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CASE STUDY

SURFACE ELECTROMYOGRAPHY ANALYSIS OF THE FREE, SMITH AND SPLIT SQUATS PERFORMED BY STRENGTH-TRAINED MALES

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ABSTRACT

Introduction: Squats recruit a large proportion of the body's muscular system and provide a foundation for strength training programs for athletes. However, our understanding of electromyographical activity in variations of the high-bar back-squat, notably the split squat, is limited. Therefore, this study aims to investigate surface electromyography (EMG) in the free, Smith and split types of squat.

Method: A randomised sample of 10 healthy strength-trained males (mean ± SD age, 20.3 ± 0.5 years; height, 1.7 ± 0.6 m; mass, 78.1 ± 9.5 kg; strength training, 2.5 ± 0.5 years) performed 3 repetitions of each type of squat at 75% of their one repetition maximum. A Noraxon EMG - Raxon system was used to collect peak EMG, root-mean-square EMG (RMS EMG), and integrated EMG (iEMG) data for the eccentric and concentric phases of the squat. EMG data from the free and split squats were normalised to the Smith squat. Two-way ANOVAs were used for the analysis of type-of-squat and phase-of-squat ($p \leq 0.01$).

Results: Statistically significant effects for type-of-squat were found for peak EMG and iEMG of the bicep femoris (BF), lateral gastrocnemius (LG) and tibialis anterior ($0.001 \leq p \leq 0.003$), and for RMS EMG of the BF ($p = 0.002$) and LG ($p = 0.001$). Significant differences in phase-of-squat were found for peak EMG and RMS EMG of BF ($p = 0.001$).

Discussion: The split squat elicited higher BF and LG muscle activity compared to the free and Smith squats. The findings suggest that the split squat effectively stimulates the BF and LG muscles and should consequently form an integral part of strength programs for athletes.

Keywords: Biceps femoris, Lateral Gastrocnemius, Muscle activity, Squat type, Strength and conditioning.

INTRODUCTION

The barbell back squat provides a functional transfer into numerous sporting movements and it is the predominant exercise in strength programs [1]. Previous research confirms the effectiveness of the bilateral barbell squat in developing maximal strength and power of the lower extremities in athletes [2-5]. Specifically, the squat has been reported to improve speed and acceleration in sprinting, and performance in countermovement jumps [6-9]. The literature contains extensive research on squat depth, foot placement, and muscle activation in the two-legged squat [10]; however, the biomechanics of the split squat are less well understood.

Popular forms of the squat include the free, Smith and split squats. A Smith machine constrains the squat movement to a straight-line translatory motion of a barbell guided by a set of rails [11]. In contrast, the free squat entails a less stable motion. In fact, it has been put forward that the free squat involves higher levels of hip and knee stabilisation which benefit individuals that aim to strengthen the hip and knee musculature compared to the Smith squat [12]. The electromyography (EMG) research conducted by Schwanbeck *et al.* [12] evaluated the discrepancies in lower limb muscle function between the free and the Smith squat. The root-mean-square EMG (RMS EMG) activity was significantly greater by 49% in the *vastus medialis oblique* (VMO), 26% in the *biceps femoris* (BF), and 34% in the *lateral gastrocnemius* (LG) in healthy males during the free squat compared to the Smith squat [12]. The distal attachment of the LG crosses the ankle joint and the proximal attachment crosses the knee joint, and both the LG and soleus become more active in unstable movements such as the free squat [12]. The literature suggests that greater EMG activity is necessary to stabilise the ankle, knee and hip joints in the free squat, and that the free squat is more advantageous than the Smith squat for strengthening the hip and knee extensors, and plantar flexors [12].

