Electric Muscle Stimulation of the Quadriceps in the Treatment of Patellofemoral Pain

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Objective: To compare a commercially available electric muscle stimulation regimen with a novel form of stimulation for the rehabilitation of the quadriceps muscle, in patients with patellofemoral pain syndrome.

Design: Double-blinded randomized trial with a parallel control group and stratified randomization.

Setting: Home-based rehabilitation program assessed in research center.

Participants: Eighty patients (47 women, 33 men) with patellofemoral pain syndrome.

Interventions: One group (EMPI) received 1 uniform constant frequency component of 35Hz. The other (EXPER) group received an experimental form of stimulation that contained 5 simultaneously delivered frequency components of 125, 83, 50, 2.5, and 2Hz. Stimulation was applied to the quadriceps muscles of the affected leg for 1 hour daily for 6 weeks, a total of 42 treatments.

Main Outcome Measures: Lower-limb isometric and isokinetic torque, quadriceps fatigue, knee flexion, patellar pain, a step test, quadriceps cross-sectional area, and Kujala patellofemoral score for pain before and after treatment.

Results: Seventy-four patients (43 women, 31 men) completed the trial. Patients in both groups showed significant improvements in all outcomes ($P<.05$). No significant differences existed between the 2 stimulators in any outcome ($P>.05$) except for quadriceps cross-sectional area ($P=.023$).

Conclusions: One form of stimulation was just as efficacious as the other in improving subjective and objective measures.

Key Words: Electric stimulation; Knee; Pain; Rehabilitation.

PATELLOFEMORAL PAIN SYNDROME (PFPS) refers to the clinical presentation of anterior knee pain related to changes in the patellofemoral joint.[1] It has been described as the "black hole of orthopedics,"[2] presenting a difficult problem for surgeons, therapists, and patients alike. Of the several cited theories for PFPS, dysfunction of the extensor mechanism is commonly accepted. Attempts have been made to correct extensor dysfunctions such as quadriceps weakness by various methods of exercising. Unfortunately, exercise, which is a crucial component of conservative treatment,[3,4] often increases patellar irritation, with a subsequent worsening of patellofemoral pain.[5]

Electric muscle stimulation (EMS) is an artificial means of activating muscle that bypasses the processes associated with a voluntary contraction.[6] EMS has been used for quadriceps rehabilitation in some knee conditions either as part of a rehabilitation prescription[7-10] or occasionally as part of a research trial,[11] but there has been no randomized controlled evidence of its efficacy in PFPS. EMS has several advantages over commonly used voluntary regimens. First, treatment can be standardized and the pattern of stimulation delivered to the muscle can be precisely controlled independently of the patient.[12] Second, thanks to integral electronic data collection, progress and compliance can be monitored. Third, the new generation of portable electric stimulators permits home treatment, thus reducing costs to outpatient physiotherapy and the patient.

For a muscle such as the quadriceps to operate to optimum efficiency it must have both strength and endurance characteristics. Existing EMS is designed to produce a continuous uniform pulse train of either low- or high-frequency stimulation. This pattern is problematic, because low-frequency stimulation (characteristically between 1–10Hz) is used to increase fatigue characteristics of a muscle, but at the expense of power generation.[13] On the other hand, if stimulation is used to increase power, this benefit is gained at the expense of endurance capability.[14] Many existing EMS devices use frequencies between 30 and 50Hz, giving little choice of frequency selection to the clinician and patient. A combination of these 2 elements in a simultaneous stimulation regimen may be advantageous. Also, it has been known for some time that adding a burst of high-frequency stimulation with very short interpulse intervals at the beginning of a pulse train (the "doublet") can significantly increase the muscle's tension output.[15,16] This stimulation pattern provides a more physiologic approach because it mimics motor nerve firing patterns that usually address all factors simultaneously.

The object of the present study was to evaluate a new form of EMS that incorporated a simultaneously delivered, mixed-frequency pulse train compared with a commercially available, uniform-frequency EMS device. Our aim was to discover the relative efficacy of both devices on the quadriceps muscles of a general patient group with PFPS.

METHODS

Both devices were portable, designed for home use. The experimental form of EMS (EXPER) was a 2-channel preprogrammed stimulator[a] that produced a balanced, asymmetric biphasic pulse (maximum amplitude, 90mA; duty cycle, 10:50 delivering 90 impulses/min; pulse duration, 200μs)[17] incorporating simultaneously delivered frequency components of 83, 50, 2.5, and 2Hz with a doublet of pulses (125Hz) at the

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beginning of each pulse train.[13] The pulse train was repeated once every minute and consisted of the following interpulse intervals: 8, 12, 20, 20, 20, 400, and 500ms. Daily stimulation lasted for 60 minutes in total. Two self-adhesive electrodes (10×17cm; total area, $340cm^2$)[b] were used over the quadriceps muscle group, 1 placed on the upper lateral thigh and the other on the lower medial thigh.

