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Original Article

Muscular Adaptations Between Very Low Load Resistance Training With Pulsed Direct Current Stimulation (Neubie) and Traditional High Load Training

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Abstract

Objectives: This study compared muscle growth in response to very low load resistance training with direct pulsed current (DPC) stimulation and traditional high load training. **Methods**: Twenty-six resistance trained individuals had each leg assigned to one of two unilateral knee extension protocols: 1) 4 sets of 20 repetitions at ~10% one-repetition maximum (1RM) and inter-set rest periods of 30 s (DPC) and 2) 4 sets to muscular failure at ~70% 1RM (TRAD). Muscle thickness (MTH), 1RM strength, and local muscular endurance (LME) were measured before and after 8-weeks of training. An alpha level of 0.05 was used for all comparisons. **Results**: MTH increased similarly between TRAD and DPC at the 50% (0.24 cm, 95%CI: 0.11-0.36), and the 60% anterior sites (0.25 cm, 95%CI: 0.10-.040), as well as the lateral (0.25 cm, 95%CI: 0.10-.040) and medial sites (0.21 cm, 95%CI: 0.10-0.31), but was greater for TRAD at the 40% anterior site (0.3 cm, 95%CI: 0.16-0.43). Changes in 1RM were greater for TRAD (10.2 kg, 95%CI: 5.8-14.4). LME increased similarly between protocols (5 repetitions, 95%CI: 3-7). **Conclusions**: The current data suggest that very low load knee extension resistance training with DPC could be a viable training strategy for promoting skeletal muscle growth and local muscular endurance.

Keywords: Direct Pulsed Current, High Load Training, Resistance training, Very Low Load Training

Introduction

In the past decade, there has been a considerable amount of research conducted that has aimed to find potential alternatives to traditional high load resistance training (i.e., ≥70% one-repetition maximum; 1RM)[1–7]. The results from these studies indicate that muscle growth adaptations are not limited to higher load training protocols, but rather appear to be driven by exercising with a high degree of voluntary effort (i.e., to or near task failure)[1,2,6,8]. Counts et al.[1], for example, demonstrated similar increases in muscle size between a "NO LOAD" training protocol (i.e., maximal effort elbow flexions without an external load) and a traditional high load training protocol (i.e., 4 sets of 8-12RM at 70% 1RM). Interestingly, however, the authors[1] observed greater variability with respect to increases in muscle size for the NO LOAD training protocol. Counts et al.[1] speculated that such findings may be related to each individual's ability to maximally contract the muscle throughout the full range of motion. If true, then this would seem to invite a search for alternative training techniques which are capable of augmenting muscle activation during situations of very low external tension (i.e., to provide a more homogenous stimulus for muscle growth).

Direct pulsed current (DPC) stimulation is a form of neuromuscular electrostimulation characterized by the delivery of successive pulses (i.e., separated by an inter-pulse interval) at low/moderate and high stimulation frequencies and intensities, respectively[9]. Compared to other forms of electrostimulation (e.g., alternating current stimulation), DPC stimulation is purported to generate high degrees of muscle activation whilst inducing relatively less amounts of fatigue[10]. To date, however, limited research has proven its theory[11–13]. Acute work from our laboratory[14] demonstrated that 4 sets

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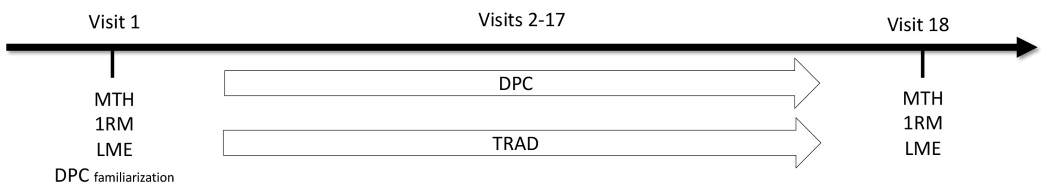

Figure 1. Muscle thickness (MTH), 1RM strength, and local muscular endurance (LME) of the knee extensors were measured before and after 8-weeks of unilateral knee extension training. Visit 1 consisted of MTH measurements, followed by unilateral 1RM strength and LME assessments on both legs, and DPC familiarization. Participants then enrolled in the 8-week training study (i.e., Visits 2-17). A randomized, within-participant design was used whereby each participant trained both legs (i.e., one in each protocol) on two days per week. Post measurements of MTH, 1RM strength, and LME occurred on Visit 18, which took place 48-72 hours after the last training session.

