J Musculoskelet Neuronal Interact 2022; 22(4):474-485

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

NMES superimposed on movement is equally effective as heavy slow resistance training in patellar tendinopathy

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Abstract

Objective: This study aimed at investigating the effectiveness of an 8-week training protocol, based on neuromuscular electrical stimulation of the quadriceps, which was superimposed onto voluntary exercise (NMES+), in comparison to a traditional heavy slow resistance training (HSRT), in individuals with patellar tendinopathy. **Methods**: Thirty-two physically active participants, aged: 33.6±10.2 years, were divided into two groups: NMES+ or HSRT. Maximal voluntary isometric contraction (MVIC) of knee extensor and flexor muscles, power during a countermovement jump (CMJ), and VISA-p questionnaire scores were recorded at the start(T0), 2-weeks(T1), 4-weeks(T2), 6-weeks(T3), 8-weeks(T4) and 4-months post-training (T5). Knee pain and rate of perceived exertion (RPE) were recorded at each training session with a 0-10 scale. **Results**: Knee pain was significantly lower in NMES+ compared to HSRT during all training sessions. No significant between-group differences were found for VISA-p scores and forces recorded during MVICs at T0,T1,T2,T3,T4 and T5. A significant increase of VISA-p and peak forces during MVIC was recorded across-time in both groups. No significant between-group or across-time differences were found for RPE and CMJ parameters. **Conclusions**: NMES+ and HSRT were equally effective in decreasing tendinopathy symptoms and increasing strength, with NMES+ having the advantage to be a pain-free resistance training modality.

Keywords: Countermovement Jump, Knee Pain, Muscle Strength, Resistance Training, Tendon

Introduction

Patellar tendinopathy is defined as a persistent patellar tendon pain and loss of function due to mechanical loading[1]. Both excessive loading and lack of loading may cause the tendon to lose the ability to manage and adapt to loads. It has been suggested that there is a "mechanostat point" at which mechanical stimuli maintain tendon homeostasis and guarantee tendon adaptations[2]. Mechanical stimuli above or below this point may lead to a maladaptive response, which is featured by either an increase in inflammatory cytokines or degradation enzymes[2].

As a result of this evidence, resistance training appears to be essential for the prevention and treatment of tendinopathy, since it provides adequate tendon loading, whereas drugs, injections and instrumental physical therapies are not only ineffective, but may also damage the tendon cells[3]. In addition, it has been suggested that tendinopathy is linked to an altered cortico-spinal control of the muscle-tendon complex, resulting in a reduced ability of the central nervous system to recruit motor units[4].

In light of this, it is not surprising that strength training is currently the most effective treatment for tendinopathy, first and foremost heavy slow resistance training (HSRT)[5]. Slow movement execution prevents the tendon from being overloaded by fast stretch-shortening contractions, making it possible for the tendon to manage high loads effectively[3]. In addition, structured strength training sessions with well-defined durations of concentric and eccentric contraction can improve motor control and voluntary muscle activation[4,6].

The authors have no conflict of interest.

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Edited by: G. Lyritis
Accepted 4 August 2022

Table 1. Participant inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
- Diagnosis of patellar tendinopathy, which was confirmed by the presence of characteristic features on ultrasound imaging (e.g., hypoechoic area and/or tendon thickening)[21]; - Exercise-related pain; - Focal / non-radiating pain at inferior pole of the patella since at least six months; - VISA-P score <80 at baseline; - Aged between 18 and 50 years old; - Sport participation of at least three times a week.	- Other knee pathology, or acute knee or acute patellar tendon injuries; - Inflammatory disorder; - Diabetes and/or hypercholesterolemia; - Medical conditions in which heavy loads or electrical stimulation training were contraindicated; - Use of corticosteroid or other types of injections in the last 3 months; - Inability to attend the training program 3 times per week; - Sedentary behavior.

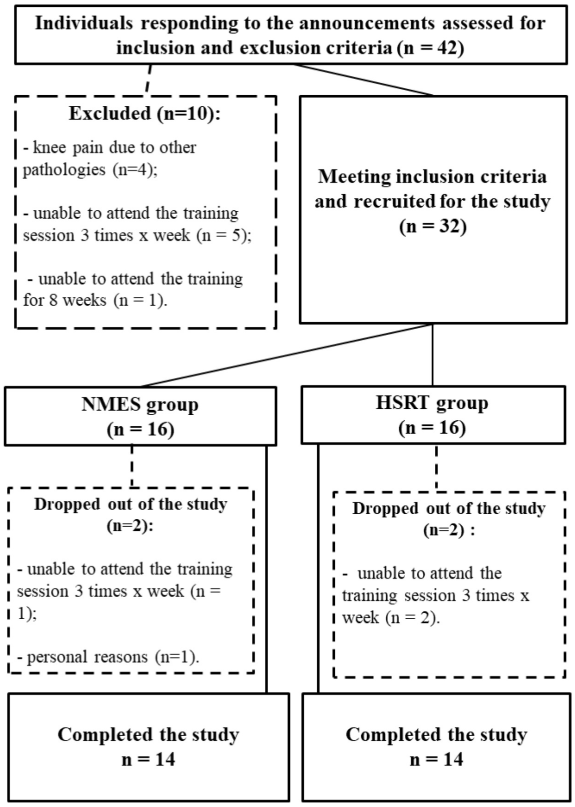

Figure 1. Flow-chart illustrating participants recruitment.

