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Muscle activity during leg strengthening exercise using free weights and elastic resistance: Effects of ballistic vs controlled contractions

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ABSTRACT

The present study's aim was to evaluate muscle activity during leg exercises using elastic vs. isoinertial resistance at different exertion and loading levels, respectively. Twenty-four women and eighteen men aged 26–67 years volunteered to participate in the experiment. Electromyographic (EMG) activity was recorded in nine muscles during a standardized forward lunge movement performed with dumbbells and elastic bands during (1) ballistic vs. controlled exertion, and (2) at low, medium and high loads (33%, 66% and 100% of 10 RM, respectively). The recorded EMG signals were normalized to MVC EMG. Knee joint angle was measured using electronic inclinometers. The following results were obtained. Loading intensity affected EMG amplitude in the order: low < medium < high loads ($p < .001$). Ballistic contractions always produced greater EMG activity than slow controlled contractions, and for most muscles ballistic contractions with medium load showed similar EMG amplitude as controlled contractions with high load. At flexed knee joint positions with elastic resistance, quadriceps and gluteus EMG amplitude during medium-load ballistic contractions exceeded that recorded during high-load controlled contractions. Quadriceps and gluteus EMG amplitude increased at flexed knee positions. In contrast, hamstrings EMG amplitude remained constant throughout ROM during dumbbell lunge, but increased at more extended knee joint positions during lunges using elastic resistance. Based on these results, it can be

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concluded that lunges performed using medium-load ballistic muscle contractions may induce similar or even higher leg muscle activity than lunges using high-load slow-speed contractions. Consequently, lunges using elastic resistance appear to be equally effective in inducing high leg muscle activity as traditional lunges using isoinertial resistance.

1. Introduction

Musculoskeletal disorders occur commonly in the working population as well as in sports and recreational exercise. Among a representative sample of 5600 blue- and white-collar workers the prevalence of severe pain was 33% and 29% in the neck/shoulders, 33% and 25% in the low back, and 16% and 12% in the knees, respectively (Andersen, Mortensen, Hansen, & Burr, 2011). Such types of pain causes individual suffering and increases the risk for long-term sickness absence (Andersen, Clausen, Mortensen, Burr, & Holtermann, 2011; Andersen, Kjaer, et al., 2008). During recent decades high-intensity strength training has gained increasing popularity in the rehabilitation of musculoskeletal disorders. While athletes commonly use leg-exercises to strengthen lower limb muscles, rehabilitation strategies in work-setting environments typically have focused on low back and upper extremities only (Coury, Moreira, & Dias, 2009). As a possible explanation, leg strengthening exercises may be more difficult to perform in a work-setting environment. Thus, a strong need seems to exist for the development of effective leg strengthening exercises that are easy to implement both in workplace and athletic settings and feasible for rehabilitation and prophylactic prevention of musculoskeletal disorders.

The forward lunge is a unilateral leg exercise involving substantial knee and hip extensor activity. Clinicians have implemented the forward lunge as an effective leg rehabilitation exercise after ACL injury and knee surgery (Alkjaer, Simonsen, Magnusson, Aagaard, & Dyhre-Poulsen, 2002; Mattacola, Jacobs, Rund, & Johnson, 2004) and the forward lunge may also serve important diagnotic purposes (Thorlund, Damgaard, Roos, & Aagaard, 2012). Furthermore, evaluation of electromyographic (EMG) activity has shown that the forward lunge involves high muscle activity ranging from 70–150% of MVC in the quadriceps, gluteus and hamstring muscles (Ebben et al., 2009; Jönhagen, Halvorsen, & Benoit, 2009; Pincivero, Aldworth, Dickerson, Petry, & Shultz, 2000; Thorlund et al., 2012), respectively, depending on the external load, movement velocity and the magnitude of body deceleration/acceleration. Accordingly, Jönhagen et al. (2009) recently observed that the high-velocity jumping forward lunge is associated with higher EMG activity in the rectus femoris, biceps fermoris and lateral gastrocnemius compared with the walking forward lunge.

Sakamoto and Sinclair (2012) recently investigated EMG and median power frequency (MPF) during varying lifting speeds and intensities using isoinertial bench press manoeuvres, and observed greater EMG amplitudes for faster and heavier lifting whereas MPF was similar during all conditions. Whether similar mechanisms are present in resistance training using elastic bands remains uninvestigated.

Resistance training is typically performed using training machines or free weight exercises (Andersen et al., 2006; Andersen, Andersen, et al., 2008). In recent years, elastic resistance bands have gained popularity because of their low cost, simplicity, versatility, and portability. While elastic resistance has shown to be equally effective in strengthening smaller muscles in the neck, shoulder and arm compared to free weight training (Andersen et al., 2010; Andersen, Saervoll, et al., 2011), their proficiency for effectively stimulating larger and stronger muscles of the lower extremities remains questionable. In addition, the EMG – joint angle relationship that is well described for conventional isoinertial strength exercises (i.e., Andersen et al., 2006) remain largely unexplored for elastic resistance exercise.