An advantage of using a Smith machine to perform squats is that less experience in strength training with barbells and coordination are required compared to using a free barbell. This makes the Smith machine popular amongst recreational sports participants [13]. However, substantial increases in strength and power have been achieved through the use of the free back squat [1]. There is difference of opinion amongst strength and conditioning coaches regarding the effectiveness of Smith machines. It has been suggested that because the motion of the barbell in the Smith machine is constrained to a straight line it may increase the risk of injury as this is not a natural movement [14]. Also, the literature presents inconclusive research findings in muscle recruitment in the free and Smith squats, which can be attributed to methodological differences in squat technique, stance width, squat depth, and foot positioning [12,15]. For example, Paoli *et al.* [16] found that a wide stance elicits a greater recruitment of the gluteus maximus and hamstrings in the back squat. An important consideration regarding muscle recruitment is related to barbell positioning [17]. In the high-bar back squat the barbell is placed on top of the trapezius muscles, whereas in the low-bar back squat the bar is positioned lower on the back just above the spine of the scapula and immediately above the rear deltoids. The high-bar squat prompts the athlete to adopt a more upright trunk posture which elicits a greater contribution from the quadriceps [17]. In the low-bar technique the torso is bent further forward in order to keep the bar over the mid-foot. Low-bar squatting activates the hamstrings and gluteus more intensely and usually allows lifting heavier weights, therefore setting appropriate conditions to develop greater muscular power. Evaluation of the literature points to the need for further research that explores EMG muscle activation patterns in different types of squat.

Lower body strength and conditioning routines place an emphasis on bilateral squatting, however athletes perform many sporting movements unilaterally [18,19]. Research has shown that unilateral exercises increase stimulation of the neuromuscular system to stabilise the musculature of the trunk and hip. Unilateral exercises require advanced stability and control in the athlete, often causing a reduction of lifted loads and power output during strength training [20]. Thus, there is disagreement amongst strength and conditioning coaches regarding the importance of bilateral and unilateral exercises to improve athletic performance. Saeterbakken and Fimland [21] explained that the split squat helps develop the lateral subsystem, described as the frontal plane stabilisation provided by the lumbo-pelvic-hip muscle complex responsible for transferring force between the lower and upper body during single-leg movement patterns. The main muscles engaged in the lateral subsystem include the gluteus medius, hip adductors and quadratus lumborum which show higher EMG activity when performing unilateral exercises [22]. Previous research suggests that unilateral training such as the split squat stimulates the lateral subsystem musculature and may elicit higher EMG activity than bilateral squats.

The EMG activity in the free back squats, rear-leg elevated split squats, and split squats has been previously investigated by de Forest *et al.* [23]. The muscles studied included the *gluteus maximus*, BF, semitendinosus, rectus femoris, vastus lateralis oblique (VLO), VMO, tibialis anterior (TA) and medial gastrocnemius (from the front leg in unilateral squats). Muscle activity was similar between free and split squats, apart from activity of the BF. The BF muscle showed considerably higher activation in the free squat than in the split squat during the concentric phase of the exercise with a mean difference of 1.78 mV. In contrast, research conducted by Longpre *et al.* [24] found that the quadriceps yields higher activation in the lunge exercise compared to the free squat in healthy young females. In-depth understanding of EMG activity in different types of squat may assist in designing strength programs that further recruit the BF to reduce antagonistic muscular imbalances and injury risk in athletes [8,14].

There is limited kinesiological insight into how EMG activity differs between bilateral and unilateral squat types. Therefore, the aim of this study was to evaluate EMG activity in the free, Smith and split squats. Specific objectives included assessment of peak EMG, RMS EMG, and integrated EMG (iEMG) for the three types of squat and the two phases of the movement (eccentric and concentric). The peak EMG is the peak amplitude of the EMG signal which represents a measure of the maximal activity of a given muscle during an exercise. The RMS EMG is defined as the square root of the average power of the raw EMG which reflects the level of the physiological activity in the motor unit during muscle contraction. The iEMG is the mathematical integral of the rectified EMG signal that provides an estimate of the total amount of muscle activity [25]. The findings of this study may provide practical information for coaches and athletes to optimise strength programs, promote antagonistic muscle balance, prevent injury, and enhance our understanding of EMG spatio-temporal and co-activation characteristics of lower-limb muscles in the free, Smith and split squats.

