Human Movement Science 40 (2015) 134–153

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

An EMG comparative analysis of quadriceps during isoinertial strength training using nonlinear scaled wavelets

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ARTICLE INFO

Article history:
Available online 29 December 2014

PsycINFO classification:
2530

Keywords:
Time–frequency analysis
Wavelet analysis
Power training
Pneumatic resistance training

ABSTRACT

High-speed resistance training is used to increase power; however, momentum can reduce the effectiveness of high-speed (HS) training when using weight-stack (WS) machines. This study used a non-linear scaled wavelet analysis to assess differences between pneumatic (*P*) and WS during seven HS or controlled speed (CS) repetitions. Vastus medialis (VM) and lateralis (VL), and rectus femoris (RF) EMG data were collected during leg extension exercises performed by five regular weight-trainers (mean age ± SD, 23.2 ± 2.9 years). Data were analyzed using continuous wavelet analysis to assess temporal Intensity distribution across eight frequency bands. Significant differences occurred due to speed for all muscles ($p < .0001$). *P* produced higher Intensity than WS for all muscles during HS ($p < .0001$), and VM and RF during CS ($p < .001$). The CON phase produced higher Intensity than ECC for the vasti muscles during CS ($p < .0003$), and VM and RF during HS ($p < .0001$). Intensity increased across repetitions plateauing earlier

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http://dx.doi.org/10.1016/j.humov.2014.12.009

for the vasti than RF during CS. Regardless of the machine, Intensity levels peaked between the 25–53 Hz and 46–82 Hz (2nd and 3rd wavelets) bands. The results indicate that when the objective is increasing power through isoinertial training, *P* machines at HS appear to be the most effective alternative.

1. Introduction

One of the controlling factors used to dictate the response of the neuromuscular system to resistance training is movement speed. Low-speed training is commonly used when the training goal is hypertrophy, since lower speed movements are proposed to prolong time under tension and increase exercise-induced muscle damage (Schoenfeld, 2010, 2012). In contrast, the majority of studies that have been designed to increase power have used high-speed training methods to influence both force and velocity as contributing factors (Fielding et al., 2002; Hakkinen, Komi, & Kauhanen, 1985; Sayers, 2007; Signorile, Carmel, Lai, & Roos, 2005). While free weights, tubing, and weight-stack machines have all been used to train power and strength, the preferred methods used with non-athletic and older populations have been weight-stack and pneumatic machines (Adams et al., 2001; Fiatarone et al., 1993; Fielding et al., 2002; Frontera, Meredith, O'Reilly, Knuttgen, & Evans, 1988). One of the main differences between weight-stack and pneumatic machines is how forces change within a contraction due to momentum. Momentum changes during weight stack exercises are similar to those experienced during free weight lifts. When free weight exercises are performed at high velocities using relatively light load lifts, alternating periods of acceleration and deceleration of the weights occur throughout the concentric phase (Cronin, McNair, & Marshall, 2003; Newton, Kraemer, Hakkinen, Humphries, & Murphy, 1997). This causes an off-loading and subsequent reloading of the weight within the contraction due to changes in inertia. In order to manage the changes in inertia and momentum associated with the plate loaded exercises, pneumatic resistance technology was developed, which provides resistance using pressurized air that is not affected by inertia and momentum (Frost, Cronin, & Newton, 2008). This produces a more constant force throughout the contraction.

Surface electromyography (sEMG) is commonly used to assess localized muscle activity. These assessments typically examine two characteristics of the signal: amplitude and frequency. Amplitude is generally quantified using either the root mean square of the EMG signal (rmsEMG), or the integrated area under the EMG curve (IEMG). The most common technique for assessing changes in the frequency domain has been the Fourier Transform (Basmajian & DeLuca, 1985). The power spectral density of the sEMG signal is determined by applying the magnitude-square of the Fourier Transform to the signal of interest. (Rieke, Warland, de Ruytervan Steveninck, & Bialek, 1999). However, Fourier methods limit the practicality of the analysis (Pinsky, 2002) as the mathematics within Fourier transformations are based on the assumption that the signal is stationary and composed of an infinite number of sine and cosine waves that are infinitely long. This is problematic since sEMG is a non-stationary and linearly enveloped Gaussian distribution (Karlsson, Yu, & Akay, 1999, 2000; Karlsson & Gerdle, 2001). In most practical applications, we define stationarity by the criteria set for a wide-sense stationary random process. This implies we have a constant mean and our autocorrelation function does not change with time. Therefore a non-stationary signal will have a mean that is not constant and the variance will change overtime. A simplistic way of thinking about this is that the frequency of the signal changes across time; therefore, the underlying assumption of a stationary signal is invalid. To comprehensively examine sEMG the use of wavelet analysis has become more common (von Tscharner, 2000) because it provides a time–frequency analysis of sEMG in which the time resolution for each frequency band is different, giving higher time resolution for high frequency bands (wider) and lower time resolution for low frequency bands (narrower). This approach better fits the time–frequency dynamics of physiological signals compared to the Short Time Fourier Transform that has the same time resolution for all frequency bands. In typical Fourier analysis we can obtain high frequency resolution. However, the temporal information is hidden in the phase terms, making it very difficult to determine where a transitory event occurs. In order to gain temporal information, windowing with fixed lengths can be provided by using Short Time Fourier Transform (MacIsaac, Parker, & Scott, 2001). This still hampers the analysis since we only know that these spectral components occur in this fixed window length and still do not have information regarding the actual location within the window. Reducing the window length further can increase the temporal resolution; however, this prevents lower frequencies from being captured within the window causing a loss in frequency resolution. This dilemma of obtaining high frequency resolution and poor time resolution, or poor frequency resolution and high time resolution, is known as the Signal Processing Uncertainty Principle (Gabor, 1946), and is related to the Heisenberg's Uncertainty Principle in physics (Heisenberg, 1930). The Wavelet Transform implements a multi-resolution windowing method that aids in addressing this issue by allowing researchers to assess changes in spectral content as they occur at a specific instance in time. This is essential for several sEMG analyses including Intensity and fatigue. Additionally, wavelet analysis is not affected by the non-stationary properties of sEMG as it has been shown to accurately decompose and reconstruct non-periodic, non-stationary signals (Bertrand, Bohorquez, & Pernier, 1994).

The purpose of the current study was to explore whether or not the wavelet Intensity distributions of the sEMG signal of the superficial quadriceps indicate performance differences of pneumatic and weight-stack resistance exercise performed under high-speed and low-speed conditions.

2. Methods

2.1. Participants

Five undergraduate and graduate students (2 females, 3 males), between the ages of 19–27 years, participated in the study. All participants had prior training experience with the leg extension, and currently performed leg extensions as part of their regular training. Subject characteristic are presented in Table 1.

2.2. Testing apparatus

The Keiser Warrior biaxial leg extension machine (Keiser Corp., Fresno, CA) was used for this study (see Fig. 1a). The machine provides weight stack resistance (WS) on the right side and pneumatic pressure resistance (*P*) on the left (see Fig. 1b). The resistance on the WS can be adjusted by placing a locking pin under the desired plate. Resistance on the *P* side is adjusted by changing the pressure within the pneumatic cylinder. Resistance levels for the *P* side are shown on a gauge located immediately to the right side of the Warrior seat. Additionally resistance on both the *P* and WS sides of the machine could be measured throughout the range of motion using the computer system interfaced with the Warrior. To ensure that the same level of resistance was used for both the *P* and WS conditions, pneumatic values corresponding to a specific number of weight plates were found by matching force–velocity curves. These values are presented in Table 2.

Table 1
Subject demographics.

	Sample	Women	Men
N	5	2	3
Age (yrs)	23.2 ± 2.9	23.0 ± 0.0	23.3 ± 4.0
Height (m)	1.70 ± 0.07	1.66 ± 0.02	1.72 ± 0.09
Weight (km)	72.2 ± 17.4	59.5 ± 0.6	80.7 ± 18.3
Dominant Leg	*R* = 4 *L* = 1	*R* = 2 *L* = 0	*R* = 2 *L* = 1
Lifting experience (yrs)	4.7 ± 3.4	8.0 ± 2.8	2.5 ± 0.9
Training frequency (times wk^{-1})	2.8 ± 2.3	2.0 ± 0.0	3.3 ± 3.1

