Effectiveness of Accelerated Recovery Performance for Post-ACL Reconstruction Rehabilitation

Anne R. Wright MD; Andrew B. Richardson MD; Christian K. Kikuchi MD;
Daniel B. Goldberg MD; Jay M. Marumoto MD; and Darryl M. Kan MD

Abstract

Atrophy and protracted recovery of normal function of the ipsilateral quadriceps femoris muscle following anterior cruciate ligament reconstruction surgery is well documented. The Accelerated Recovery Performance trainer is a type of electrical stimulation device that delivers a high-pulse frequency via a direct current, making it unique from many other devices on the market. The purpose of the present study was to investigate the effects of the direct current (via the Accelerated Recovery Performance trainer protocol) on gains in thigh circumference following anterior cruciate ligament reconstruction. Twenty-five patients were enrolled following isolated anterior cruciate ligament reconstruction and randomly assigned to either an isometric rehabilitation protocol augmented with the Accelerated Recovery Performance trainer protocol (experimental group) or the isometric rehabilitation protocol alone (control group). The two groups participated in sixteen sessions of directed rehabilitation over a two-month time period. Patients were followed with serial thigh circumference measurements at 5, 10, 15, and 20 centimeters above the superior patellar pole. Comparison of the overall mean circumferential gains in thigh circumference of the involved leg demonstrated approximately 3:1 gains in the ARP group over the control group, demonstrating it to be superior to isometric rehabilitation alone with regards to gains in thigh girth. The Accelerated Recovery Performance trainer protocol should be considered for post-anterior cruciate ligament reconstruction rehabilitation in order to reverse disuse atrophy of the ipsilateral quadriceps femoris.

Keywords

Electrical Stimulation, Anterior Cruciate Ligament Reconstruction, Quadriceps Atrophy

Abbreviations

AC: Alternating Current
ACL: Anterior Cruciate Ligament
ARP: Accelerated Recovery Performance
DC: Direct Current
ES: Electrical Stimulation
QF: Quadriceps Femoris

Introduction

Disuse atrophy is a well-established phenomenon that follows disease, trauma or surgery of the affected limb. Atrophy of the ipsilateral quadriceps femoris (QF) muscle and consequent protracted recovery of normal function following anterior cruciate ligament (ACL) reconstruction surgery is well documented in the literature.[1-3] Arangio, et al, showed in 33 patients a 1.8% decrease in thigh circumference, a 10% decrease in average quadriceps torque, and a 8.6% decrease in quadriceps cross-sectional area by MRI at an average of 49 months post-surgery despite aggressive rehabilitation.[1] Atrophy of QF following ACL reconstruction greatly impedes stability, strength, and recovery because QF serves as the primary stabilizer of the knee joint during translation.

Current approaches attempting to address muscle atrophy following ACL reconstruction emphasize early post-operative motion, full passive knee extension, immediate weight bearing, and closed-kinetic-chain exercises.[4] In addition, multiple groups have studied the adjunctive use of electrical stimulation (ES) in post-operative rehabilitation and have suggested that the addition of ES can improve muscle strength and size.[5,6] Delitto, et al, found that ES provides greater isometric strength gains than voluntary exercise alone.[7,8] The mechanisms for this observed increase in muscle strength have been attributed to both changes in neural factors and direct muscle hypertrophy.[9] Possible neural factors contributing to QF weakness include attenuation of gamma loop 1A afferent fibers.[10] ES has been suggested to modulate action potentials in both intramuscular nerve branches and cutaneous receptors, thus inducing force production directly by activation of motor axons and by direct reflex recruitment of spinal motor neurons.[9,10] Additionally, Gondin, et al, noted that simultaneous use of ES during volitional isometric exercises served to further improve the efficacy of the rehabilitation program.