METHODS

Experimental Design

This study consisted of an experimental repeated measures design using strength trained males chosen at random in which the participants performed one set of 3 repetitions of the free, Smith and split squats at a parallel depth using a load of 75% of the participants' one repetition maximum (RM) [26,27]. The participants' 1RM loads were established one week prior to data collection, according to the American College of Sports Medicine [28] 1RM protocol: Start with 5-10 repetitions at perceived 40 – 60% RM, rest for 1 min, perform 3-5 repetitions at 60 – 80% RM, rest for 3 mins, add 5 – 10 lbs (2.27 - 4.54 kg) and perform a single rep. If the latter attempt is successful, then rest for 3-5 mins and continue adding 5 – 10 lbs until a failed attempt occurs. Record the last successfully completed lift as the 1RM. Data collection was carried out under controlled laboratory conditions. The order of performance of squat type was randomised to control the effects of fatigue on EMG muscle activation patterns. The dependent variable was *muscle EMG activity*. The independent variables included *type-of-squat* and *phase-of-squat*. Extraneous variables encompassed *cross-talk*, individual *variations in posture* when lifting, and *unrelated voluntary contractions* [25]. Standardised squat instructions were implemented [27].

Participants

Ten healthy strength-trained males of mean ± SD age of 20.3 ± 0.5 years, height of 1.7 ± 0.6 m and mass of 78.1 ± 9.5 kg participated in the study. The participants were three 100m sprinters, three rugby players and four football players of university level. The participants trained for their sport two times per week and were experienced in using a variety of squats for strength training. They were free from injury at the time of testing and had no history of lower back or lower limb injuries. For 48 hours prior to data collection the participants did not take part in any sport or strength training. This ensured their muscles were fully recovered from previous training sessions and prevented delayed onset of muscle soreness from influencing the individual's lifting technique [28]. Risk assessments were evaluated prior to data collection and all participants provided informed consent for participation. The study was approved by the Institutions' Ethics Committee.

Electromyography Procedures

A Noraxon EMG - Raxon system (Noraxon USA inc, Arizona, USA) was used to evaluate the VMO, VLO, BF, LG and TA which are the predominant muscles in the execution of squats [27]. Preparation of the skin overlying the muscle sites was carried out by cleaning the skin with alcohol wipes, shaving with a razor and lightly abrading the skin with sand paper [25]. Disk-shaped 10 mm pre-gelled electrodes were attached to the skin overlying the centre of the belly of the muscles of the right leg. Placement of the electrodes was as follows [29]:

VMO – Location: Electrodes placed at 80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament. Orientation: Almost perpendicular to the line between the anterior superior iliac spine and the joint space in front of the anterior border of the medial ligament.

VLO – Location: Electrodes placed at 2/3 on the line from the anterior superior iliac spine to the lateral side of the patella. Orientation: In the direction of the muscle fibres.

BF – Location: Electrodes placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. Orientation: In the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia.

LG – Location: Electrodes placed at 1/3 of the line between the head of the fibula and the heel. Orientation: In the direction of the line between the head of the fibula and the heel.

TA – Location: Electrodes placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus. Orientation: In the direction of the line between the tip of the fibula and the tip of the medial malleolus.

The muscles of the right leg were analysed in all three types of squats. The front leg in the split squats was the right leg. Two bio-tab electrodes were placed along the direction of the muscle fibres with an inter-electrode distance of 20 mm. A 2 x 1000 pre-amplifier was positioned adjacent to the electrode recording sites secured with double sided tape to prevent the short wires from moving and adding noise to the EMG signal. The telemetric modules transmitted the surface EMG signals to a receiver (Noraxon Telemyo DTS System, Noraxon USA inc, Arizona, USA) that was connected to a personal computer. To ensure optimal transfer of the EMG signal via Wi-Fi, the EMG system initially high-pass filtered the data at 10 Hz and then low-pass filtered at 500 Hz. The recorded EMG signals were analysed using the manufacturer's software (MyoResearch 3.4, Noraxon, USA). The quality and stability of the EMG signal and the presence of cross-talk were assessed [25].