Last, but not least, the reduction of pain and increase in muscle strength that occurs in response to resistance training, which has been reported in a number of orthopaedic conditions[7-10], disrupts the vicious circle featured by joint pain leading to physical inactivity, which in turn leads to a further decrease of strength and thus an increase in pain[2].

There are, however, some individuals who are unable to handle heavy loads during training due to pain or lack of experience[9]. Neuromuscular electrical stimulation superimposed during the performance of functional voluntary movements (NMES+) is a training modality not requiring the use of external loads, and thus seems to be a valid training alternative to HSRT in individuals with patellar tendinopathy. NMES+ has been shown to be as effective in increasing muscle strength and improving functional performance[11-13] as traditional strength training[14]. Actually,

Table 2. NMES+ training parameters. Duration of the concentric and the eccentric phases of the sit-to-stand-to-sit, number of sets and repetitions at each session, frequency and intensity settings of the stimulation, and resting period between repetitions and between sets.

Week	Concentric phase	Eccentric phase	Sets x Reps	Pulse Frequency	Pulse Intensity	Intensity ramps up/down	Rest between reps/sets
1	2 seconds	6 seconds	4 x 10	30 Hz and 50 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
2	2 seconds	6 seconds	4 x 10	30 Hz and 50 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
3	2 seconds	6 seconds	4 x 10	40 Hz and 60 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
4	2 seconds	6 seconds	4 x 10	40 Hz and 60 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
5	2 seconds	6 seconds	4 x 10	50 Hz and 80 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
6	2 seconds	6 seconds	4 x 10	50 Hz and 80 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
7	2 seconds	6 seconds	4 x 10	60 Hz and 85 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds
8	2 seconds	6 seconds	4 x 10	60 Hz and 85 Hz alternate days	Maximum tolerated	0.5/0.5 seconds	8/120 seconds

during strength training based on NMES+ it is possible to gradually increase loading by means of very small increases in the current intensity, without using external loads. Further, there is evidence on the effectiveness of superimposed NMES in improving neural function at both central and peripheral level[15-17]. In addition, a reduction in pain has been reported following training interventions based on NMES+ in individuals with low back pain[11-14] and in individuals with anterior knee pain due to surgical damage to the patellar tendon[18].

Regarding tendon responses to loading and tendinopathy, it has been shown that symptomatic athletes with patellar tendinopathy show abnormalities in tendon thickness[19], but it seems that strength training programs do not lead to either an increase or a decrease in tendon thickness[20]. To the best of the authors knowledge, it is unknown how and if tendon adaptations to NMES+ training interventions occur.

Thus, the aim of this preliminary study was to compare the effects of NMES+ versus HSRT on muscle strength, knee pain, functional performance and tendon thickness in physically active individuals with patellar tendinopathy. It was hypothesized that the two training interventions would have similar effects on strength, pain, and tendon thickness.

Materials and methods

Participants

Participants of the study were recruited in sporting centres and physical therapy centres in Rome. Inclusion and exclusion criteria to participate in the study are reported in Table 1. Participants were divided into two groups according to a randomization accounting for gender and age. Fourteen participants (age: 31.4±11.6 years; body mass: 74.0±8.2 kg; height: 1.78±0.08 m), 3 females and 11 males, composed the NMES+ group. Fourteen participants (age: 33.6±10.2 years; body mass: 73.8±9.6 kg; height: 1.77±0.08 m), 3 females and 11 males, composed the heavy slow resistance training (HSRT) group. Six out of 14 participants in the NMES+ group and 5 of the 14 participants in the HSRT group had monolateral tendinopathy. Data of single limbs were used for the statistical analysis. Thus, a total of 22 limbs in the NMES+ group, and 23 in the HSRT group were analyzed. Participant recruitment is represented in Figure 1. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the University of Rome "La Sapienza" (prot. n. 311/19). All participants signed an informed consent form prior to participating in the study.

Training interventions

The NMES+ and HSRT training interventions lasted 8 weeks, and participants were asked to train 3 times a week under the supervision of a trainer who was not blinded on participants' allocation.

For the NMES+ group, training consisted of NMES treatment to the quadriceps muscle superimposed to a number of slowly performed sit-to-stand-to-sit movements. The NMES was delivered with two wireless portable battery-powered stimulators (Chattanooga Wireless Professional, bi-phasic rectangular pulse shape). Self-adhesive electrodes (Compex Dura-Stick Plus, 5x5 cm) were placed over the motor points of the vastus medialis, vastus lateralis and rectus femoris muscles. Frequencies of stimulation ranged from 30 to 85 Hz, while intensity was set as the maximum tolerated by each participant. A detailed description of the training parameters is reported in Table 2. The intensity of stimulation was increased at each repetition of each session in accordance with participants' tolerance. In most cases, it was necessary to set a higher current intensity in the vastus medialis than in the vastus lateralis and rectus femoris muscles in order to have a similar perception of current intensity for each of the three muscles. The frequencies of stimulation ranged between 30 and 85 Hz with the aim to provide an effective stimulus to optimize motor units' recruitment and thus strength gain. Frequencies higher than 85 Hz were excluded, since these frequencies would have required contractions of shorter duration and longer recovery phases in accordance with the electrical stimulator protocols of stimulation. The height of the seat was adjusted to create a 90° knee angle while sitting. However, it was adjusted during the training sessions to avoid pain at the knee joint. Participants were

Table 3. HSRT training parameters. Duration of the concentric and the eccentric phases of the leg-press exercise, number of sets at each session, intensity of the training in terms of RM, and resting period between sets.

