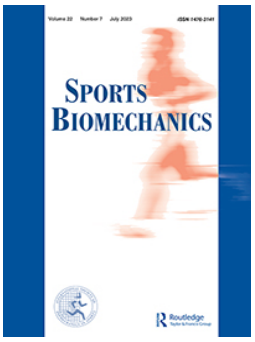

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An exploration of the motor unit behaviour during the concentric and eccentric phases of a squat task performed at different speeds

Eva Orantes-Gonzalez [a], Jose Heredia-Jimenez [b], Steven B Lindley [c], Jim D Richards [d] and Graham J Chapman [d]

[a]Department of Sports and Computer Science, Faculty of Sports, University of Pablo de Olavide, Seville, Spain; [b]Department of Physical Education and Sport, Faculty of Education, Economy and Technology, University of Granada, Ceuta, Spain; [c]Delsys Europe, Manchester, UK; [d]Allied Health Research Unit, University of Central Lancashire, Preston, UK

ABSTRACT
Despite squatting being important in strength training and rehabilitation, few studies have investigated motor unit (MU) behaviour. This study explored the MU behaviour of vastus medialis (VM) and vastus lateralis (VL) during the concentric and eccentric phases of a squat exercise performed at two speeds. Twenty-two participants had surface dEMG sensors attached over VM and VL, and IMUs recorded thigh and shank angular velocities. Participants performed squats at 15 and 25 repetitions per minute in a randomised order, and EMG signals were decomposed into their MU action potential trains. A four factor (muscle × speed × contraction phase × sexes) mixed methods ANOVA revealed significant main effects for MU firing rates between speeds, between muscles and between sexes, but not contraction phases. Post hoc analysis showed significantly greater MU firing rates and amplitudes in VM. A significant interaction was seen between speed and the contraction phases. Further analysis revealed significantly greater firing rates during the concentric compared to the eccentric phases, and between speeds during the eccentric phase only. VM and VL respond differently during squatting depending on speed and contraction phase. These new insights in VM and VL MU behvaviour may be useful when designing training and rehabilitation protocols.

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Decomposition EMG; vastus lateralis; vastus medialis; motor unit behaviour; squatting

Introduction

Squatting exercises have been suggested as a useful assessment, which can provide information on muscle power and performance (Young, 1995; Young et al., 1997), and have been recommended as an important part of strength training in sport (Loturco et al., 2016; Wu et al., 2020) and rehabilitation (Stephen et al., 2020). During squatting, there is a strong activation of the quadriceps during the eccentric and concentric phases (Dionisio et al., 2008; Slater & Hart, 2017).

CONTACT Graham J Chapman gchapman2@uclan.ac.uk

A number of studies have considered different aspects of the squat, including knee alignment (Slater & Hart, 2016), squat depth (Jaberzadeh et al., 2016) altering hip abduction (Bevilaqua-Grossi et al., 2006) and unilateral squats (Ayotte et al., 2007; Caterisano et al., 2002), to better understand the role of lower limb muscle activation on the control during different squatting exercises. Yoo (2015) demonstrated that the vastus medialis (VM)/vastus lateralis (VL) ratio was significantly higher when performing slow squats compared to normal speeds. Whilst these studies utilised surface electromyography (EMG), these did not detail how the muscle is specifically working in order to control movement as the analysis was limited to traditional methods of EMG amplitude and timing. Furthermore, to the authors knowledge, no research has reported the effect of speed of movement on muscle activity during the eccentric and concentric phases during squat exercises.

With the advancement in technology and analysis algorithms, surface EMG decomposition (dEMG) has the potential to provide new insights in how the neuromuscular system controls movement. Previous work using dEMG has shown that motor unit (MU) behaviour may be recorded using surface EMG, which can yield information such as MU recruitment thresholds, MU firing rates and MU amplitudes (Nawab et al., 2008). Previously, this has been restricted to isometric tasks (De Luca et al., 2006; Del Vecchio et al., 2019; Miller et al., 2019), and it has been shown that different isometric loads change the MU recruitment thresholds and MU firing rates (De Luca & Hostage, 2010). This technique has been used to explore the effects of training of VL and rectus femoris (Stock & Thompson, 2014) and the effects of age (Girts et al., 2020). To the authors knowledge, De Luca et al. (2015) is the only study to demonstrate that such details on MU behaviour can now be identified during cyclic dynamic contractions of muscles in the upper and lower limbs.