Execution of the Squats

The participants performed the high-bar back free, Smith and split squats using cross-trainer sports shoes for consistency among the participants and to replicate their usual strength training environment. In the free and Smith squats, they used the squat technique model illustrated by Baechle and Earle [27]: Squat depth characterised by thigh(s) parallel to the ground, shoulder width stance, unrestricted knee forward displacement relative to the toes, and push through the heels. The performance of the split squat is illustrated in figure 1. The free and split squats were executed using an Olympic 20 kg barbell

Figure 1: Depiction of the bottom-of-the-squat criterion in the free (left), Smith (middle) and split (right) squats.

and a LifeFitness Hammer Strength squat rack (LifeFitness, Ely, Cambridgeshire, UK). The mass of the Smith bar was 12 kg unloaded. The Smith squat was performed using a LifeFitness Hammer Strength 7° backward-inclined Smith machine. The participants used their individual 1RM load. The mean ± SD 1RM of the participants was 124.5 ± 24.1 kg in the free squat, 104.5 ± 28.3 kg in the Smith squat, and 104.0 ± 25.1 kg in the split squat. Data collection was as follows. A free squat warm up was first completed using 2 sets of 10 repetitions at 50% of 1RM. Subsequently, one set of 3 repetitions with a load of 75% of 1RM were performed for EMG recording. All squats were performed on the same day using a randomised order of squat type. Participants were allowed 3-5 mins of rest between each squat to prevent fatigue affecting the validity of the EMG data [28]. The squat was performed in a slow and controlled manner. The bottom-of-the-squat criterion was monitored by a qualified strength and conditioning coach using visual observation to monitor that the thigh(s) were parallel with the ground (figure 1).

EMG Signal Processing

The raw EMG signals were amplified and filtered using an analogue to digital converter. The variables collected included peak EMG, RMS EMG and iEMG which were calculated over the time windows for the concentric and eccentric phases of the squat separately [25]. Data were averaged for 3 trials of each squat type [25]. Values of peak EMG, RMS EMG and iEMG for the free and split squats were normalised as a percentage of the values for the Smith squat, where the Smith squat is considered the most controlled type of squat that requires less stabilisation of the lower limb joints [30].

Statistical Analyses

The data were assessed for normality of distribution using Q-Q plots, histograms with superimposed normal curves, box plots and Kolmogorov-Smirnov tests; $p \leq 0.05$ [31]. Based on the data not meeting the assumptions of normality, the p value was modified from $p \leq 0.05$ to $p \leq 0.01$ as a correction factor to account for the infringements of the normality assumption [31]. Two-way ANOVAs were used to accommodate the two independent variables *type-of-squat* and *phase-of-squat* using IBM SPSS Statistics 22 software. The eta squared (η^2) and power statistics were obtained and Scheffe post-hoc tests were conducted.

RESULTS

The mean ± SD peak EMG, RMS EMG and iEMG for the three types of squat, eccentric and concentric phases, and 5 muscles are presented in figures 2 – 4. The VMO and VLO showed the highest EMG activity in all three types of squat in

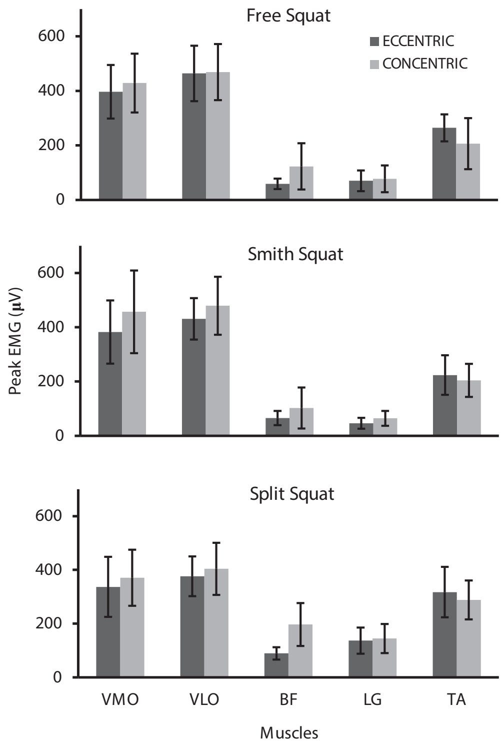

Figure 2: Mean ± SD peak EMG for lower limb muscles in the free, Smith and split squats. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

