FitnessResearch.edu.au

CASE STUDY

ELECTROMYOGRAPHIC ACTIVITY IN SUPERFICIAL MUSCLES OF THE THIGH AND HIP DURING THE BACK SQUAT TO THREE DIFFERENT DEPTHS WITH RELATIVE LOADING

Eric Chauhan, Benjamin Hammond, Craig Bridge, Pascual Marques
Faculty of Arts & Sciences, Edge Hill University
Corresponding Author: Pascual Marques
CFaculty of Arts & Sciences, Edge Hill University, St. Helen's Road, Ormskirk, L39 4QP, United Kingdom.
Tel: +44 0 1695 584183; Fax: +44 0 1695 584812
marquesp@edgehill.ac.uk

ABSTRACT

Introduction: Inconclusive previous research on squat depth and the evoked electromyography (EMG) activity muddles our understanding of muscle recruitment in the back squat. This study determined EMG activity as a function of squat depth in four superficial muscles of the lower limb using relative loading.

Method: Eight resistance trained males (mean ± SD age: 21 ± 1 years) performed back squats to partial, parallel and full depth using depth-relative 5-repetition–maximum loads. Muscle activity in the vastus medialis oblique (VMO), vastus lateralis (VL), gluteus maximus (GM), and biceps femoris (BF) during the concentric and eccentric phases of the squat was determined using surface electromyography. Peak (Peak EMG), mean (Mean EMG), and integrated (iEMG) EMG normalised to their respective maximum voluntary isometric contraction (MVIC) for each muscle were evaluated.

Results: Three-way Anovas and Sidak post-hoc analysis revealed significant effects for squat type (p = 0.021 - 0.001), squat phase (p = 0.001), and muscle (p = 0.001). The significant differences were between the partial and the parallel squat (p = 0.016 - 0.001); for iEMG significant effects were also found between the partial and full squat (p = 0.001). The VMO elicited the highest EMG activity (e.g., Peak EMG 93.4 ± 36.9% MVIC; parallel squat, concentric) and the BF the lowest (e.g., Peak EMG 49.9 ± 14.7%). Greater GM activity occurred in parallel squats compared to full squats (mean difference in Peak EMG = 9.1% MVIC).

Conclusion: The findings suggest that squatting to the parallel position or lower induces optimal contractile stimulation of the quadriceps. Squatting to parallel depth maximises EMG activation of the GM, possibly due to a more advantageous external moment arm or a reduction in neural drive.

Keywords: Biceps femoris, Gluteus maximus, Squat depth, Surface EMG, Vastus lateralis, Vastus medialis oblique.

ISSN 2201-5655

INTRODUCTION

The free barbell back squat is a closed-chain, multi-joint movement frequently incorporated into the strength and conditioning programmes of athletes [1,2]. It is imperative that coaches are equipped with underlying research evidence regarding the contribution of different muscles of the lower limb to the squat. In strength training programs, variations in the lifting technique are applied in an attempt to target certain muscle groups by altering the joint torques [3,4]. However, the physiological stresses associated with high levels of muscle activity and time-under-tension are central to stimulating a training effect [5]; simply shifting joint torques does not guarantee augmentations in muscle fibre recruitment. For this reason, surface electromyography (EMG) is commonly employed to determine the potential effectiveness of an exercise variation and the associated neuromuscular adaptive stimulus [6]; whereby, measures typically include peak (Peak EMG), mean (Mean EMG), and integrated (iEMG) EMG normalised to maximum voluntary isometric contraction (MVIC). Altering the depth to which an athlete descends in the squat is one approach that may permit favourable outcomes in muscle activity and concomitant physiological perturbations, and hence optimise neuromuscular adaptations in athletes. Existing literature supports that small alterations in squat technique can impact on the muscle activity evoked [7]. The three squat depths most commonly adopted in strength training are the partial squat, parallel squat, and full squat [8,9].

It has been reported that with increased hip and knee flexion in the squat, relative muscular effort at these joints increases in the concentric phase [5]. An increase in muscle activity and concomitant stimuli for neuromuscular adaptation has been implied. However, Bryanton *et al.* [5] used inverse dynamics to compute net joint moments and an isokinetic dynamometer matched for joint angle at each squat depth to establish a maximal force for relative comparisons; and EMG analysis was not used. Joint moments are a product of both mechanical leverage and muscle tension, and involve all muscles acting to produce extension about the joint. To this end, EMG analysis must be employed for the analysis of the squat. The only investigation on the muscular activity of the GM at different squat depths is the research by Caterisano and colleagues [10]. In their analysis of the GM, vastus medialis oblique (VMO), vastus lateralis (VL) and biceps femoris (BF), the authors found only the GM to become significantly more active with depth in partial, parallel and full squats during the concentric phase (iEMG: 26.8%, 27.4% and 40.5% MVIC; respectively). Nonetheless, our understanding of GM contribution to the squat is limited.

Previous research report that lifted load decreases with squat depth due to mechanical factors that include a greater range of motion through which the load must be moved and thus an increased time under tension and concomitant demands on the muscle, and an unfavourable length-tension relationship created by the increased muscle lengths of the vasti and GM [9]. Therefore, a complex control strategy is required in the squat movement since the joint moments, muscle activity, relative contribution of the lower limb joints, and lifted load are influenced by squat depth [11,12]. Uncovering a limitation of previous research [10], the same absolute barbell load was used for each squat depth. Therefore, the maximum exercise intensity possible at each depth was not used; posing implications for muscle activity [1,5]. The greater intensities associated with increased squat depth would thereby ostensibly elicit greater muscle activity in the prime movers [5,7] and point to the need for further research.