The EMPI device is commercially available.[c] The treatment protocol for PFPS consisted of daily stimulation periods lasting 60 minutes with a fixed frequency of 35Hz. It used an asymmetric biphasic rectangular waveform (maximum amplitude, 100mA; duty cycle, 10:50 delivering 350 impulses/min; pulse duration, 300μs). Four self-adhesive electrodes were placed over the quadriceps muscle group in accordance with the manufacturer's instructions[c] (5×9cm; total area, $180cm^2$). To preserve the blinding for the study, both devices were fully explained to and demonstrated on the patients by an independent investigator. Patients were given diagrams of electrode placements and compliance diaries in which they were to record each day if stimulation took place. Stimulation intensity for both devices was the highest comfortably tolerable for all the patients. Patients were instructed to maintain knee extension and not to walk or do other activities during stimulation, to ensure equality of muscle length during stimulation and to minimize any differential effect of stretch on the results obtained.[18] A CONSORT diagram showing enrollment and progress of patients through the study is in figure 1.

Sample Power Calculations

Sample size estimations were performed from a previous study by using EMS on the same knee condition[19] taking isokinetic strength as the main outcome. Putting the power of the study at 85% with an α value of .05, each group required 40 subjects.

Participants

Inclusion criteria. Patients were referred from orthopedic and rheumatology clinics if they had atraumatic peripatellar pain for greater than 6 months and not longer than 10 years. Patellofemoral pain was provoked by 1 of the following actions alone or in combination: prolonged sitting, deep squatting, kneeling, and ascending or descending stairs. Patients were also included if they had a normal radiograph, normal magnetic resonance imaging scan, or normal arthroscopy, if performed.

Exclusion criteria Patients were excluded from the study if they had epilepsy, cancer, a cardiac pacemaker, a suspected heart problem, or if they had recent surgery (not including arthroscopy). To exclude abnormal foot and ankle pronation as the cause of patellofemoral pain, patients were screened by using kinetic gait analysis[d] to detect abnormal values of mediolateral force as previously described.[20] Patients had further clinical examination to assess their suitability and to determine the presence of other lower-extremity dysfunction that may account for the knee symptoms.[21]

Randomization

To ensure broadly comparable groups with regard to baseline variables of gender and body mass index (BMI), patients were stratified into 1 of 4 groups (men: BMI $\leq26kg/m^2$ and $>26kg/m^2$; women: BMI $\leq26kg/m^2$ and $>26kg/m^2$), on entry into the trial. Randomization was performed by consulting 4 computer-generated randomization lists, 1 for each of the 4 stratified groups. Patients were randomized into the 2 treatment groups after they had given informed consent and had formally entered the study. The randomization list provided a trial number on which was based the corresponding treatment group (EXPER, EMPI). The lead investigator who examined and measured the patients was not part of the randomization process, thus ensuring blindness to the stimulator allocation.

Outcome Measures

The need for an assessment session that fully replicates the assessment that is proper to cancel out training effects has been previously reported.[22] Thus, assessments were performed twice before treatment (the first set of data being discarded) and once after completing the study 6 weeks later and not more than 1 week after treatment cessation. The study was approved by the ethics committee of the local National Health Service Trust.

Muscle Strength

Isometric and isokinetic concentric extension torque of the lower limb was measured by using the Biodex system 2 isokinetic dynamometer[e] with a multijoint attachment as supplied by the manufacturer. Multijoint effort has been advocated for patients with PFPS because it lowers the patellofemoral joint reaction force and patellofemoral stress.[23]

Isokinetic torque. Subjects were placed on a chair with hip flexion set at 90° and shoulder and waist straps applied. The foot was placed flat against the footplate attachment and was held in place by Velcro straps. With the knee at full extension, the knee joint axis was aligned with the axis of the power head. Limits were then set at 0° and 90° of flexion. The angular velocity was set at 90°/s. Each subject had 6 submaximal repetitions as a warm-up, and verbal instruction during data collection was strictly standardized. The concentric peak extension torque was recorded.

Isometric torque. Subjects were positioned as for the isokinetic tests but with the knee angle fixed at 45° of flexion. Twitch interpolation was used to overcome central fatigue and to ensure a maximum voluntary isometric contraction.[24] Subjects performed 3 maximum contractions of 10 seconds in duration with 2-minute rests between each. The peak extension torque was recorded.