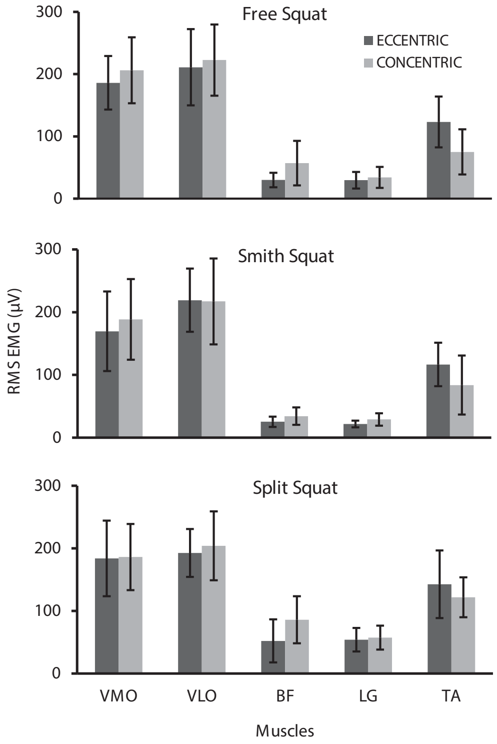

Figure 3: Mean ± SD RMS EMG for lower limb muscles in the free, Smith and split squats. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

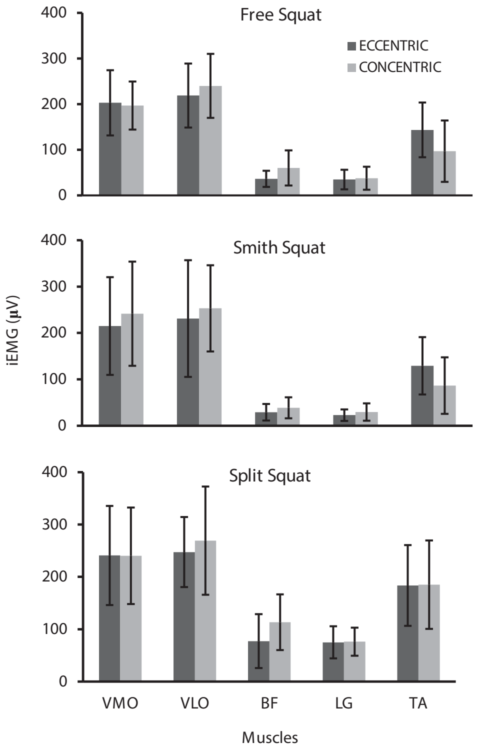

Figure 4: Mean ± SD iEMG for lower limb muscles in the free, Smith and split squats. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

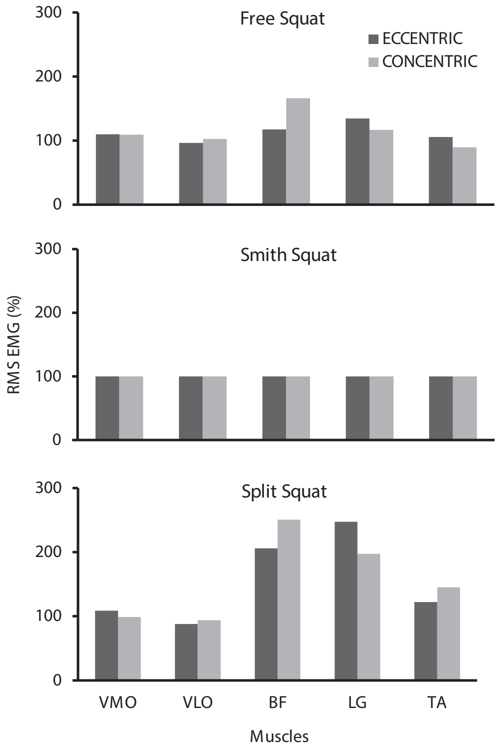

Figure 5: Normalised RMS EMG for lower limb muscles in the free, Smith and split squats. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

Table 1: Kolmogorov-Smirnov tests of normality. Significant values for EMG variables, muscles, types of squat, and phases of the squat. VLO = vastus lateralis oblique, BF = biceps femoris, and TA = tibialis anterior.