The Accelerated Recovery Performance (ARP) Trainer is a type of ES device manufactured in the United States by Accelerated Recovery Performance Program. Similar to most ES devices, ARP's primary use is for the rehabilitation of musculoskeletal injuries in athletes. ARP's proprietary ES mode has been proposed to deliver a pulse-delivery frequency higher than most other devices, allowing supra-physiologic stimulation of muscle fibers, capable of producing tetany, if desired. The ability of the ARP protocol to achieve a higher pulse-delivery frequency may be attributed to the fact that it uses a direct current (DC), rather than the alternating current (AC) used by many popular ES devices. Direct current may decrease the pain and burning sensation felt by the subjects, thus allowing for a greater amplitude and frequency. Outcomes for ARP treatment have been based primarily on clinical observations during rehabilitation of ankle sprains, hamstring injuries, and distal radius fractures in elite athletes. The aim of the present study was to investigate how augmenting rehabilitation with the ARP trainer affects thigh circumference in patients who underwent ACL reconstructive surgery and demonstrated post-operative QF atrophy.

Methods

Twenty-five patients from a single orthopedic sports medicine group with an isolated ACL injury and subsequent surgical reconstruction (with autograft or allograft) were included in this study and randomly assigned to either the experimental or control protocol group based on birth year. All patients completed a standard 15-week post-operative physical therapy immediately prior to beginning the study and demonstrated atrophy of their QF as compared to the ipsilateral side. The six female and nineteen male patients ranged in age from sixteen to fifty-four years (mean and standard deviation, 30.76±11.74). The experimental group consisted of 9 males and 5 females with a mean age of 29.0 years and an age range of 17-51 years. The control group consisted of 10 males and 1 female with a mean age of 32.9 years and an age range of 16-54 years. Figure 1 outlines the patient recruitment and randomization process. The institutional review board approved the study protocol and all patients gave written informed consent.

Pre-intervention thigh circumference was measured at 5, 10, 15, and 20 centimeters above the superior patellar pole. All data including subsequent serial thigh circumference measurements, ARP trainer intensity, and adverse events was collected on a Case Report Form during the primary visit and at every subsequent session. Each patient received 16 one-hour sessions of individual therapy, based on the following protocol, over the course of 6 weeks. Following completion of all sessions, final thigh circumference measurements were taken at 5, 10, 15, and 20 centimeters above the superior patellar pole. Thigh circumference measurements recorded from both the experimental and control group were analyzed according to t-test for statistical significance; a Mann-Whitney Rank Sum test was utilized alternatively to analyze the data.

Protocol

The patients who received ARP therapy were managed three times a week throughout the entire treatment period with either a "heavy" (sessions #1, 3, 4, 8, 9, 13, 14) or a "light" (sessions #2, 5, 6, 7, 10, 11, 12, 15, 16) session (Table 1). At the beginning of every session, a brief physical exam was done involving inspection of the QF muscle of each leg with specific attention