Muscle Fatigue

Fatigue indices of the vastus medialis oblique, vastus lateralis, and rectus femoris were assessed by using bipolar electrode surface electromyography. By using a TEL100D receiver module and a MP100 acquisition unit,[f] electromyographic signals were high-pass (8Hz) and low-pass (500Hz) filtered (Butterworth filter), with a sharp notch filter of 50Hz to remove direct current noise. The amplifier was set with a gain of 10, a minimum common mode rejection ratio of 110dB, and a minimum signal-to-noise ratio of 65dB. There was a differential input impedance of $2M\Omega$. The signal was analog-to-digital converted at a sampling rate of 1024Hz. The electromyographic signal was subjected to fast Fourier transform to extract the median frequency calculated at 1-second intervals during a sustained 60-second contraction at 60% maximal voluntary isometric contraction. Median frequency was normalized against initial median frequency, and a linear regression was constructed over the contraction time of 60 seconds from which a slope was derived to express the fatigue rate.[25,26]

Quadriceps Cross-Sectional Area

Cross-sectional area (CSA) was assessed prestimulation and immediately poststimulation. We used a static B compound ultrasound scanner[g] with 5- and 2.25-MHz transducers. Scans were taken at the thigh midpoint between the lateral joint line of the knee and the greater trochanter. This location was

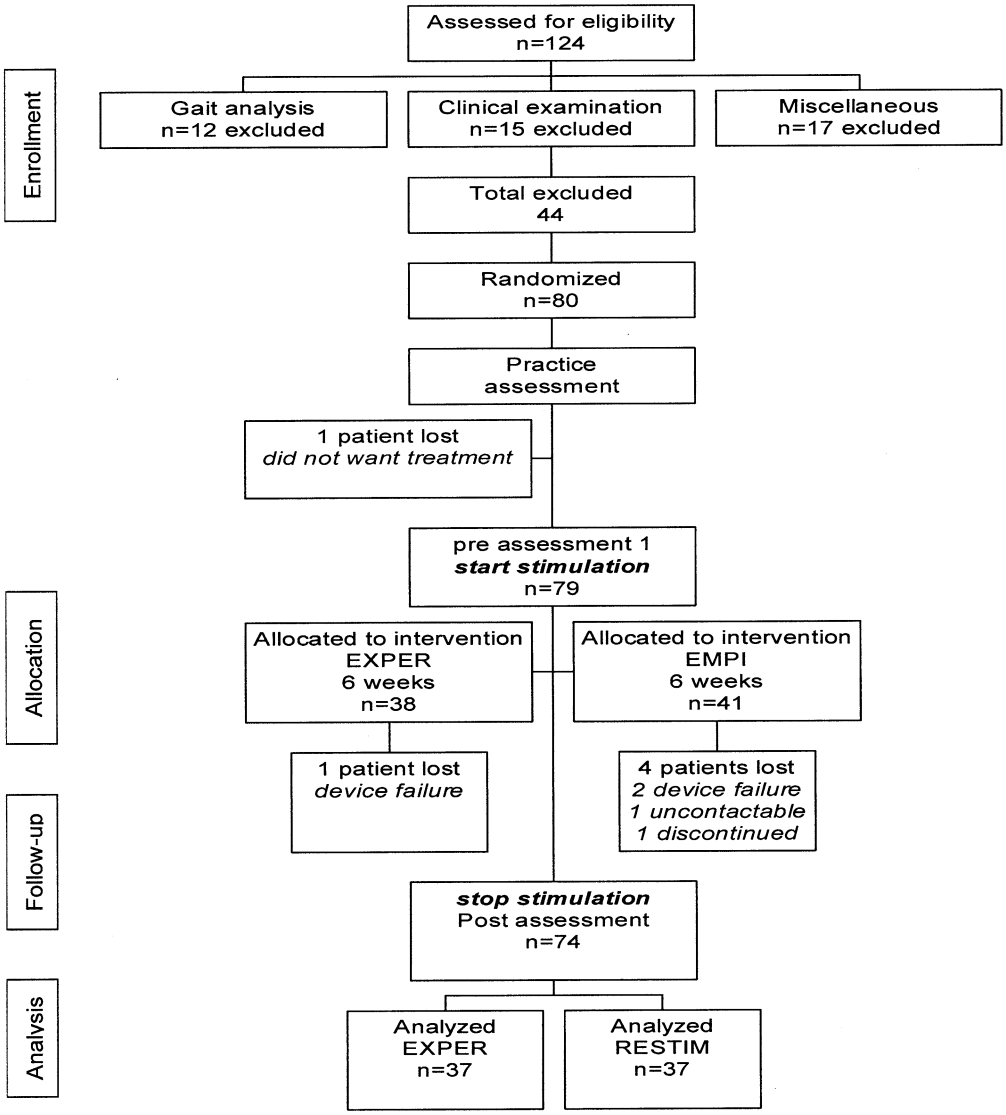

Fig 1. Patients' progress through the study.

marked on an acetate sheet to ensure exact reproduction of the position for the posttreatment scan. A hard copy of each scan was obtained and the area of the quadriceps calculated by using the Digiteye software.[h]

Function

We assessed knee function by means of the Kujala patellofemoral score (KPS). The KPS is a self-reported questionnaire scoring system with values ranging from 100 (a normal, painless, fully functioning knee) to 0 at the other extreme of the scale (severe knee pain and dysfunction). It is valid and reliable in the measurement of function in PFPS.[27]

Pain

Patellar pain on the day of assessment was assessed with a visual analog scale[28] (VAS) comprising a 10-cm line with 0 representing no pain and 10 representing worst pain ever.