Variable	Muscle	Type of Squat	Kolmogorov-Smirnov Significance
Peak EMG	BF	Back	0.009
		Smith	0.001
Mean EMG	BF	Smith	0.004
iEMG	BF	Split	0.001
iEMG	TA	Smith	0.001
Variable	**Muscle**	**Type of Squat**	**Kolmogorov-Smirnov Significance**
RMS EMG	BF	ECC	0.001
		CON	0.004
iEMG	VLO	ECC	0.001
	BF	ECC	0.005
		CON	0.001

Table 2: Results of the two-way ANOVAs for peak EMG. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

		VMO	VLO	BF	LG	TA
Type of Squat	p	0.143	0.028	0.003	0.001	0.001
	F ratio	2.020	3.819	6.378	26.900	7.621
	η^2	0.700	0.124	0.191	0.499	0.220
	Power	0.399	0.670	0.885	1.000	0.935
Squat Phases	p	0.125	0.251	0.001	0.291	0.079
	F ratio	2.430	1.344	20.800	1.136	3.206
	η^2	0.430	0.024	0.279	0.021	0.560
	Power	0.750	0.207	0.994	0.182	0.420
Type of Squat * Phases	p	0.844	0.769	0.143	0.831	0.668
	F ratio	0.170	0.264	2.016	0.186	0.407
	η^2	0.006	0.100	0.069	0.007	0.015
	Power	0.750	0.900	0.398	0.077	0.112

Statistically significant values in bold ($p \leq 0.01$)

Table 3: Results of the two-way ANOVAs for RMS EMG. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

		VMO	VLO	BF	LG	TA
Type of Squat	p	0.772	0.566	0.002	0.001	0.193
	F ratio	0.259	0.575	6.923	24.291	1.695
	η^2	0.010	0.021	0.204	0.474	0.059
	Power	0.089	0.141	0.910	1.000	0.341
Squat Phases	p	0.268	0.336	0.001	0.186	0.110
	F ratio	1.254	0.943	11.402	1.793	2.634
	η^2	0.023	0.017	0.174	0.032	0.047
	Power	0.196	0.159	0.912	0.260	0.357
Type of Squat * Phases	p	0.765	0.957	0.658	0.897	0.881
	F ratio	0.269	0.044	0.421	0.109	0.127
	η^2	0.010	0.002	0.015	0.040	0.005
	Power	0.900	0.056	0.115	0.066	0.068

Statistically significant values in bold ($p \leq 0.01$)

Table 4: Results of the two-way ANOVAs for iEMG. VMO = vastus medialis oblique, VLO = vastus lateralis oblique, BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

		VMO	VLO	BF	LG	TA
Type of Squat	p	0.354	0.791	0.001	0.001	0.001
	F ratio	1.057	0.236	18.338	0.482	24.871
	η^2	0.038	0.009	0.404	50.209	0.479
	Power	0.226	0.085	1.000	1.000	1.000
Squat Phases	p	0.782	0.489	0.061	0.624	0.190
	F ratio	0.077	0.485	3.665	0.004	1.760
	η^2	0.001	0.009	0.064	0.243	0.032
	Power	0.059	0.105	0.468	0.077	0.256
Type of Squat * Phases	p	0.820	0.978	0.320	0.970	0.499
	F ratio	0.200	0.022	1.165	0.001	0.704
	η^2	0.007	0.001	0.041	0.600	0.025
	Power	0.800	0.053	0.245	0.054	0.163

Statistically significant values in bold ($p \leq 0.01$)

Table 5: Significant post-hoc tests. BF = biceps femoris, LG = lateral gastrocnemius, and TA = tibialis anterior.