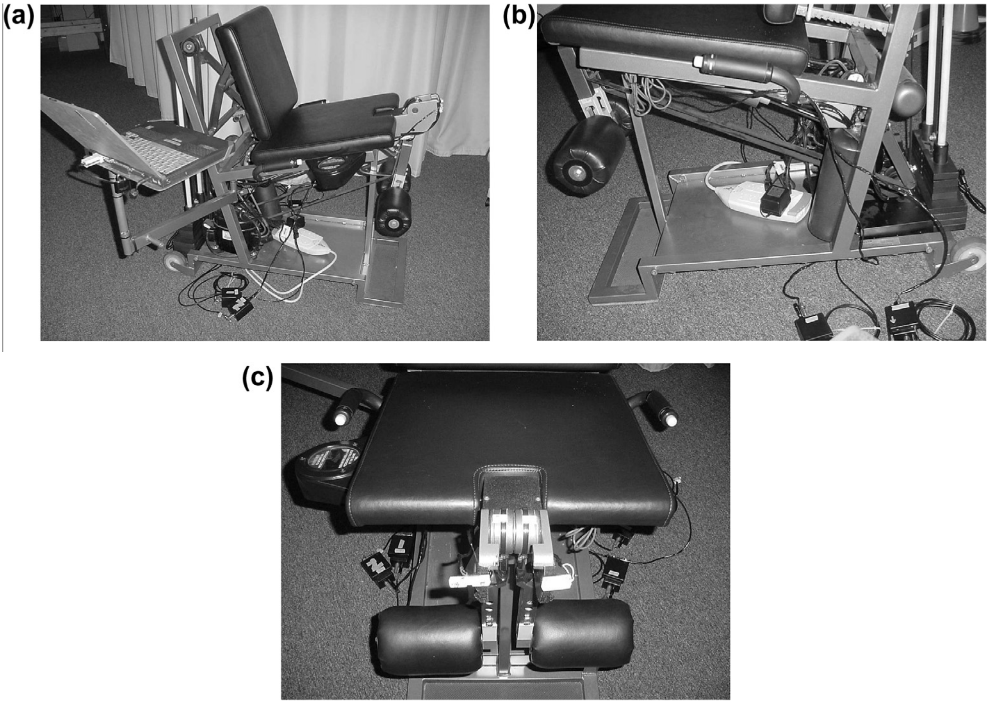

Fig. 1. (a) The Keiser Warrior biaxial leg extension machine (Keiser Corp., Fresno, CA) (b) showing weight stack resistance on the right side and pneumatic pressure resistance on the left, (c) and magnetic closure switches, interfaced with a 5 V power source, located on the frame of the leg extension machine at the beginning and end of each subject's ROM and the magnet attached to the arm of the machine.

2.3. Electromyography

EMG data were collected from the three large superficial quadriceps muscles (vastus lateralis: VL; rectus femoris: RF; and vastus medialis: VM) using a bipolar surface configuration (Basmajian & DeLuca, 1985). Andreassen and Rosenfalck (1978) have reported that aligning with the longitudinal axis of the muscle returns the most selective surface configuration. Additionally, given that (Lynn, Bettles, Hughes, & Johnson, 1978) estimated that the area of detection by a bipolar surface configuration is equal to the interelectrode distance, the likelihood of crosstalk was minimal since the girth of the muscles examined was considerably greater than the 1.5-cm interelectrode distance. The exact location of each motor point was determined using a low-voltage stimulation unit (Grass Corp., West

Table 2
Equivalents between weight plates and pneumatic resistance values.

Number of plates	Pneumatic equivalent (kg-m)
1	6
2	13
3	20
4	28
5	49
6	70
7	84
8	95

Warwick, RI) delivering a series of 5 ms pulses at a rate of 5 pulses per second. Voltage was progressively reduced from approximately 50 V until only one point elicited a response. This point was then used as the motor point for that muscle. After motor points were located, the skin surface distal to each site was shaved; rubbed with a disposable, light abrasive paper and cleaned with alcohol to remove dead surface tissues and oils that might reduce the fidelity of the signal. Disposable Ag/AgCl pre-gelled disk surface electrode pairs (Marquette Medical Systems, Jupiter, FL) were positioned immediately distal to each motor point, 1.5 cm apart and parallel with the underlying muscle fibers, as determined by the pennation of the muscle. A reference electrode was placed on the head of the fibula of the same leg. A wireless EMG telemetry system (TeleMyo DTS, Noraxon USA, Inc., Scottsdale, AZ) was used to collect the data and the quality of the signals was visibly assessed for each muscle before data collection. The Noraxon system used to collect the EMG data had an input impedance of 100 M and a common mode rejection ratio of >100 dB. The gain was set at 2000 with band-pass filtering set between 10 and 500 Hz. Signals were sampled at a speed of 1024 Hz, digitized using a 16-bit A/D converter (DataPac, Laguna Beach, CA), and stored on a personal computer. Interclass correlation coefficients were computed between 2 maximal isokinetic contractions at 1.57 $rad{\cdot}s^{-1}$ performed by 24 subjects (12 men, 12 women; mean age ± *SD*, 23.7 ± 4.0 yrs). The analyses yielded values of 0.94 for the VM, 0.93 for the RF, and 0.98 for the VL. Comparisons were made using isokinetic contractions to reduce the potential impact of differences in velocity between the two contractions, and two contractions were used to reduce the impact of fatigue on the analysis (see Table 3).

2.4. Collection procedure

Participants reported to the laboratory on two separate days. On Day 1 the study was thoroughly explained to the participant and he or she signed an informed consent approved by the University of Miami's Medical Science Subcommittee for the Protection of Human Subjects. The participant then completed a training questionnaire indicating height, weight, arm and leg dominance and training history including exercise type, frequency and experience. Any neuromuscular issues that would affect performance during the leg extension were also determined, rendering those subjects ineligible to participate.

We then determined the participant's 12RM figure for the fast and slow training conditions using the following protocol. Participants were shown the leg extension machine and we explained the difference between the WS and *P* machines. Seat adjustments were made and recorded to ensure proper alignment of the knee joint with the fulcrum on the leg extension machine. The ROM for the leg extension movement was individually established for each subject. Two magnetic closure switches (reed switches), interfaced with a 5 V power source, were placed on the frame of the leg extension machine at each end of the subject's ROM and a magnet was attached to the arm of the machine (see Fig. 1c). When the magnet passed a reed switch, a 5 V spike was produced and sent to the analog-to-digital board of the EMG collection system. These spikes were used to mark the beginning and ending of the concentric and eccentric portions of the lift (see Fig. 2). The first reed switch was placed at the bottom position of the lift. The participant was then asked to maximally extend his or her leg, and the second reed switch was placed on the machine frame at this position to mark the upper end of the subject's ROM. A buzzer was also incorporated into each circuit so that an audible

Table 3
Parameters for the designed wavelets.

Wavelet number	Center frequency (Hz)	Low cutoff (Hz)	High cutoff (Hz)	Bandwidth (Hz)	Time resolution (ms)
0	6.9	0.3	14.7	14.4	63.3
1	19.3	10.8	31.4	20.5	45.0
2	37.7	25.2	53.6	28.4	36.7
3	60.1	45.7	82.0	36.3	30.0
4	92.4	72.1	116.3	44.2	25.0
5	128.5	104.3	156.2	51.9	21.7
6	170.4	142.4	202.1	59.8	20.0
7	218.1	186.6	251.7	65.0	18.3

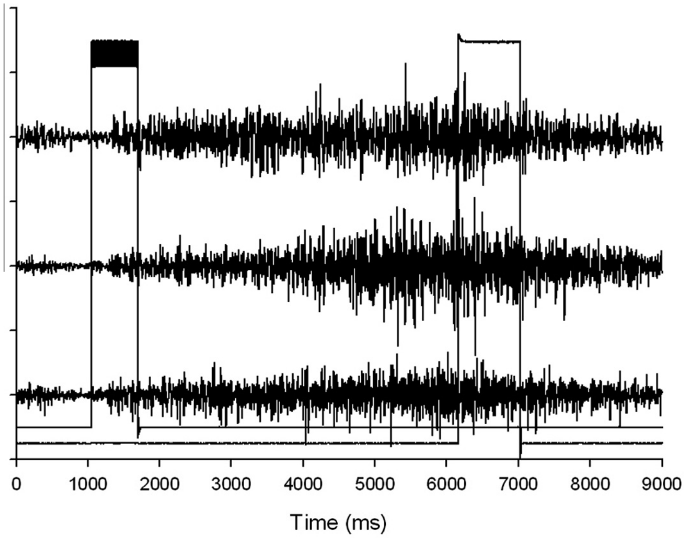

Fig. 2. Graphic representation of the 5 V spike produced when the magnet passed the reed switch at each end of a subject's range of motion.

signal was produced. This audible signal indicated to the participant when he or she had completed the full ROM for the concentric or eccentric phase of a repetition, while the spikes collected at the beginning and end of each phase of a repetition allowed us to accurately mark the events for EMG analysis.

Participants were instructed to perform the leg extension to a count of 2 s up and 3 s down. A metronome was set at 60 bpm and subjects were instructed to use the clicks on the metronome to pace their movements. Participants performed a warm-up set of 12 reps on each leg with 2–3 WS and corresponding *P* settings of 13 or 30 respectively. The testing order (leg and movement speed) was randomly assigned. Participants were required to hit the bottom and top buzzer to ensure full range of motion while staying on the controlled count for each repetition. Three minutes of rest was allowed between testing sets. The weight was then increased by 1 plate, and the corresponding pneumatic pressure set for the second set of 12 warm-up repetitions on each leg. For the third set, the weight and pneumatic pressure were selected using a self-assessed approximation of the participant's 12RM. This step was repeated until the participant was no longer able to achieve 12 repetitions at which time the weights and pneumatic pressures for the previous set were recorded as his or her 12RM figures. The 12RM for every participant was determined within 5 testing sets.