Previous studies have shown that the MU firing rates are significantly greater during the concentric phase compared to the eccentric phase during lower force levels (Søgaard et al., 1996). Similarly, significantly greater MU firing rates of tibialis anterior are shown during faster contraction velocities (20°/s) compared to slower velocities (10°/s and 5°/s) (Oliveira & Negro, 2021). The majority of studies examining MU behaviour have been conducted during isometric contractions (Lulic-Kuryllo & Inglis, 2022). Recently, Yokoyama et al. (2022) demonstrated that significantly more MUs were recruited during isometric contractions compared to a slow walking task (0.6 ms^{-1}). Furthermore, MU firing rates were significantly greater during the stance phase compared to the swing phase of walking. Whilst the above studies demonstrate insights into MU behaviour during different isometric and slow walking tasks. To the authors knowledge, no studies have examined the effect of speed on MU behaviour or the interaction between movement speed and contraction phase at higher force levels in different muscles. Therefore, the aim of this study was to explore the MU behaviour of VL and VM during the concentric and eccentric phases of a squat exercise performed at 15 and 25 repetitions per minute (RPM). We hypothesised that the neuromuscular demand would be greater during the concentric versus the eccentric contraction phases and during the faster squatting speed. In addition, we hypothesised that the MU firing rates would be higher in VM compared to VL due to their different roles during the squat exercise.

Methods

Participants

Twenty-two healthy adults (10 females and 12 males) volunteered and participated in this study. The average (standard deviation) age was 31.2 (6) years, height 1.78 (0.01) m and weight 78.4 (14.6) kg. Participants were recruited from a university staff and student population and were eligible for the study if they met the following inclusion criteria: no history of surgical interventions of the lower limb, absence of any neuromuscular disorder or other diseases that may limit physical activity, currently not pregnant and with no joint pain or inflammation. Ethical approval was obtained from the University Ethics Committee prior to data collection (STEMH 962) and participants gave written informed consent prior to data collection.

Protocol

Two four-channel surface EMG sensors (Trigno Galileo, Delsys Inc., Boston, USA) were attached to the skin using hypoallergenic double-sided tape over the VM and VL muscles of the dominant leg of each participant in accordance with the Seniam guidelines (Hermens et al., 2000). The dominant limb was defined as the limb the participant would kick a ball with or draw a figure of eight on the floor (van Melick et al., 2017). Prior to the electrode application, the skin was cleaned using a 70% alcohol swab and any hair was removed using hair removal cream to ensure an optimal skin–electrode interface. Before data collection, baseline noise was assessed and values under ± 0.2 microvolts was deemed acceptable, when this threshold was exceeded the skin preparation procedure was repeated. EMG signals were sampled at 2222 Hz at 16-bit resolution using a 20-450 Hz analogue bandwidth filter. Two inertial measurement units (IMUs) sensors (Trigno Avanti, Delsys Inc., Boston, USA) were attached to the skin on the lateral thigh and shank, 2 cm superior to the lateral femoral epicondyle and lateral malleoli of the dominant limb, which were used to record thigh and shank angular velocities at 148 Hz at 16-bit resolution.

Participants took part in a single testing session and were required to squat, with no additional load, under two different speed conditions, 15 and 25 RPM, for 45 seconds per trial. Participants were instructed to place their feet shoulder width apart, with their arms crossed on their chest and squat until their knees reached 90° of flexion and their buttocks lightly touched an adjustable bench. A digital metronome was used to guide the speed of movement (Pulse Technology Inc., Plutonium Apps, Atlanta, USA) with the downwards part of the squat performed to alternate beats. For each speed, a familiarisation period was carried out where participants were instructed to complete three trials at each speed. A researcher visually checked each participant to ensure the participants completed the task in time with the metronome. The higher speed was selected to place greater demand on the participants whilst minimising any fatigue effects with the slower speed selected to approximate half of the higher speed.