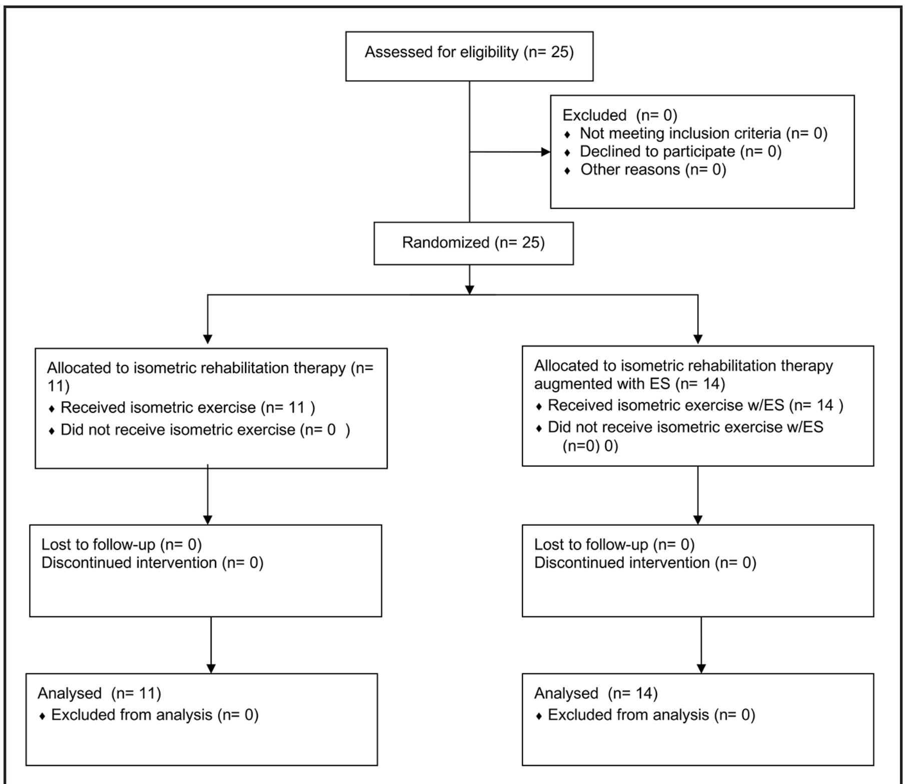

Figure 1. Patient Recruitment and Randomization. Twenty-five Patients were Enrolled and Randomized to the Experimental or Control Group. All Patients Met Inclusion Criteria. No Patients were Lost to Follow-up.

paid to the relative difference in size of the vastus medialis and vastus lateralis. Two electrodes were placed: one over the muscle belly of the distal aspect of the vastus medialis, and one over the belly of the rectus femoris [5 – 25 milliamps, 15 – 30 volts, 500 Hz]. Because the ARP trainer can contract the muscle to tetany, the dose of ES was titrated by subjective feedback of the patient at each session. Under no circumstances was the patient subjected to intolerable pain or tetany throughout treatment.

ARP protocol included a combination of steady work (holding position while resisting gravity) and fast pulses (repeated isometric contractions). Background stimulation consisted of a pulse frequency of 10,000 cycles/sec and an intensity of 2 – 5 volts. The patient was instructed to perform each exercise until failure for 3 minutes per exercise. Once failure occurred, we stopped the clock and allowed the patient to briefly recover (<15s), repositioned them, restarted the clock and repeated until 3 minutes of total work was performed.

The patients who were assigned to the control group were also managed three times a week throughout the entire treatment period with either "weighted" (sessions #1, 3, 4, 8, 9, 13, 14) or "physioball" (sessions #2, 5, 6, 7, 10, 11, 12, 15, 16) sessions (Table 2). Females started with 5 lbs of weight and males with 10 lbs. Weights were increased throughout subsequent sessions to encourage strengthening.

After completion of the 16 rehabilitation sessions, outcome measures were collected on both the injured limb and the healthy contralateral limb. Pre and post treatment thigh circumferences served as the primary outcome measures.

Results

Comparison of the overall mean circumferential gains in thigh circumference of the involved leg demonstrated approximately 300 percent greater gains in the ARP cohort over the control cohort. The mean total gain across all data points for the experimental group was 12.293 cm (SD = 2.826), while the control group had a mean gain of 4.009 cm (SD = 2.141). There was a total difference of 8.384 cm, or a difference of 2.07 cm at each measured point, thus the ARP cohort had a gain ratio of 3.06:1 when compared to the control cohort. The mean gain across all measurement data points for both study groups was analyzed using a t-test analysis. Validation of the summary data passed both the normality test ($P = .402$) and equal variance test ($P = .627$). T-test analysis resulted in a statistically significant t-value of 8.157 and a P-value of $< .001$. The 95% confidence interval for the summary data was 6.258 to 10.510. Power of analysis at alpha = 0.05 was 1.000.

Table 1. Experimental Group "Heavy" and "Llight" Day Protocols. Patients Participated in the Heavy Day Protocol for Sessions 1, 3, 4, 8, 9, 13, 14 and Light Day Protocol for Sessions 2, 5, 6, 7, 10, 11, 12, 15, 16. All Sessions were Augmented for Electrical Stimulation Via the ARP Trainer Protocol.

Heavy Day Protocol		
Isometric Rehabilitation	**ARP Trainer Protocol**	**Sets**
Isometric wall squat	3 min/Steady work	1
Isometric lunge (bilaterally)	3 min/Steady work	1
Seated isometric leg extension	3 min/Steady work	1
Rest	5 min/Background Stimulation	
Isometric wall squat	3 min/Fast pulse	1
Isometric lunge (bilaterally)	3 min/Fast pulse	1
Seated isometric leg extension	3 min/Fast pulse	1
Light Day Protocol		
Isometric Rehabilitation	**ARP Trainer Protocol**	**Sets**
Isometric wall squat	10 sec fast pulse, followed by 10 sec steady work	5
Isometric lunge (bilaterally)	10 sec fast pulse, followed by 10 sec steady work	5
Seated isometric leg extension	10 sec fast pulse, followed by 10 sec steady work	5
Rest with background stimulation	5 min	

Table 2. Control Group "weight" and "physioball" Protocols. Patients participated in the weight protocol for sessions 1, 3, 4, 8, 9, 13, 14 and physioball protocol for sessions 2, 5, 6, 7, 10, 11, 12, 15, 16.