Week	Concentric phase	Eccentric Phase	Sets	Intensity	Rest between sets
1	2 seconds	6 seconds	4	10 RM	120 seconds
2	2 seconds	6 seconds	4	10 RM	120 seconds
3	2 seconds	6 seconds	5	8 RM	120 seconds
4	2 seconds	6 seconds	5	8 RM	120 seconds
5	2 seconds	6 seconds	7	6 RM	120 seconds
6	2 seconds	6 seconds	7	6 RM	120 seconds
7	2 seconds	6 seconds	10	4 RM	120 seconds
8	2 seconds	6 seconds	10	4 RM	120 seconds

asked to quantify the knee pain on an 11-point numerical rating scale[22]. If the referred pain was equal or greater than 4, then the height of the seat was increased.

For the HSRT group, training consisted in slowly executing single leg-press exercises on a horizontal leg-press machine (Technogym, Forlì-Cesena, Italy). Training intensity ranged from a load corresponding to 10 RM to one corresponding to 4 RM. A detailed description of the training parameters is reported in Table 3. In order to identify the training load for the first session, participants in the HSRT group, following a warm-up made by one set of 10 repetitions with a load corresponding to 50% of body weight, and a second set made by 8 repetitions at 100% of body weight, were asked to give an estimate of the load corresponding to 10 RM. Then, they performed a third set of 6 repetitions at 75% of estimated 10 RM, and a fourth set of 4 repetitions at 90% of estimated 10 RM. Based on the outcome of the last set, a further set was performed to identify the 10 RM load. At each session, the load was increased by 2-10% in accordance with participants' individual improvements, and in accordance with the American College of Sports Medicine guidelines[23]. The load was increased by 20% when the training protocol required an increase of the intensity in terms of RM (i.e., from 10 RM to 8 RM, from 8 RM to 6 RM, and from 6 RM to 4 RM), and adjusted based on individuals' feedback to identify the load corresponding to the desired intensity. The position of the seat was adjusted to create a 90° knee angle while sitting. However, it was adjusted during the training sessions to avoid pain at the knee joint. Participants were asked to quantify the knee pain on an 11 points numerical rating scale[22]. If the pain referred was equal or greater than 4, then the knee angle was increased.

For both the exercises the concentric phase of movement lasted 2 seconds and the eccentric phase lasts 6 seconds. Emphasis was given to the eccentric phase in light of its importance in treating patellar tendinopathy[9] and inducing neural adaptations[24]. The two training programs were matched for time under tension and resting phases. Prior to each training session, both groups of participants performed 10 minutes of pedalling at light load on a cycle-ergometer as general warm-up, which was followed by a specific warm-up. In the NMES group the specific warm-up consisted in 5 minutes of NMES at low intensity without muscle contractions and a set of 10 sit-to-stand-to-sit with superimposed NMES at low intensity. In the HSRT group, the specific warm-up consisted in a set of 10 repetitions with 100% of body weight, a set of 6 repetitions at 75% of estimated 10 RM, and finally a set 4 repetitions at 90% of estimated 10 RM. At the end of both the NMES and HSRT sessions, 5 minutes of exercise at low-resistance were performed on a cycle-ergometer as cool-down phase.

All of the participants were, at baseline, involved in sport activities including volleyball, soccer, dance, judo and basketball. They were asked to avoid any strength training for lower limb muscles to rule out confounding factors. They were also asked to avoid anti-inflammatory and pain drugs during the intervention.

Assessments were performed at the start of training (T0), at two weeks (T1), at four weeks (T2), at six weeks (T3), at eight weeks, i.e., the end of the training (T4), and four months post-training (T5). Participants were asked to refrain from any kind of exercise training the day before the sessions of assessments (T0, T1, T2, T3, T4 and T5).

Assessments and data analysis

The assessors were blinded on participants allocation and data were anonymized before data analysis.

Knee extensor and flexor muscles strength

Maximal voluntary isometric contraction (MVIC) of the knee extensor muscles was assessed at 30° and 90°. MVIC of knee flexor muscles was assessed at 60° and 90°. The MVICs were performed on a leg-extension and a leg-curl machine (Technogym, Forli-Cesena, Italy), respectively, which were instrumented with a load cell connected to a computerized system (MuscleLab; Bosco-System Technologies, Rieti, Italy) as in previous studies[25,26]. Before testing, participants performed 10 minutes of warm-up on a cycle-ergometer and were allowed to familiarize with all the procedures. After the familiarization, the two lower limbs were tested separately. Three MVIC trials were performed for each angle and for each muscle group. If the third trial exceeded the previous trials, participants were asked to perform a fourth attempt. More in details, a fourth trial was performed if the difference between the best two trials was greater than the 5%, as in previous studies[27,28]. Peak forces exerted by each limb during all the assessments were recorded and normalized by body weight of each participant and used for further analysis. The hamstrings to quadriceps (H/Q) strength ratio was also calculated by dividing peak forces recorded for knee flexor muscles during the MVIC at 90° and peak forces recorded for knee extensor muscles during the MVIC at 90°.

Symptoms, function and ability to participate in sport

Symptoms, function and ability to participate in sport was assessed using the Italian version of the Victorian Institute Sports tendon Assessment for patellar tendon (VISA-p) questionnaire[29]. Total score of the questionnaire was calculated and used for further analysis.