of unloaded elbow flexion exercise (20 repetitions) with DPC resulted in favorable skeletal muscle responses (i.e., acute changes in muscle thickness and fatigue-associated decreases in isometric strength). In addition, the DPC exercise protocol showed lower ratings of perceived exertion compared to traditional high load resistance exercise (i.e., 4 sets of 8-12RM at 70% 1RM)[14]. We interpreted these findings as evidence to suggest that the use of DPC may provide a potential alternative to high load resistance training, particularly if combined with very low external loads[14]. What remains to be determined, however, is whether those acute responses are indeed capable of inducing skeletal muscle growth. The primary aim of this study was to examine changes in muscle size following 8-weeks of very low load resistance training with DPC (4 sets of 20 repetitions at ~10% 1RM) and traditional high load resistance training (4 sets to task failure at ~70% 1RM). Other aims were to compare adaptations in 1RM strength and local muscular endurance between each distinct training protocol.

Methods

Experimental Approach

Using a randomized, within-participant design, we measured muscle size, strength, and local muscular endurance of the knee extensors before and after 8-weeks of unilateral knee extension training. Participants visited our laboratory a total 18 times. On the initial visit, if the individual met inclusion criteria, they proceeded to complete and sign a Physical Activity Readiness Questionnaire (PAR-Q) and written informed consent document. Anthropometric measurements (i.e., height and body mass) were then taken, followed by measurements of muscle thickness, unilateral 1RM strength and local muscular endurance assessments, DPC familiarization. On Visits 2-17, participants completed the 8-week training study, wherein exercise was performed twice weekly with a minimum of 48 hours between each visit. Post measurements occurred on Visit 18, which took place 48-72 hours after the last training session and mirrored the pre-intervention testing procedures (with the exception of paperwork, anthropometrics, and familiarization). Participants were allowed to continue their own resistance training regimens over the course of the study and were not required to report their previous quadricep muscle training volume (i.e., the total number of weekly sets performed per muscle group before the resistance training experiment)[15]. They were, however, asked to refrain from all resistance exercises targeting the knee extensors (i.e., squat, leg press, knee extension, lunge, et cetera), and to maintain their habitual diets, and completely refrain from physical activity 24 hours prior to all pre- and post-intervention measurements.

Participants

Twenty-nine resistance trained individuals volunteered to participate in the study after being informed about the benefits, discomforts, and possible risks of the study. To enroll in the study, participants needed to be between the ages of 18-35, and currently performing lower body resistance exercise (i.e., ≥2 days per week in the 6 months prior to beginning the study). Participants were further excluded from the study if: they regularly used tobacco products or had any orthopedic problems preventing them from completing strength testing/ unilateral knee extension exercise. Three total participants dropped out of the study; two prior to the start of training, and one during the training period for reasons unrelated to the study. No adverse responses to training were observed or reported and as such, the data were analyzed and presented for the 15 males and 11 females who completed all 18 visits. A schematic illustration of the experimental study design can be found in Figure 1.

Procedures

Muscle Thickness. Muscle thickness was measured using B-mode ultrasound (Mindray DP50, Shenzhen, China) on the initial visit and 48-72 h after the final training session.