Training and practice for each of the conditions marked the final component of Day 1. Participants completed this training according to their randomly assigned conditions. The sequences for the four conditions were as follows: condition 1, weight stack under controlled speed (WSCS), pneumatic under controlled speed (PCS), weight stack using fast speed (WSHS), and pneumatic using fast speed (PHS); condition 2 was WSHS, PHS, WSCS, PCS; condition 3, PCS, WSCS, PHS, WSHS; condition 4, WSHS, PHS, PCS, WSCS.

During the HS condition, the subjects were asked to perform the leg extension as fast as possible while maintaining full range of motion marked by the buzzer sensor at the top and bottom of the movement. The CS conditions were performed using the movement speed employed during the establishing of the 12RM. Participants performed 4 repetitions each under HS and CS conditions on each leg in randomized order using their 12RM. A 3-min recovery was provided between sets. Participants were required to continue practice repetitions until they performed each condition correctly.

Finally, the force–velocity curves were monitored during a four repetition set using both legs to confirm that the pneumatic pressure selected matched the weight resistance. If an adjustment was needed, the force–velocity curve was monitored during 4 more repetitions after the adjustment was made. Once the force–velocity curve for both the *P* and WS machines matched, the pneumatic pressure and weight settings were recorded on the subject's data sheet. Before leaving, participants were reminded of their appointment for Day 2, asked to wear shorts, and instructed to refrain from exercise for the 24-h period preceding their appointments.

The second day began with electrode preparation and placement. Following electrode placement, isometric knee extensions were performed on a Biodex System 2 dynamometer (Biodex Corp, Shirley, NY) to allow normalization of the EMG signals for each muscle. The right leg was always tested first. The proper seat back distance, powerhead height and ankle pad position were set according to the Biodex manual. Restraint straps were placed across the chest and thigh of the participant to prohibit movement. For warm up, participants performed a series of low-Intensity leg extensions while the researcher started the Biodex program. The knee angle was then set at 130 degrees. Limb weight was measured and recorded by the Biodex. The procedure was explained to participants. The participants arms remained crossed on their chest throughout the measurement to reduce their contribution to the leg extension movement. On the sound command from the Biodex, participants were asked to extend their legs by contracting their quadriceps muscles as strongly as possible and to hold the contraction until instructed by the researcher to relax. The Biodex was locked in place which inhibited further extension of the knee joint; thus, the participants were performing an isometric contraction. Three repetitions were performed for 3 s each with 5 s recovery between repetitions. This procedure was then repeated on the left side. EMG data were collected from all superficial quadriceps throughout each repetition.

Finally, the participants were moved to the Keiser leg extension and the seat setting, weight and pneumatic resistance were adjusted corresponding to their 12RM established on day one. The testing procedure was again explained to participant emphasizing the necessity for them to listen for a buzzer at the top and bottom of each repetition and follow the correct speed. Each of the 4 conditions was performed according the randomly assigned condition order. Three minutes rest was provided between sets. If a buzzer was missed, participants were asked to perform an extra repetition. Additionally, the EMG signal was visually inspected at rest and during the exercise to ensure that no noise or visible artifacts were evident.

2.5. EMG analysis procedures

EMG data from each muscle were collected using DATAPAC 2K2 software (Run Technologies, Mission Viejo, CA). The proposed wavelet analysis method by von Tscharner (2000), has demonstrated merit describing signal Intensity as function of time and frequency in subsequent studies (Mummidisetty, Bohórquez, & Thomas, 2012; So, Ng, Lam, Lo, & Ng, 2009). This wavelet transform methodology differs from conventional biomedical wavelet analysis: conventional wavelet analysis linearly scales the mother wavelet while altering its time resolution (von Tscharner, 2000) while our method designs the mother wavelet in the frequency domain, treating each wavelet as a bandpass filter and the entire set of wavelets as a filterbank. Each wavelet is tuned by scale and center frequency to achieve an appropriate constant plateau value and time resolution making the resultant wavelets non-linearly scaled. This provides a method to adapt the non-stationary nature of the EMG signal to return the EMG Intensity while providing a good compromise between time and frequency resolutions.

Upon completing the Intensity calculations for the sEMG signals for all the subjects, the new Intensity signals were divided into repetitions based upon the temporal markers of each repetition as was determined from the initial data collection. The electronic sensors that registered swing points were used to create repetitions for the new Intensity signals. Each signal was divided into seven repetitions in accordance with how the data were collected and the repetitions were divided into concentric and eccentric swing phases based on the kinematic parameters, i.e. velocity changes. This allowed a comparison of each swing phase of each repetition for each muscle examined.

2.6. Statistical analyses

A $2 \times 2 \times 7 \times 2 \times 7$ (speed $\times$ machine type $\times$ repetition $\times$ contraction type $\times$ frequency band) repeated measures ANOVA with a Tukey HSD *post hoc* adjustment was employed to examine differences in wavelet patterns. All statistical analyses were completed using SAS version 9.2 statistical package (SAS Institute Inc., Cary, NC). Statistical significance was set a priori to $p < .05$.

3. Results

Given that significant differences were detected due to speed for all muscles (VM, (HS = 2.18 ± 0.34; CS = 0.83 ± 0.50; $F = 17127.8$, $p < .0001$); RF, (HS = 2.12 ± 0.46, CS = 0.70 ± 0.53; $F = 13524.0$, $p < .001$) and VL, (HS = 2.08 ± 0.43; CS = 0.80 ± 0.49; $F = 11243.7$, $p < .0001$)), the analysis was further broken down by speed creating separate 2 × 7 × 2 × 7 (machine type × repetition × contraction type × frequency band) repeated measures ANOVA.

3.1. Vastus medialis

3.1.1. Controlled speed

ANOVA performed on the VM during CS training revealed a significant main effects for machine ($F = 18.94$, $p < .001$), wavelet ($F = 352.6$, $p < .001$), swing phase ($F = 57.16$, $p < .0001$) and repetitions ($F = 13.61$, $p < .05$); and, a significant machine × wavelet interaction ($F = 2.39$, $p = .02$). Tukey's *post hoc* analysis revealed that the *P* machine produced significantly greater overall Intensity than WS (*P* = 2.21 ± 0.34, WS = 2.16 ± 0.34) and the CON phase power was greater than ECC (CON = 2.23 ± 0.35; ECC = 2.14 ± 0.33). Table 4 shows the patterns of change across repetitions. The patterns of change across wavelets for each machine are shown in Fig. 3.

3.1.2. High speed

Significant main effects were detected by machine (F = 40.0, $p < .0001$), wavelet ($F = 355.2$, $p < .0001$), swing phase ($F = 1000.6$, $p < .0001$) and repetition ($F = 6.18$, $p < .0001$). Additionally, machine × wavelet ($F = 2.11$, $p = .04$), machine × swing phase ($F = 21.01$, $p < .0001$), and wavelet × swing phase ($F = 26.05$, $p < .0001$) interactions were seen for the VM under the high speed training condition. *Post hoc* analysis showed that machine *P* produced significantly higher Intensity levels than WS (*P* = 0.87 ± 0.02; WS = 0.78 ± 0.02) and the CON phase produced higher Intensity levels than ECC (CON, 1.06 ± 0.02; ECC, 0.60 ± 0.01). Table 5 shows the differences in Intensity across repetitions. The results of the *post hoc* analyses for the machine × wavelet and swing phase × wavelet interactions are presented in Fig. 4a and b, respectively.

3.2. Vastus lateralis

3.2.1. Controlled speed

For the VL during CS training, significant main effects were detected for swing phase ($F = 12.44$, $p = .0004$), and among wavelets ($F = 121.82$, $p < .0001$), and reps ($F = 4.92$, $p < .0001$). *Post hoc* analyses revealed significantly higher Intensity levels during the concentric (2.18 ± 0.02 μV) versus eccentric

Table 4
Patterns of change in Intensity (mV^2) across repetitions for the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) during controlled speed movements.

Repetition[a]	VM	Grouping	VL	Grouping	RF	Grouping
1	2.08 ± 0.03	A	1.98 ± 0.03	A	2.07 ± 0.04	A
2	2.13 ± 0.03	AB	2.03 ± 0.03	B	2.10 ± 0.04	A
3	2.18 ± 0.03	BC	2.09 ± 0.03	B	2.16 ± 0.04	AB
4	2.20 ± 0.03	C	2.10 ± 0.03	B	2.17 ± 0.04	B
5	2.21 ± 0.03	C	2.12 ± 0.03	B	2.17 ± 0.04	BC
6	2.23 ± 0.03	C	2.12 ± 0.03	B	2.19 ± 0.04	C
7	2.23 ± 0.03	C	2.13 ± 0.03	B	2.20 ± 0.04	C

[a] Repetitions with different grouping letters are significantly different from one another.