Functional performance

Participants were asked to perform a maximal vertical countermovement jump (CMJ). Ground reaction forces were measured by means of two, six-component force platforms (KISTLER, model 9281B; Winterthur, Switzerland; 1000 Hz sampling frequency), which were positioned below each foot. Vertical components of the ground reaction force were analysed according to previous literature30-32 to identify the highest power value (Peak Power). Peak forces exerted during the eccentric (Ecc) and concentric (Con) phases were also calculated. Data of the CMJ were analysed and considered with the aim to assess whole body functional performance. Thus, data refers to the forces exerted by both lower limbs. All data were normalized by the body weight of each participant and used for further analysis.

Knee pain and rate of perceived exertion (RPE) during training

Participants were asked to verbally quantify pain at the knee joint and the RPE at the end of each series during all training sessions. Pain was quantified using a numerical rating scale (0-10), which was numerically graded at each unit, and additional explanatory information was reported as follows: 0, no pain; 2, light pain; 4, moderate pain; 6, high pain; 8, very high pain; and 10, the worst imaginable pain. RPE was quantified by means of a 1 to 10 Borg rating scale, in which 0 represented a resting condition and 10 represented the maximal effort. The weekly mean of the maximum scores recorded in each training session was calculated and used for further analysis.

Outcome satisfaction and post-intervention training

Satisfaction for the outcomes of training was recorded at T5 by asking participants to indicate a number on an eleven point (0-10) numerical rating scale, in which 0 was "absolutely not satisfied" and 10 was "extremely satisfied".

Tendon thickness

Tendon thickness was assessed at T0, T1, and T4. Ultrasound assessments were all performed by the same medical radiologist, who had more than 30 years of clinical imaging experience for musculoskeletal disorders and was blinded on the group allocation of the participants. A Philips iU22 ultrasound machine with a 17.5 MHz linear array transducer (Philips, Amsterdam, The Netherlands) was used on all the symptomatic patellar tendons. Proximal, mid and distal tendon thicknesses were measured. Subjects were examined in a supine position with the knees flexed at approximately 20°. Gray-scale examinations were performed using 2D with a depth of 18-20 mm, A0=100%, DR=70 and gain=68. Longitudinal and axial view of the tendon were obtained by means of a specific panoramic viewing system in the sagittal plane to obtain a single image of the entire patellar tendon. Anterior-posterior patellar tendon thickness was measured from the superficial to the deep peritenonium, 0.5 cm distal from the apex of the patella, 0.5 cm proximal from the tibial tuberosity, and in the centre of these two points. These measuring sites were chosen according to typical pathological findings as in previous studies[5,33]. The mean of the three thickness measurements for each site was calculated.

Sample size and statistical power

Sample size was a priori calculated with a significance level of 0.05 and a power of 95% on the basis of data of a preliminary pilot investigation on 6 patients who were randomly assigned to one of the two groups (NMES+ and HSRT). On the basis of the VISA-p scores which were 65.9 in NMES+ and 56.8 in HSRT and an effect size of 0.606, a minimum of 13 patients for each group were required for the study. Additional patients were recruited to allow for dropouts.

Statistical analysis

Descriptive statistics were used to summarize data. The Shapiro-Wilk test was used to test data distribution. Normally distributed data were analysed as follows. A mixed model ANOVA (within-factor: time; between-factor: group) was performed for MVIC, H/Q ratio, CMJ and tendon thickness. If the main effect F value was significant, the Bonferroni method was used to locate the significant differences. A one-way ANOVA was used to assess the between-group differences for outcome satisfaction data. Non-normally distributed data were analysed as follows. A Mann-Whitney test was used to assess between-group differences for VISA-p questionnaire data, training knee pain and RPE data, while a Kruskal-Wallis ANOVA was performed to assess the effect of time. A significance level of $p<0.05$ was adopted. All analyses were performed using SPSS version 23 (SPSS, Inc., Chicago, IL).