EMG processing

EMGworks (Delsys, Inc., Boston, USA) was used to record the EMG and angular velocity data. NeuroMap software v.1.1.0 (Delsys, Inc., Boston, USA) was used to decompose the

EMG signals into individual MUs using an artificial intelligence algorithm (Nawab et al., 2010). Neuromap Explorer (Delsys, Inc., Boston, USA) was then used to extract the MU firing rates and amplitudes that had an accuracy of 80% or greater, which is supported by De Luca et al. (2015) who demonstrated that 80% is appropriate for identify a comparable number of MU action potential trains during dynamic, cyclic tasks. The MU firing rates, MU amplitudes and angular velocity data were then exported to Visual 3D v.6.0 (C-Motion Inc, Germantown, USA) for further analysis. The mean and maximum MU firing rates were identified for the eccentric and concentric phases of the squat, which were defined by the zero crossing of the angular velocity from the thigh IMU data. In addition, MU firing rates were divided into low, middle and upper tertials to provide explore additional, objective firing rate characteristics of early, middle and later recruited MUs, respectively (Balshaw et al., 2017).

Statistical analysis

The data distributions were tested using Shapiro–Wilk tests, and all data were found to be suitable for parametric analysis. A four factor Mixed Methods ANOVA was used to explore differences in the MU firing rates and mean and peak MU amplitudes between the two squat speeds (15 RPM and 25 RPM) during the two movement phases (eccentric and concentric) in two muscles (VL and VM) for males and females. For significant main effects, pairwise comparisons were used to explore the differences between the two speeds, and two phases of movement in the two muscles, and for any parameters that showed interactions paired t-tests were performed. The level of statistical significance was set at $p < 0.05$. All statistical analysis was performed using SPSS software v.28 (IBM SPSS, Armonk, NY). Effect sizes of Mixed Methods ANOVA were reported using partial Eta^2 (ηp^2). Effect sizes were contextualised using the following guidelines; small. 0.01, medium. 0.06 and large. 0.14 (Cohen, 1988).

Results

Table 1 shows the means, standard deviations and effect sizes (ηp^2) for all dEMG and thigh angular velocities during the concentric and eccentric phases under the two speed conditions. In total, 5013 motor units were measured across the 22 participants and the four conditions with similar MU yields between the two muscles. The four factor Mixed Methods ANOVA showed significant main effects for the MU firing rates between the two speeds, VM and VL, and between males and females, but not between the concentric and eccentric phases. Significant interactions were seen between the squat speeds and contraction phases for all MU firing rate measures, but no interactions were seen between sex and the other factors. Therefore, the data analysis was collapsed to a three factor repeated measure ANOVA (squat speeds × movement phases × muscles) (Table 1), which showed significant within subject main effects for the MU firing rates between the two speeds and VM and VL, but not between the concentric and eccentric phases, and significant main effects were seen for MU amplitudes with greater amplitudes and firing rates seen in VM compared to VL, and significantly greater MU amplitudes at 25 RPM compared with 15 RPM. As no interactions were seen between sex and the other factors, the post hoc pairwise comparisons were reported separately (Table 2). These showed

Table 1. Mean and standard deviation and main effects for dEMG measures and angular velocity during a squat task in the concentric and eccentric phases (Con/Ecc) at two different speeds (15 and 25 RPM) for Vastus Lateralis and Vastus Medialis. RPM: repetitions per minute; PPS: pulse per second; MU: motor unit; ηp^2: effect size.