Clinical Tests

Commonly used clinical tests also were done to ascertain if improvement or deterioration in the physiologic and pain tests of lower-limb function were also apparent in the simpler, yet functionally important, movements.

Step test. We assessed this by counting the number of steps up and down that the patient could perform by using a 25-cm step until the onset of patellar pain.

Knee flexion. We assessed the amount of knee flexion patients could achieve in squatting until the onset of their patellar pain. This was measured in the standard way by using a universal goniometer, aligned with the greater trochanter, through the lateral joint line to the lateral malleolus.

Statistical Analysis

Statistical analyses were performed by using SPSS, version 9,[i] for Windows. A value of P less than .05 was considered statistically significant for all analyses for a 2-tailed test. The data were tested for normal distribution by using a Kolmogorov-Smirnov test and were found to be normally distributed ($P>.05$) for all parameters except pain ($P=.001$) and steps ($P=.02$). Therefore, all data were analyzed by using parametric statistics except these 2 measures, which were analyzed with nonparametric equivalents.

Table 1: Descriptive Statistics of Patients Completed

Group	n (women/men)	BMI (kg/m^2)	Age (y)	Duration of Symptoms (wk)
EXPER	37 (21/16)	25.7±5.7	36.5±13.6	122±61
EMPI	37 (22/15)	25.9±5.9	33.2±9.4	103±62
Total	74 (43/31)	25.8±5.7	35±11.4	112±62

NOTE. Values are mean ±1 standard deviation (SD).

Between-group comparisons were made before treatment by using independent *t* tests for all outcome measures but Mann-Whitney *U* tests for pain and steps outcomes. The posttreatment differences between the groups were analyzed using independent *t* tests for normally distributed data or Mann-Whitney *U* tests for nonnormally distributed data. Pre- and posttreatment analyses were also performed within each group by using paired *t* tests or Wilcoxon signed-rank tests for parametric and nonparametric data, respectively.

RESULTS

Of the 80 patients who were recruited and consented to enter the trial, 6 were withdrawn. Two of these patients were withdrawn because of device failure. Three did not continue with the stimulation regimen and did not wish to have a posttreatment assessment. One patient never attended the posttreatment assessment and remained uncontactable. This left a remaining study group for posttreatment analysis of 74 patients. Table 1 provides descriptive statistics of the patients. There were no significant pretreatment differences between the groups (P=.193). Sixty-nine patients completed and returned a compliance diary. The diaries revealed that the mean number of treatments ± standard deviation (SD) were 35±6.5 for the EXPER group and 35±6.5 for the EMPI group. The between-groups difference was not statistically significant (P=.915).

Isometric and Isokinetic Torque

There were no significant differences between the groups for isometric strength (t=1.870, P=.066) or isokinetic strength (t=−1.119, P=.267). There were significant within-group improvements for isometric strength (EXPER=9.7%, P=.0001) and for isokinetic strength (EMPI=7.8%, P=.008) (tables 2, 3).

Quadriceps Fatigue

We combined the slopes for vastus medialis oblique, vastus lateralis, and rectus femoris to produce an overall quadriceps fatigue rate. No significant differences existed between the groups (t=−.355, P=.724) or within the groups for quadriceps fatigue rates (P>.05) (tables 2, 3).

Pain

A Mann-Whitney *U* test showed no significant differences between the groups for posttreatment pain levels (z=−1.153, P=.249). A Wilcoxon signed-rank test for within-groups analyses revealed significant pre- and posttreatment VAS improvements of −1 for the EXPER (33%, P=.004) and −1 for the EMPI (33%, P=.047) groups (see tables 2, 4).

Clinical Tests

Steps. The number of steps up and steps down were added to give a cumulative posttreatment steps score. A Mann-Whitney *U* test showed no significant differences between the groups for posttreatment values (z=−.493, P=.562). A Wilcoxon signed-rank test revealed significant within-group differences for the EXPER (6 steps, 68.7% improvement; P=.0001) and for the EMPI (8 steps, 112% improvement; P=.0001) groups (see tables 2, 4).

Knee flexion. No significant differences in knee flexion existed between the groups (t=.449, P=.654). Within-group analysis showed significant improvement for the EXPER group, 15° (15%, P=.003), and for the EMPI group, 12° (12.9%, P=.0001) (see tables 2, 3).

KPS for pain. There were no significant differences between the groups for posttreatment KPSs (t=−.772, P=.443). Within-group analysis revealed significant improvements between pre- and posttreatment values for the EXPER (7.8%, P=.007) and for the EMPI (11.1%, P=.0001) groups (see tables 2, 3).