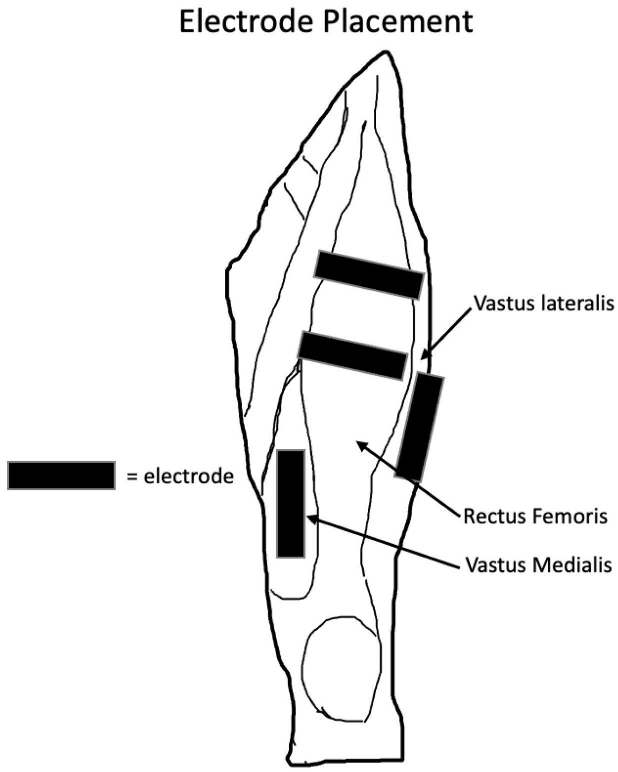

Figure 2. Electrode placement for direct pulsed current training condition.

Whilst the participant was standing with feet shoulder width apart, the ultrasound probe (5-12 MHz) was coated with transmission gel and placed against the skin of the upper leg, perpendicular to the femur, with care taken not to depress the muscle belly during image acquisition. Two images were taken in duplicate and saved for each site corresponding site on the anterior, lateral, and medial aspects of both legs. The 5 sites measured include 40, 50, and 60% of the distance from the greater trochanter to the lateral condyle of the femur for the anterior aspect of the upper leg, as well as the lateral aspect of the thigh musculature at 50% of the distance from the greater trochanter to the lateral condyle of the femur, and the medial aspect at 8 cm proximal from the insertion of the vastus medialis (in line with the muscle). Muscle thickness was determined as the average distance between the muscle-bone and muscle-adipose interfaces from the two stored images, as assessed to the nearest 0.01 cm. All measurements and analyses of muscle thickness were taken by the same investigator throughout the study. To limit any bias, the investigator was blinded to each condition during measurements and image analyses, which were done only after all testing was completed. The reliability for this investigator (in the elbow flexor muscles) was determined previously[16], using a small sample (n=4) of individuals tested over an 8-week time period. The mean difference (SD) was -0.01 (0.09) cm with a %CV of 1%[16].

One-Repetition Maximum (1RM) Strength. A unilateral 1RM for the knee extension exercise was used as a strength outcome and to determine the appropriate training loads. 1RM strength was assessed on the initial visit and 48-72 h after the final training session. Participants began the test following a warmup of a self-determined number of unloaded repetitions, followed by 3-5 repetitions each of an estimated 30 and 50% 1RM. For testing, participants were asked to move a given load from a starting position (knee angle of approximately 90°) to full knee extension 1 time per attempt. The load was progressively increased until the participant was no longer able to lift a load greater than their previous successful attempt. If unsuccessful, the load was decreased, and the process continued until load adjustments could no longer be made. The smallest possible increment for 1RM strength assessment was 6.80 kg. Participants were given a 90 s period of rest before attempting each load. 1RM strength was determined by finding the greatest load that participants could lift one time through a full concentric range of motion using a unilateral knee extension machine (StarTrac). A 5 minute rest period was allotted between each leg. All 1RM tests were supervised by trained personnel, and typically obtained within 3-5 attempts.

Local Muscular Endurance. To compare changes in local muscular endurance between conditions, participants were asked to complete one set of unilateral knee extension exercise to task failure. Local muscular endurance was assessed on the initial visit and 48-72 h after the final training sessions The load utilized for the pre- and post-intervention assessments was ~40% of the participant's pre-training 1RM (rounded to the nearest 6.80 kg). Participants were instructed to lift the load through a full concentric and eccentric range of motion to the beat of a metronome, at a cadence of 3 s per contraction (1.5 s concentric and 1.5 s eccentric). This cadence was chosen based on previous work from our laboratory[7]. The test was terminated if a participant failed to complete a full range of motion or maintain proper cadence. The last successful repetition completed was used for analyses. Muscular endurance was completed on one leg first, followed by the contralateral leg (the same order in which 1RM strength was assessed). A 5 minute rest period was allotted between each leg. All muscular endurance tests were supervised by trained personnel.