	Squat 15 RPM		Squat 25 RPM		Speed p value (ηp^2)	Con/Ecc p value (ηp^2)	Interaction Speed and Con/Ecc p value (ηp^2)
Variables	**Eccentric**	**Concentric**	**Eccentric**	**Concentric**			
VL Mean Firing Rate (PPS)	13.60 (2.8)	14.80 (3.2)	14.28 (2.2)	14.59 (2.5)	0.375 (0.04)	**0.008 (0.29)**	**<0.001 (0.42)**
VM Mean Firing Rate (PPS)	14.90 (3.2)	16.28 (3)	15.83 (2.7)	16 (2.6)			
VM/VL p value (ηp^2)	**0.021 (0.23)**						
VL Maximum Firing Rate (PPS)	20.43 (3.6)	21.18 (4)	21.32 (3.6)	21.34 (3.8)	0.056 (0.16)	**0.021 (0.23)**	**0.003 (0.36)**
VM Maximum Firing Rate (PPS)	22.65 (4.5)	23.51 (4.7)	23.79 (3.9)	23.85 (4)			
VM/VL p value (ηp^2)	**<0.001 (0.45)**						
VL Upper Tertial (PPS)	18.29 (3.6)	19.33 (3.9)	19.01 (3.2)	19.17 (3.6)	0.243 (0.06)	**0.012 (0.26)**	**0.002 (0.38)**
VM Upper Tertial (PPS)	20.40 (4)	21.52 (4.2)	21.46 (3.6)	21.56 (3.7)			
VM/VL p value (ηp^2)	**0.001 (0.39)**						
VL Middle Tertial (PPS)	14.07 (3.4)	15.36 (3.7)	14.96 (2.6)	15.31 (2.8)	0.280 (0.07)	**0.012 (0.26)**	**0.001 (0.40)**
VM Middle Tertial (PPS)	15.40 (3.6)	16.95 (3.3)	16.59 (3.1)	16.75 (3.2)			
VM/VL p value (ηp^2)	**0.034 (0.20)**						
VL Lower Tertial (PPS)	7.99 (2.1)	9.27 (2.5)	8.69 (1.9)	9.17 (1.9)	0.838 (0.01)	**0.005 (0.32)**	**<0.001 (0.43)**
VM Lower Tertial (PPS)	8.51 (3)	9.99 (2.6)	8.97 (2.3)	9.21 (1.8)			
VM/VL p value (ηp^2)	0.509 (0.02)						
VL Mean MU Amplitude	0.83×10^{-4} (5.09×10^{-5})		0.92×10^{-4} (5.41×10^{-5})		**0.016 (0.28)**	N/A	N/A
VM Mean MU Amplitude	1.13×10^{-4} (5.51×10^{-5})		1.25×10^{-4} (6.47×10^{-5})				
VM/VL p value (ηp^2)	**0.004 (0.38)**						
VL Peak MU Amplitude	1.14×10^{-4} (7.39×10^{-5})		1.26×10^{-4} (7.94×10^{-5})		**0.024 (0.25)**	N/A	N/A
VM Peak MU Amplitude	1.57×10^{-4} (8.20×10^{-5})		1.73×10^{-4} (9.32×10^{-5})				
VM/VL p value (ηp^2)	**0.007 (0.34)**						
Angular velocity (°/s)	66.3 (17.0)	63.9 (20.2)	100.1 (18.1)	96.1 (20.5)	0.000 (0.91)	0.240 (0.07)	0.53 (0.02)

significantly higher firing rates in the maximum and upper tertile firing rates in males compared with females in VL and even greater sex differences across average, maximum, upper and middle tertile firing rates in VM. Unsurprisingly, a significantly greater thigh angular velocity was seen in the 25 RPM compared with 15 RPM.

As significant interactions were seen between the squat speeds and contraction phases for all MU firing rate measures post hoc analysis using paired t-tests were performed to explore the concentric and eccentric phases in VL and VM (Table 3), and the two different speeds in VL and VM (Table 4). These revealed significantly greater MU amplitudes and firing rates in VM compared with VL with the exception of the later recruited MUs.