Variable & muscle	Types of squat	p value
Peak BF	Smith vs. Split	0.007
	Back vs. Split	0.001
Peak LG	Smith vs. Split	0.001
	Back vs. Split	0.002
Peak TA	Smith vs. Split	0.002
RMS BF	Smith vs. Split	0.003
	Back vs. Split	0.001
RMS LG	Smith vs. Split	0.001
	Back vs. Split	0.001
iEMG BF	Smith vs. Split	0.001
	Back vs. Split	0.001
iEMG LG	Smith vs. Split	0.001
	Back vs. Smith	0.001
iEMG TA	Back vs. Split	0.010
	Smith vs. Split	0.001

both the eccentric and concentric phases. The free squat elicited higher peak EMG for the VMO and VLO than the Smith and split squats in the eccentric phase; however in the concentric phase the Smith squat yielded higher peak EMG. The VMO and VLO showed generally greater RMS EMG activity in the free squat, and higher iEMG activity in the split squat.

The BF and LG posterior muscles yielded low myo-electrical activity in the three types of squat; however, the split squat involved higher activation of the BF and LG. There was approximately 25% higher EMG activation of the BF in the concentric phase compared to the eccentric phase for all the types of squat. The TA was moderately active throughout all types of squat for both phases, whereby the EMG activity of the TA was highest in the split squat.

Normalised RMS EMG data are presented in figure 5. The BF shows 106% (eccentric phase) and 151% (concentric) and the LG shows 98% (eccentric phase) and 147% (concentric) EMG activity in the split squat compared to the Smith squat.

Tables 1 – 5 display the statistical findings. The BF muscle, Smith squat type, and eccentric phase are the main sources of lack of normality of distribution in the EMG data (Table 1). The differences in peak EMG for the BF ($p = 0.003$), LG ($p = 0.001$) and TA ($p = 0.001$) were statistically significant regarding *type-of-squat*. Only the peak EMG for the BF ($p = 0.001$) showed significant effects for *phase-of-squat* (Table 2). For the RMS EMG, the BF ($p = 0.002$) and LG ($p = 0.001$) were significant in terms of *type-of-squat* and BF ($p = 0.001$) in *phase-of-squat* (Table 3). For iEMG the BF, LG and TA yielded a significance level of $p = 0.001$ in *type-of-squat* (Table 4). Table 5 shows that the statistical differences were principally between the free squat and the two other squat types.

DISCUSSION

The VMO and VLO were considerably active in the three types of squat and both eccentric and concentric phases (figures 2 - 4). This finding is well established across various studies that have reported significantly higher quadriceps activation compared to the hamstrings in squats [12,18]. More specifically the free squat shows the higher peak EMG for the VMO and VLO compared to the Smith machine and split squat (figure 2). The VLO yielded higher EMG activity than the VMO. In contrast, Schwanbeck *et al.* [12] reported that the free squat elicited greater VMO EMG activity compared to the VLO in the Smith squat. However, Schwanbeck *et al.* [12] used a weight that the participants could lift 8 times (i.e., 8RM); the difference in lifted weight between the studies may explain the discrepancy in muscle activity pre-dominance. The BF and LG posterior muscles showed low EMG activity in the three types of squat. However, higher levels of BF activation were recorded in the concentric phase compared to the eccentric phase. In agreement, Escamilla *et al.* [26] found that hamstring activity was greatest during the ascent (concentric) phase of the free back squat. This finding illustrates the contribution of the hamstrings to effective force production in the concentric phase of the squat. Interestingly, the normalised RMS EMG for the BF reveals higher activity in the free and split squats compared to the Smith squat (figure 5). The TA was moderately active in all types of squat, whereby the split squat entailed greater recruitment of the TA. The TA played an important role in the eccentric phase. The iEMG was considerably higher for the BF, LG and TA in the split squat compared to the Smith squat (figure 4). This finding can be explained by the increased time to complete the split squat and total amount of muscle activity [25], as this type of squat is particularly demanding in terms of required balance and control.