The purpose of the present study was to evaluate EMG activity during leg strengthening exercises using either elastic or conventional isoinertial resistance while examining the effects of varied movement velocity (controlled vs fast) and modulations in external loading intensity. We hypothesized that lunge exercise performed with elastic bands would induce similar EMG activity as lunge exercise performed with isoinertial resistance (dumbbells).

2. Methods

2.1. Subjects

The study was performed in Copenhagen, Denmark. A group of 42 untrained adults (24 women and 18 men) were recruited from a large workplace with various job tasks. Exclusion criteria were blood pressure above 160/100, disc prolapse, or serious chronic disease. Table 1 shows demographics. Complete testing was performed on all participants, i.e., with both elastic resistance and dumbbells.

All subjects were informed about the purpose and content of the project and gave written informed consent to participate in the study, which conformed to The Declaration of Helsinki, and was approved by the Local Ethical Committee (H-3-2010-062).

2.2. Maximal voluntary isometric contraction (MVC)

Prior to the dynamic exercises described below, isometric MVC ramp contractions (3-s duration) were performed according to standardized procedures during (1a + b) static knee extension and flexion manoeuvres (positioned in a Biodex dynamometer: knee angle: 70° and hip angle: 110°), (2) hip adduction (laying flat on the back and pressing the knees against a solid ball), (3) hip abduction (laying flat on the back and pressing the knees outwards against a rigid band) and (4) hip extension (laying flat on the stomach with the knee flexed (90°) and pressing the foot upwards against the instructors hands), and (5) trunk extension (in standing posture and pelvis fixated the trunk was extended against a rigid band) to induce a maximal EMG response in the tested muscles (Zebis et al., 2008). Two isometric MVCs were performed for each muscle and the trial with the highest EMG was used for normalization of the peak EMGs recorded during the resistance exercises. Subjects were instructed to gradually increase muscle contraction force towards maximum over a period of two seconds, sustain the MVC for three seconds, and then slowly release the force again. Strong and standardized verbal encouragement was given during all trials.

2.3. Exercise equipment

Two different types of training equipment were used; (1) elastic 41 inch bands in a closed loop with resistances ranging from light to very heavy (Iron Woody, MT, USA) and (2) dumbbells (1 to 40 kg).

2.4. Exercise description

A week prior to testing, the participants performed a 10 repetition maximum test (10 RM) for the two exercises. All exercises were performed unilaterally with the dominant leg (preferred leg) serving as the leading leg. On the day of EMG measurements participants warmed up with submaximal loads and then performed three consecutive repetitions for each exercise using a 10 RM load to avoid the influence of fatigue on the subsequent exercises. Exercises were performed with three different loadings: low, medium and high corresponding to 33%, 66% and 100% of 10RM, respectively. Exercises were performed either in a (1) controlled manner at a slow constant speed (each repetition lasting ~3 s), or (2) by performing the lunge movement as fast as possible (ballistic contractions). The latter

Table 1
Demographics of the men and women of this study.

	Men	Women
n	18	24
Age, yrs	41 (13)	45 (9)
Height, cm	178 (7)	165 (6)
Weight, kg	78 (9)	64 (11)
BMI	25 (2)	24 (4)

was performed solely using medium loads in both loading modalities (elastic and isoinertial). The order of exercises was randomized for each subject, and the rest period between different exercises was approximately five minutes. The exercises are described in detail below (Fig. 1):