Table 2: Pre- and Poststimulation Data

Variable	Prestimulation	Poststimulation	Mean % Change Pre-Post (95% CI)	*P* Value
EXPER				
Isometric strength (Nm)	107.6±30.8	118.1±37.4	9.7% (4.56–15.23)	.0001*†
Isokinetic strength (Nm)	104.2±35.3	108.1±36.8	3.7% (−0.70 to 11.6)	.191†
Pain (points)	3 (2–5)	2 (0–4)	−33% (−55.2 to 9.64)	.004*‡
Steps (n)	16 (9–24)	27 (16–46)	68.7% (12.96–326.4)	.0001*‡
Flexion (deg)	104±27	119±29	15% (8.35–32.35)	.003*†
KPS (points)	72±12.9	78±14.6	7.8% (2.30–16.24)	.007*†
CSA (cm^2)	17.11±4.24	17.69±4.29	3.3% (0.51–7.45)	.021*†
Quads total (%/s)	−0.071±0.07	−0.081±0.09	−14.1 (1.04–199.88)	.352
EMPI				
Isometric strength (Nm)	117.8±43.5	120.9±39.9	2.8% (0.75–9.97)	.291†
Isokinetic strength (Nm)	110.5±44	119.1±47.7	7.8% (2.44–14.43)	.008*†
Pain (points)	3 (1–4)	2 (1–4)	−33% (−46.97 to −4.12)	.047*‡
Steps (n)	13 (7–60)	28 (11–60)	112% (44.98–162.7)	.0001*‡
Flexion (deg)	97±30	109±29	12.9% (7.97–26.31)	.0001*†
KPS (points)	69.3±14.5	77.1±15	11.1% (6.69–18.55)	.001*†
CSA (cm^2)	18.70±4.51	18.52±4.61	−0.97% (−3.12 to 1.46)	.422†
Quads total (%/s)	−0.072±−0.08	−0.075±0.08	−8.5 (−183.41 to 527.49)	.874

NOTE. Values are mean ±1 SD, medians (interquartile range), or mean percentage changes and 95% confidence interval (CI).
*Statistically significant (P<.05); †paired *t* test; ‡Wilcoxon signed-rank test.

Table 3: Between-Group Analysis for Posttreatment Values

Variable	*t* Value	*P* Value
Isometric strength	1.870	.066
Isokinetic strength	−1.119	.267
Quadriceps fatigue	−0.355	.724
Flexion	0.449	.654
KPS	−0.772	.443
Quadriceps CSA	−2.329	.023*

NOTE. Independent *t* tests for normally distributed data.
*Statistically significant.

Quadriceps CSA

Because of problems of appointment availability, not all patients had ultrasound scans performed on the poststimulation assessment. Therefore, scans were performed on 33 patients in each group. A significant difference existed between the groups in the posttreatment CSA ($t=-2.329$, $P=.023$). A paired *t* test revealed significant improvements between pre- and posttreatment values of .58cm^2 (3.3%) for the EXPER group ($P=.021$), but a decrease of −.18cm^2 for the EMPI group (.97%, $P=.422$) (see tables 2, 3). This could imply that the EXPER intervention had a clinically worthwhile effect on muscle size. However, caution should be exercised when interpreting this result, because the value of .58cm^2 is smaller than the measurement error of 3.4% (.80cm^2).[29]

DISCUSSION

Even though patients in both groups improved in almost every outcome measure, this study found no differences between the 2 groups except for quadriceps CSA, which could not be deemed clinically significant.

Strength

Comparing the absolute torque values with previous studies is difficult, because few studies have observed the effect of EMS on muscle strength in patients with PFPS. Williams,[30] Johnson et al,[31] and Horodyski and Sharp[32] all failed to provide raw data or adequate statistical analysis to elucidate the observed substantial strength improvements after using EMS.

A more robust study by Werner et al[11] found modest single joint improvements of 5.9% at 60°/s and 6.1% at 180°/s after 40-Hz EMS on PFPS patients that are similar to those in this study of multijoints at 90°/s.

An improvement in isometric strength for the EXPER group was not complemented by an isokinetic improvement, and the converse was true for the EMPI group. This finding may be explained by the difference in dynamics between the isometric and isokinetic tests. Isometric testing used a twitch interpolation technique,[24] which was used to overcome central fatigue in isometric testing but was not feasible with isokinetic testing. Therefore, the isometric tests may have registered an extension torque that was nearer to a true maximal value. Second, the EXPER intervention was designed with a doublet at the beginning of each pulse train that could augment peak force and average force (force/time integral) production,[33,34] while helping to reduce the number of impulses in the stimulation pattern required to produce this force. It has recently been found that the doublet augments force in a muscle by using the first impulse to take up the slack and stiffen the muscle before delivering the second impulse.[35] Therefore, assessing the leg with a dynamic contraction such as isokinetic extension may not have reflected the physiologic improvement from the doublet as much as isometric assessment at a fixed knee flexion angle. Indeed, it is now known that a decrease in force augmentation is associated with delivering doublets with dynamic as opposed to isometric contractions.[36] Therefore, the isometric measure in the present study may have been a truer reflection of muscle strength improvement than the isokinetic measure.