Post hoc t-tests exploring the interaction effects showed significant differences in the maximum firing rate between the two squat speeds during the eccentric phase in VL and VM, with the higher speed producing 5% maximum firing rates for VL ($p = 0.02$) and VM ($p = 0.01$). This was reflected during the eccentric phase in the upper and middle tertial firing rates of VM ($p = 0.04$), and the lower tertial firing rates of VL ($p = 0.04$), Table 3.

Table 2. Paired T-test exploring the sex difference for motor unit firing rate measures during a squat task in the concentric and eccentric phases (Con/Ecc) at two different speeds (15 and 25 RPM) for Vastus Lateralis and Vastus Medialis. RPM: repetitions per minute; PPS: pulse per second; MU: motor unit.

	Vastus Lateralis				Vastus Medialis			
	Females Mean (sd)	Males Mean (sd)	Diff	p -value	Females Mean (sd)	Males Mean (sd)	Diff	p -value
Mean Firing Rate 15RPM Ecc	12.78 (3.09)	14.16 (2.52)	1.38	0.261	12.83 (0.17)	16.33 (2.45)	3.50	**0.008**
Mean Firing Rate 25RPM Ecc	13.41 (2.55)	14.89 (1.87)	1.48	0.135	13.77 (0.40)	17.27 (1.75)	3.50	**0.010**
Mean Firing Rate 15RPM Con	13.60 (3.36)	15.63 (2.88)	2.03	0.144	14.12 (3.23)	17.77 (1.71)	3.65	**0.002**
Mean Firing Rate 25RPM Con	13.63 (2.69)	15.26 (2.25)	1.63	0.138	14.06 (2.70)	17.36 (1.42)	3.30	**0.001**
Max. Firing Rate 15RPM Ecc	18.14 (3.64)	22.01 (2.76)	3.87	**0.010**	18.62 (4.05)	25.45 (1.95)	6.83	**<0.001**
Max. Firing Rate 25RPM Ecc	18.54 (2.86)	23.24 (2.66)	4.70	**0.001**	19.98 (3.17)	26.43 (1.36)	6.45	**<0.001**
Max. Firing Rate 15RPM Con	18.58 (3.70)	22.98 (3.18)	4.40	**0.007**	19.29 (4.21)	26.42 (2.14)	7.13	**<0.001**
Max. Firing Rate 25RPM Con	18.68 (2.98)	23.18 (3.11)	4.50	**0.003**	20.14 (3.25)	26.42 (1.69)	6.28	**<0.001**
Upper Tertial 15RPM Ecc	16.45 (3.89)	19.56 (2.89)	3.11	**0.043**	17.02 (3.77)	22.75 (2.09)	5.73	**<0.001**
Upper Tertial 25RPM Ecc	16.99 (3.15)	20.41 (2.54)	3.42	**0.011**	18.24 (3.23)	23.69 (1.73)	5.45	**<0.001**
Upper Tertial 15RPM Con	17.07 (3.92)	20.89 (3.17)	3.82	**0.020**	17.92 (3.93)	24.00 (1.87)	6.08	**<0.001**
Upper Tertial 25RPM Con	17.11 (3.25)	20.59 (3.13)	3.48	**0.020**	18.41 (3.37)	23.75 (1.86)	5.34	**<0.001**
Middle Tertial 15RPM Ecc	13.16 (3.77)	14.69 (3.04)	1.53	0.154	13.03 (3.55)	17.04 (2.57)	4.01	**0.003**
Middle Tertial 25RPM Ecc	14.22 (2.87)	15.48 (2.41)	1.26	0.140	14.39 (2.88)	18.10 (2.34)	3.71	**0.002**
Middle Tertial 15RPM Con	13.97 (3.96)	16.31 (3.33)	2.34	0.074	14.45 (3.49)	18.69 (1.79)	4.24	**0.001**
Middle Tertial 25RPM Con	14.39 (3.04)	15.94 (2.61)	1.55	0.108	14.62 (3.24)	18.23 (2.14)	3.61	**0.002**
Low Tertial 15RPM Ecc	8.19 (1.96)	7.84 (2.25)	−0.35	0.713	7.98 (2.52)	8.88 (3.28)	0.90	0.498
Low Tertial 25RPM Ecc	8.76 (2.19)	8.65 (1.76)	−0.11	0.907	8.15 (1.59)	9.53 (2.61)	1.38	0.175
Low Tertial 15RPM Con	9.24 (2.57)	9.28 (2.56)	0.04	0.974	9.49 (2.52)	10.33 (2.45)	0.84	0.445
Low Tertial 25RPM Con	9.12 (2.22)	9.19 (1.76)	0.07	0.933	8.63 (2.03)	9.60 (1.57)	0.97	0.219