Direct Pulsed Current Familiarization

The leg assigned to the DPC was familiarized with the Neubie device for the unilateral knee extension exercise. Four dry and reusable electrodes (Neufit NF06, 5x10 cm, Austin TX) were placed on the anterior (2 electrodes), lateral (1 electrode), and medial (1 electrode) portions of the participant's thigh in attempt to activate the muscle bellies of the rectus femoris, vastus lateralis, and vastus medialis musculatures. The Neubie device was set to 55 hertz (Hz), after which participants were asked to perform 5 to 10 knee extension repetitions at ~10% 1RM. The intensity on the Neubie device was progressively increased from 0 mA until the participant indicated that the intensity corresponded to a 7 out of 10 on the Borg discomfort scale (CR10+).

Perceptual Responses. Participants were informed in depth on how to rate their exertion (RPE) and discomfort to ensure they understood the scales being used. Participants were asked to rate their level of exertion using the standard Borg 6–20 scale for RPE prior to beginning exercise and immediately following each set of exercise. Participants were told that a rating of 6 meant they were not exerting themselves at all, and a rating of 20 meant that they were giving maximal effort and would be unable to exert themselves any further. A rating of discomfort was obtained using Borg's Discomfort Scale (CR10+). Explained to participants was that the scale ranged from 0–10, with a score of 0 representing no discomfort at all, 10 representing their previously worst felt discomfort, and 10+ representing a discomfort greater than what they have ever felt before. Ratings of discomfort were taken immediately before exercise, as well as 20 s after sets 1, 2, and 3, and immediately after set 4[17].

Training Protocols. The 8-week training protocol required participants to come to our laboratory to perform two supervised training sessions per week. Both legs trained each session with the leg that trained first alternating between each session[5]. Exercise consisted of 4 sets of unilateral knee extension exercise under the respective (randomly assigned via coin flip) condition. The DPC training protocol performed 4 sets of 20 repetitions or as many repetitions as possible, whichever occurred first, with a load equal to ~10% 1RM and interset rest periods of 30 s. DPC stimulation was applied during the exercise protocol with the Neubie pulsed direct current device. In brief, 4 dry and reusable electrodes (Neufit NF06, 5x10cm, Austin TX) were placed on the anterior (2 electrodes), lateral (1 electrode), and medial (1 electrode) portions of the participant's thigh in attempt to activate the muscle bellies of the rectus femoris, vastus lateralis, and vastus medialis musculatures (Figure 2). The Neubie device was set to a stimulation frequency of 55 hertz (Hz) and amplitude (intensity) that corresponded to a 7 out of 10 on the Borg's Discomfort Scale (CR10+). The Neubie intensity (range 1-100 mA, with increments of 1%) was made relative to each participant and determined during each training session, for each set of exercise. The intensity reading (i.e., mA) correlates 1:1 with voltage; for example, 1% output is 1V peak amplitude of the main direct current pulse, 50% is 50V, and 100% is 100V. Of note is that the electrode pads remained on the skin for the duration of the DPC protocol, but the intensity dropped down to ~10% of the intensity used for exercise during the rest periods. Participants performed 4 sets of 20 repetitions or as many repetitions as possible, whichever occurred first, with a load equal to ~10% 1RM and interset rest periods of 30 s[14]. Also of note is that the Neubie device allows for stimulation to be applied using a positive or negative direct pulsed current; we applied positive and negative currents in an alternating fashion (i.e., sets 1 and 3 had positive currents applied, and sets 2 and 4 had negative currents applied). The TRAD protocol completed 4 sets of exercise to task failure with a load equal to ~70% 1RM and interset rest periods of 60 s. The load was adjusted accordingly after each set and throughout the training period to allow for 8-12 repetitions. All participants were instructed to perform each repetition to the beat of a metronome, at a cadence of 2 s per contraction (1 s concentric and 1 s eccentric). Because task failure was considered the inability to complete the concentric phase of a repetition, the final repetitions before exercise cessation were sometimes performed at a slower (but not faster) pace than the requested repetition duration.

Table 1. Demographics Information of Study Sample.

	(n = 26)
Age (yrs)	21.2 (3.1)
Height (cm)	171.1 (9.7)
Body weight (kg)	72.8 (16.4)
Sex (n = females)	11

Table 2. Ratings of Perceived Exertion Across Exercise Sets.