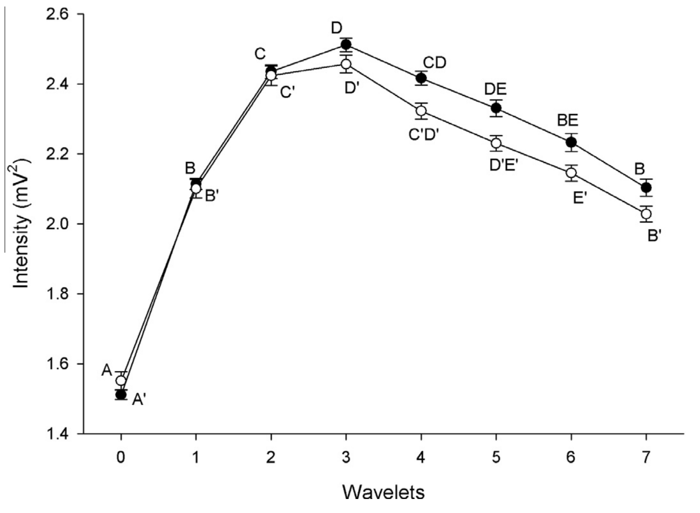

Fig. 3. Differences in Intensity among wavelets for the pneumatic (●) and plate-loaded (○) machines for the vastus medialis under the controlled speed condition. Wavelets with the same letter are not significantly different.

Table 5
Patterns of change in Intensity across repetitions for the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) during high speed movements.

Repetition[a]	VM	Grouping	VL	Grouping	RF	Grouping
1	0.77 ± 0.04	A	0.76 ± 0.04	A	0.70 ± 0.02	A
2	0.79 ± 0.04	AB	0.77 ± 0.04	AB	0.68 ± 0.02	B
3	0.79 ± 0.04	ABC	0.76 ± 0.04	AB	0.66 ± 0.02	C
4	0.82 ± 0.04	ABC	0.78 ± 0.04	AB	0.68 ± 0.02	CD
5	0.86 ± 0.04	BCD	0.82 ± 0.04	C	0.72 ± 0.02	E
6	0.85 ± 0.04	BCD	0.83 ± 0.04	C	0.72 ± 0.02	BE
7	0.90 ± 0.04	D	0.85 ± 0.04	D	0.74.±0.02	BDE

[a] Repetitions with different grouping letters are significantly different from one another.

(2.05 ± 0.02 μV) phase. The Intensity levels across repetitions are presented in Table 4, while Fig. 5 shows the pattern of Intensity change across wavelets.

3.2.2. High speed

Significant main effects were seen for machine ($F = 233.8$, $p < .0001$), wavelet ($F = 797.0$, $p < .0001$), swing phase ($F = 1210.1$, $p < .0001$), and repetition ($F = 6.26$, $p < .0001$) for the VL under the HS training condition. Additionally, significant machine × wavelet ($F = 14.01$, $p < .0001$), swing phase × wavelet ($F = 69.67$, $p < .0001$) machine × swing phase ($F = 33.31$, $p < .0001$), and machine × rep ($F = 5.13$, $p < .0001$) interactions were detected. *Post hoc* analyses revealed that Intensity for *P* (0.89 ± 0.02) was greater than WS (0.72 ± 0.02) and for lifting phase, CON (0.98 ± 0.02) was higher than ECC (0.61 ± 0.02). Pairwise comparisons by repetition are presented in Table 5. Machine × wavelet and swing phase × wavelet comparisons are presented in Fig. 6a and b. Machine × swing phase interactions are illustrated in Fig. 7. Finally, the machine × repetition *post hoc* analysis is shown in Fig. 8.

3.3. Rectus femoris

3.3.1. Controlled speed

When examining wavelet analyses under controlled speed conditions, for the RF significant main effect were seen for machine ($F = 10.92$, $p < .0001$), wavelet ($F = 207.1$, $p < .0001$), and repetitions

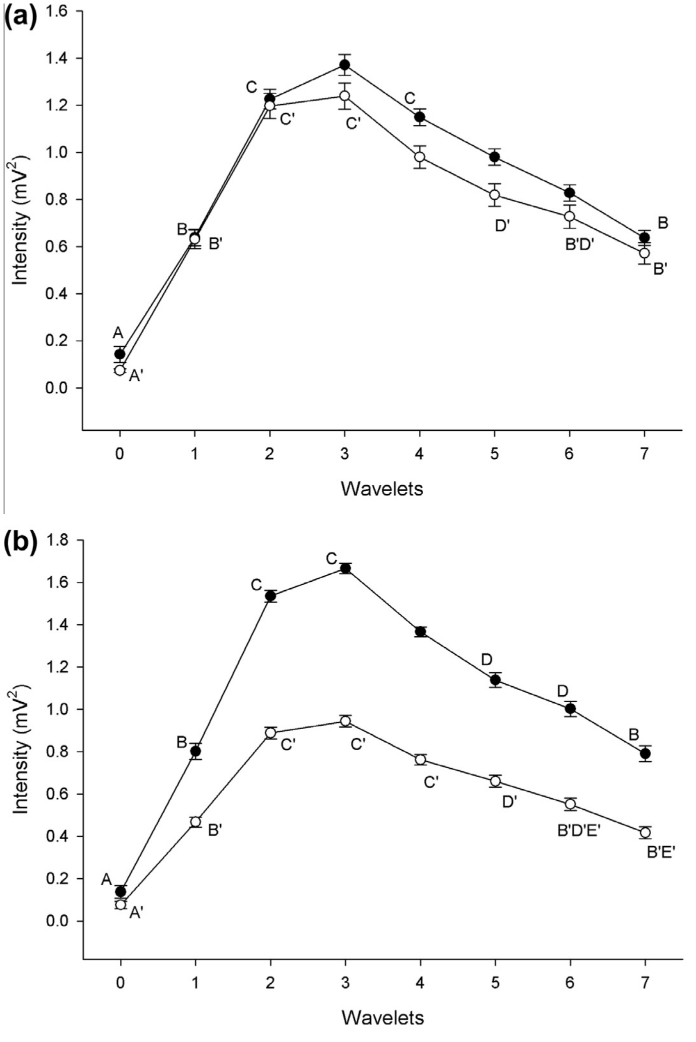

Fig. 4. (a) Differences in Intensity among wavelets for the pneumatic (●) and plate-loaded (○) machines; and, (b) differences in Intensity among wavelets for concentric (●) and eccentric (○) contractile phases for the vastus medialis for the high speed condition. Wavelets with the same letter are not significantly different.

($F = 3.72$, $p < .0011$). A significant machine × wavelet × swing phase interaction ($F = 3.60$, $p < .0011$) was also detected. Pairwise comparisons showed that *P* produced significantly greater Intensity than WS ($P = 2.18 \pm 0.01$; $WS = 2.12 \pm 0.01$). The *post hoc* analysis of the main effect for wavelets is presented in Fig. 9, and *post hoc* analysis for the main effect by repetitions is presented in Table 4. *Post hoc* analyses of the machine × wavelet × swing phase interaction is provided in Table 6.

3.3.2. High speed

For the RF under high speed conditions, significant main effects were detected for machine ($F = 135.1$, $p < .0001$), wavelet ($F = 738.9$, $p < .0001$), swing phase ($F = 1536.5$, $p < .0001$) and repetition ($F = 3.27$, $p = .003$). Additionally, significant machine × wavelet ($F = 3.34$, $p = .0016$), machine × repetition ($F = 7.14$, $p < .0001$), machine × swing phase ($F = 32.44$, $p < .0001$), wavelet × swing phase ($F = 61.54$, $p < .0001$), and machine × wavelet × swing phase interactions ($F = 3.07$, $p = .0034$) were

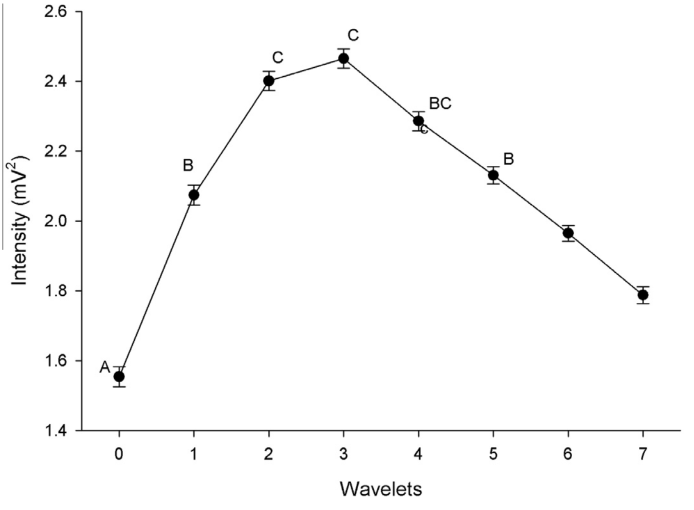

Fig. 5. Differences in Intensity across wavelets for the vastus lateralis under the controlled speed condition. Wavelets with the same letter are not significantly different.

detected. *Post hoc* analysis for machine showed that *P* produced greater Intensity than WS ($P = 0.77 \pm 0.01$, $WS = 0.63 \pm 0.01$); and for swing phase, CON produced significantly greater Intensity than ECC ($CON = 0.93 \pm 0.01$, $ECC = 0.47 \pm 0.01$). *Post hoc* analysis across repetitions is presented in Table 5; while Table 7 presents the machine × swing phase pairwise comparisons. *Post hoc* analysis for wavelet is presented in Fig. 9. Pairwise comparison showing differences in wavelet Intensity by machines are presented in Fig. 10a and in Intensity across repetitions by machine in Fig. 10b. Differences in Intensity across wavelets by swing phase are presented in Fig. 11.