Research [13] found a sudden increase in hip and knee extensor EMG activity during the initial ascent from full squats, consistent with pertinent literature regarding increases in activity after transitioning from the eccentric to the concentric phases of the movement [2,4]. However, the results of Robertson *et al.* [13] depict a gradual increase in GM activity thereafter, apparent over the first two thirds of the ascent. This suggests that Peak EMG activity of the GM may be attained by squatting to a partial or parallel depth only; however, the study does not compare muscle activity between squats to different depths, warranting further research.

Unlike the quadriceps femoris, which have demonstrated near maximal levels of recruitment during full squats [13], hamstring activity during the back squat, including that of the BF is seemingly low, with studies having repeatedly documented the BF as contributing minimally to the movement in terms of absolute EMG [7,14]. For instance, Ebben [14] showed 2.7 times less activity in the hamstrings muscles relative to the quadriceps; however, squat depth comparisons are largely absent. Gorsuch and colleagues [15] examined the effect of squat depth on the myoelectrical activity of the BF and reported only marginal and statistically non-significant differences in EMG across squat depth conditions; only partial (0.066 ± 0.044 mV) and parallel (0.075 ± 0.056 mV) squat depths were compared. Further research is required to unveil the EMG patterns of the hamstrings as a function of squat depth.

From the available literature, one can deduce that the vasti are moderately-to-highly active, while the BF is minimally active in the parallel squat [2,4]. Limited research has investigated muscle activity of the GM in the back squat [13]. Also, the literature is equivocal regarding EMG activity at varying squat depths. Muscle recruitment is highly dependent on bar load [7]. However, few EMG studies have explored intensities greater than 3 repetition maximum (3RM) in the back squat; intensities which are most conducive to maximal strength development [16]. Therefore, the aim of this study was to determine EMG activity of the VMO, VL, GM and BF muscles at different depths of the back squat using relative loads. The findings of the study have implications for optimisation of squat training.

METHODOLOGY

Experimental Design

Participants were requested to attend three data collection sessions separated by at least 72 hours to neutralise the effects of fatigue: 1. familiarisation session and determination of five repetition maximum (5RM) loads, 2. tests for MVIC, and 3. experimental session. Independent variables included squat depth (partial squat, parallel squat, and full squat), squat phase (concentric and eccentric), and muscle (VMO, VL, GM and BF). The dependent variables were Peak EMG, Mean EMG and iEMG. Peak EMG allows for the highest level and near-instantaneous changes in muscle activation to be observed. Mean EMG is robust to both movement artefact and time, thus providing a reliable EMG amplitude over the entire movement [17]. The iEMG best illustrates mechanical work performed by the muscle. The partial squat was defined by a femur-to-shank angle of approximately 120° (Figure 1). The position at which the femur was parallel to the floor denoted the parallel squat. The full squat was determined based on the acetabulofemoral joint distinctly below the horizontal plane of the knee whilst within the mobility confines of the participant (i.e., maintaining heel contact with the ground) [16]. At the instant the desired squat depth was reached, an investigator situated to the side of the participant provided verbal cues to participants instigating the concentric portion of the lift; video analysis was used to verify that each depth was achieved [10]. To account for circadian variations [6], experimental testing and MVIC trials were undertaken consistently between

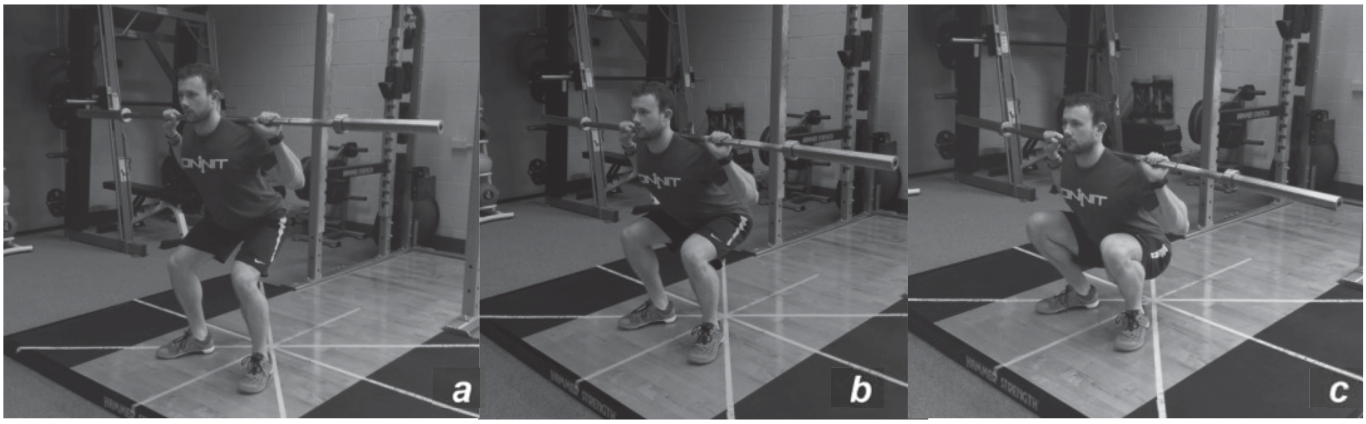

Figure 1. Partial (a), parallel (b) and full squat (c) depths.

the hours of 10:30 am and 1:00 pm. Furthermore, participants were asked to abstain from any lower body resistance training or exhaustive activity in the 48 hours preceding all testing to ensure no muscle soreness was present that may have compromised the validity of the data. Testing was conducted using a randomised and counterbalanced repeated measures design to mitigate order effects [18].