The eccentric function of the BF muscle was identified as the main contributor to non-normality of distribution of the EMG data (Table 1). Surprisingly, the Smith squat, despite benefitting from the added control provided by the steel rails, also contributed to non-normality of the data. The BF, LG and TA showed significant differences according to squat type (typical statistical power above 0.88; Tables 2-4), where the post-hoc analysis revealed significantly higher EMG activity in the split squat (Table 5). The BF was the only muscle in which EMG activation differed significantly between squat phases, with statistical power above 0.9 for peak EMG and RMS EMG (Tables 2 and 3). Similarly, Schwanbeck *et al.* [12] found that the BF produced significantly higher RMS EMG activity ($p < 0.05$) in the concentric phase compared to the eccentric phase in both the free and Smith squats.

The findings suggest that the three types of squat loaded the VMO, VLO and TA anterior muscles much more than the BF and LG posterior muscles. Therefore, squats may be complemented with other strength exercises that place focus on hamstring strength; including stiff deadlifts, nordic curls, and glute hamstring raises [27]. These exercises will significantly improve eccentric hamstring strength in athletes whilst reducing loads on the ACL [8,14,27]. The findings of the present study have implications for selecting squat type for strength training. An approach of heavy eccentric training reduces power output but allows for muscular hypertrophy while gaining strength, therefore eccentric squat training could be used in pre-season training [14]. During the competitive season an eccentric plyometric based approach would be most suitable as this develops explosiveness and power [14]. These plyometric exercises could incorporate split squats, lunges, squat jumps, box jumps and single leg hopping particularly beneficial for sprinters [27]. Further, the free and Smith squats were completed in approximately 6–10 s, whereas the split squat took about 12 s, indicating that the two short-duration bilateral squats may be used for the development of power of the quadriceps in strength training. As the split squat takes longer to perform, this exercise is appropriate as a strength training exercise for both the quadriceps and hamstrings, whilst developing stabilisation capability of the lateral subsystem at the knee and hip [21].

The present study is limited to strength trained males, thus further research may include a wider population of male and female athletes. Discrete analysis of specific sports may provide greater insight into EMG activity according to predominant muscle fibre types in athletes. Also, in the split squat the placement of the front foot was not specified for the participants, however foot position may affect the spatio-temporal pattern of EMG activation. In particular, farther forward placement of the leading foot recruits the gluteus maximus and hamstrings more intensely [6]. Future studies of EMG muscle functionality in the squat could incorporate measures of forces and knee angular kinematics using ground reaction force platforms combined with automated motion analysis systems, respectively. The squats could be performed at differed speeds of the eccentric and concentric phases, using different loads to evaluate the ensuing EMG activity. The present EMG analysis was carried out using the high-bar squat modality, in which the quadriceps and gluteus act as the primary movers to compensate for the lack of involvement of the hamstrings [17]. The more vertical position of the torso associated with the high-bar technique is thought to reduce the EMG activity of the hamstrings and the spinal erectors [17], which decreases the maximum weight that the athlete can lift due to limited capability to utilize the posterior muscle chain. It has been proposed [17] that a more pronounced forward lean of the torso and hip flexion in the low-bar squat modality causes the hamstrings to be under tension at the bottom of the squat. This allows the hamstrings to contribute prominently to hip extension during the ascent, utilisation of the posterior chain musculature and lifting heavier weight. Therefore, future research should examine EMG muscle activity of squat variants using the low-bar technique. Further kinesiological analysis may be more comprehensive and measure the EMG activity of other muscles including the gluteus maximus, adductors and abductors [3]. It is apparent that unilateral exercises are important in strength training for improved performance and injury prevention, especially for sprinting [8]. Therefore, unilateral variations of the squat should be investigated further using EMG.

CONCLUSION

In this study, EMG activity of the free, Smith and split squats in strength trained males was analysed. Muscular activity was higher in the concentric phase phase of the three types of squat compared to the eccentric phase in all muscles examined with the exception of the TA. The split squat elicited higher BF and LG muscle activity compared to the free and Smith squats. Ultimately, the free and Smith squats are of great value in the development of VMO, VLO and TA strength. However, the split squat should be incorporated into strength programs to develop the BF and LG in athletes and more effectively achieve strength gains in the posterior muscle chain.

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