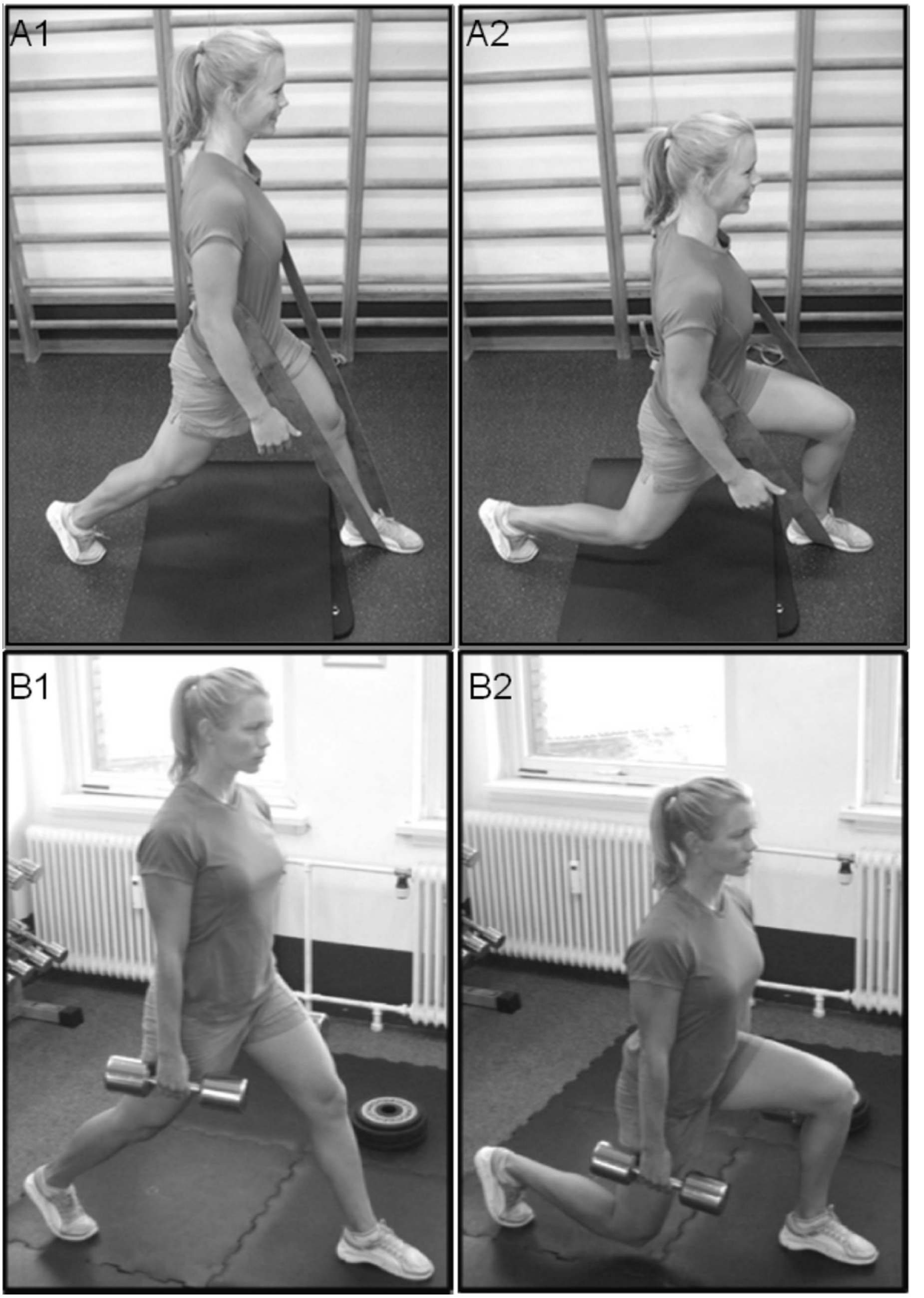

Fig. 1. Illustration of the resistance exercises with elastic band (A1, A2), dumbbells (B1, B2). The exercises are lunges using elastic resistance and dumbbells.

2.5. Lunge with elastic resistance (Fig. 1a)

The participant was standing upright with one foot in front and the other behind the body. Toes and feet were pointing straight ahead. The front foot was placed on one end of the elastic band while the other end of the elastic band was placed over the contralateral shoulder. The participant then lowered the body (eccentric phase) until the back knee reached the floor ($\sim$90° knee joint angle), and subsequently returned the body to the starting position (concentric phase). The upper body was maintained in an upright position throughout the exercise.

2.6. Lunge with dumbbells (Fig. 1b)

The participant was standing upright with one foot in front and the other behind the body. Toes and feet were pointing straight ahead. The participant held a dumbbell in each hand. The participant then lowered the body (eccentric phase) until the back knee reached the floor ($\sim$90° knee joint angle), and then raised the body up to the starting position (concentric phase). The upper body was maintained in an upright position throughout the exercise.

2.7. Perceived loading

Immediately after each set of exercise the Borg CR10 scale (Borg, 1998) was used to rate perceived loading during the resistance exercise. We have previously validated this scale in the evaluation of neck/shoulder resistance exercises with elastic resistance and dumbbells (Andersen et al., 2010).

2.8. EMG signal sampling and analysis

EMG signals were recorded from nine leg and lower back muscles: vastus medialis, vastus lateralis, rectus femoris, biceps femoris, semitendinosus, gluteus medius, gluteus maximus, and the left and right erector spinae. A bipolar surface EMG configuration (Blue Sensor N-00-S, Ambu A/S, Ballerup, Denmark) and an inter-electrode distance of 2 cm were used (Andersen et al., 2006; Jakobsen et al., 2011). Before affixing the electrodes, the skin of the respective area was prepared with scrubbing gel (Acqua gel, Meditec, Parma, Italy) to effectively lower the impedance to less than 10 k Ω. Electrode placements followed SENIAM recommendations (http://www.seiam.org).

The EMG electrodes were connected directly to wireless probes that preamplified the signal (gain 400) and transmitted data in real-time to a 16-channel 16-bit PC-interface receiver (TeleMyo DTS Telemetry, Noraxon, Arizona, USA). The dimension of the probes was 3.4 cm $\times$ 2.4 cm $\times$ 3.5 cm. Data sampling rate was 1500 Hz with a bandwidth of 10–500 Hz to avoid aliasing. Common mode rejection ratio was higher than 100 dB.

For each individual muscle, the root mean square (RMS) of the filtered EMG signal was calculated within each 10° angle interval (0°–10°, 10°–20°, ... 80°–90°) ($\sim$100–200 ms time constant) in the active knee extension (i.e., concentric) phase and normalized to the maximal moving RMS (500-ms time constant) EMG amplitude obtained during the MVC manoeuvres (Andersen et al., 2010; Jakobsen et al., 2011; Sundstrup et al., 2011). Further, median power frequency (MPF) was determined in the concentric phase, from the raw EMG signals using a 1024–4096 point FFT spectral analysis. Before FFT transformation, a detrending procedure was performed to remove any dc-component (off-set) and, subsequently, a Hanning window function was applied (Aagaard et al., 2000; Andersen, et al., 2008; Jakobsen et al., 2011).