4. Discussion

4.1. Speed

The significantly higher Intensity levels for high speed versus controlled speed movements across all muscles regardless of loading method, contractile phase or repetition number were expected. Correlations between increases in movement velocity and EMG amplitude and rate of amplitude increase have been demonstrated in a number of muscles under numerous exercise conditions (Arendt-Nielsen, Sinkjaer, Nielsen, & Kallesoe, 1991; Fujii & Moritani, 2012; Sakamoto & Sinclair, 2012; Van Cutsem, Duchateau, & Hainaut, 1998). The higher Intensity levels seen with HS versus CS exercise may be the result of a number of proposed mechanisms including: increased motor unit synchronization, earlier and more substantial recruitment of larger, fast contracting motor units, increased rate coding, and the emergence of doublets. Given the non-stationary nature of the EMG signal and tissue filtering due to the varying locations of motor pools recruited with changes in contractile speed, patterns of change in central markers of the frequency power spectrum during high-speed movements and correlations between these central markers and conduction velocity are tenuous at best (Merlo et al., 2005). Therefore, employing a time–frequency analysis, such as the one used in this study, may provide a more accurate picture of the changes occurring with speed during the exercises conditions examined (see Table 8).

4.2. Machines

The significantly higher Intensity levels seen for the *P* versus WS machine, especially during HS training, reflect results reported by Peltonen, Hakkinen and Avela (2013) in their comparison between

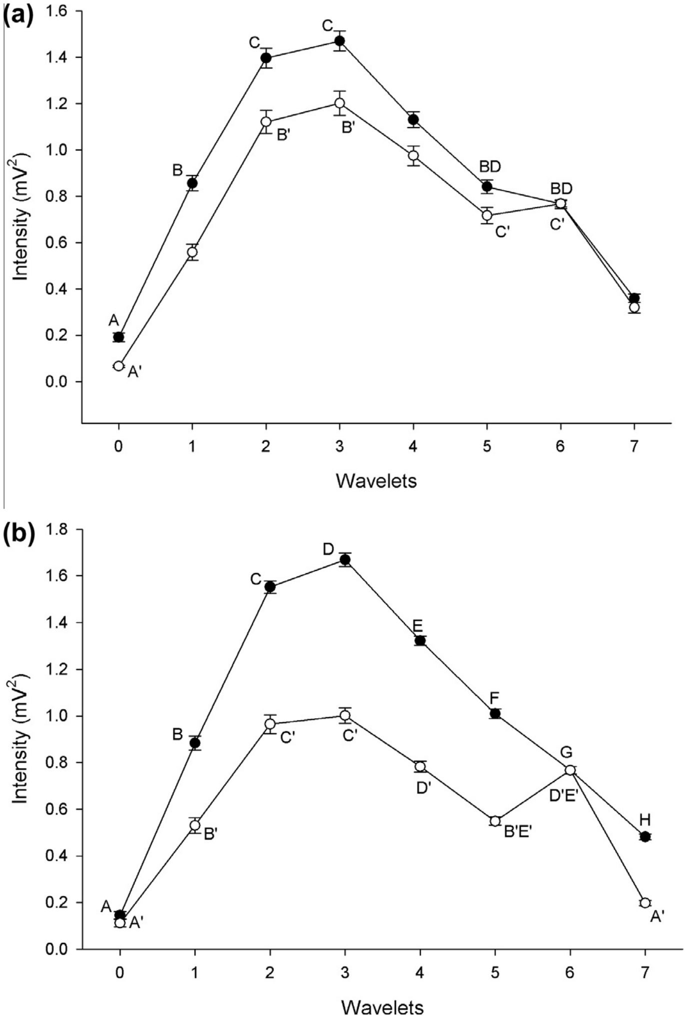

Fig. 6. (a) Differences in Intensity among wavelets for the pneumatic (●) and plate-loaded (○) machines; and, (b) differences in Intensity among wavelets for concentric (●) and eccentric (○) contractile phases for the vastus lateralis under the high speed condition. Wavelets with the same letter are not significantly different.

pneumatic and weight stack machines during hypertrophy, strength and power based resistance training sets. These researchers reported that on the weight stack machine, angular velocities increased significantly from knee joint angles 60 through 140 degrees across all loads, while no velocity changes were seen across angles for pneumatic training. At the beginning of the knee extension exercise, they recorded accelerations 4–10 times greater during pneumatic compared to weight stack training. And finally, average mechanical power was significantly higher on the pneumatic device than on the weight stack device for all loading conditions with the exception of when repetitions were performed at 100% 1 RM. 2d). They noted that the higher activity levels of the superficial quadriceps during pneumatic training were seen under the lower loading conditions, but differences between machines diminished as higher loads reduced movement velocities for both machines diminishing the impact of momentum and inertia during the weight-stack condition.

As noted by these researchers and others, the fact that resistance on weight stack machines is dependent on mass, while resistance for pneumatic devices is proportional to the air pressure, means

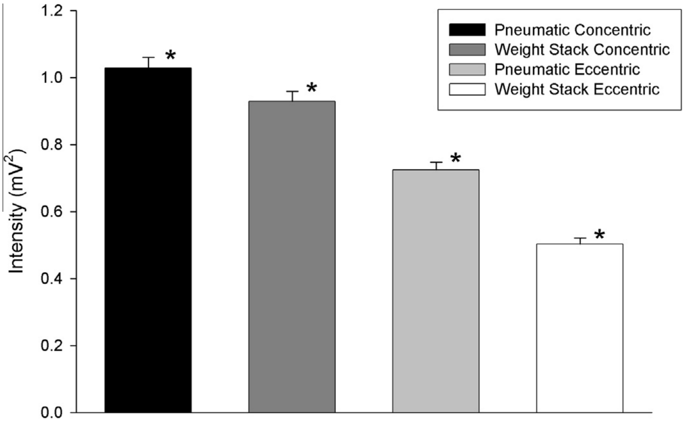

Fig. 7. Machine × swing phase interactions for the vastus lateralis under the high speed condition. *Significantly different from all other machine × swing phase conditions.

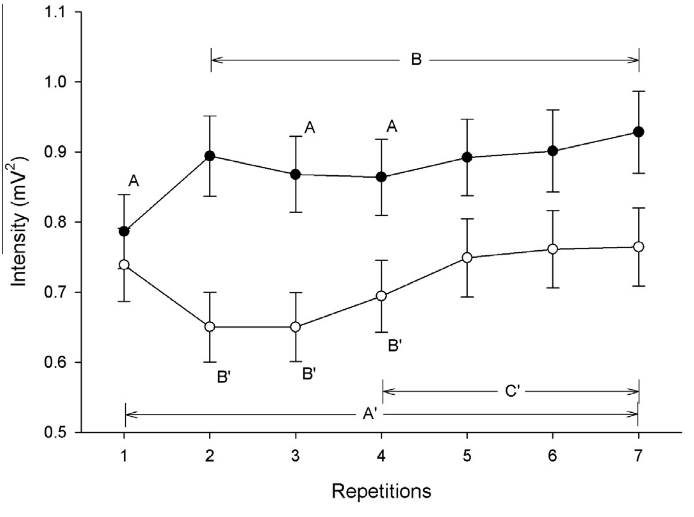

Fig. 8. Differences in Intensity among repetitions for the pneumatic (●) and plate-loaded (○) machines for the vastus lateralis under the high speed condition. Wavelets with the same letter are not significantly different.

that the former is affected dramatically, especially at lower resistances during high-speed movements, by momentum, while the resistance provided by pneumatic machines is relatively constant throughout loads and range of motion (Frost et al., 2008; Peltonen et al., 2013). The results of the current study showed that during CS the *P* training produced significantly greater Intensity for the VL and RF. The higher levels of Intensity produced by the quadriceps muscles with *P* training suggests that this training method provides a better approach for increasing muscle power than WS training, a finding supported by previous research (Frost et al., 2008). A possible explanation is the uninterrupted loading patterns seen for both CS and HS conditions for the *P* versus WS condition (see Fig. 12a and b).

Given the inconsistent nature of the EMG signal during dynamic contractions, especially during the HSWS condition, the wavelet analysis used in this study can be expected to provide a more accurate assessment of the levels of EMG response across the frequency spectrum. As noted by (Karlsson et al., 2000) during dynamic movements changes in membrane conduction velocity, the number of active

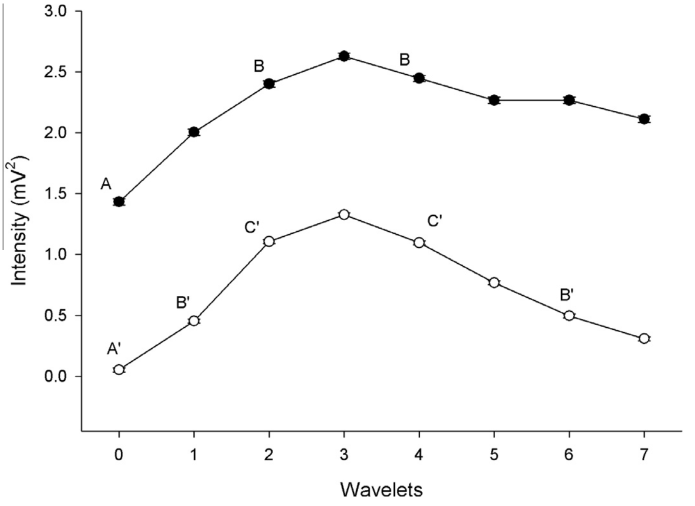

Fig. 9. Differences in Intensity among wavelets for the high-speed (●) and controlled speed (○) for the rectus femoris. Wavelets with the same letter are not significantly different.