Participants

Eight healthy males of mean ± SD age of 21 ± 1 years, height of 176 ± 5 cm, mass of 80 ± 9 kg, and training experience in the free barbell back squat of 5 ± 1 years were recruited. Exclusion criteria encompassed a history of lower body injury or pathology that may influence patterns of activation in lower body musculature. Insufficient dorsiflexion preventing full squat depth reached safely using correct squatting technique was contraindicated [19], as was excessive lumbar flexion attributable to inherent anatomical or immobility induced posterior pelvic tilt [16]. Criteria for insufficient dorsiflexion was assessed by an experienced Strength & Conditioning coach by ascertaining whether the participants were able to maintain heel contact with the ground during full squats, and excessive lumbar flexion was gauged visually by the coach based on own experience and kinesiological education. The use of eight participants elicited medium and large statistical effect sizes [20]. The study was approved by the Ethics Committee at Edge Hill University.

Squat Technique

Participants performed the back squat wearing their own cross-training shoes with a firm and stable sole. The feet were positioned slightly wider than shoulder width apart while maintaining a naturally neutral or slightly abducted orientation. Foot position was standardised between trials. The barbell was held using a pronated grip at a width as narrow as shoulder flexibility and thoracic mobility would permit, and placed behind the neck across the upper trapezius in the 'high bar' position, with the scapulae retracted [16]. During the squat, the knees were aligned with the toes and tracked them throughout the movement. A cue for abduction and external rotation of the hips was given to facilitate this action and mitigate gravity induced hip adduction torque and deleterious knee valgus in the presence of lower–body strength and mobility deficits [21]. The lumbar and thoracic spinal regions maintained their natural or slightly extended curvatures throughout the movement, with slight hyperextension of the cervical spine, as participants faced forward [22]. Lumbar and thoracic spinal curvature and forward lean were visually monitored by the experienced Strength & Conditioning coach. A visual indicator of excessive forward lean was when the hips rose up too quickly relative to the shoulders from the start of the ascent, in which case the data were discarded and the trial repeated [10]. Participants were instructed to "control" their descent and not to "bounce" off their calves in the full squat. No belts or knee wraps were permitted due to their attenuation effect on EMG activity [1].

Familiarisation Trial and 5RM Procedures

A 5RM load was selected as 5 repetitions is common place in strength training programs and within the recommended repetition range for developing maximum strength [16]. The 5RM load at each depth was used to allow the prescription of relative loading [7]. During a familiarisation session participants established their 5RM to the nearest 2.5 kg at each squat depth; ten minutes recovery was provided between the 5RM trials [1]. The participants performed two warm up sets before attempting the first estimated 5RM load using a free Olympic barbell. Three 5RM squat attempts were carried out to determine the 5RM at each depth [12]. With consideration to circadian rhythm [6], all 5RM trials took place between the hours of 11:00 am and 2:00 pm. Attained 5RM loads by all participants ranged from 112.5 to 185.0 kg (partial squat), 92.5 to 125.0 kg (parallel squat) and 75.0 to 110.0 kg (full squat).

Electromyography Procedures

Disposable silver-silver chloride (Ag Ag–Cl), bipolar configured passive wet gel surface electrodes were affixed in pairs, spaced 20 mm apart, to the belly of each muscle according to SENIAM guidelines and oriented parallel with the muscle fibres [2]. To reduce signal artefact, the skin at the sites of electrode placement was shaved, and cleansed with alcohol wipes. Small telemetric modules were connected to the electrodes via a two-snap lead and secured to the skin using double sided adhesive tape. These modules housed a reference electrode which contacted the skin. The myoelectrical signals were relayed wirelessly from the modules to the telemetric EMG system (Noraxon Telemyo DTS system, Noraxon USA Inc, Arizona, USA), and sampled at 1000 Hz. To optimise transmission, signals were high pass filtered using a bandpass at 10-500 Hz. All EMG data was saved using the manufacturer's software (Myoreseacrh XP, Noraxon USA Inc, Arizona, USA). Raw EMG traces were full wave rectified and smoothed using a root mean square (RMS) algorithm with a 50 ms time window. Peak EMG, Mean EMG and iEMG were collected and normalised to MVIC trials [17].

MVICs

The MVICs at each muscle of interest were performed to obtain a reference EMG denominator [23]. The MVIC was chosen as the normalisation method because of its established efficacy as a normalisation technique [24] and its exclusivity in providing estimates of the degree of motor-unit recruitment relative to a muscle's maximum activation potential, permitting comparisons between muscles [18,23]. The following tasks have been identified as eliciting maximum muscle activity and were implemented in the study. For the GM, an MVIC was performed with the participants assuming a prone quadruped position, their right knee flexed to approximately 90° and full extension of their right hip [21]. The vasti MVICs were achieved while seated on a commercial gym based 'leg extension' machine (LifeFitness), with the right knee and hips flexed to approximately 60° and 90°, respectively [25]. Applying a resistance great enough to deny movement, a maximum effort knee extension was then performed against an immovable pad. Similarly, for the BF, the MVIC was completed at circa 60° of knee flexion and 90° of hip flexion while seated [25,26]; though a commercial 'leg curl' machine (LifeFitness) was used for this task. Here, maximum effort knee flexion was instructed, while resistance prohibited movement. A pad placed atop the upper thighs prevented any unwanted movement of the thighs or hips during the assessment. All repetitions were preceded by a verbal cue to contract the muscle as quickly as possible [1]. After two sub-maximal warm-up sets of 10 full ROM repetitions, three five-second maximal isometric efforts were performed for each muscle group, intervened by a minimum of two minutes to lessen fatigue effects [1]. The highest EMG reading obtained from these repetitions subsequently denoted the normalisation reference for the corresponding muscle.