The comparisons between the concentric and eccentric phases within VL and VM showed significant differences between the concentric and eccentric phases in all dEMG variables at 15 RPM, with the concentric phase producing significantly greater firing rates than the eccentric phase, with only the lower tertial in VL showing differences at 25 RPM, Table 4.

Discussion and implications

The present study investigated the influence of the concentric and eccentric phases and movement speed on MU behaviour of VM and VL during a bilateral squat exercise. To our knowledge, this is the first paper to demonstrate that MU behaviour of VM and VL during a weight bearing, dynamic task changes depending on movement speed and phase of muscle contraction.

Table 3. Paired T-test exploring the interactions between the two different squat speeds (15 RPM, 25 RPM) in Vastus Lateralis and Vastus Medialis.

	Vastus Lateralis			Vastus Medialis		
	Mean	Diff	p-value	Mean	Diff	p-value
Mean Firing Rate 15RPM Ecc	13.6 (2.8)	−0.7	0.07	14.9 (3.2)	−0.9	0.08
Mean Firing Rate 25RPM Ecc	14.3 (2.2)			15.8 (2.7)		
Mean Firing Rate 15RPM Con	14.8 (3.2)	0.2	0.45	16.3 (3.0)	0.3	0.46
Mean Firing Rate 25RPM Con	14.6 (2.5)			16.0 (2.6)		
Max. Firing Rate 15RPM Ecc	20.4 (3.6)	−0.9	**0.02**	22.7 (4.5)	−1.1	**0.01**
Max. Firing Rate 25RPM Ecc	21.3 (3.6)			23.8 (3.9)		
Max. Firing Rate 15RPM Con	21.2 (4.0)	−0.2	0.55	23.5 (4.7)	−0.3	0.36
Max. Firing Rate 25RPM Con	21.3 (3.7)			23.9 (4.0)		
Upper Tertial 15RPM Ecc	18.3 (3.6)	−0.7	0.09	20.4 (4.0)	−1.1	**0.04**
Upper Tertial 25RPM Ecc	19.0 (3.2)			21.5 (3.6)		
Upper Tertial 15RPM Con	19.3 (3.9)	0.2	0.58	21.5 (4.2)	0	0.88
Upper Tertial 25RPM Con	19.2 (3.6)			21.6 (3.7)		
Middle Tertial 15RPM Ecc	14.1 (3.4)	−0.9	0.05	15.4 (3.6)	−1.2	**0.04**
Middle Tertial 25RPM Ecc	15.0 (2.6)			16.6 (3.1)		
Middle Tertial 15RPM Con	15.4 (3.7)	0.1	0.89	17.0 (3.3)	0.2	0.62
Middle Tertial 25RPM Con	15.3 (2.8)			16.8 (3.1)		
Low Tertial 15RPM Ecc	8.0 (2.1)	−0.7	**0.04**	8.5 (3.0)	−0.4	0.43
Low Tertial 25RPM Ecc	8.7 (1.9)			9.0 (2.3)		
Low Tertial 15RPM Con	9.3 (2.5)	0.1	0.74	10.0 (2.5)	0.8	0.16
Low Tertial 25RPM Con	9.2 (1.9)			9.2 (1.8)		

Table 4. Paired T-test exploring the interactions between the concentric and eccentric phases (Con/Ecc) in each speed tested (15 or 25 repetitions per minute) in vastus lateralis and vastus medialis.