Weight Protocol		
Isometric Rehabilitation	**Repetitions/Extremity**	**Sets**
Dumbbell front squat	12	3
Dumbbell split squat lunge, bilaterally	12	3
Manual resistance hamstring, bilaterally	3	1
Dumbbell Romanian deadlift, 2 legs	12	3
Dumbbell Romanian deadlift, 1 leg, bilaterally	12	3
Physioball Protocol		
Isometric Rehabilitation	**Repetitions/Extremity**	**Sets**
Squat	24	2
Hip twist	24	2
Inchworm	24	2
Leg circles, bilaterally	24	2
Kickbacks	24	2
Single leg lunges, bilaterally	24	2

The mean gain at 5 cm for the experimental group was 2.864 cm with a standard deviation of 0.719, while the control group had a mean gain of 0.936 cm with a standard deviation of 0.622. The difference between the two means was 1.928, which was statistically significant, t-value 7.056 with a *P*-value of <.001. The 95% confidence interval was 1.363 to 2.493. Data at 5 cm above the superior patella was validated with the normality test (*P*=.488).

The mean gain at 10 cm for the experimental group was 2.950 cm with 25th percentile and 75th percentile values of 2.700 cm and 3.600 cm respectively. For the control group, the median gain was 1.000 cm with 25th and 75th percentile values of 0.350 cm and 1.175cm respectively. The difference between the two mean values was 1.950, which was statistically significant. Data at 10 cm failed the t-test analysis for normality test (*P*<.050); thus, data analysis proceeded with a Mann-Whitney Rank Sum test. The Mann-Whitney U statistic value was 154.000 and resulted in a statistically significant T value of 66.000 with a *P*-value of <.001.

The mean gain at 15 cm for the experimental group was 3.143 cm with a standard deviation of 0.903. The control group had a mean gain of 0.99 cm with a standard deviation of 0.607. The difference between the two mean values was 2.152. The t-test analysis resulted in a statistically significant t-value of 6.778 and a *P*-value of <.001. The 95% confidence interval was 1.495 to 2.809.

At 20 cm above the superior patella, mean gain for the experimental group was 2.914 cm, while the control group had a mean gain of 1.245 cm. The data was statistically significant (*P*<.001). Figure 2 demonstrates the differences in mean thigh circumference between the ARP and control group at the final follow-up.

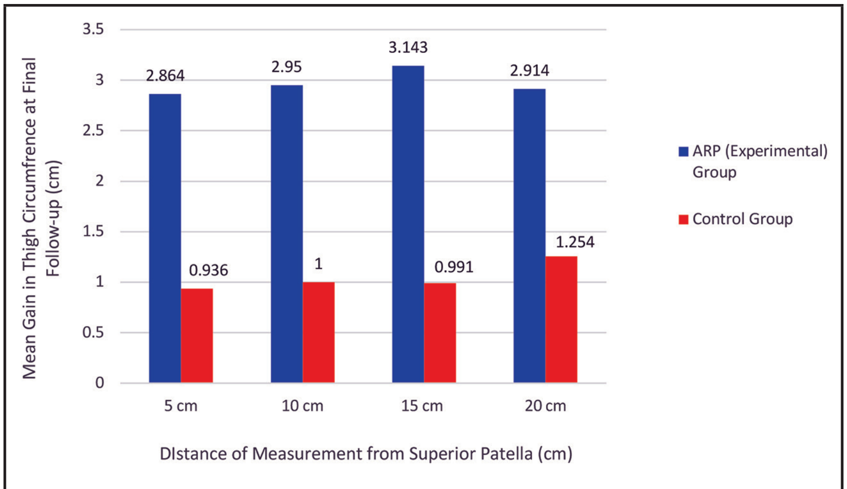

Figure 2. Mean Gain in Thigh Circumference at Final Follow-Up. Mean Thigh Circumference of Bboth the ARP (Experimental) and Control Group at Final Follow-up was Ccalculated. The Mean Thigh Circumference in the ARP Group was Three Times Greater at All Measured Points han that Seen in the Control Group at Final Follow-up. The Differences Between the Two Groups were Statistically Significant (*P*<.001).