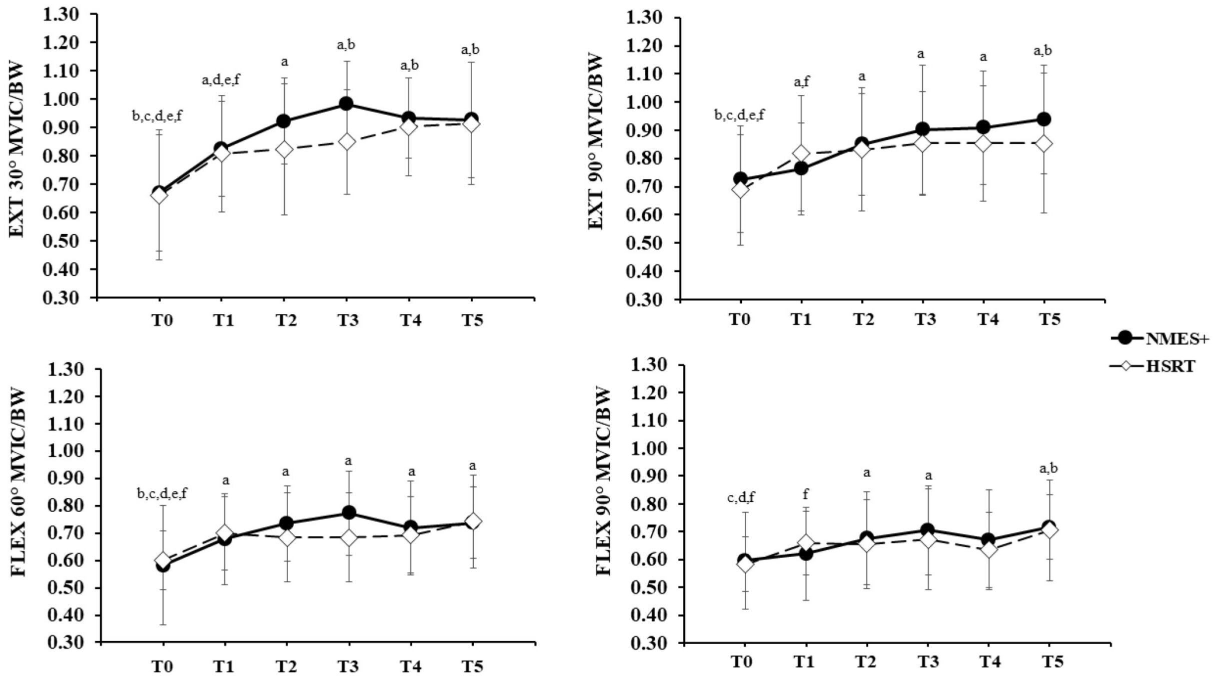

Figure 2. Peak forces recorded during MVIC normalized by body weight of each participant at T0, T1, T2, T3, T4 and T5 with significant grouped post hoc significances. EXT 30°=MVIC of knee extensors at 30° (up-left). EXT 90°=MVIC of knee extensors at 90° (up-right). FLEX 60°=MVIC of knee flexors at 60° (down-left). FLEX 90°=MVIC of knee flexors at 90° (down-right). Significant differences across time are reported as follows: a = significantly different from T0; b=significantly different from T1; c=significantly different from T2; d=significantly different from T3; e=significantly different from T4; f=significantly different from T5.

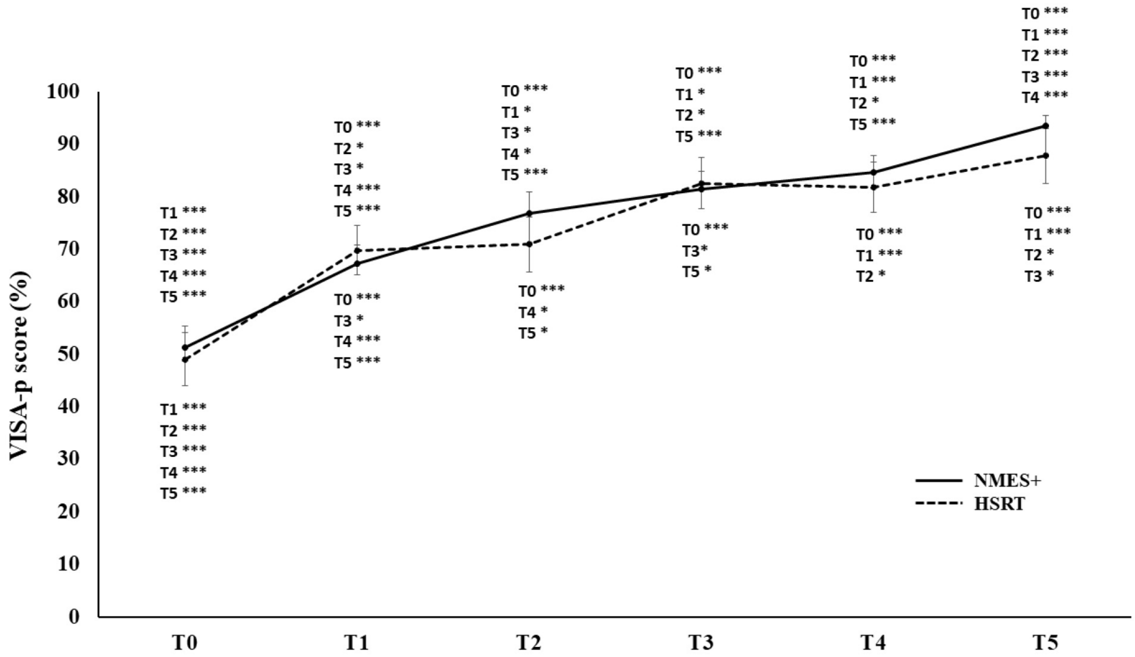

Figure 3. VISA-p questionnaire scores (means and st. error) recorded at T0, T1, T2, T3, T4 and T5. Above the lines are reported significant differences across time for the NMES+ group, while under the lines are reported significant differences across time for the HSRT group. For all the significant differences is reported also the level of significance: * p<0.05; ** p<0.01; *** p 0.001.

Table 4. Mean values and standard deviations of peak forces of the eccentric (peak ECC) and concentric (peak CON) phases of the countermovement jump (CMJ), and peak Power. Data of peak forces (N) and peak power (W) have been normalized by body weight of each participant (N).

	Countermovement Jump											
	T0				T2		T3		T4		T5	
	NMES	HSRT	NMES	HSRT	NMES	HSRT	NMES	HSRT	NMES	HSRT	NMES	HSRT
Peak ECC	1.69 ± 0.59	2.03 ± 0.46	1.82 ± 0.59	1.95 ± 0.51	1.76 ± 0.63	1.70 ± 0.59	2.23 ± 0.60	1.88 ± 0.59	2.00 ± 0.63	1.72 ± 0.69	1.97 ± 0.66	1.82 ± 0.65
Peak CON	2.32 ± 0.24	2.21 ± 0.25	2.20 ± 0.21	2.20 ± 0.20	2.24 ± 0.21	2.16 ± 0.25	2.40 ± 0.29	2.23 ± 0.26	2.33 ± 0.32	2.03 ± 0.67	2.30 ± 0.27	2.33 ± 0.34
Peak Power	4.47 ± 1.03	4.29 ± 0.95	4.45 ± 0.97	4.26 ± 0.98	4.24 ± 0.81	4.02 ± 0.79	4.62 ± 0.53	3.39 ± 1.73	4.19 ± 1.03	3.82 ± 1.35	4.48 ± 0.71	3.98 ± 0.62