	Vastus Lateralis			Vastus Medialis		
	Mean	diff	p-value	Mean	diff	p-value
Mean Firing Rate 15RPM Ecc	13.60 (2.79)	−1.2	**0.001**	14.90 (3.22)	−1.38	**0.002**
Mean Firing Rate 15RPM Con	14.80 (3.18)			16.28 (3.00)		
Mean Firing Rate 25RPM Ecc	14.28 (2.24)	−0.32	0.116	15.84 (2.66)	−0.17	0.578
Mean Firing Rate 25RPM Con	14.59 (2.52)			16.01 (2.59)		
Max. Firing Rate 15RPM Ecc	20.43 (3.63)	−0.76	**0.007**	22.65 (4.50)	−0.85	**0.004**
Max. Firing Rate 15RPM Con	21.18 (3.99)			23.51 (4.72)		
Max. Firing Rate 25RPM Ecc	21.32 (3.57)	−0.03	0.856	23.79 (3.93)	−0.06	0.653
Max. Firing Rate 25RPM Con	21.34 (3.75)			23.85 (3.96)		
Upper Tertial 15RPM Ecc	18.29 (3.61)	−1.04	**0.002**	20.40 (4.03)	−1.11	**0.004**
Upper Tertial 15RPM Con	19.33 (3.91)			21.52 (4.15)		
Upper Tertial 25RPM Ecc	19.01 (3.23)	−0.16	0.355	21.46 (3.63)	−0.1	0.588
Upper Tertial 25RPM Con	19.17 (3.56)			21.56 (3.68)		
Middle Tertial 15RPM Ecc	14.07 (3.36)	−1.29	**0.002**	15.40 (3.56)	−1.55	**0.003**
Middle Tertial 15RPM Con	15.36 (3.70)			16.95 (3.32)		
Middle Tertial 25RPM Ecc	14.96 (2.62)	−0.34	0.13	16.59 (3.13)	−0.16	0.632
Middle Tertial 25RPM Con	15.31 (2.83)			16.75 (3.15)		
Low Tertial 15RPM Ecc	7.99 (2.10)	−1.28	**0.001**	8.52 (2.97)	−1.47	**0.001**
Low Tertial 15RPM Con	9.27 (2.51)			9.99 (2.46)		
Low Tertial 25RPM Ecc	8.70 (1.90)	−0.47	**0.036**	8.97 (2.32)	−0.24	0.545
Low Tertial 25RPM Con	9.17 (1.91)			9.21 (1.80)		

At the faster squatting speed (25 RPM) both VM and VL produced higher MU firing rates compared to the slower squatting speed (15 RPM). These findings are consistent with past research that demonstrated that the MU firing rate of the first dorsal interosseous muscle increased with increasing speed in healthy participants when using intramuscular dEMG (Masakado et al., 1995). Similarly, tibialis anterior MU firing rates were greater during faster contractions compared to slower speeds (Oliveira & Negro, 2021).

These findings suggest that when individuals are required to perform faster movements, the neuromuscular control system increases the MUs firing rate to adapt to the demand being placed on the neuromuscular control system. However, when examining the firing rate by tertials, VM and VL appear to be working differently depending on the speed of movement. It would appear that the early and middle recruited MUs (upper and middle tertials) of VM and the later recruited MUs of VL showed higher firing rates under the faster squat condition, which could potentially be due to the different roles of VM and VL. Anatomical research has shown that VL has a larger cross-sectional area, thus having greater potential for force production than other knee extensor muscles (Lieber & Fridén, 2000; Ward et al., 2009), whereas weakness or delayed activation of VM has shown to alter knee stability and increase the risk of patellofemoral pain (Alsaleh et al., 2021; Chester et al., 2008).