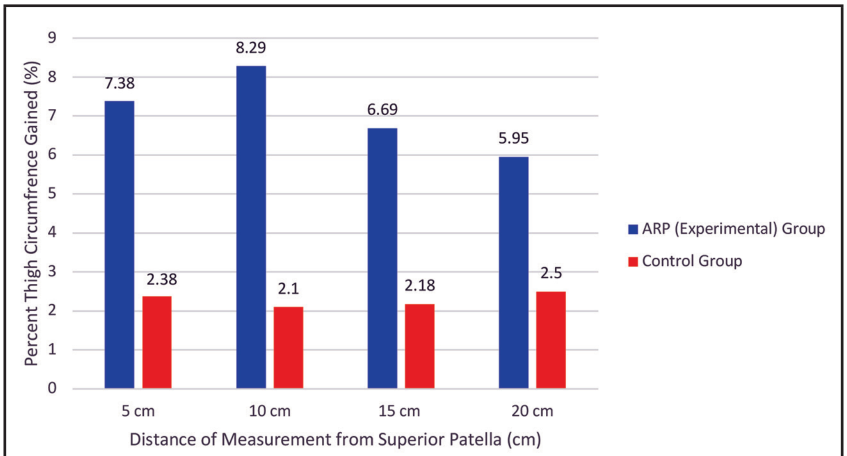

Figure 3. Average Percent Gain in Thigh Circumference. Average Percent Gain in Thigh Circumference in ARP (Experimental) Ggroup and the Control Group from the Initial Evaluation to the Final Follow-up was Calculated and is Demonstrated in the Above Graph.

The average percent gain in thigh circumference for the ARP and control groups are shown in Figure 3. The average percent gain in thigh circumference for the experimental group was 7.38%, 8.29%, 6.96%, and 5.95% at measurements made at 5 cm, 10 cm, 15 cm, and 20 cm above the superior patella respectively. For the control group, average percent gain in thigh circumference was 2.38%, 2.10%, 2.18%, and 2.50% at 5 cm, 10 cm, 15 cm, and 20 cm above the superior patella respectively.

Discussion

Our study demonstrates that an accepted isometric rehabilitation program augmented with the ARP trainer protocol is superior to an isometric rehabilitation protocol alone in correcting disuse atrophy of the QF after ACL reconstruction. Patients using the ARP trainer protocol had a three-times increase in thigh circumference compared to the control group.

Persistent weakness and disuse atrophy of the QF has been a consistent finding after ACL reconstruction. Persistent weakness is associated with patellofemoral pain that prevents the patient from exercising properly.[11] Different physiologic mechanisms have been proposed for this phenomenon and have different implications on the maximum efficacy that can be expected of rehabilitation protocols post-ACL reconstruction. Urbach, et al, supported the theory of central nervous system inhibition after joint damage by the finding of bilateral voluntary activation deficits by twitch interpolation following unilateral injury.[12] Likewise, if weakness is due to voluntary activation failure as further suggested by Terese, et al, rehabilitation protocols that stress voluntary quadriceps exercise alone may not result in a complete recovery of QF muscle strength.[13] Because the activities of gamma motor neurons can influence alpha motor neurons through the gamma loop, a decrease in gamma efferent input caused by loss of joint afferents from the native ACL might also explain QF weakness in ACL lesions.[10,14-16]

ES has been used for strengthening especially in cases involving immobilization, contraindication to dynamic exercise, patient inability to exert muscular force, and as an adjunct to traditional voluntary exercise protocols. Several studies used ES to target the proposed central mechanism of inhibition.[17,18] Dean, et al, showed that development of torque through surface ES was dependent on a central mechanism and proposed that the evoked sensory volley recruited motoneurons in the spinal cord. The study also suggested that post-tetanic potentiation increased neurotransmitter release from sensory axons through repeated stimulation, potentially activating higher threshold motoneurons.[18] Powers et al studied high-frequency ES of human upper limb muscles and showed that ES of the flexor pollicis longus and biceps evoked greater torques than could be attributed to direct activation of the motor axons, further indicating that the central mechanism was responsible for the development of extra torque.[19] These studies demonstrated the efficacy of direct activation and recruitment of centrally inhibited motoneurons.