DPC	Rest	Set 1	Set 2	Set 3	Set 4
Visit 2*	6.2 (5.9-6.4)[a]	13.8 (13.0-14.6)b[#]	15.6 (14.7-16.5)[c]	16.3 (15.6-17.0)[d]	17.1 (16.3-17.9)[e]
Visit 9*	6.1 (5.9-6.4)[a]	12.9 (11.8-14.0)b[#]	14.9 (14.0-15.9)[c]	16.0 (15.0-17.0)[d]	16.9 (15.9-17.9)[e]
Visit 17*	6.0 (5.9-6.2)[a]	12.8 (11.8-13.8)b[#]	14.5 (13.5-15.6)[c#]	15.9 (14.9-16.9)[d#]	16.6 (15.6-17.6)[e]
TRAD					
Visit 2	6.2 (5.9-6.5)[a]	15.4 (14.6-16.2)[b]	16.0 (15.3-16.8)[c]	16.5 (15.8-17.2)[d]	17.0 (16.3-17.8)[d]
Visit 9	6.1 (5.8-6.3)[a]	14.7 (13.7-15.7)[b]	15.6 (14.7-16.6)[c]	16.3 (15.7-17.0)[d]	17.0 (16.3-17.6)[d]
Visit 17	6.0 (5.9-6.2)[a]	14.8 (13.7-15.9)[b]	15.9 (14.9-16.8)[c]	16.4 (15.5-17.2)[d]	16.9 (16.1-17.7)[e]

Ratings of perceived exertion for both training protocols (DPC and TRAD) across each set of exercise (rest-set 4) for the first training visit (visit 2) the 8th training visit (visit 9) and the final training visit (Visit 17). An asterisk indicates a training protocol (DPC vs. TRAD) by set (rest, set 1, set 2, set 3, set 4) in-teraction (p<0.01) within a given visit. For each visit, within each protocol (across sets), a different letter indicates a significant difference (p<0.01) between sets. An octothorp# represents a significant difference (p<0.05) between training protocols for a given set.

Statistical Analysis

All data were analyzed using SPSS 26.0 (SPSS Inc., Chicago, IL, USA). Descriptive data are presented in Table 1. Three 2 x 2 [training protocol (DPC vs. TRAD) x time (pre vs. post)] repeated measures of ANOVA were used to examine changes in muscle thickness, 1RM strength, and local muscular endurance (repetitions) over time. If there was a significant interaction (training protocol x time), a follow-up one-way repeated-measures ANOVA was performed across time (pre-post) within each training protocol, and paired samples t-tests were used to compare whether the changes from baseline differed across protocol (DPC vs. TRAD) within each time point. If there was no interaction, main effects of training protocol (DPC vs. TRAD) and time (pre vs. post) were examined. Paired samples t-tests were used to examine differences in RPE and discomfort between training protocols (DPC vs. TRAD) for each exercise set. Data are presented as mean (SD).

Muscle Thickness

For anterior muscle thickness at the 40% muscle site, there was an interaction (p<0.001). The TRAD training protocol increased muscle size from pre- to post-intervention (mean difference=0.3 cm [0.16-0.43], p < 0.001), whereas the DPC protocol did not increase from pre- to post-intervention (mean change=0.087 cm [-0.05-0.22], p=0.203). For the 50% muscle site, there was no interaction (p=0.065). However, there was a main effect for time; muscle thickness increased from pre- to post-intervention (mean change=0.24 cm [0.11-0.36], p<0.001). For the 60% site, there was no interaction (p=0.780). However, there was a main effect for time; muscle thickness increased from pre- to post-intervention (mean change=0.25 cm [0.10-.040], p=0.002). For the lateral muscle thickness site, there was no interaction (p=0.32) or main effect for training protocol (p=0.44). However, there was a main effect for time (p=0.009); muscle thickness increased from pre- to post-intervention (mean difference=0.09 cm [0.02-0.15], p<0.001). For the medial muscle thickness site, there was no interaction (p=0.054) or main effect for training protocol (p=0.96). However, there was a main effect for time (p<0.001); muscle thickness increased from pre- to post-intervention (mean change=0.21 cm [0.10-0.31], p<0.001).

Maximal Strength and Local Muscular Endurance

For 1RM strength, there was an interaction (p<0.001). The TRAD training protocol increased 1RM strength from pre- to post-intervention (mean change=10.2 [5.8-14.4] kg, p<0.001), whereas the DPC protocol did not increase from pre- to post-intervention (mean change=1.04 [-1.3-3.4] kg, p=0.381). For local muscular endurance, there was no interaction (p=0.08). However, there was a main effect for time (p<0.001); the number of repetitions increased for the two training protocols from pre- to post-intervention (mean change=5 [3-7] repetitions).