Table 6
Comparison of wavelets Intensity across machines and phases for the rectus femoris under the controlled speed condition.

Wavelet[a]	Frequency range	Pneumatic concentric		Pneumatic eccentric		Weight stack concentric		Weight stack eccentric	
		Mean ± SE	Grouping	Mean ± SE	Grouping	Mean ± SE	Grouping	Mean ± SE	Grouping
0	0.3–14.7	1.538 ± 0.028	A	1.429 ± 0.019	A	1.257 ± 0.110	A	1.508 ± 0.003	A
1	10.8–31.4	2.196 ± 0.027	B	2.051 ± 0.021	B	1.702 ± 0.130	B	2.071 ± 0.002	B
2	25.2–53.6	2.594 ± 0.027	C	2.431 ± 0.019	C	2.145 ± 0.133	C	2.433 ± 0.002	C
3	45.7–82.0	2.742 ± 0.024	D	2.562 ± 0.018	CD	2.656 ± 0.026	D	2.552 ± 0.003	C
4	72.1–116.3	2.460 ± 0.054	BE	2.400 ± 0.018	CD	2.503 ± 0.029	DE	2.421 ± 0.003	C
5	104.3–156.2	2.298 ± 0.058	BCEF	2.248 ± 0.024	BCE	2.235 ± 0.026	CEF	2.282 ± 0.003	BC
6	142.4202.1	2.117 ± 0.054	BCF	2.055 ± 0.027	BE	2.101 ± 0.035	CF	2.175 ± 0.003	BCD
7	186.6–251.7	1.911 ± 0.057	C	1.871 ± 0.022	B	1.538 ± 0.028	BC	1.977 ± 0.004	BD

[a] Different letters indicate statistical significance between wavelets.

Table 7
Pairwise comparisons of Intensity levels for contractile phase by machine during contraction of the rectus femoris using high speed training.

	Concentric	Eccentric
Pneumatic	0.963 ± 0.034	0.575 ± 0.024*
Weight stack	0.894 ± 0.034	0.374 ± 0.018*

* Significantly different than all other conditions.

motor units, electrodes' relative position to the targeted muscle fibers, the geometric relation between electrodes and the muscle's moor point and muscle length, all add to the non-stationary nature of the EMG signal and support the use of a time–frequency analysis method. In their analysis of the most accurate and precise time–frequency analysis during dynamic contractions the continuous wavelet transform was deemed most effective. In the context of the vast array of movement speeds, length changes, and changes in detection area inherent to the comparisons between machines at different

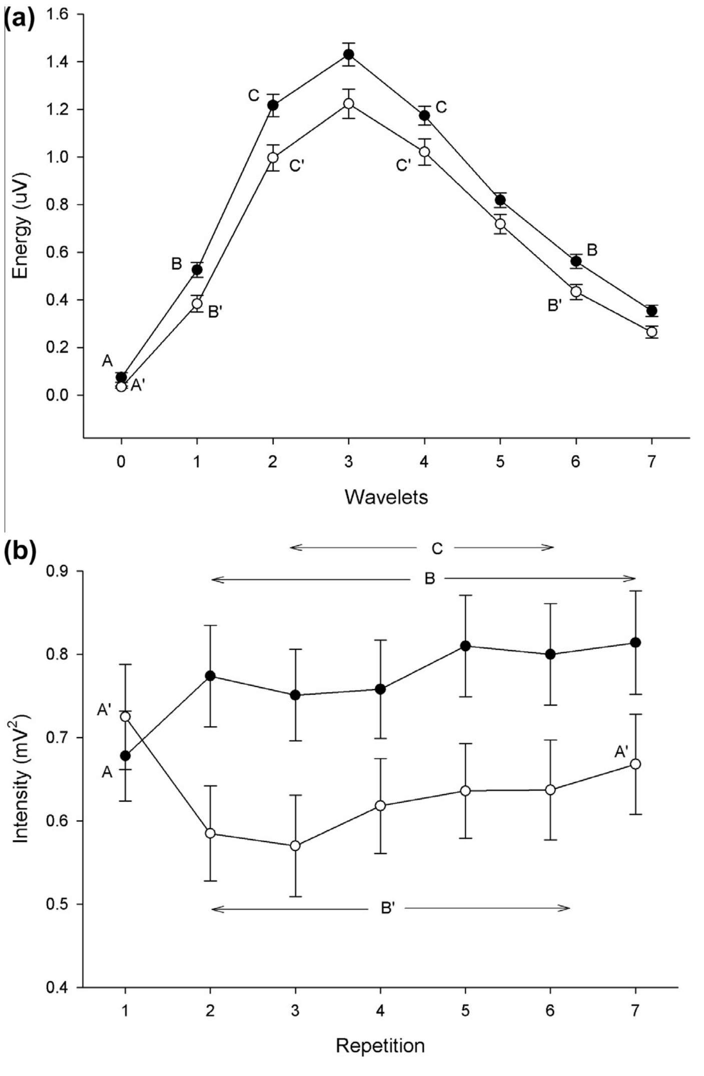

Fig. 10. (a) Differences in wavelet Intensity and (b) Intensity across repetitions by pneumatic (●) and plate-loaded (○) machines machine for high-speed training of the rectus femoris. Repetitions with the same letter are not significantly different.

training speeds in this study the wavelet analysis should be considered the most appropriate diagnostic tool.

4.3. Repetitions

The increases in Intensity levels across repetitions for the VL, VM, and RF under both HS and CS conditions reflect the increases in amplitude and decreases in mean and median power frequencies of the EMG signal typically reported across multi-set resistance training workouts (Gomez, Ma, Adams, Stoutenberg, & Signorile, 2005; Stoutenberg, Pluchino, Ma, Hoctor, & Signorile, 2005) and dynamic exercise protocols (Beck et al., 2005; Petrofsky & Lind, 1980; Zuniga & Malek, 2013). However, the impact of dynamic protocols on EMG amplitude and frequency components are often

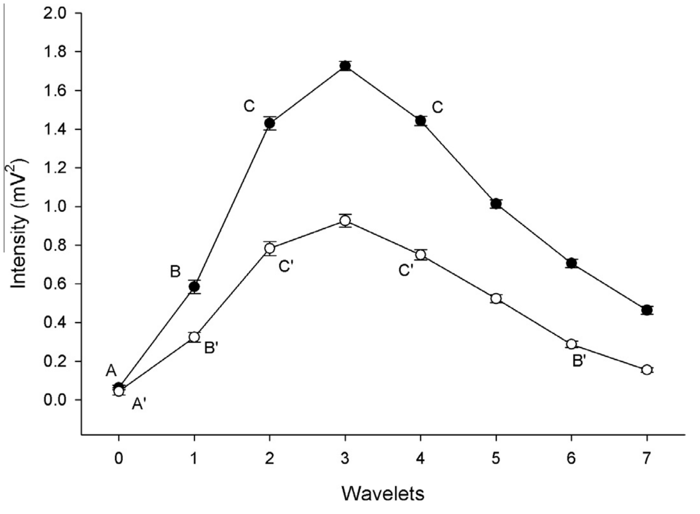

Fig. 11. Differences in wavelet Intensity during concentric (●) and eccentric (○) phases for the rectus femoris. Wavelets with the same letter are not significantly different.

Table 8
Comparison of wavelets across machines and phases for the rectus femoris under the high speed condition.

Wavelet[a]	Frequency range	Pneumatic concentric		Pneumatic eccentric		Weight stack concentric		Weight stack eccentric	
		Mean ± SE	Grouping	Mean ± SE	Grouping	Mean ± SE	Grouping	Mean ± SE	Grouping
0	0.3–14.7	0.077 ± 0.021	A	0.071 ± 0.036	A	0.051 ± 0.009	A	0.017 ± 0.003	A
1	10.8–31.4	0.611 ± 0.045	B	0.441 ± 0.037	B	0.559 ± 0.052	B	0.208 ± 0.020	B
2	25.2–53.6	1.472 ± 0.052	C	0.960 ± 0.049	C	1.387 ± 0.044	C	0.605 ± 0.034	C
3	45.7–82.0	1.765 ± 0.035	D	1.095 ± 0.038	D	1.688 ± 0.031	D	0.758 ± 0.036	D
4	72.1–116.3	1.468 ± 0.023	C	0.878 ± 0.025	C	1.418 ± 0.041	C	0.623 ± 0.037	CD
5	104.3–156.2	1.032 ± 0.025	E	0.604 ± 0.024	E	0.994 ± 0.037	E	0.443 ± 0.028	E
6	142.4202.1	0.769 ± 0.025	F	0.353 ± 0.022	F	0.644 ± 0.032	B	0.222 ± 0.021	B
7	186.6–251.7	0.512 ± 0.025	G	0.195 ± 0.016	G	0.415 ± 0.031	F	0.115 ± 0.012	F

[a] Different letters indicate statistical significance between wavelets.

inconsistent and less impressive than those seen with prolonged isometric contractions; perhaps owing to the variations in muscle length, contractile phase, and intermittent levels of blood flow (Christensen, Søgaard, Jensen, Finsen, & Sjøgaard, 1995; Komi & Tesch, 1979; Moritani, Muramatsu, & Muro, 1987; Nardone, Romanò, & Schieppati, 1989) .