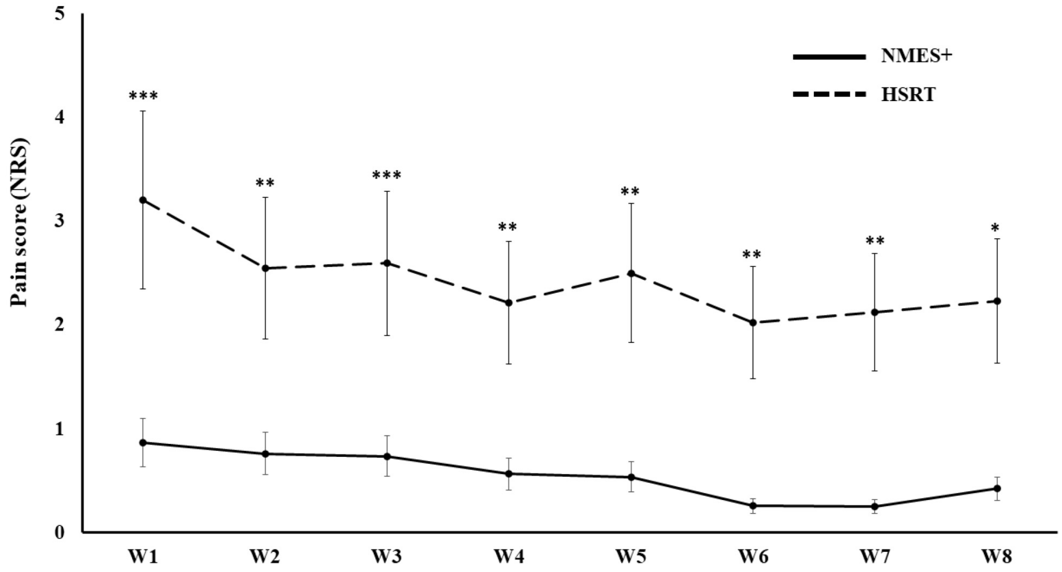

Figure 4. Anterior knee pain scores (mean and st. error) referred during the 8 weeks of training (W1-W8) in the two groups. * p<0.05; ** p<0.01; *** p 0.001.

Results

Knee extensor and flexor muscles strength

There was a significant effect of time for MVIC of knee extensor muscles at 30° (F=10.454, p<0.001), MVIC of knee extensor muscles at 90° (F=8.978, p<0.001), MVIC of knee flexor muscles at 60° (F=4.691, p<0.01), and MVIC of knee flexor muscles at 90° (F=8.016, p<0.001). No group by time interaction was found for either of the MVIC assessments. Mean values, standard deviations and significant grouped post-hoc differences across time are reported in Figure 2.

No effect of group (F=0.172; p=0.683) and time (F=1.626; p=0.210) were observed for the H/Q ratio (NMES+group: T0=0.83±0.15; T1=0.81±0.15; T2=0.81±0.16; T3= 0.81±0.19; T4=0.76±0.18; T5=0.79±0.17. HSRT group: T0=0.90±0.23; T1=0.81+0.29; T2=0.83±0.26; T3= 0.81±0.25; T4=0.77±0.21; T5=0.86±0.25).

Symptoms, function and ability to participate in sport (VISA-p questionnaire)

The Mann-Whitney test showed no differences between the two groups, while the Kruskall-Wallis ANOVA revealed a significant (p<0.001) effect of time. Mean values, standard deviations and significant post-hoc differences across time are reported in Figure 3.

Functional performance

No group by time interaction and time effect were found for peak forces recorded during the eccentric (group*time:

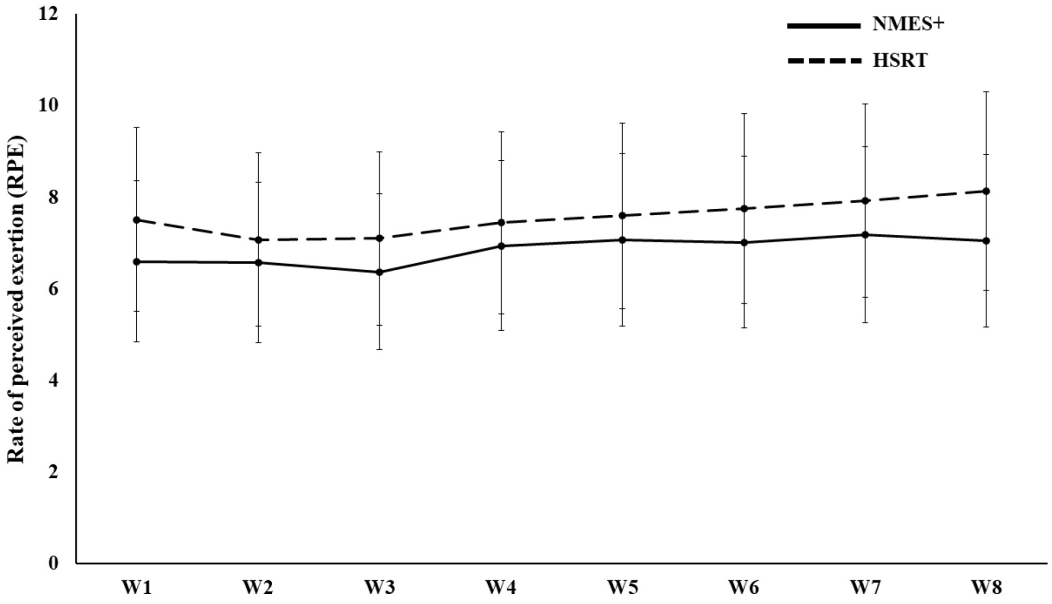

Figure 5. Rate of perceived exertion scores (mean and st. error) referred during the 8 weeks of training (W1-W8) in the two groups.