Rating of Perceived Exertion

For the first training visit (Visit 2), there was a training protocol x set interaction (p<0.01); RPE was higher during the first set of exercise in the TRAD training protocol compared to the DPC protocol (p<0.001) and increased across exercise sets for both protocols (Table 2). For the 8th training visit (Visit 9), there was a training protocol x set interaction (p<0.001); RPE was higher during the first set of exercise in the TRAD training protocol compared to the DPC protocol (p=0.002) and increased across exercise sets for both protocols (Table 2). For the final training visit (Visit 17) there was a training protocol x set interaction (p<0.00); RPE was higher during the first (p<0.001), second (p<0.001), and third (p=0.04) sets of exercise in the TRAD training protocol compared to the DPC protocol and increased across exercise sets for both protocols (Table 2).

Table 3. Discomfort Ratings Across Exercise Sets.

DPC	Rest	Set 1	Set 2	Set 3	Set 4
Visit 2Ω	0.29 (0.0- 0.53)[a]	4.7 (3.8 - 5.5)[b]	5.6 (4.7-6.5)[c]	6.1 (5.2-7.0)[c]	7.1 (5.8-8.4)[d]
Visit 9*	0.09 (-0.01-0.21)[a]	4.0 (2.9-5.0)[b#]	5.2 (4.2-6.2)[c]	6.1 (5.1-7.1)[d]	6.9 (5.9-7.9)[e]
Visit 17*	0.10 (-0.02- 0.22)[a]	4.0 (3.1-4.9)[b]	4.9 (3.9-5.9)[c]	6.0 (4.9-7.0)[d]	6.2 (5.1-7.4)[e]
TRAD					
Visit 2	0.17 (-0.01-0.36)[a]	4.8 (4.0-5.6)[b]	5.9 (5.0-6.8)[c]	6.1 (5.2-7.1)[c]	6.5 (5.5-7.6)[d]
Visit 9	0.05 (-0.02-0.24)[a]	4.6 (3.6-5.6)[b]	5.3 (4.4-6.3)[c]	5.9 (4.9-6.8)[d]	6.5 (5.4-7.5)[e]
Visit 17	0.02 (-0.02 - 0.06)[a]	3.8 (2.9-4.6)[b]	5.0 (4.1-6.0)[c]	5.3 (4.3-6.2)[c]	6.0 (4.9-7.1)[d]

Discomfort displayed for both training protocol (DPC and TRAD) across sets (rest-set 4) for the first training visit (Visit 2) the 8th training visit (visit 9) and the final training visit (Visit 17). An asterisk in-dicates a training protocol (DPC vs. TRAD) by set (rest, set 1, set 2, set 3, set 4) interaction (p<0.01) within a given visit. An omega$^{\Omega}$ indicates a main effect for time within a given visit across sets. For each visit, within each protocol (across sets), a different letter indicates a significant difference (p<0.01) between sets. An octothorp$^{\#}$ represents a significant difference (p<0.05) between training proto-cols for a given set.

Discomfort

For the first training visit (Visit 2), there was no training protocol x set interaction (p=0.13) or main effect for training protocol (p=0.88). However, there was a main effect for time (p<0.001); discomfort increased from rest to set 1 (p<0.001), from set 1 to set 2 (p<0.001) and set 3 to set 4 (p=0.004) but did not increase from set 2 to set 3 (p=0.08). For the 8th training visit (Visit 9) there was a training protocol x set interaction (p<0.001). Discomfort was higher during the first set of exercise in the TRAD training protocol compared to the DPC protocol (p=0.05) and increased across exercise sets for both protocols (Table 3). For the final training visit (Visit 17) there was a training protocol x time interaction (p<0.009), but no differences in discomfort between training protocols for any given set. For the DPC training protocol, discomfort increased across all sets (p<0.01). Discomfort increased for the TRAD training protocol from rest to set 1 (p<0.001), from set 1 to set 2 (p<0.001) and from set 3 to set 4 (p<0.001), but was not different from set 2 to set 3 (p=0.056).

Discussion

The main finding of the present study was that the application of DPC to very low load knee extension resistance training was similarly as effective for increasing muscle size as TRAD. In addition, both training protocols demonstrated an increase in local muscular endurance; however, the TRAD training protocol showed greater increases in 1RM strength compared to the DPC protocol. With respect to RPE and ratings of discomfort, we found that both training protocols elicited increases across exercise sets for the DPC and TRAD training protocols.