2.9. Inclinometer sampling and analysis

Knee joint angle was continuously measured using two electronic inclinometers placed at the lateral side of the tibia and femur, respectively. The inclinometer data were synchronously sampled with the EMG data using the 16-channel 16-bit PC-interface receiver (TeleMyo DTS Telemetry, Noraxon, Arizona, USA). The dimension of the probes was 3.4 cm $\times$ 2.4 cm $\times$ 3.5 cm. During subsequent analysis the inclinometer signals were digitally lowpass filtered using a 4th order zero-lag Butterworth filter (3 Hz cutoff frequency).

The instantanous knee joint angle was calculated as the difference in angular position, with respect to the gravitational line, between the tibia and femur inclinometers. Knee joint angles typically ranged from full knee extension (0°) to a 90° flexed position (90°).

2.10. Statistical analysis

A two-way (2×4) repeated analysis of variance (Proc Mixed, SAS version 9, SAS Institute, Cary, NC) was used to locate differences between exercises and loading intensity for each muscle. Factors included in the model were exercise (elastic resistance and dumbbells), intensity (33% controlled, 66% controlled, 66% ballistic, 100% controlled). Normalized EMG was the dependent variable. Values are reported as least square means (*SE*) unless otherwise stated. p-values $\leqslant .05$ were considered statistically significant.

3. Results

3.1. Normalized EMG

Figs. 2–5 shows normalized EMGs for the selected muscles during elastic and dumbbell lunges during the 0–90° knee joint range of motion. For most muscles (vastus lateralis, vastus medialis, rectus femoris gluteus maximus) EMG was higher towards more flexed knee joint positions where the lunge movement is reversed and a need therefore exists for exerting high ground reaction forces. The hamstring muscles showed a somewhat different EMG-angle pattern. For the dumbbell lunge hamstring EMG activity remained rather constant throughout the range of motion, whereas for the elastic lunge EMG increased towards the more extended knee joint position probably as a result of elastic force generation (i.e., external loading) being greatest at the more extended body positions. Medial hamstring muscle activity (ST) generally was lower than lateral hamstring activity (BFcl) irrespectively of choice of exercise.

There was a significant effect of loading intensity on EMG signal amplitude ($p < .001$), which generally was observed to increase from low to medium to high loadings in all of the examined muscles. As an exception, the power set at medium load showed EMG levels that were similar or even greater (for the quadriceps and gluteus muscles during lunges with elastic resistance) than using high loading intensity at slow controlled speed. Conversely, during more extended knee joint angles during lunges with elastic resistance, hamstring and gluteus EMG amplitudes were greater during the high loading set than the power set.

When averaging across all muscles, velocities, angles and loadings, normalized EMG during lunges using elastic resistance ($37 \pm 1.2\%$) was significantly higher ($p < .001$) than during lunges using conventional isoinertial loading (dumbbells) ($29 \pm 1.2\%$).

3.2. Median power frequency (MPF)

There was a significant effect of loading on MPF ($p < .001$), with low, medium, high and power loadings showing MPF of 96.8 ± 1.9, 95.4 ± 1.9, 93.9 ± 1.9 and 91.2 ± 1.9 Hz, respectively (averaged for all muscles). There was also an effect of exercise ($p < .001$), with elastic and dumbbell lunges showing MPF of 92.4 ± 1.9 and 96.2 ± 1.9 Hz, respectively. There was also a significant effect of muscle ($p < .001$), with the lowest MPF observed in gluteus maximus, 62.1 ± 2.1 Hz, and the highest MPF observed in the erector spinae, 114.7 ± 2.1 Hz.

3.3. Contraction time

There was no significant difference in contraction time (i.e., time under tension) during the concentric phase between elastic lunges (1251 ± 32 ms) and dumbbell lunges (1270 ± 32 ms) (averaged