The amplitude changes seen with prolonged isometric contractions are commonly attributed to the need to recruit more motor units and synchronization to compensate for the reduced force outputs of those already in use (Person & Kudina, 1968). The underlying mechanisms offered for the changes in the frequency characteristics of the EMG are far more complex and include: widening of the action-potential wavelength, potentially due to high lactate, hydrogen ions, extracellular potassium or inorganic phosphate concentrations and subsequent reduced efficiency of the sodium/potassium pump leading to reduced fiber conduction velocity; increased motor unit synchronization, leading to a compression of the frequency spectrum; and finally, derecruitment of fatigable muscle fibers which may also contribute to the downward shift in frequency (Beck, Stock, & DeFreitas, 2012; Beck et al., 2005; Sadoyama, 1983; Tesch, Komi, Jacobs, Karlsson, & Viittasalo, 1983).

Our results, showing increases in Intensity across repetitions suing wavelet analysis, reflect those reported by Beck et al. (2012); but to a lesser magnitude, since their testing protocol incorporated 50

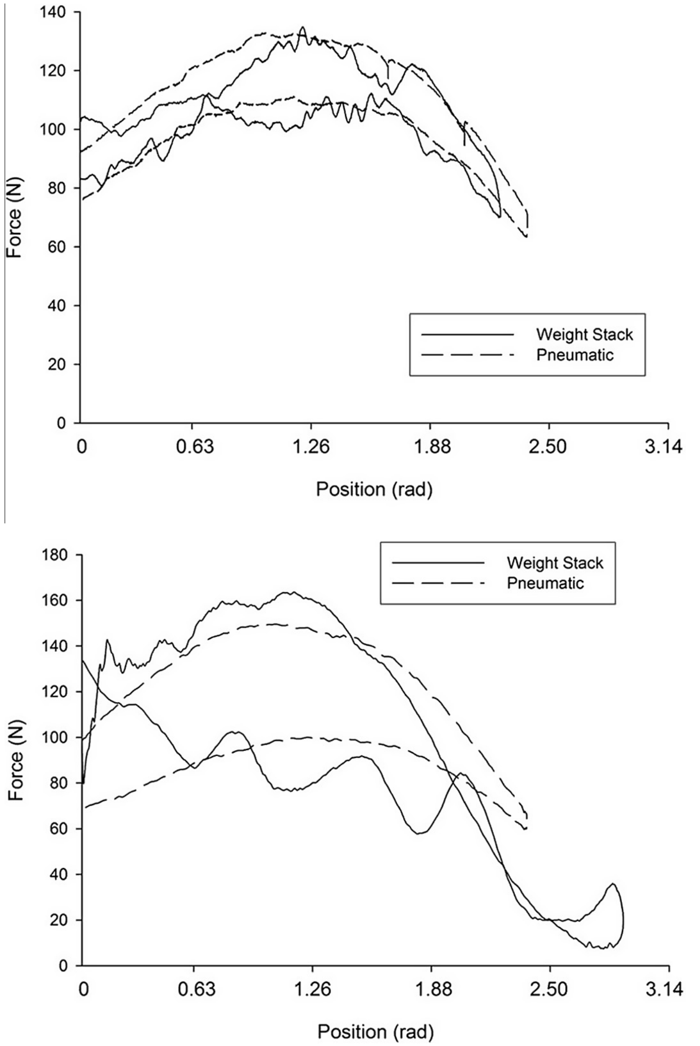

Fig. 12. Sample pneumatic and weight Stack curves for controlled speed (a) and high speed (b) conditions from subject 14, repetition 3.

maximal isokinetic repetitions at 3.14 rad s^{-1} (180 deg/s). Our data also indicated decreases in overall Intensity as reported by So et al. (2009) using a similar 50 maximal isokinetic repetition protocol as Beck et al. during knee extension. However, no wavelet × repetition interaction was evidenced under any of the tested conditions, which does differ to some extent from the findings of So et al. who reported their greatest shifts in Intensity for VM, VL, and RF in wavelet domain four. The methodological differences between the studies offer a possible explanation. As was the case when comparing our results to those of Beck et al., clearly the testing protocol was considerably longer and used isokinetic rather than isoinertial resistance. Additionally, their analyses were performed at five equally spaced was ranges of motion between 80 and 180 degrees. These differences make unambiguous comparisons between the studies impossible.

Finally, the larger number of significant differences seen across repetitions for the HS compared to CS conditions for all muscles tested is consistent with our expectation that higher speed, and therefore higher Intensity, protocols would induce greater levels of fatigue.

4.4. Contractile phase

For both vasti muscles higher values for the CON versus ECC phase were seen during HS training, and these were increasingly more evident across wavelets 2 through 5. Additionally, these differences were greater for the *P* compared to WS machine. The data for the rectus femoris also showed higher Intensity levels for the CON versus ECC phase. These results were predictable given the higher EMG amplitude levels typically reported for concentric compared to eccentric contractions, coupled with the notably smaller differences between the two contractile states seen in measures of central tendency in the frequency domain (Pincivero, Coelho, & Campy, 2008; Tesch, 1990).

4.5. Wavelets

The wavelet patterns seen in the current study are analogous to those reported by So et al. (2009) in their study. For an appropriate comparison to be made, we compared the peak Intensity seen at the first time interval (initial ten repetitions) to our data across the seven repetition set. Our results showed that for both vasti muscles and the RF for the *P* and WS machines under HS and CS Intensity peaked within wavelet 3. This is the same pattern reported by So et al. (2009) for these muscles during the initial 10 repetitions of their 50 repetition set used in their fatigue protocol. Given the limited number of repetitions used in the current study and the submaximal isoinertial versus the maximal isokinetic in the study by (So et al., 2009), the minor shift toward the lower bands appears appropriate.

Our data confirm the feasibility of using wavelet analysis to detect changes in the frequency characteristics of the EMG signal during resistance training. Given the changes in a number of factors during dynamic exercise compared to static contractions the time–frequency analysis used here may be more effective at detecting changes in the frequency. More importantly, our analysis demonstrates that *P* training increases muscle power at both high and low speeds to a greater degree than weight-stack training. The capacity of the non-linear discrete wavelet analysis technique to detect differences among exercise speeds, mechanical loading techniques, contractile states and repetition numbers indicate its effectiveness as a tool for evaluating muscular activity levels during dynamic movements, especially at high contractile speed.

5. Conclusion

The major findings of this study were that overall Intensity levels and patterns of Intensity distribution across wavelets of the superficial quadriceps during a set of leg extension are affected by movement speed, loading method, contractile phase and repetition number. These data fortify the idea that high-speed isoinertial exercises can lead to an increase in recruitment patterns that positively affect muscular power. Additionally, the paucity of significant differences between weight stack and pneumatic machines at controlled speeds compared to the substantial number observed at high speeds, demonstrates the positive impact of using pneumatic equipment where momentum and inertial changes are controlled. Finally, these data are especially relevant in a study using dynamic resistance training since the assumption of stationary waveforms on which Fourier analysis is based is inappropriate (Karlsson et al., 2000; Ranniger, 1997).

Acknowledgment

The authors would like to thank Ms. Elizabeth Foley for her careful editing and preparation of this manuscript for publication.

References

Adams, K. J., Swank, A. M., Berning, J. M., Sevene-Adams, P. G., Barnard, K. L., & Shimp-Bowerman, J. (2001). Progressive strength training in sedentary, older African-american women. *Medicine and Science in Sports Exercise, 33*(9), 1567–1576.

Andreassen, S., & Rosenfalck, A. (1978). Recording from a single motor unit during strong effort. *IEEE Transactions on Biomedical Engineering, 25*(6), 501–508.