Fatigue

It is difficult to discuss the muscle fatigue results in the context of previous quadriceps studies, because no other previous studies have assessed this aspect after treating PFPS with EMS. All other published studies assessing EMS on PFPS have used uniform frequencies of 35Hz or higher[11,30-32] and so may not have considered this aspect of muscle performance. In theory, the low-frequency background component of an EMS mixed-frequency pattern like the EXPER intervention should have been able to preserve and indeed improve the fatigue characteristics of the muscle, thus counterbalancing the other high-frequency components. In the present study this improvement did not occur, because there was a lack of significant pre- and posttreatment differences in the fatigue slopes between the groups. Karba et al[12] had a similar result from their experiments on the human vastus lateralis muscle. Their observed 15% increase in contraction speed but with unchanged fatigue rates indicated, in their opinion, that the vastus lateralis was undergoing transformation to type IIa muscle (fast-fatigue resistant) rather than wholly to type I or type IIb. One may also argue that surface electromyography, although advocated for this use, may not be sensitive enough to detect changes in the fatigue characteristics of muscle.

Pain

The statistically significant within-group improvements for the EXPER and EMPI groups appear impressive (see table 2), yet no statistically significant differences existed between the groups (tables 3, 4). A common explanation for pain relief in PFPS is that an improvement in quadriceps strength provides patellar stability: normal patellar tracking resumes during knee extension and flexion and pain is consequently reduced.[23] The correction to normal function and movement puts less stress on the pain-sensitive patellar retinaculum and other peripatellar tissues, with a resulting improvement in knee stability.[37] Nevertheless, Morrissey's review[38] implied that EMS could bring about pain relief *either* from a correction of quadriceps muscle imbalance *or* by blocking pain signals because EMS offers an alternative sensory stimulus via the pain gate theory. In effect, EMS acts as a transcutaneous electric nerve stimulation (TENS) or an interferential current. However, some[39,40] have suggested that TENS and interferential therapy only have an analgesic effect when the patients receive the stimulation and this effect rapidly dissipates when the treatment session stops. Because all patients in the present study were assessed at least several hours after completing the treatment program, it seems more likely that the pain improvement was because of a carryover effect from the EMS rather than a TENS effect.

Table 4: Between-Group Analysis for Posttreatment Values

Variable	*z* Value	*P* Value
Pain	−1.153	.249
Steps	−0.493	.562

NOTE. Mann-Whitney *U* tests for nonnormally distributed data.

Clinical Tests

Clinical tests were included to assess the effect of EMS on knee function. McConnell[41] stated that these tests form part of a dynamic evaluation of muscle action, symptomology, and treatment effectiveness and advocated them for patellofemoral joint evaluation. Similar tests have been used in recent studies of PFPS by Witvrouw et al[42] who noted that 2 different non-EMS exercise regimes improved knee flexion and the number of steps a person could perform before pain occurred.

Steps. The highly significant improvements we found for the EXPER and EMPI groups could be explained by corresponding improvements in strength and pain, because both these factors would help the step up and down activity considerably. Evidence pointed to the latter, because a correlation existed between posttreatment steps and decreased pain ($r=.373$, $P=.001$), but no association occurred with increased strength. It is difficult to explain why a 68% improvement for EXPER in the step test was accompanied by only a 10% increase in strength. Witvrouw[42] also noted a functional improvement far in excess of strength increase and could offer little explanation.

Knee flexion. The weight-bearing knee flexion assessment used in the present study is a more functional and relevant test than non–weight-bearing tests for patients with PFPS.[21] The improvement in flexion could have been because of the patient feeling less discomfort on knee flexion or feeling stronger and using the knee better in functional everyday circumstances, resulting in greater range of motion and better stretch of the quadriceps and other knee tissues. There were correlations between pain score and flexion ($r=.426$, $P<.0001$) but not with strength ($r=.085$, $P=.471$), indicating that (as with the increase in steps) the increase in flexion is likely to be explained by a decreased pain rather than increased strength.

KPS for pain. The concomitant improvements in muscle strength, pain, steps, knee flexion, and KPS for both groups were not surprising, because the KPS has been used in previous studies of PFPS as a representation of "functionality."[43] Indeed, the improvements between pre- and posttreatment KPS were significantly associated with improvements in isokinetic and isometric strength, steps, flexion, and pain. Witvrouw[42] recorded similar between- and within-group KPSs when comparing single joint and multijoint exercise regimes.