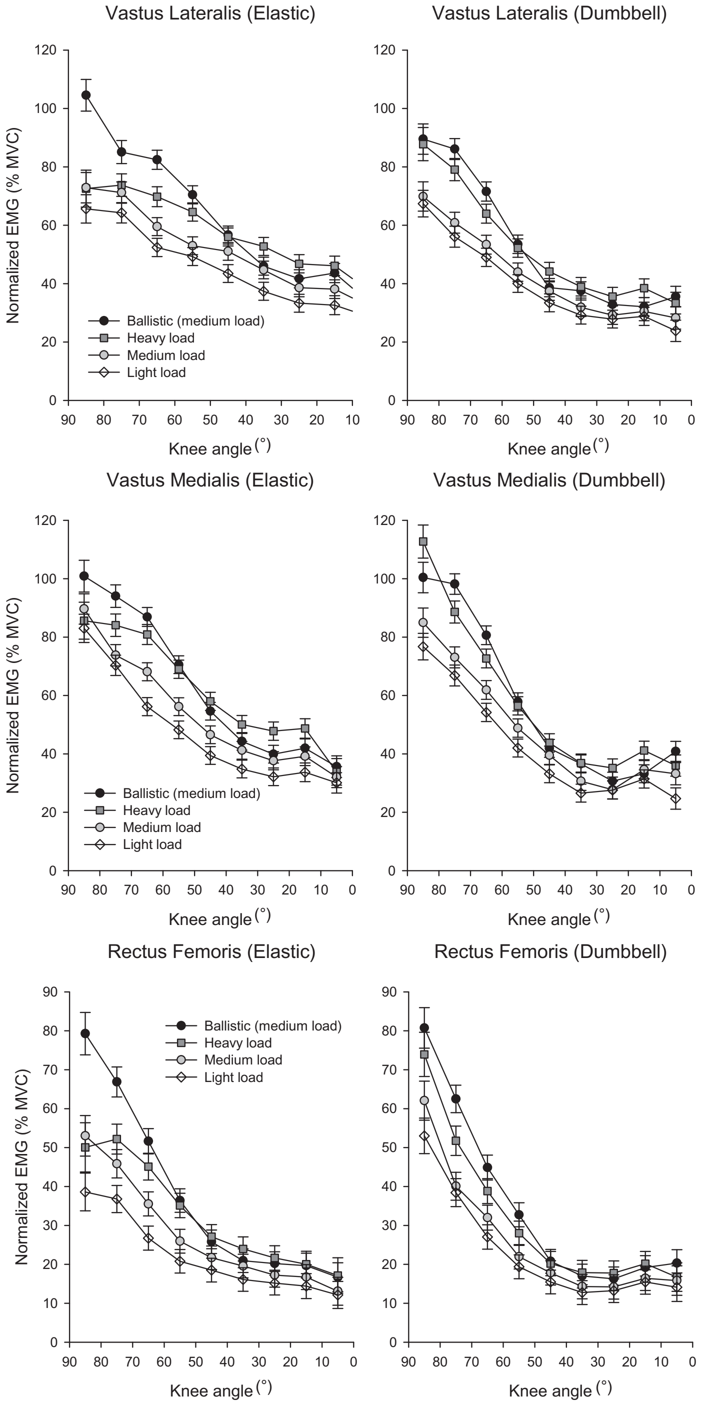

Fig. 2. Normalized electromyography (nEMG) and angular position during lunges with elastic band (left), lunges with dumbbells (right) in the vastus medialis (top), vastus lateralis (middle) and rectus femoris (bottom) muscles.

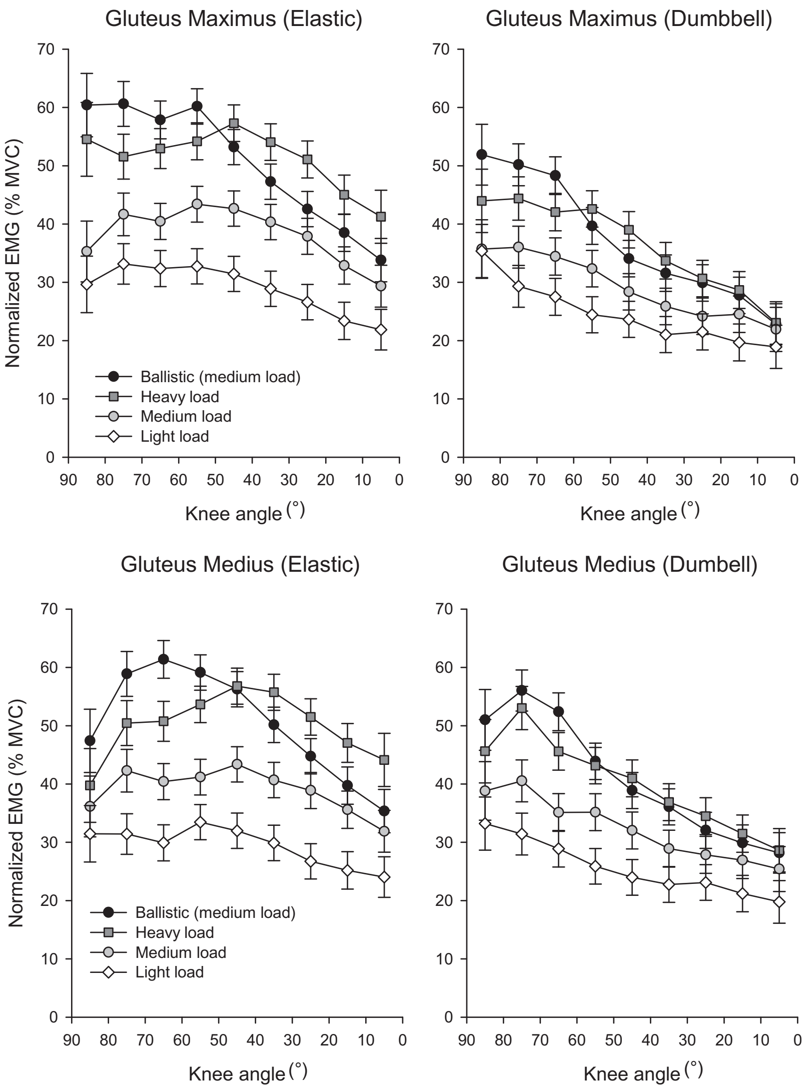

Fig. 3. Normalized electromyography (nEMG) and angular position during lunges with elastic band (left), lunges with dumbbells (right) in the biceps femoris (top) and semitendinosis (bottom) muscles.

across all loading). Contraction time during low, medium, high and power loadings were 1324 ± 34, 1331 ± 35, 1319 ± 35 and 1069 ± 35 ms, respectively. Additionally, the ballistic loading displayed shorter ($p < .001$) contraction time than the low, medium and high loadings with controlled exertion.