Studies have also proposed that the effects of ES are mainly due to electroanalgesic properties that facilitate earlier movement, QF contraction, and earlier weight bearing than would otherwise not be tolerated post-ACL reconstruction.[20,21] Other effects of ES on physiology have been hypothesized to include: increase in muscle fiber size, changes in fiber type composition, and prevention of reduction in myofibrillar adenosine triphosphate.[11]

Multiple studies support ES therapy as effective in preventing the degree of atrophy following knee surgery and subsequently increasing post-operative muscle function.[5,22,23] In contrast, however, Anderson, et al, showed that ES therapy showed no reduction in volumetric atrophy observed and concluded that it was only effective in minimizing strength decreases due to immobilization.[24] Given the conflicting results, this study decided to take a unique approach to solving the problem of disuse atrophy: Electrical stimulation delivered by the ARP unit was not used to prevent disuse atrophy, but rather, was used to restore thigh girth lost following ACL reconstruction.

It is postulated that exercising the QF muscle at maximum work intensity results in compensatory hypertrophy, allowing the muscle to generate greater force than would be possible without ES therapy. Further, it is thought that the use of ES in conjunction with isometric or isokinetic exercise can increase work intensity and result in increased thigh girth. Yet several studies were unable to correlated ES with an increase in QF circumference.[25-27] Halback, et al, attributed the lack of apparent hypertrophy in healthy individuals training with ES to a decrease in fat and an increase in muscle. This speculation is shared by Nobbs et al, who suggested that training for a longer period of time (greater than six weeks) would result in significant QF hypertrophy. An increased training time of 8 weeks was used by Gondin, et al, which showed a six percent increase in the anatomical cross-sectional area of the QF in healthy individuals. Additionally, they suggest that ES might be useful in rehabilitation programs targeting the atrophied QF after periods of immobilization.[9] This application of ES is supported by our findings, which demonstrated an 8.29 percent increase in thigh circumference measured at 10 cm above the superior patella using the ARP protocol on post-ACL reconstruction patients. Furthermore, the ARP protocol allowed for 300 percent greater gains in thigh girth in the ARP cohort over the control cohort. To our knowledge, no other study has been able to show mean circumferential gains of this magnitude.

Our positive results may be attributed to the direct current (DC) compounded with high frequency double exponential patented background waveform produced by the ARP unit. This unique waveform allows for several advantages including limited production of inhibitory protective muscle contractions, more efficient permeation of the QF and possibly decrease in pain associated with electrical current. Many ES apparatuses use fast-pulsed AC currents, such as faradic current, which has been shown to cause a level of sensory discomfort in patients training with ES greater than that experienced by patients performing strenuous conventional exercise.[28] This discomfort, in the form of pain and burning sensation, has been a major limiting factor in the amplitude and frequency reached with ES.[26]

The results of this study may have a significant impact for patients attempting to return to sport. It is well-documented that, although cleared, as few as thirty-three percent of patients return to competitive sport after ACL reconstruction.[29] It has been suggested that this is due to persistent symptoms of instability coming from QF weakness and the subsequent fear of reinjury.[30,31] We wonder whether the appearance of QF atrophy may also contribute to athletes fear of reinjury and whether the gains in thigh circumference may lead to a higher rate of return to sport and/or an earlier return to sport.