Cross-Sectional Area

The only statistically significant result between the groups may be interpreted as the EXPER treatment having an effect on muscle size that was clinically worthwhile. However, the mean .58cm^2 increase in quadriceps size is smaller than the measurement error value of .80cm^2.[29] Therefore, the results may simply be caused by limitations in the measurement technique.

A limitation of the present study was the lack of a placebo-control group. The explanation is 2-fold. First, patients were referred from the clinical settings of orthopedic clinics and general practice, and so there were ethical considerations when withholding treatment from a patient who was referred for treatment, albeit in a research environment. Second, because of the chronicity of the patients' condition (mean duration, 112wk), it was unlikely that any significant natural improvement would have occurred during the time scale of the study. This limitation has also been acknowledged in previous studies comparing 2 or more types of EMS (after anterior cruciate ligament repair)[44,45] or exercise programs on PFPS patients.[42,46] One alternative would have been to use the patient's contralateral limb as an internal control. However, other researchers in the field of EMS have advised against this method. It raises the possibility of EMS having a bilateral training effect, showing the phenomenon of cross transfer within the nervous system affecting both motoneuron pools.[47]

All other aspects of the trial were controlled as rigorously as possible by adopting the criterion standard, randomized controlled trial approach, ensuring that it was adequately powered and the outcome measures were valid, and reliable. Further, the heterogeneous nature of the patient sample supports the external validity of the trial results.

CONCLUSIONS

This study was the first to use a double-blinded, randomized, parallel control group design for the treatment of PFPS with EMS. Results showed that delivering EMS in a simultaneous mixed-frequency pattern or a uniform frequency pattern to the human quadriceps resulted in similar outcomes for patients with PFPS. Apparently, the effects of both types of stimulation are similar, being neither better nor worse than any other documented approach to this clinical problem. Finding a more effective, evidence-based approach to treatment remains a challenge to all health professionals involved in the management of patients with this condition.

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References

1. Tria AJ, Palumbo RC, Alicea JA. Comprehensive care for patellofemoral pain. Orthop Clin North Am 1992;23:545-53.
2. James SL. Chondromalacia of the patella in the adolescent. In: Kennedy JC, editor. The injured adolescent knee. Baltimore: Williams & Wilkins; 1979. p 205-51.
3. Kannus P, Niittymaki S. Which factors predict outcome in the nonoperative treatment of patellofemoral pain syndrome? A prospective follow-up study. Med Sci Sport Exerc 1993;26:289-96.
4. Kannus P, Natri A, Niittymaki S, Jarvinen M. Effect of intraarticular glycosaminglycan polysulfate treatment of patellofemoral pain syndrome. Arthritis Rheum 1992;35:1053-61.
5. Dye SF, Vaupel GL. The pathophysiology of patellofemoral pain. Sports Med Arthrosc Rev 1994;2:203-10.
6. Trimble MH, Enoka RM. Mechanisms underlying the training effects associated with neuromuscular electrical stimulation. Phys Ther 1991;71:273-82.
7. Williams JG, Street M. Sequential faradism in quadriceps rehabilitation. Physiotherapy 1976;62:252-4.
8. Devereaux MD, Lachmann S. Patellofemoral arthralgia in athletes attending a sports injury clinic. Br J Sports Med 1984;18:18-21.
9. Garrick JG. Anterior knee pain. Phys Sportsmed 1989;17:75-84.
10. Woodall W, Welsh J. A biomechanical basis for rehabilitation programs involving the patellofemoral joint. J Orthop Sports Phys Ther 1990;11:535-42.
11. Werner S, Arvidsson H, Arvidsson I, Eriksson E. Electrical stimulation of vastus medialis and stretching of lateral thigh muscles in patients with patello-femoral symptoms. Knee Surg Sports Traumatol Arthrosc 1993;1:85-92.
12. Karba R, Stefanovska A, Dordevic S. Human skeletal muscle: phasic type of electrical stimulation increases its contractile speed. Ann Biomed Eng 1990;18:479-90.
13. Kwende MM, Jarvis JC, Salmons S. The input output relations of skeletal muscle. Proc R Soc Lond B Biol Sci 1995;261:193-210.
14. Selkowitz DM. Improvement in isometric strength of the quadriceps femoris muscle after training with electrical stimulation. Phys Ther 1985;65:186-96.
15. Burke RE, Rudomin P, Zajac FE. Catch property in single mammalian motor units. Science 1970;168:122-4.