3.4. Perceived loading

Irrespectively of loading modality, a significant effect of loading intensity on perceived loading ($p < .001$) was observed, increasing in the order 33% controlled <66% controlled <66% power <100% controlled (Table 2). Perceived loading was significantly higher ($p < .001$) during elastic lunges (4.4 ± 0.36) compared with dumbbell lunges (4.0 ± 0.34) (averaged across all loading).

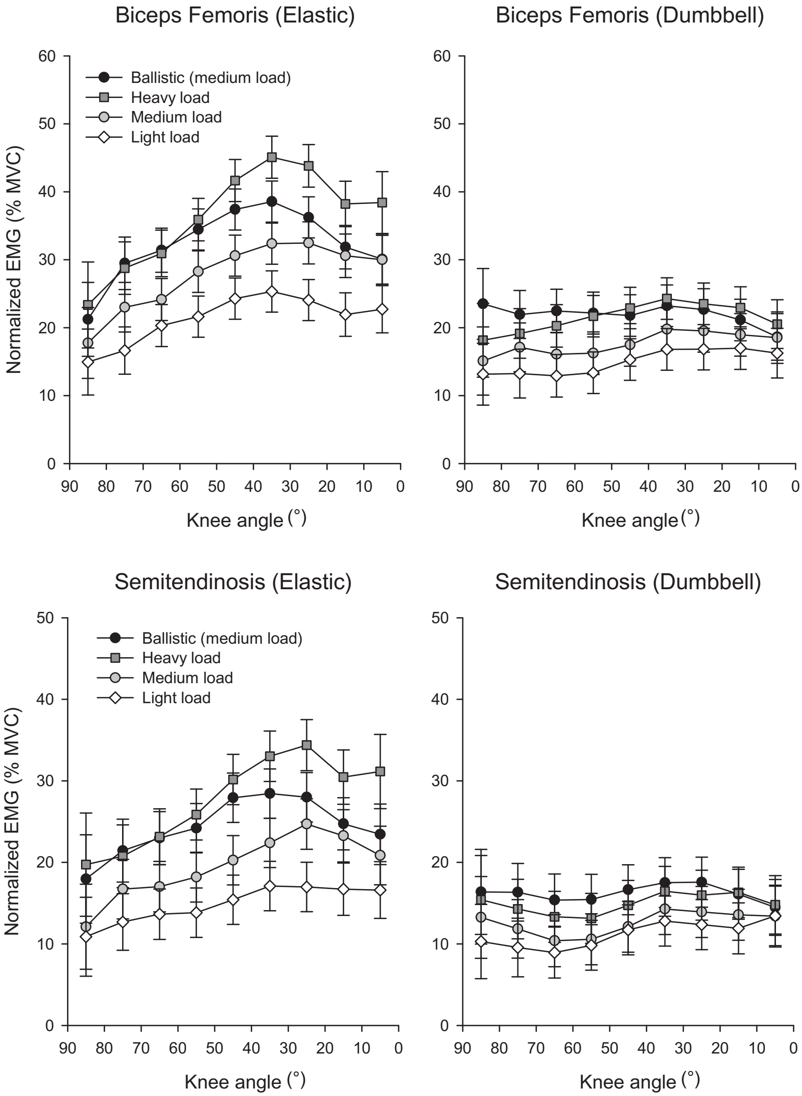

Fig. 4. Normalized electromyography (nEMG) and angular position during lunges with elastic band (left), lunges with dumbbells (right) in the gluteus maximus (top) and gluteus medius (bottom) muscles.

3.5. Dumbbell loading

A significant effect of dumbbell loads ($p < .001$) was observed at low, medium, high loads and in ballistic contractions (medium loads) with loading levels of 4.92 ± 0.01, 10.00 ± 0.03, 15.01 ± 0.04 and 10.18 ± 0.03 kg, respectively.