Arendt-Nielsen, L., Sinkjaer, T., Nielsen, J., & Kallesoe, K. (1991). Electromyographic patterns and knee joint kinematics during walking at various speeds. *Journal of Electromyography and Kinesiology, 1*(2), 89–95.
Basmajian, J. V., & DeLuca, C. J. (1985). *Muscles alive*. Baltimore: Williams & Wilkins.
Beck, T. W., Housh, T. J., Cramer, J. T., Weir, J. P., Johnson, G. O., Coburn, J. W., et al (2005). Mechanomyographic amplitude and frequency responses during dynamic muscle actions: A comprehensive review. *Biomedical Engineering Online, 4*(1), 67.
Beck, T. W., Stock, M. S., & DeFreitas, J. M. (2012). Time–frequency analysis of surface electromyographic signals during fatiguing isokinetic muscle actions. *Journal of Strength and Conditioning Research/National Strength and Conditioning Association, 26*(7), 1904–1914.
Bertrand, O. O., Bohorquez, J., & Pernier, J. (1994). Time–frequency digital filtering based on an invertible wavelet transform: An application to evoked potentials. *IEEE Transactions on Biomedical Engineering, 41*(1), 77–88.
Christensen, H. H., Søgaard, K., Jensen, B. R., Finsen, L., & Sjøgaard, G. (1995). Intramuscular and surface EMG power spectrum from dynamic and static contractions. *Journal of Electromyography and Kinesiology, 5*(1), 27–36.
Cronin, J. B., McNair, P. J., & Marshall, R. N. (2003). Force–velocity analysis of strength-training techniques and load: Implications for training strategy and research. *Journal of Strength and Conditioning Research, 17*(1), 148–155.
Fiatarone, M. A., O'Neill, E. F., Doyle, N., Clements, K. M., Roberts, S. B., Kehayias, J. J., et al (1993). The boston FICSIT study: The effects of resistance training and nutritional supplementation on physical frailty in the oldest old. *Journal of the American Geriatrics Society, 41*, 333–337.
Fielding, R. A., LeBrasseur, N. K., Cuoco, A., Bean, J., Mizer, K., & Fiatarone Singh, M. A. (2002). High-velocity resistance training increases skeletal muscle peak power in older women. *Journal of the American Geriatrics Society, 50*(4), 555–662.
Frontera, W. R., Meredith, C. N., O'Reilly, K. P., Knuttgen, H. G., & Evans, W. J. (1988). Strength conditioning in older men: Skeletal muscle hypertrophy and improved function. *Journal of Applied Physiology, 64*(3), 1038–1044.
Frost, D. M., Cronin, J. B., & Newton, R. U. (2008). A comparison of the kinematics, kinetics and muscle activity between pneumatic and free weight resistance. *European Journal of Applied Physiology, 104*(6), 937–956.
Fujii, S., & Moritani, T. (2012). Rise rate and timing variability of surface electromyographic activity during rhythmic drumming movements in the world's fastest drummer. *Journal of Electromyography and Kinesiology, 22*(1), 60–66.
Gabor, D. (1946). Theory of communication. *Journal of the Institution of Electrical Engineers, 93*(26), 429–457.
Gomez, T. R., Ma, F., Adams, J. B., Stoutenberg, M., & Signorile, J. F. (2005). The impact of seatback angle on electromyographical activity of the lower back and quadriceps muscles during bilateral knee extension. *Journal of Strength and Conditioning Research, 19*(4), 908–917.
Hakkinen, K., Komi, P. V., & Kauhanen, H. (1985). Effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises. *Scandinavian Journal of Sports Science, 7*(2), 65–76.
Heisenberg, W. (1930). *The physical principles of the quantum theory*. Chicago, IL: University of Chicago Press.
Karlsson, S., Yu, J., & Akay, M. (1999). Enhancement of spectral analysis of myoelectric signals during static contractions using wavelet methods. *IEEE Transactions on Biomedical Engineering, 46*(6), 670–684.
Karlsson, S., Yu, J., & Akay, M. (2000). Time–frequency analysis of myoelectric signals during dynamic contractions: A comparative study. *Transactions on Biomedical Engineering, 47*(2), 228–238.
Karlsson, S., & Gerdle, B. (2001). Mean frequency and signal amplitude of the surface EMG of the quadriceps muscles increase with increasing torque—a study using the continuous wavelet transform. *Journal of Electromyography and Kinesiology, 11*(2), 131–140.
Komi, P. V., & Tesch, P. (1979). EMG frequency spectrum, muscle structure, and fatigue during dynamic contractions in man. *European Journal of Applied Physiology, 42*, 41–50.
Lynn, P. A., Bettles, N. D., Hughes, A. D., & Johnson, S. W. (1978). The influence of electrode geometry on bipolar recordings of the surface electromyogram. *Medical and Biological Engineering and Computing, 16*(6), 651–660.
MacIsaac, D., Parker, P. A., & Scott, R. N. (2001). The short-time Fourier transform and muscle fatigue assessment in dynamic contractions. *Journal of Electromyography and Kinesiology, 11*(6), 439–449.
Merlo, E., Pozzo, M., Antonutto, G., di Prampero, P. E., Merletti, R., & Farina, D. (2005). Time–frequency analysis and estimation of muscle fiber conduction velocity from surface EMG signals during explosive dynamic contractions. *Journal of Neuroscience Methods, 142*(2), 267–274.
Moritani, T., Muramatsu, S., & Muro, M. (1987). Activity of motor units during concentric and eccentric contractions. *American Journal of Physical Medicine, 66*(6), 338.
Mummidisetty, C. K., Bohórquez, J., & Thomas, C. K. (2012). Automatic analysis of EMG during clonus. *Journal of Neuroscience Methods, 204*(1), 35–43.
Nardone, A., Romanò, C., & Schieppati, M. (1989). Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *The Journal of Physiology, 409*(1), 451.
Newton, R. U., Kraemer, W. J., Hakkinen, K., Humphries, B. J., & Murphy, A. J. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *Journal of Applied Physiology and Occupational Physiology, 5*(4), 333–342.
Peltonen, H., Hakkinen, K., & Avela, J. (2013). Neuromuscular responses to different resistance loading protocols using pneumatic and weight stack devices. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 23*(1), 118–124.
Person, R. S., & Kudina, L. P. (1968). Cross-correlation of electromyograms showing interference patterns. *Electroencephalography and Clinical Neurophysiology, 25*(1), 58–68.
Petrofsky, J. S., & Lind, A. R. (1980). Frequency analysis of the surface electromyogram during sustained isometric contractions. *European Journal of Applied Physiology and Occupational Physiology, 43*(2), 173–182.
Pincivero, D. M., Coelho, A. J., & Campy, R. M. (2008). Contraction mode shift in quadriceps femoris muscle activation during dynamic knee extensor exercise with increasing loads. *Journal of Biomechanics, 41*(15), 3127–3132.
Pinsky, M. (2002). *Introduction to fourier analysis and wavelets*. Pacific Grove, CA: Brooks/Cole.
Ranniger, C. U. (1997). EMG mean power frequency determination using wavelet analysis. *Proceedings of the annual international conference of the IEEE Engineering in Medicine and Biology Society, 4*, 1589–1592.

Rieke, F., Warland, D., de Ruytervan Steveninck, R., & Bialek, W. (1999). *Spikes: Exploring the neural code (computational neuroscience)*. Cambridge, MA: MIT Press.
Sadoyama, T. (1983). Relationships between muscle fibre conduction velocity and frequency parameters of surface EMG during sustained contraction. *European Journal of Applied Physiology and Occupational Physiology, 51*(2), 247–256.
Sakamoto, A., & Sinclair, P. J. (2012). Muscle activations under varying lifting speeds and intensities during bench press. *European Journal of Applied Physiology, 112*(3), 1015–1025.
Sayers, S. P. (2007). High-speed power training: A novel approach to resistance training in older men and women: A brief review and pilot study. *Journal of Strength and Conditioning Research, 21*(2), 518–526.
Schoenfeld, B. J. (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *Journal of Strength and Conditioning Research, 24*(10), 2857–2872.
Schoenfeld, B. J. (2012). Does exercise-induced muscle damage play a role in skeletal muscle hypertrophy? *Journal of Strength and Conditioning Research, 26*(5), 1441–1453.
Signorile, J. F., Carmel, M. P., Lai, S., & Roos, B. A. (2005). Early plateaus of power and torque gains during high- and low-speed training in older women. *Journal of Applied Physiology, 98*(4), 1213–1220.
So, R., Ng, J. K., Lam, R. W., Lo, C. K., & Ng, G. Y. (2009). EMG wavelet analysis of quadriceps muscle during repeated knee extension movement. *Medicine and Science in Sports and Exercise, 41*(4), 788.
Stoutenberg, M., Pluchino, A., Ma, F., Hoctor, J., & Signorile, J. F. (2005). The impact of foot position on electromyographical activity of the superficial quadriceps muscles during leg extension. *Journal of Strength and Conditioning Research, 19*(4), 931–938.
Tesch, P. A. (1990). Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. *Acta Physiologica Scandinavica, 138*(3), 263–271.
Tesch, P. A., Komi, P. V., Jacobs, I., Karlsson, J., & Viittasalo, J. T. (1983). Influence of lactate accumulation of EMG frequency spectrum during repeated concentric contractions. *Acta Physiologica Scandinavica, 119*(1), 61–67.
Van Cutsem, M., Duchateau, J., & Hainaut, K. (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *The Journal of Physiology, 513*(Pt 1), 295–305.
von Tscharner, V. (2000). Intensity analysis in time–frequency space of surface myoelectric signals by wavelets of specified resolution. *Journal of Electromyography and Kinesiology, 10*(6), 433–445.
Zuniga, J. M., & Malek, M. H. (2013). Electromyographic responses of the superficial quadriceps femoris muscles during incremental treadmill running treadmill EMG responses. *Muscle and Nerve*.