Experimental Procedures

Participants undertook a standardised warm-up, comprising activation exercises, dynamic stretching and un-weighted Olympic barbell squats before incremental warm-up sets of 6 repetitions at 40%, 60% and 80% of their first tested squat depth 5RM using a standard 20 kg Olympic barbell [27]. Succeeding the warm-up, participants performed 3 consecutive repetitions at each depth with the 5RM loads. Three repetitions, rather than 5, were used to circumvent possible fatigue induced deterioration of technique that may affect relative muscle contribution during the final repetitions of each set [28]. Video analysis was set up perpendicular to the line of action at approximately 1 metre from the floor and 3 metres from the bar and synchronised to the EMG trace for an accurate interpretation of results. This included the partitioning of data into respective concentric and eccentric phases and provided verification of squat depth. All three trials were performed during the same session to mitigate the influence of highly variable physiological and biochemical states and extrinsic factors (e.g., re-placing electrodes in their exact positions) on the EMG signal and consequentially compromising the reliability of data [23,24]. This technique has previously demonstrated high intra-class correlation coefficients (ICCs = 0.945 - 0.992) for thigh and hip musculature in the back squat [29]. Each trial was interspersed with ten minutes of rest to allow fatigue to fully dissipate and any re-synthesis of ATP-PCr stores to occur [1]. The back squat was performed inside a power rack, while

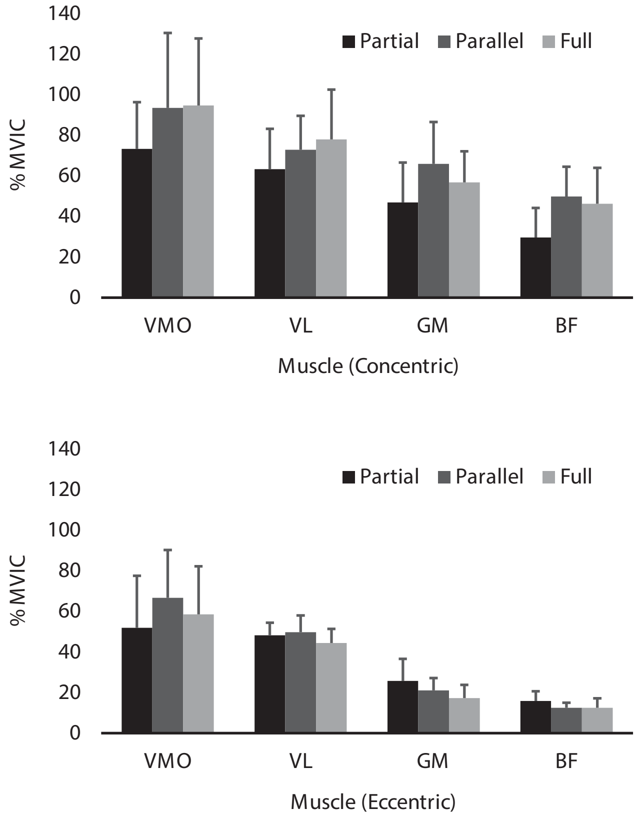

Figure 2. Peak EMG presented as mean + SD normalised to MVIC.

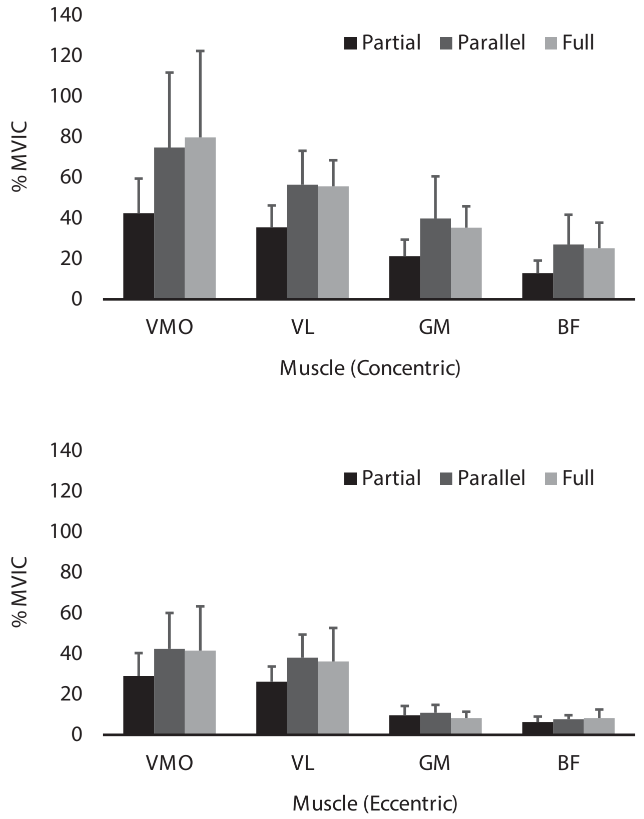

Figure 4. iEMG presented as mean + SD normalised to MVIC.