The comparisons between the concentric and eccentric phases showed significantly greater MU firing rates in the concentric phase, perhaps indicating that the same MUs are being driven faster during the concentric phase compared to the eccentric phase. These findings are supported by Kallio et al. (2013), who reported a significantly higher MU firing rate in the concentric contractions compared to isometric or eccentric muscle activations in the soleus muscle. This is also supported by Muyor et al. (2020) who showed that VM and VL EMG amplitude was greater during the concentric phase than the eccentric phase during a unilateral squat. The greater firing rates seen during the concentric contractions may be associated with the force production required during the concentric phase, however this may also be due to the muscle activation during the eccentric phase being stronger or more efficient than the muscle activation during the concentric phase (Cormie et al., 2010). An additional explanation could be associated with the angular velocity at which the eccentric phase is executed, which is generally lower than that of the concentric phase to maintain an adequate execution technique and prevent possible musculotendinous lesions (Matheson et al., 2001); however, this current study showed differences in the MU behaviour during the concentric and eccentric phases but showed no difference in angular velocity between the two contraction phases.

When considering the interactions observed between the speed and phases of movement, although the eccentric phase showed that the MUs are driven at 5% higher firing rates in VL and VM at the greater speed, indicating that the same MU pool is being driven faster due to an increase in the neuromuscular demand, this was seen during the eccentric phase only, with no such change being seen during the concentric phase. This could be related to greater control being required during the eccentric phase of the squat. A further comparison of the responses of VM and VL showed that VM had consistently higher MU firing rates compared to the VL regardless of speed or phase of movement. This finding is consistent with de Souza et al. (2018) who demonstrated that VM mean MU firing rates were significantly greater than those in VL during a knee extension task, which is further supported by Avrillon et al. (2021) who reported a lower mean MU discharge rate for VL when compared with VM. Although the response to the different speeds and phases were the same in both males and females, differences in firing rates were observed with males showing higher firing rates than females in VL and VM, with this being more notable in VM. These sex differences contrast the findings in a recent review, which demonstrated that females have a tendency to have greater MU firing rate than males during isometric contraction tasks (Lulic-Kuryllo & Inglis, 2022). One explanation for these differences could be a greater load in both muscles due to a less valgus position in males whilst performing the dynamic, closed chain squatting task, although this cannot be confirmed by this current study the effect of lower limb postures on MU firing rates warrants further investigation whilst performing such tasks.

This study had a few limitations. The sample size could be viewed as a limitation of the present study. Given the number of factors within the interactions, our sample size could be deemed as small despite the large number of significant interactions and main effects. Furthermore, future research may wish to increase the sample size to fully explore sex differences in MU behaviour, in particular, during dynamic tasks. We did not control for weight, height, or lower limb alignment of the participants and therefore moments and load on the knee were not considered which directly affect the muscle forces, and are known to affect MU behaviour. Therefore, future work should consider biomechanical models to estimate muscle forces and their relationship with MU firing rates during dynamic contractions.

Conclusion

The findings from the present study suggest that the MU behaviour responds differently to the conditions of speed and phase of movement, with the concentric phase showing higher firing rates when compared to the eccentric, and an increase in MU firing rates during the faster squatting speed during the eccentric phase only. In addition, our results indicate larger MUs in VM were being driven at higher firing rates and at greater amplitudes compared with VL which could be attributed to the different roles of the two muscles during squatting tasks. This offers insights into MU behaviour which may be useful when considering the design of training and rehabilitation protocols.

Disclosure statement

Orantes-Gonzalez, Heredia-Jimenez, Richards and Chapman have no conflict of interest. Lindley works for Delsys Europe, the company that developed the sEMG decomposition technology.

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ORCID

Eva Orantes-Gonzalez http://orcid.org/0000-0001-8893-3996
Jose Heredia-Jimenez http://orcid.org/0000-0003-0053-5884
Steven B Lindley http://orcid.org/0000-0001-7419-8644
Jim D Richards http://orcid.org/0000-0002-4004-3115
Graham J Chapman http://orcid.org/0000-0003-3983-6641

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