinical setting, and found that the progressive nature of the intervention may have a detrimental effect on PeakTT performance. Adequate practice of desired motor patterns appears to be an important aspect of PT for ACL reconstructed knees and may be overlooked by many clinicians. As well, despite the current major emphasis on PT after ligament injuries, restoring and increasing quadriceps strength post ACL reconstructions remains essential for maximizing functional ability of the affected knee joint.

Key words: rehabilitation; ACL injury; neuromuscular control.

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