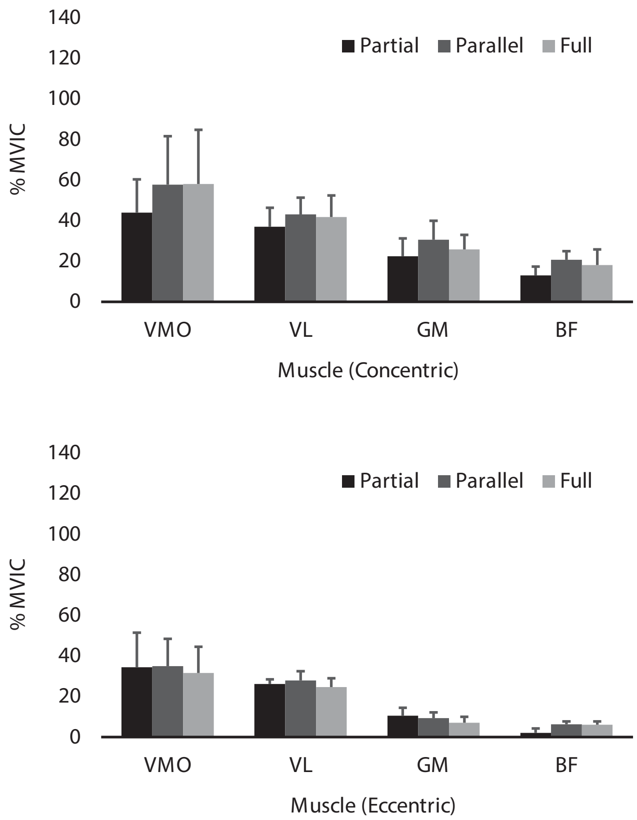

Figure 3. Mean EMG presented as mean + SD normalised to MVIC.

two spotters, one at each end of the barbell, were present during each lift to ensure safety [16].

Statistical Analyses

Statistical analysis was carried out using IBM SPSS 22.0 software (IBM, 2013). Assessment of the normality of raw data assumption was performed using Sharipo-Wilk's test and visual inspection of Q-Q plots. Assessment of the normality of residuals and homogeneity of residuals assumptions was accomplished using Q-Q plots and scatter graphs to inspect homoscedasticity, and Cook's distance [30]. Raw data were mathematically transformed using a logarithmic function. Three-way Anovas were performed, wherein Peak EMG, Mean EMG and iEMG within squat types, squat phases, and muscle effects were calculated ($p < 0.05$). Sidak post-hoc tests were performed on any measure that achieved a main effect. Partial η^2 (η_p^2) effect sizes and statistical power were calculated and reported. η_p^2 was interpreted based upon the guidelines of [20]; that is, a η_p^2 of .02 is small, .13 is medium, and .26 is large.

RESULTS

Mean + SD Peak EMG, Mean EMG and iEMG normalised to MVIC are presented in Figs. 2-4. The EMG activity was higher in the concentric phase. The general trend of EMG activity was characterised by a progressive reduction in activity in the order VMO (highest activity), VL, GM, BF (lowest activity).

Tables 1-3 show statistically significant results of the three-way Anovas and Sidak post-hoc tests. Significant effects were found for squat type (p = 0.001 – 0.021), squat phase (p = 0.001) and muscle (p = 0.001); and the interactions specified (p = 0.001 – 0.015). The η_p^2 yielded medium and large effects (η_p^2 = .05 - .76) for the main and most of the interaction effects, and power was ≥ 0.70 for all statistically significant findings. Post-hocs revealed that the significant differences were between the partial and the parallel squat (example mean differences: Peak EMG of VMO concentric = 20.1% MVIC, p = 0.016; iEMG of VMO = 32.2% MVIC, p = 0.001); for iEMG significant effects were also found between the partial and full squat (for example, iEMG of VMO concentric = 37.3% MVIC, p = 0.001). Muscles of the quadriceps differed significantly from the GM and BF; for example difference in Peak EMG between VMO and GM concentric in the full squat = 37.9% MVIC, p = 0.001; and difference between VMO and BF = 48.4% MVIC, p = 0.001;. There were also significant differences between the GM and BF; for example difference in Peak EMG concentric in the full squat = 10.5% MVIC, p = 0.001.

DISCUSSION

This study aimed to determine EMG activity of the VMO, VL, GM and BF muscles at different depths of the back squat using relative loads. With reference to the knee extensors, the VMO and VL were more active in the parallel (e.g., Mean EMG of VMO = 57.7, VL = 43.0) and full (VMO = 58.0, VL = 41.8) squats than at partial depths (VMO = 43.9, VL = 37.0) during the concentric phase (Figures 2-4). This was also the case for the eccentric phase with regards to iEMG (partial: VMO = 29.0, VL = 26.2; parallel: VMO = 42.3, VL = 38.0; full: VMO = 41.5, VL = 36.1); Figure 4. The higher muscle activity of the vasti in the parallel compared to the partial squat is likely due to the mechanical disadvantage that occurs as a result of the initial flexion of the hips and knees [3]. It has also been reported [1] that during concentric contractions, neural drive to the quadriceps is greater for intermediate and large muscle lengths (i.e., at parallel and full squat depths) than for short muscle lengths (i.e., partial squat depth). Hence, lower EMG activity of the quadriceps femoris in the partial squat may in part be attributed to sub-optimal motor-unit firing rates [1]. Negligible differences in EMG activity were found between the parallel and full squats in both vasti muscles for all EMG parameters. This finding is in agreement with Wretenberg and colleagues [31], who observed no differences in Peak EMG activity of the VL between parallel and full squats. However, Robertson *et al.* [13] found that peak VL activity was maximum at the bottom of the squat suggesting that the EMG activity of the VL should be explored

Table 1: Statistically significant results of the three-way Anova and Sidak post-hoc statistical tests (Peak EMG).