There were limitations to this study. First, we only used the end-point of measured thigh circumference. We did not use imaging modalities such as computed tomography or ultrasound to assess QF atrophy and hypertrophy, so gains appreciated in end-thigh circumference were not distinguishable from mass gained due to simultaneous increase of subcutaneous tissues as described by Halkjaer, et al, and Arvidsson et al.[22,32] Second, our study was limited by our small sample size. This was mainly because this was a single-center study completed within one year. Third, our study was randomized, but not blinded to either the patients or the administrators. This may have affected the voluntary effort of patients in both groups but was unavoidable due to logistics of protocol administration. Finally, there was also no control for exercise of patients outside of the study. Individuals may have experienced gains in size due to activity exclusive of the study protocol. Further trials with greater sample size, control for physical activity outside of rehabilitation protocol, and assessment of pre- and posttest strength of both extremities and pre- and posttest imaging assessment should be pursued. Additionally, future studies should look at whether the APR cohort scores higher on return to sport functional testing and whether they have a higher rate of return to sport.

In conclusion, ES from the ARP trainer can be used to activate muscle fibers at frequencies far greater than both the critical fusion frequency (the minimum firing rate that produces a tetanic response) and the normal firing rate for QF fibers. In the present study, this resulted in 3:1 gains in thigh girth in those patients receiving post-operative rehabilitation augmented with the ARP trainer versus patients who underwent a standard isometric rehabilitation program alone. These findings demonstrate an advantage in the use of the ARP trainer protocol to restore thigh girth after disuse atrophy following ACL reconstruction.

Conflict of Interest

None of the authors identify a conflict of interest.

Disclosure Statement

Dr. Darryl Kan is a member of the Accelerated Recovery Performance special projects team. To date there has been no associated financial gains related to the subject matter or materials discussed in the article.

Authors' Affiliation:
- Division of Orthopaedic Surgery, John A. Burns School of Medicine, University of Hawai'i, Honolulu, HI

Correspondence to:
Anne R. Wright MD; 1356 Lusitana St., 6th Fl., Honolulu, HI 96813;
Email: anner@hawaii.edu