4. Discussion

The main findings of this study were that (1) lunges performed in a ballistic manner at medium load induces similar high or even higher leg muscle activity as lunges using high load exercise at slow

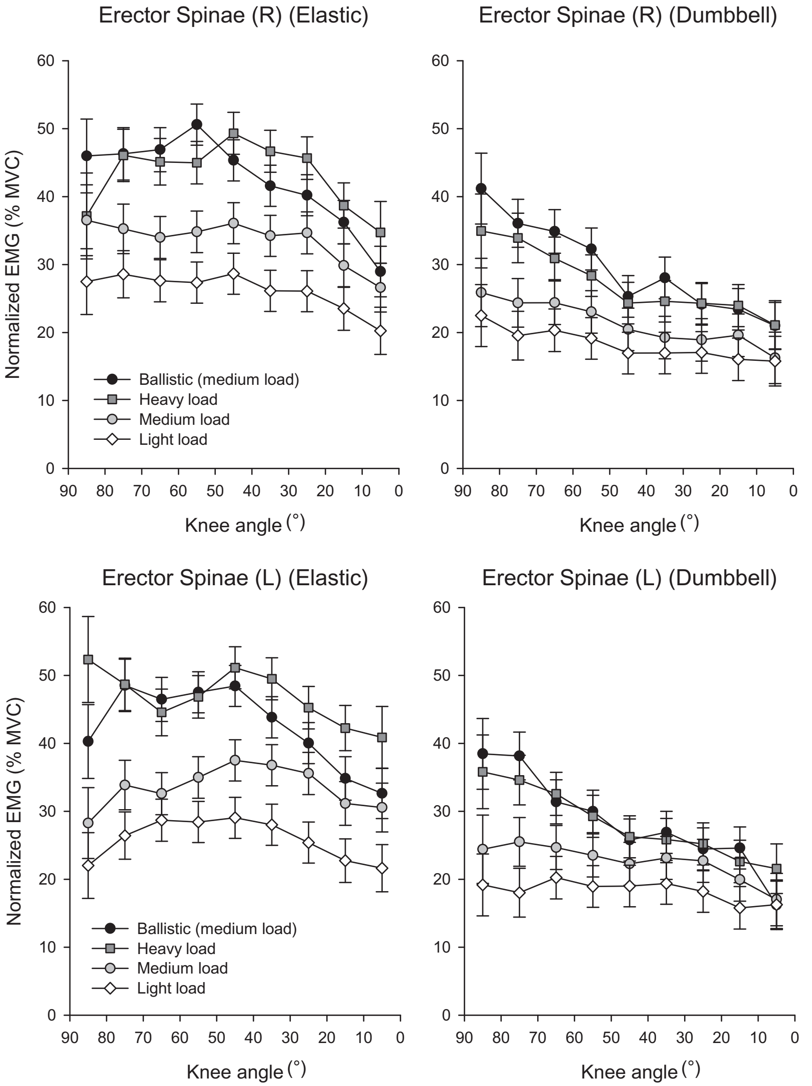

Fig. 5. Normalized electromyography (nEMG) and angular position during lunges with elastic band (left), lunges with dumbbells (right) in the erector spinae right (top) and left (bottom) side muscles.

Table 2
Perceived loading (Borg CR10 Scale) at each relative intensity and exertion during forward lunge exercises with dumbbells and elastic resistance.

		Elastic		Dumbbell	
Intensity	Exertion	Mean	Std	Mean	Std
33%	Controlled	2.5	0.8	2.0	0.9
66%	Controlled	4.4	1.6	3.8	1.4
100%	Controlled	6.1	1.8	5.9	1.8
66%	Ballistic	4.6	1.5	4.2	1.4

controlled speed, (2) lunges using elastic resistance appear to be equally effective of inducing high muscle activity as traditional lunges using isoinertial resistance.

4.1. Ballistic vs controlled execution

Increased movement acceleration is typically accompanied by increased EMG activity (Desmedt & Godaux, 1977; Frost, Cronin, & Newton, 2008; Sakamoto & Sinclair, 2012). Accordingly, ballistic lunges performed with high speed at medium loadings showed broadly similar EMG amplitudes as that seen during slower controlled speeds with high loading. Furthermore, for the quadriceps and gluteus muscles EMG activity during the power set even exceeded that of the high loading set during the most flexed knee joint positions with elastic resistance. Conversely, during elastic resistance lunges EMG activity recorded at the extended knee joint positions during the high-loading set exceeded the power set for the hamstrings and gluteus muscles. The initial acceleration during the more flexed knee angles might have been higher during ballistic contractions, leading to higher propulsive momentum and thereby minimizing the need for high hip extensor activity during the more extended part of the concentric contraction phase when using elastic band resistance. Nevertheless, as the elastic band becomes more stretched when approaching full body extension elastic resistance is greatest at the extended knee joint positions, which eliminates the need for active deceleration (i.e., the necessity of a shutdown in propulsive force generation) in the final phase of the lunge movement. Consequently, lunges performed using elastic resistance may inherently allow greater muscle forces to be exerted towards the terminal ROM compared to using conventional isoinertial resistance (dumbbells).