F=0.741; p=0.612. time: F=1.631; p=0.247) and concentric (group*time: F=0.843; p=0.552. time: F=2.100; p=0.157) phases of the CMJ. Also, for peak power recorded during CMJ, no group by time interaction (F=0.811; p=0.570) and time effect (F=1.199; p=0.382) were found. Mean values and standard deviations are reported in Table 4.

Knee pain and RPE during training

Knee pain during training was significantly lower in NMES+ compared to HSRT group in all the training sessions. No other significant differences between-groups or across time were found for pain and RPE. Mean values of knee pain scores and RPE with significant differences are represented in Figure 4 and Figure 5. Across all the training sessions and for all the subjects, the knee angle for training (i.e., the height of the seat or the angle of the leg-press) need to be adjusted for pain higher or equal to 4, two times in the NMES+ group and forty-four times in the HSRT group.

Outcome satisfaction and post-intervention training

Satisfaction level was high in both groups and no significant differences between the two groups were observed (NMES+= 9.3±0.9; HSRT=9.2±1.1; F=0.034; p=0.85).

Tendon thickness

There were no significant differences between the two groups. A significant effect of time (F=7.909; p<01), but no group by time interaction (F=0.551; p=0.581) were found for distal tendon thickness, which was significantly higher at T4 compared to T0 in the HSRT group. Mean values and standard deviations with significant differences after the post-hoc analysis are reported in Table 5.

Discussion

The main finding of this study is that the novel NMES+ training was as effective in decreasing symptoms and increasing muscle strength in physically active individuals with patellar tendinopathy as the traditional HSRT. However, NMES+ training has the advantage of being a pain-free exercise method.

To date, HSRT has been shown to be the most effective training method for patellar tendinopathy, as it embraces all of the characteristics for a good outcome, i.e: it provides gradual loading of the tendon without carrying out fast stretch/shortening contractions, which are detrimental for the tendon[2,3]; it provides an adequate intensity to generate neuromuscular and tendon adaptation[5,34]; it enhances motor control if the duration of concentric and eccentric muscle actions are performed at structured interval of time[4]. These three featuring points can also be found in the novel protocol of intervention based on superimposing NMES to voluntary movements. First, the NMES can be superimposed to slow functional movements; second, the intensity of the stimulation can be gradually increased, thus reaching high intensities; third, training sessions can be structured based on concentric and eccentric contraction duration. Strength training coupled with motor control exercise seems to be the key factor for effective training in patellar tendinopathy, and this is probably why training interventions primarily focused on muscle strength, motor control, or passive treatments

Table 5. Mean values and standard deviations of anterior-posterior (AP) proximal, mid and distal patellar tendon thickness at T0, T1 and T4. *(of * = significant difference between T0 and T4).*

AP thickness (mm)	T0		T1		T4	
	NMES+	HSRT	NMES+	HSRT	NMES+	HSRT
Proximal	6.07 ± 1.08	5.60 ± 1.7	6.03 ± 1.2	5.60 ± 1.7	6.66 ± 1.4	6.24 ± 1.5
Mid	5.05 ± 1.3	4.89 ± 0.9	4.85 ± 0.9	5.15 ± 0.9	5.36 ± 0.7	5.30 ± 1.0
Distal	5.20 ± 0.9	4.78 ± 0.9*	5.21 ± 1.0	5.15 ± 1.0	5.46 ± 1.0	5.50 ± 0.9*

do not always improve recovery[4]. It is difficult to compare the results of this study with previous work. Basas et al.[35] combined NMES, which was superimposed to isometric contractions, to other strengthening exercises without stimulation in athletes with patellar tendinopathy and found some positive outcomes, although there was no control group in the study. To the best of the authors' knowledge, the present study is the first adopting NMES+ as a "*per se*" resistance training protocol, during dynamic shortening/lengthening contractions, without combining other strength trainings. In addition, the results were compared with a matched control group of HSRT.

In this study NMES+ and HSRT were matched for duration of eccentric and concentric muscle actions and resting time, while intensity was increased in terms of RM in the HSRT group and in terms of pulse intensity and frequency in the NMES+ group. In addition, there was an attempt to match also the knee joint range of motion, from 90° to full extension. However, while participants in the NMES+ group performed the sit-to-stand-to-sit from 90° to 0° without knee pain, participants in the HSRT group referred pain equal or higher than 4 (out of 10) when, initially, the starting angle of the leg-press exercise was set at 90°. It has been reported that strain of the patellar tendon is high at 90° [36] and, for the muscle force/length relationship, quadriceps muscle strength is higher at knee angles lower than 90° [37,38]. Thus, a higher tendon strain, which was associated to a lower muscle strength during lifting of an external load, may have triggered nociceptors activation and pain neural circuits. In contrast, it is possible to speculate that, when NMES was superimposed to voluntary contraction, muscle strength and activation were supported and enhanced by NMES, thus generating less passive stress on the tendon and, as a result, less pain. However, no differences in adaptations to training were observed for muscle strength between the two groups, suggesting that both training interventions were effective. As the increase in muscle strength was observed in both groups since the early phases of training, it is likely that adaptations occurred at neural level, more than at tendon or muscle level[39].