Variables	F ratio	df	p	η_p^2	power
Squat type	4.1	2,156	0.018	0.05	0.72
Squat phase	228.0	1,156	0.001	0.61	1.00
Muscle	101.0	3,156	0.001	0.67	1.00
Squat type * Phase	9.2	2,156	0.001	0.11	0.98
Squat phase * Muscle	10.3	3,156	0.001	0.17	1.00
Sidak post-hocs					
Squat type					
Partial vs. parallel			0.016		
Muscle					
VMO vs. GM			0.001		
VMO vs. BF			0.001		
VL vs. GM			0.001		
VL vs. BF			0.001		
GM vs. BF			0.001		

Table 2: Statistically significant results of the three-way Anova and Sidak post-hoc statistical tests (Mean EMG).

Variables	F ratio	df	p	η_p^2	power
Squat type	3.9	2,156	0.021	0.05	0.70
Squat phase	205.6	1,156	0.001	0.57	1.00
Muscle	166.6	3,156	0.001	0.76	1.00
Squat type * Phase	4.9	2,156	0.009	0.06	0.80
Squat phase * Muscle	13.3	3,156	0.001	0.02	1.00
Sidak post-hocs					
Squat type					
Partial vs. parallel			0.07*		
Muscle					
VMO vs. GM			0.001		
VMO vs. BF			0.001		
VL vs. GM			0.001		
VL vs. BF			0.001		
GM vs. BF			0.001		

** Approaching significance*

Table 3: Statistically significant results of the three-way Anova and Sidak post-hoc statistical tests (iEMG).

Variables	F ratio	df	p	η_p^2	power
Squat type	22.1	2,156	0.001	0.22	1.00
Squat phase	165.7	1,156	0.001	0.51	1.00
Muscle	112.8	3,156	0.001	0.68	1.00
Squat type * Phase	4.3	2,156	0.015	0.05	0.74
Squat phase * Muscle	9.5	3,156	0.001	0.15	1.00
Sidak post-hocs					
Squat type					
Partial vs. parallel			0.001		
Partial vs. full			0.001		
Muscle					
VMO vs. GM			0.001		
VMO vs. BF			0.001		
VL vs. GM			0.001		
VL vs. BF			0.001		
GM vs. BF			0.001		

further.

The most prominent finding was that squatting to parallel evoked greater Peak EMG, Mean EMG, and iEMG activity of the GM during the concentric phase (e.g., Peak EMG = 65.9% MVIC) than squatting to partial (46.9%) and full depths (56.8%); Figure 2. This finding opposes the results of Caterisano *et al.* [10], who reported the GM significantly more active in the full squat, and the mechanical analysis carried out by Bryanton *et al.* [5] who reported that the largest hip joint moment and relative muscular effort occurred in the deep squat. However, our finding substantiates other reports [13] that found GM activity to increase slightly after rising from the bottom of a full squat to a parallel depth.

The higher GM activity in the parallel squat may be explained by a number of factors. Examination of the time-motion analysis of the full squat [1] reveals that the external moment arm imposed on the GM appears to attenuate once the participant descends beyond the parallel position, as dorsiflexion is maximised and the femur to shank angle is reduced, bringing the acetabulofemoral joint closer to the vertical plane of the bar [1]. This observation submits that less torque and thus less EMG activity of the GM is required to overcome inertia against the lifted load compared to the parallel squat [22]. However, no published kinematic data exists to substantiate this claim. Also, it may be speculated that increased relative muscular effort of the knee extensor with greater squat depth [5] and higher VMO EMG activity (Figures 2-4) may reduce the muscular demand on the GM. Another factor that may explain why GM muscle activity did not increase in the full squat is the role of soft tissue in supporting the load at the end of range of motion. It has been suggested that an optimal length-tension relationship of the GM exists at about 90° of knee angle (slightly above parallel), conducive to muscle force production [3] and suggestive that perhaps less activation is required to generate tension in the partial squat [22]. It is unclear whether the angle of hip flexion peaks at the parallel depth and remains constant, whereby muscle length and involvement would not necessarily change as the squats deepens. These factors offer an explanation for the higher GM activity at parallel depth.

The BF was more active at parallel (Mean EMG = 20.7% MVIC) than during partial (13.0%) squats during the concentric phase, similarly to the vasti and in-line with previous findings [11]. However, negligible differences were found between parallel and full squats (18.1%); Figure 3. Upholding existing literature regarding the small contribution of the BF to the squat in terms of absolute EMG [7,14], the level of muscle activity in the BF was comparatively low (Figures 2-4). In fact, in the parallel squat, the BF displayed Mean EMG concentric activity of 20.7 ± 4.2% MVIC. This is comparable to previous findings [4] of 26 ± 11% and [2] of approximately 24% even though they used lighter loads. Accordingly, both vasti were significantly more active than the BF regarding Mean EMG and iEMG activity in both the concentric and eccentric phases (Tables 1-3). During the eccentric phase, both knee extensors were active to a significantly greater level than both hip extensors (GM and BF). However, comparing vasti activity during the concentric phase, the Mean EMG activity levels of both the VMO (57.7 ± 23.9%) and VL (43.0 ± 8.3%) in our study are similar to those reported previously [18] of 50.0 ± 9.0% and 47.0 ± 6.0%, respectively. Yet, these values are markedly lower than those reported by the other studies, as is our value for Peak EMG activity of the GM compared to other work [13], which is unexpected as greater loads were used in the present study.