4.2. Elastic vs isoinertial loading

When averaging across all muscles, movement velocity and loadings, lunges with elastic resistance showed higher EMG than lunges with dumbbells, which also resulted in a slightly but significantly higher level of perceived loading on the Borg CR10 scale. Whereas EMG activity in knee and hip extensor muscles (vastus lateralis, vastus medialis, rectus femoris, gluteus maximus) was higher in the more flexed knee joint positions (i.e., in the reversal phase), the hamstring muscle demonstrated a different EMG-angle pattern. For the dumbbell lunge EMG remained rather constant throughout the range of motion, whereas in lunges using elastic resistance EMG increased when approaching more extended knee joint position (cf. Fig. 4). Furthermore, as indicated by visual differences (cf. Fig. 5), the elastic resistance resulted in higher levels of erector spinae and gluteus activity compared to dumbbells. Notably, lunges with elastic resistance were more posterior kinetic chain-dominant, since generally characterized by higher levels of hamstring, gluteus and erector spinae activity compared to dumbbell lunges (cf. Figs. 3–5). In biomechanical terms, the distal attachment of the band below the leading foot from which the band runs to the contralateral shoulder results in an anterior pull on the upper body, which in turn creates the need for generating a high net hip extensor moment. In result, as indicated by visual differences (cf. Figs. 3–5), gluteus, erector spinae and hamstring muscle activity seemed to be elevated in lunges using elastic resistance indicating an effective targeting of the hip and spinal extensor muscles throughout the range of motion. Thus, lunges performed with elastic resistance appear to stimulate a variety of leg and hip muscle groups, which makes it effective for thigh, hip and back strengthening and thereby an ideal exercise modality for the rehabilitation and prophylactic prevention of musculoskeletal disorders.

4.3. Time course: accelerated vs controlled speeds

Performing lunges with powerful exertion was in average 23% faster than the controlled exertions. Although the power set performed at medium loadings showed broadly similar EMG amplitudes as during slower controlled speeds with high loading intensity, the actual time under tension differs between the two contraction modes. Accordingly, the training volume during power set training should increase with ~23% to achieve the same accumulated time under tension. For example, performing 10 powerful repetitions with medium load would provide the same EMG amplitude and time under tension as 8 repetitions with high load at a controlled speed.

4.4. EMG spectral analysis

There was a significant effect of loading intensity on MPF, with frequencies systematically decreasing from low to high loads. Notably, MPF during powerful exertion was lower compared to using slow controlled contraction speeds. This is somewhat in conflict with previous reports of a simultaneous rise in MPF (Gamet, Duchêne, Garapon-Bar, & Goubel, 1990; Linnamo et al., 2000) or unaltered MPF (Sakamoto & Sinclair, 2012) with increases in movement speed and acceleration. Notably, higher MPF was revealed during dumbbell training compared with elastic resistance training. Decreased MPF may reflect decreases in muscle fiber conduction velocity (Eberstein & Beattie, 1985; Lindstrom, Magnusson, & Petersén, 1970) and/or more synchronized patterns of motor unit firing (Day & Hulliger, 2001; Yao, Fuglevand, & Enoka, 2000), causing a shift of MPF towards lower frequencies (Bigland-Ritchie, Donovan, & Roussos, 1981; Yao et al., 2000). A decrease in muscle fiber conduction velocity, induced by accumulating neuromuscular fatigue, seems highly unlikely since exercises were performed in a randomized order separated by long rest intervals. It is possible, therefore, that the decrease in MPF with increasing muscle contraction force was caused by the progressive recruitment of large-sized motor units with a high innervation-ratio (high number of myofibers innervated per motor neuron) inherently resulting in a relative more synchronized summation of single motor unit action potentials, which potentially could cause MPF to level off or even decrease at the highest contraction intensities.

4.5. Perceived loading

Our study shows a clear association between increased intensity and increased perceived loading rated on the Borg CR10 scale. For the 10 repetition maximum loading the Borg value was on average 6. In spite of inter-individual differences, the Borg CR10 scale can be used to determine intensity of exercise when maximal strength testing is contraindicated. Small but statistically significant differences existed between lunges with elastic resistance and dumbbells. This may be explained by the fact that average EMG activity was slightly higher during elastic resistance lunge.

4.6. Study limitations

As the recruited motor unit pool and acquired area of muscle fibers may differ between dynamic and isometric muscle contractions (Tax, Denier van der Gon, Gielen, & van den Tempel, 1989), the fact that the EMG was obtained during dynamic leg exercises and normalized to EMG obtained during isometric MVC may limit the findings of the present study. Nevertheless, this procedure has been widely used (Andersen et al., 2006; Jakobsen et al., 2011) and has shown to generate greater test–retest reliability scores compared with non-normalized data (Alkjaer, Simonsen, Jørgensen, & Dyhre-Poulsen, 2003; Kellis & Baltzopoulos, 1996; Rutherford, Purcell, & Newham, 2001; Wilk et al., 1996).

5. Conclusions

In novice trainees, lunge exercises performed with powerful exertion at medium load show high levels of leg muscle activity of similar or greater magnitude than seen using high load exercise at slow controlled speed. Furthermore, elastic-based resistance exercise targeting the hip and knee muscles induces muscle activity levels that are comparable to (knee extensors) or greater (hip extensor, low back extensors) than achieved by using conventional isoinertial loading. The forward lunge exercise performed with elastic resistance seems to be a feasible and simple method for evoking high levels of neuromuscular activity in major muscles at the hip, knee and back. Its feasibility makes the lunge exercise ideal for rehabilitation and prophylactic prevention of musculoskeletal disorders at work sites or in training settings with limited resources for extensive and expensive training equipment.

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