At the same time an improvement of symptoms was recorded, as shown by an increase in VISA-p score for both groups. These results are in accordance with previous studies, showing that neural adaptations to training are essential in patellar tendinopathy, and that the related increase in muscle strength is associated with improvements in symptoms[4]. It should also be mentioned that the results were maintained in the long-term after the end of the training interventions (at T5) in both groups. It is thus not surprising that high satisfaction outcomes were reported in both groups.

Even if knee flexor muscles were not specifically trained, an increase of muscle strength across time was observed in both groups. This result may be ascribed to the fact that both training protocols potentially provided a consistent knee flexor muscles activation in some phases of the exercises, with the main aim to stabilize the knee joint, thus providing co-contraction during the eccentric phase of the leg-press exercise, and opposing NMES elicited quadriceps' contraction during the stand-to-sit phase of the NMES+ protocol. Noteworthy, the H/Q ratio did not show any significant change across time despite a significant general increase in muscle strength. It should be also discussed that even if the results were not significant, the H/Q ratio decreased slightly from T0 to T5 in both groups, thus suggesting a major strength gain in favour of the quadriceps muscle. In addition, at the end of the training interventions (T4), both groups showed mean values of the H/Q ratio (NMES+=0.76 and HSRT=0.77) within the normality range usually observed in healthy individuals (0.50-0.80)[40]. On the contrary, at the start of the training protocol both groups showed higher mean values (NMES+=0.83 and HSRT=0.90) with respect to the normative values.

Although there is evidence in the literature that both traditional heavy resistance training and NMES improve the performance of functional and sport-specific tasks[13], the two training interventions performed in this study had no effects on functional performance, as shown by the lack of changes across time in peak forces and peak power during the CMJ. This could partly be attributed to the fact that all participants in this study were involved in sporting activities, such as volleyball, soccer, basketball and dancing, thus they had a high level of performance during jumping activities at baseline. Moreover, this result is supported by evidence showing that functional performance is generally not affected by patellar tendinopathy[41]. Regarding tendon morphology the only significant result of this study was the observation of a higher distal AP thickness in HSRT group at T4 compared to T0. The increase in tendon size has been reported as a physiological adaptation to training[42]. Since there was a trend towards an increase in all the measurements for both groups, a longer duration of training may have shown clearer results. It is likely that the duration of training in this study was too short to observe such adaptations in tendon size. However, our results are in accordance with previous literature, reporting strength and clinical improvements despite no changes in tendon morphology[43]. It should also be mentioned that recent evidence reported higher Achilles' tendon force despite no increase in tendon size following 12 weeks of NMES training in healthy individuals[44].

A final issue should be discussed. For NMES+ training, we used frequencies of stimulation ranging from 30 to 85 Hz. The purpose of this choice was to maximize motor unit recruitment and theoretically train both slow twitch and fast twitch fibres at the same time. There is a lack of studies that clearly demonstrate a relationship between NMES frequency and type of muscle fibre activation, but some observations suggest that different frequencies may have different effects. For example, it has been reported that after high frequency NMES there is an upregulation of anabolic signals[45], suggesting the latter frequencies may induce muscle hypertrophy. In addition, high frequency NMES training increased the number and size of fast twitch fibres, whereas slow fibres were reduced in size[46]. Consistently, an upregulation of type-2 myosin-heavy-chain and a downregulation of type-1 myosin-heavy-chain expression have been reported following high frequency NMES training[47]. In contrast, an increase in the enzymes regulating the Crebs' cycle has been reported following low-frequency NMES training[48-51]. Finally, a decrease in muscle fatigue has also been demonstrated by low frequency NMES compared to high frequency NMES[52]. From a practical point of view, although NMES has positive effects in terms of muscle strength gain and functional improvements, a number of literature reviews claim inconsistencies in the use of NMES frequencies and suggest further research on this topic[53-58].

Some limitations should be mentioned for this study. First, the duration of the training interventions was 8 weeks. It is reasonable to think that for some individuals this time frame may be too short to sort positive effects on tendinopathy related impairments. However, participants in this study were all involved in sporting activities and thus it can be speculated that adaptations to strength training required less time in comparison to the time required by non-trained individuals to have the same effects. A second limitation of the study is that we did not quantify the volume and the type of training in the time frame between T4 and T5. However, at the end of the training interventions (T4), all participants returned to their usual level and type of training (including resistance training) and at T5 they reported being extremely satisfied with the training interventions' effects . With this latter point in mind, as well as the high VISA-p score reported at T5, it would appear that patients were able to resume their regular sport activities without pain or restriction. Another limitation is that this study was only conducted on young physically active individuals, so its results cannot be generalized to those who are sedentary or of other ages. Further studies with longer training protocols as well as heterogenous age ranges and physical activity levels are required to address these issues.

Conclusion

In conclusion, this is the first study providing preliminary results on the effectiveness of NMES+ in patellar tendinopathy. NMES+ is equally effective in decreasing pain, improving symptoms, and increasing muscle strength as HSRT, which is currently the "gold standard" for training patellar tendinopathy. In addition, NMES+ has the advantage to be a pain-free resistance training method. Future studies should look at the effects of NMES+ in other physical conditions in which resistance training is critical to recover muscle strength, yet subjects cannot handle heavy loads due to joint pain or lack of experience.

Funding

The study was financially supported by DJO Global.

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