For athletes and coaches that advocate the back squat to facilitate GM muscle development using 5RM or equivalent loads, squatting to a parallel depth is advised. Based on our findings, the parallel squat also contributes to VMO, VL and BF development. Nonetheless, while the back squat provides an effective training stimulus for VMO and VL development, the BF is much less active during the movement. Early assertions of deleterious knee forces and anterior cruciate ligament (ACL) injury risk from squatting below parallel have since been dispelled and such forces are no longer considered an issue when concerning a healthy knee joint [22,32]. The findings of the present study indicate that the back squat will produce high VMO and VL relative to BF EMG activity and forces about the knee and thus prompt a disproportionate development of strength at parallel depth. Consequently, practitioners must be cognizant of the necessity to incorporate hamstrings specific work to compensate for this imbalance in muscle activation and reduce the potential for quadriceps dominance. Such dominance is associated with risk factors such as hamstrings inhibition during antagonistic co-activation, reduced knee joint stability and resulting anterior tibial translation; all linked with increased ACL loading and susceptibility to injury [33]. This is particularly pertinent in female athletes in whom inherent quadriceps to hamstrings dominance is apparent (34), and highly applicable to athletic performance where lateral cutting manoeuvres and landing forces demand effective joint stability [35].

A limitation of this research was the relatively small sample size used (n = 8); however, medium and large η_p^2 and high statistical power were achieved (Tables 1-3). Due to logistical constraints, though care was taken to ensure electrode placement sites were consistent, MVIC trials were performed on days separate from the experimental trials which may have caused signal variation. This research was also limited to the study of the hip and knee extensors. To this end, it would be expedient to analyse trunk activity at several squat depths in future research.

CONCLUSIONS

The findings of this study suggest that the back squat provides an effective training stimulus for VMO and VL development, moderate stimulus for GM activity, and less stimulus for BF activation. Thus, supplementary strength training exercises may be employed to optimally stimulate the BF. The VMO and VL were more active in the parallel and full squats than in the partial squat during the concentric phase, and in the eccentric phase with regards to iEMG. The higher muscle activity of the vasti in the parallel compared to the partial squat is likely due to mechanical disadvantage and greater neural drive to the quadriceps at intermediate and large muscle lengths (i.e., at parallel and full squat depths) than for short muscle lengths (i.e., partial squat depth), and sub-optimal motor-unit firing rates in the partial squat. A major finding was greater GM activity in parallel squats compared to full squats which may be explained by a number of factors related to external moment arm, relative muscular effort, and optimal length-tension relationship.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the technical support provided by Edge Hill University during the course of this project.

REFERENCES

1. Clark, D.R., Lambert, M.I., & Hunter, A.M. (2012). Muscle activation in the loaded free barbell squat: a brief review. *Journal of Strength and Conditioning Research*. 26: 1169-1178.
2. Gullett, J.C., Tillman, M.D., Gutierrez, G.M., & Chow, J.W. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *Journal of Strength and Conditioning Research*. 23: 284-292.
3. Escamilla, R.F., Fleisig, G.S., Lowry, T.M., Barrentine, S.W., & Andrews, J.R. (2001). A three-dimensional biomechanical analysis of the squat during varying stance widths. *Medicine & Science in Sports & Exercise*. 33: 984-1081.
4. Escamilla, R.F., Rafael, F., Fleisig, G.S., Zheng, N., Lander, J.E., Barrentine, S.W., Andrews, J.R., Bergemann, B.W., & Moorman, C.T. (2001). Effects of technique variations on knee biomechanics during the squat and leg press. *Medicine & Science in Sports & Exercise*. 33: 1552-1566.
5. Bryanton, M.A., Kennedy, M.D., Carey, J.P., & Chiu, L.Z.F. (2012). Effect of squat depth and barbell load on relative muscular effort in squatting. *Journal of Strength and Conditioning Research*. 26: 2820-2829.
6. Luera, M.J., Stock, M.S., & Chappell, A.D.W. (2014). Electromyographic amplitude vs. concentric and eccentric squat force relationships for monoarticular and biarticular thigh muscles. *Journal of Strength and Conditioning Research*. 28: 328-338.
7. Paoli, A., Marcolin, G., & Petrone, N. (2009). The effect of stance width on the electromyographical activity of eight superficial thigh muscles during back squat with different bar loads. *Journal of Strength and Conditioning Research*. 23: 246-250.
8. Drinkwater, E.J., Moore, N.R., & Bird, S.P. (2012). Effects of changing from full range of motion to partial range of motion on squat kinetics. *Journal of Strength and Conditioning Research*. 26: 890-897.
9. Escamilla, R.F. (2001). Knee biomechanics of the dynamic squat exercise. *Medicine & Science in Sports & Exercise*. 33: 127-141.
10. Caterisano, A., Moss, R.F., Pellinger, T.K., Woodruff, K., Lewis, V.C., Booth, W., & Khadra, T. (2002). The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. *Journal of Strength and Conditioning Research*. 16: 428-432.
11. Wretenberg, P., Feng, Y., Lindberg, F., & Arborelius, W. (1993). Joint moments of force and quadriceps muscle activity during squatting exercise. *Scandinavian Journal of Medicine and Science in Sports*. 3: 244–250.
12. Flanagan, S.P., and Salem, G.J. (2008). Lower extremity joint kinetic responses to external resistance variations. *Journal of Applied Biomechanics*. 24: 58–68.
13. Robertson, D.G.E., Wilson, J.M.J., & St. Pierre, T.A. (2008). Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics*. 24: 333-340.
14. Ebben, W.P. (2009). Hamstring activation during lower body resistance training exercises. *International Journal of Sports Physiology and Performance*. 4: 84-96.
15. Gorsuch J., Long J., Miller K., Primeau K., Rutledge S., Sossong A., & Durocher J.J. (2010). The effect of squat depth on muscle activation in male and female cross-country runners. *28th International Conference on Biomechanics in Sports*. July 19 – 23. Marquette, Michigan, USA.
16. Baechle, T.R., & Earle, R.W. (2008). Essentials of Strength Training and Conditioning. Champaign, IL: Human Kinetics.
17. Renshaw, D., Bice, M.R., Cassidy, C., Eldridge, J.A., & Powell, D.W. (2010). A Comparison of Three Computer-based Methods Used to Determine