References

1. Arangio GA, Chen C, Kalady M, Reed JF. Thigh muscle size and strength after anterior cruciate ligament reconstruction and rehabilitation. *J Orthop Sports Phys Ther.* 1997;26(5):238-243.
2. Gerber C, Hoppeler H, Claassen H, Robotti G, Zehnder R, Jakob RP. The lower-extremity musculature in chronic symptomatic instability of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1985;67(7):1034-1043.
3. Williams GN, Buchanan TS, Barrance PJ, Axe MJ, Snyder-Mackler L. Quadriceps weakness, atrophy, and activation failure in predicted noncopers after anterior cruciate ligament injury. *Am J Sports Med.* 2005;33(3):402-407.
4. Beynnon BD, Uh BS, Johnson RJ, et al. Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind comparison of programs administered over 2 different time intervals. *Am J Sports Med.* 2005;33(3):347-359.
5. Gould N, Donnermeyer D, Pope M, Ashikaga T. Transcutaneous muscle stimulation as a method to retard disuse atrophy. *Clin Orthop Relat Res.* 1982(164):215-220.
6. Laughman RK, Youdas JW, Garrett TR, Chao EY. Strength changes in the normal quadriceps femoris muscle as a result of electrical stimulation. *Phys Ther.* 1983;63(4):494-499.
7. Delitto A, Rose SJ, McKowen JM, Lehman RC, Thomas JA, Shively RA. Electrical stimulation versus voluntary exercise in strengthening thigh musculature after anterior cruciate ligament surgery. *Phys Ther.* 1988;68(5):660-663.
8. Selkowitz DM. Improvement in isometric strength of the quadriceps femoris muscle after training with electrical stimulation. *Phys Ther.* 1985;65(2):186-196.
9. Gondin J, Guette M, Ballay Y, Martin A. Electromyostimulation training effects on neural drive and muscle architecture. *Med Sci Sports Exerc.* 2005;37(8):1291-1299.
10. Konishi Y, Fukubayashi T, Takeshita D. Possible mechanism of quadriceps femoris weakness in patients with ruptured anterior cruciate ligament. *Med Sci Sports Exerc.* 2002;34(9):1414-1418.
11. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am.* 1995;77(8):1166-1173.
12. Urbach D, Nebelung W, Becker R, Awiszus F. Effects of reconstruction of the anterior cruciate ligament on voluntary activation of quadriceps femoris a prospective twitch interpolation study. *J Bone Joint Surg Br.* 2001;83(8):1104-1110.
13. Chmielewski TL, Stackhouse S, Axe MJ, Snyder-Mackler L. A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. *J Orthop Res.* 2004;22(5):925-930.
14. Konishi Y, Konishi H, Fukubayashi T. Gamma loop dysfunction in quadriceps on the contralateral side in patients with ruptured ACL. *Med Sci Sports Exerc.* 2003;35(6):897-900.
15. Konishi Y, Aihara Y, Sakai M, Ogawa G, Fukubayashi T. Gamma loop dysfunction in the quadriceps femoris of patients who underwent anterior cruciate ligament reconstruction remains bilaterally. *Scand J Med Sci Sports.* 2007;17(4):393-399.
16. Konishi Y, Fukubayashi T, Takeshita D. Mechanism of quadriceps femoris muscle weakness in patients with anterior cruciate ligament reconstruction. *Scand J Med Sci Sports.* 2002;12(6):371-375.
17. Blouin JS, Walsh LD, Nickolls P, Gandevia SC. High-frequency submaximal stimulation over muscle evokes centrally generated forces in human upper limb skeletal muscles. *J Appl Physiol (1985).* 2009;106(2):370-377.
18. Dean JC, Yates LM, Collins DF. Turning on the central contribution to contractions evoked by neuromuscular electrical stimulation. *J Appl Physiol (1985).* 2007;103(1):170-176.
19. Powers RK. "Extra" force evoked by percutaneous muscle stimulation: mechanisms and potential therapeutic applications. *J Appl Physiol (1985).* 2009;106(2):353-355.
20. Gregory CM, Bickel CS. Recruitment patterns in human skeletal muscle during electrical stimulation. *Phys Ther.* 2005;85(4):358-364.
21. Smith MJ, Hutchins RC, Hehenberger D. Transcutaneous neural stimulation use in postoperative knee rehabilitation. *Am J Sports Med.* 1983;11(2):75-82.
22. Arvidsson I, Arvidsson H, Eriksson E, Jansson E. Prevention of quadriceps wasting after immobilization: an evaluation of the effect of electrical stimulation. *Orthopedics.* 1986;9(11):1519-1528.
23. Eriksson E, Häggmark T. Comparison of isometric muscle training and electrical stimulation supplementing isometric muscle training in the recovery after major knee ligament surgery. A preliminary report. *Am J Sports Med.* 1979;7(3):169-171.
24. Anderson AF, Lipscomb AB. Analysis of rehabilitation techniques after anterior cruciate reconstruction. *Am J Sports Med.* 1989;17(2):154-160.
25. Currier DP, Mann R. Muscular strength development by electrical stimulation in healthy individuals. *Phys Ther.* 1983;63(6):915-921.
26. Halback J, Straus D. Comparison of Electro-Myo Stimulation to Isokinetic Training in Increasing -Power of the Knee Extensor Mechanism *. *J Orthop Sports Phys Ther.* 1980;2(1):20-24.
27. Nobbs LA, Rhodes EC. The Effect of Electrical Stimulation and Isokinetic Exercise on Muscular Power of the Quadriceps Femoris. *J Orthop Sports Phys Ther.* 1986;8(5):260-268.
28. Currier D, Mann R. Pain complaint: comparison of electrical stimulation with conventional isometric exercise. *J Orthop Sports Phys Ther.* 1984;5(6):318-323.
29. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* 2011;39(3):538-543.
30. Ardern CL, Taylor NF, Feller JA, Webster KE. Fear of re-injury in people who have returned to sport following anterior cruciate ligament reconstruction surgery. *J Sci Med Sport.* 2012;15(6):488-495.
31. Flanigan DC, Everhart JS, Pedroza A, Smith T, Kaeding CC. Fear of reinjury (kinesiophobia) and persistent knee symptoms are common factors for lack of return to sport after anterior cruciate ligament reconstruction. *Arthroscopy.* 2013;29(8):1322-1329.
32. Halkjaer-Kristensen J, Ingemann-Hansen T. Wasting of the human quadriceps muscle after knee ligament injuries. *Scand J Rehabil Med Suppl.* 1985;13:5-55.
33. Selkowitz DM. High frequency electrical stimulation in muscle strengthening. A review and discussion. *Am J Sports Med.* 1989;17(1):103-111.