In the current study, the magnitude of muscle growth observed for the DPC training protocol was similar to that of the TRAD protocol, as well as what has been reported in previous investigations on the lower body in non-resistance trained individuals[2,18]. Note, however, that the hypertrophic response of DPC training appeared to be specific to the muscle sites at which the electrodes were placed, as judged by the finding that significant muscle growth (i.e., compared to pre-intervention) was not observed at the 40% anterior muscle site (i.e., an area that was located above the electrodes). An examination of the Neubie device to induce regional hypertrophy (i.e., specific to the location at which electrodes are placed) remains speculative, but could be a topic of future investigation. It has been hypothesized that skeletal muscle growth may be attributed to a combination of mechanical tension and metabolic fatigue induced motor unit recruitment[19,20]. High load resistance training, for example, may rely more on mechanical tension (due to the heavier external load) than metabolic fatigue than compared to lower load training. In contrast, the greater amounts of metabolic fatigue achieved through exercising to failure with lower loads are thought to increase motor unit recruitment (i.e., to maintain force output), which in turn compensates for the lower degree of mechanical tension and ultimately provides a stimulus capable of increasing muscle size[19,21]. In the absence of an external mechanical load, it appears that the presence of sufficient internal tension can also induce skeletal muscle growth, as suggested by the work of Counts et al.[1]. They documented that maximally contracting the elbow flexor muscles through a full range of motion without an external load resulted in similar increases in muscle size compared to traditional high load elbow flexion training (i.e., 70% 1RM). When examining the acute muscular responses to DPC elbow flexion exercise, we observed a muscle swelling response that was not only comparable to traditional high load resistance exercise, but also accompanied by an 18% decrease in isometric strength[14] (i.e., surrogate for fatigue[22]). It is possible that the hypertrophic effects of the DPC training protocol were facilitated by high degrees of internal tension, which required individuals to exercise with a high degree of voluntary effort, whereby a sufficient amount of the targeted muscle was fatigued and brought to a point at (or near) task failure. These findings add to the large body of scientific evidence demonstrating that increases in muscle size are not confined to heavier load resistance training[1,2,6,23,24].

The current results show that, despite significant increases in muscle size, the DPC condition did not increase maximal strength (as measured through 1RM) compared to pre-intervention. Reasons for these findings remain speculative, but may be linked to the manner in which the muscle protein (e.g., myosin) accrued during the process of hypertrophy is incorporated into the thick filament (as hypothesized in a recent article[25]). It may also be that changes in muscle size and strength are separate, perhaps even unrelated phenomena, meaning that exercise-induced increases in muscle size may not contribute to exercise-induced increases in muscle strength[26–28]. Strength adaptation appears to be highly dependent on the specificity of the training intervention[29–31], for example, individuals who consistently exercise at or near their respective 1RM would likely become much more skilled at lifting heavier loads for that specific exercise, whereas those who have become accustomed to lifting lighter loads would have less practice exercising near their 1RM (i.e., in that particular exercise). Support for this contention can be found in a recent paper[32], where the authors examined the high versus low load resistance training literature, and found that more frequent exposure to the 1RM test largely eliminated the strength differences observed between high and low load resistance training protocols (i.e., presumably due to more "practice" with lifting heavier loads). Given that the training loads used for the DPC and TRAD protocols were ~10% and ~70% 1RM, respectively, alongside the fact that we only tested 1RM strength on two occasions (i.e., pre- and post-intervention), it is perhaps not surprising that the DPC training protocol did not increase strength similarly to the TRAD training protocol. The implication of these findings is that individuals who desire to increase 1RM strength in a specific exercise would likely benefit from performing that exercise with higher training loads.