EMG Signal Amplitude. *International Journal of Exercise Science*. 3(1): 1–7.

18. Soncin, R., Pennone, J., Guimaraes, T.M., Mezencio, B., Amadio, A.C., & Serrao, J.C. (2014). Influence of exercise order on electromyographic activity during upper body resistance training. *Journal of Human Kinetics*. 44: 202-208.
19. Macrum, E., Bell, D.R., Boling, M., Lewek, M., & Padua, D. (2012). Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat. *Journal of Sport Rehabilitation* 21: 144-193.
20. Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. London, UK: Routledge Academic.
21. Distefano, L.J., Blackburn, J.T., Marshall, S.W., & Padua, D.A. (2009). Gluteal muscle activation during common therapeutic exercises. *The Journal of Orthopaedic and Sports Physical Therapy*. 39: 532-540.
22. Schoenfeld, B.J. (2010). Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength and Conditioning Research*. 24: 3497-3506.
23. Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *Journal of Electromyography and Kinesiology*. 20: 1023-1057.
24. Halaki, M., & Ginn, K. (2012). Normalization of EMG signals: To normalize and what to normalize to? In: Computational Intelligence in Electromyography Analysis – A Perspective on Current Applications and Future Challenges. Naik, GR, ed. Rijeka, Croatia: InTech, 175-194.
25. Albertus-Kajee, Y., Tucker, R., Derman, W., Lamberts, R.P., & Lambert, M.I. (2011). Alternative methods of normalising EMG during running. *Journal of Electromyography and Kinesiology*. 21: 579-664.
26. Sousa, C.O., Ferreira, J.J.A., Veras-Medeiros, A.C., Carvalho, A.H., Pereira, R.C., Guedes, D.T., et al. (2007). Electromyographic activity in squatting at 40˚, 60˚ and 90˚ knee flexion positions. *Revista Brasileira de Medicina do Esporte*. 13: 280-285.
27. Harman, E., & Garhammer, J. (2008). Administration, scoring and interpretation of selected tests. In: Essentials of Strength Training and Conditioning. Baechle, TR, and Earle, RW, eds. Leeds, UK: Human Kinetics. pp. 249-292.
28. Duffey, M.J., & Challis, J.H. (2007). Fatigue effects on bar kinematics during the bench press. *Journal of Strength and Conditioning Research*. 21: 556-560.
29. Mccaw, S.T., & Melrose, D.R. (1999). Stance width and bar load effects on leg muscle activity during the parallel squat. *Medicine & Science in Sports & Exercise*. 31: 428-436.
30. O'Donoghue P. (2012). *Statistics for sport and exercise studies: an introduction*. London: Routledge.
31. Wretenberg, P.E.R., Feng, Y.I., & Arborelius, U.P. (1996). High- and low-bar squatting techniques during weight-training. *Medicine & Science in Sports & Exercise*. 28: 218-224.
32. Hartmann, H., Wirth, K., & Klusemann, M. (2013). Analysis of the load on the knee joint and vertebral column with changes in squatting depth and weight load. *Sports Medicine*. 43: 993-1008.
33. Vasconcelos, R.A., Arakaki, J.C., Simao, A.P., Oliveira, A.S., Paccola, C.A.J., & Bevilaqua-Grossi, D. (2007). Analysis of anterior tibial translation, peak torque, and quadriceps and hamstrings coactivation in individuals with anterior cruciate ligament injuries performing isometric open kinetic chain exercises. *Acta Ortopedica Brasileira*. 15: 14-16.
34. Hirst, H.E., Armeau, E., & Parish, T. (2007). Recognizing anterior cruciate ligament tears in female athletes: what every primary care practitioner should know. *The Internet Journal of Allied Health Sciences and Practice*. 5: 125-132.
35. Blackburn, J.T., Norcross, M.F., Cannon, L.N., & Zinder, S.M. (2013). Hamstrings stiffness and landing biomechanics linked to anterior cruciate ligament loading. *Journal of Athletic Training*. 48: 764-835.