16. Burke RE, Rudomin P, Zajac FE. The effect of activation history in tension production by individual muscle units. Brain Res 1976; 109:515-29.
17. Rutherford OM, Jones DA. Contractile properties and fatigability of the human adductor pollicis and first dorsal interosseus: a comparison of the effects of two chronic stimulation patterns. J Neurol Sci 1988;85:319-31.
18. Goldspink DF, Goldspink G. The role of passive stretch in retarding muscle atrophy. In: Nix WA, Vrbová G, editors. Electrical stimulation and neuromuscular disorders. Berlin: Springer-Verlag; 1986. p 91-100.
19. Callaghan MJ, Oldham JA, Winstanley J. A comparison of two types of electrical stimulation of the quadriceps in the treatment of patellofemoral pain syndrome. A pilot study. Clin Rehabil 2001; 15:637-46.
20. Callaghan MJ, Baltzopoulos V. Gait analysis in patients with anterior knee pain. Clin Biomech 1994;9:79-84.
21. Wilk KE, Davies GJ, Mangine RE, Malone TR. Patellofemoral disorders: a classification system and clinical guidelines for non operative rehabilitation. J Orthop Sports Phys Ther 1998;28:307-22.
22. Callaghan MJ, McCarthy C, Al-Omar A, Oldham JA. The reproducibility of multi joint isokinetic and isometric assessments in a healthy and patient population. Clin Biomech (Bristol, Avon) 2000;15:678-83.
23. Steinkamp LA, Dillingham MF, Markel MD, Hill JA, Kaufman KR. Biomechanical considerations in patellofemoral joint rehabilitation. Am J Sports Med 1993;21:438-44.
24. Belanger AY, McComas AJ. Extent of motor unit activity during effort. J Appl Physiol 1981;51:1131-5.
25. Basmajian JV, De Luca CJ. Muscles alive: their function revealed by electromyography. 5th ed. Baltimore: Williams & Wilkins; 1987.
26. Roy SH, Emley M, Buijs RJ. Spectral electromyographic assessment of back muscles in patients with low back pain undergoing rehabilitation. Spine 1995;20:38-48.
27. Kujala UM, Jaakkola LH, Koskinen SK, Taimela S, Hurme M, Nelimarkka O. Scoring of patellofemoral problems. Arthroscopy 1993;9:159-63.
28. Scott J, Huskisson EC. Graphic representation of pain. Pain 1976; 2:175-84.
29. Callaghan MJ. Electrical stimulation of the quadriceps muscle group in patients with patellofemoral pain syndrome [PhD dissertation]. Manchester (UK): Univ Manchester; 2002.
30. Williams JG. Vastus medialis re-education in the management of chondromalacia patellae. Med Aspects Sport 1974;2:16-24.
31. Johnson DH, Thurston P, Ashcroft PJ. The Russian technique for faradism in the treatment of chondromalacia patellae. Physiother Can 1977;29:1-4.
32. Horodyski MB, Sharp RL. Effects of electrical stimulation on subjects with patellofemoral pain [abstract]. Med Sci Sport Exerc 1995;17:225.
33. Karu ZZ, Durfee WK, Barzilia AM. Reducing muscle fatigue in FES applications by stimulating with N-let pulse trains. IEEE Trans Biomed Eng 1995;42:809-17.
34. Bigland-Ritchie B, Zijdewind I, Thomas CK. Muscle fatigue induced by stimulation with and without doublets. Muscle Nerve 2000;23:1348-55.
35. Binder-Macleod SA, Scott WB. Comparison of fatigue produced by various electrical stimulation trains. Acta Physiol Scand 2001; 172:195-203.
36. Binder-Macleod SA, Lee SC. Catchlike property of human muscle during isovelocity movements. J Appl Physiol 1996;80:2051-9.
37. Grelsamer RP, McConnell J. The patella: a team approach. Gaithersburg: Aspen; 1998.
38. Morrissey MC. Electromyostimulation from a clinical perspective. A review. Sports Med 1988;6:29-41.
39. Holcomb WR. A practical guide to electrical therapy. J Sport Rehabil 1997;6:272-82.
40. Johnson MI. The mystique of interferential currents when used to manage pain. Physiotherapy 1999;85:294-97.
41. McConnell J. The management of chondromalacia patellae: a long term solution. Aust J Physiother 1986;32:215-23.
42. Witvrouw E, Lysens R, Bellemans J, Peers K, Vanderstraeten G. Open versus closed kinetic chain exercises for patellofemoral pain. Am J Sports Med 2000;28:687-94.
43. Timm KE. Randomized controlled trial of Protonics on patellar pain, position, and function. Med Sci Sport Exerc 1997;30:665-70.
44. Snyder-Mackler L, Delitto A, Stralka SW, Bailey SL. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. Phys Ther 1994;74:901-7.
45. 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. J Bone Joint Surg Am 1995;77:1166-73.
46. Thomeé R. A comprehensive treatment approach for patellofemoral pain syndrome in young women. Phys Ther 1997;77:1690-703.
47. Singer KP. The influence of unilateral electrical muscle stimulation on motor unit activity patterns in atrophic human quadriceps. Aust J Physiother 1986;32:31-7.

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