We observed similar increases in local muscular endurance for both protocols, despite the fact that DPC training protocol completed more repetitions (i.e., per set and training session) compared to the TRAD training protocol. In the present study, we tested local muscular endurance at the midpoint between the training loads used for DPC and TRAD protocols (i.e., ~40% pre-intervention 1RM) and an unfamiliar repetition cadence (1.5 s concentric and 1.5 s eccentric) in attempt to avoid favoring one protocol over the next[2,16]. As a result of changes in 1RM strength, the TRAD training protocol was required to lift a lower relative percentage of their 1RM compared to the DPC training protocol (i.e., at post-intervention). Yet, there were no significant differences between the DPC and TRAD conditions. These findings provide evidence to suggest that the mechanisms underlying increased local muscular endurance adaptations to resistance training may differ between higher and lower load training protocols[33]. Potential candidates to explain the increased muscular endurance observed for the DPC protocol could be related to improvements in the ability to tolerate peripheral fatigue (via the central nervous system)[34] and/or sustained neural activation[35]. In comparison, the increased muscular endurance for the TRAD protocol may have been driven primarily through increases in maximal strength[36], which would seemingly allow for greater efficiency of muscle recruitment patterns during submaximal force contractions[37].

Apart from the first set of exercise, the RPE values for the DPC training protocol did not differ much from those reported for the TRAD protocol (Table 3). The significantly higher levels of exertion registered for the TRAD protocol in the first set of exercise may be attributed to more pronounced feelings of strain in the active muscles, which would likely have been induced by lifting a heavier external load[38]. Note however that, over the 4 sets of exercise, the levels of perceived exertion for the DPC and TRAD protocols became significantly higher without many differences between them (Table 3). These observations could be related to amounts of local muscle fatigue carrying across the sets of exercise. For example, and as discussed in great depth by Marcora et al.[39], the corollary discharge model of perceived exertion suggests that perception of effort is centrally generated by forwarding neural signals (termed corollary discharges) from motor to sensory areas of the cerebral cortex. The increase in central motor command necessary to exercise at the same degree of voluntary effort (i.e., to or near task failure and at a Neubie "intensity" of a 7/10 for the TRAD and DPC training protocols, respectively) with increased muscle fatigue from the subsequent set(s) of exercise would likely have been perceived as requiring greater effort, and explain the increased RPE values (for both protocols) across the 4 sets of exercise[39]. With respect to ratings of discomfort, participants were asked to exercise at an amplitude (intensity) on the Neubie that corresponded to a 7 out of 10 (CR10+ scale); however, the ratings of discomfort reported were mostly less than 7 (Table 3). This may be partially explained by the timing of our measurement, for example, discomfort was taken 20 s following each set of exercise, which may have resulted in participants reporting their discomfort in reference to the level of discomfort at that time rather than during the exercise set. Nonetheless, the ratings of discomfort for the DPC condition appear similar to the TRAD condition (Table 3), as well as those reported during higher pressure, low load blood flow restriction exercise in the lower body[40]. These findings suggest that if individuals intend to exercise with a high degree of voluntary effort, then some degree of discomfort may be present.

Our study is not without limitations. A primary concern of unilateral training models is a potential cross-education effect of resistance training, in which training one limb elicits strength increases in the contralateral limb through neural mechanisms[41]. Unilateral high load training has been shown to influence the change 1RM strength of contralateral limb, even when the contralateral limb exercised with a different training protocol[42]. We therefore cannot rule out the possibility that the TRAD protocol induced a cross-education effect that maintained 1RM strength for the DPC training protocol. We inferred changes in muscle size from B-mode ultrasound muscle thickness measures, which is not the "gold-standard", but has been shown to track similarly with more sophisticated methods of assessing muscle mass (e.g., magnetic resistance imagining)[43]. Third, it remains possible that higher external loads with DPC may have enhanced strength adaptation and/or induced an overall more robust growth response to training. We chose to use very low loads in combination with DPC based on our acute work[14]. Future work might therefore examine the use of different external loads in combination with DPC. Lastly, a time-matched, non-exercise control group would have added strength to the current design as it would have captured random error across time and allowed us to confidently know if the observed changes in muscle size, 1RM strength, and local muscular endurance were due explicitly to the training interventions.

Conclusion

The current data suggest that very low load knee extension resistance training with DPC could be a viable training strategy for promoting skeletal muscle growth and local muscular endurance, but not maximal strength. This form of training also appears to require a similar degree of effort and is accompanied by similar levels of discomfort compared to traditional high load resistance training. Future studies are warranted to examine different combinations of external loads under DPC.

Ethics approval

The study was approved by the University of South Florida's Institutional Review Board (Study protocol number: STUDY002030).

Consent to participate

All participants signed a free and written informed consent before participation.

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