MUSCLE ACTIVATION IN UNILATERAL BARBELL EXERCISES: IMPLICATIONS FOR STRENGTH TRAINING AND REHABILITATION

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ABSTRACT

Mausehund, L, Skard, AE, and Krosshaug, T. Muscle activation in unilateral barbell exercises: Implications for strength training and rehabilitation. *J Strength Cond Res* XX(X): 000–000, 2018—The purpose of the present investigation was to assess lower-body muscle activity and hamstrings-to-quadriceps (HQ) activation ratios during performance of the split squat (SS), single-leg squat (SLS), and rear foot elevated split squat (RFESS), while using the same relative load and performing the exercises to muscular failure. Eleven healthy, moderately strength-trained subjects performed a 6–8 repetition maximum set of each exercise while electromyographic (EMG) activity of the vastus lateralis, biceps femoris, gluteus maximus, and gluteus medius was recorded. The results show that there were no significant differences in EMG peak activity of the gluteus maximus and vastus lateralis between any of the exercises. Gluteus medius activation was significantly ($p \leq 0.05$) higher during the SLS (81.9% maximum voluntary isometric contraction [MVIC]), compared with the RFESS (54.9% MVIC) and SS (46.2% MVIC). The RFESS elicited higher ($p \leq 0.05$) biceps femoris activity (76.1% MVIC) than the SS (62.3% MVIC), as well as higher ($p \leq 0.05$) HQ activation ratios (0.83) than the SS (0.69) and SLS (0.63). During the SLS and the SS, HQ activation ratios increased significantly in the course of the repetition maximum set. In conclusion, although absolute loading differs between exercises, similar training stimuli of the gluteus maximus and quadriceps femoris can be expected for all exercises. The SLS is likely to induce the greatest improvements in gluteus medius strength, whereas the RFESS should be preferred if high hamstring coactivation is desired. To improve validity in EMG studies, strength training exercises should be performed close to failure while using the same relative loading.

KEY WORDS electromyography, EMG, split squat, single-leg squat

INTRODUCTION

Appropriate exercise selection is an important part of resistance training program design and involves matching the demands of the exercise with the specific needs of the individual. This requires a thorough understanding of the mechanical demands which the exercise imposes on the musculoskeletal system. Unilateral weight-bearing exercises are commonly integrated in lower-body resistance training programs, both for rehabilitation (44), sport performance (45), fitness as well as for injury prevention (40). These exercises involve multiple joints, target large muscle groups, and can be used to improve lower-body strength, stability, and balance. In comparison with bilateral exercises, such as squats and deadlifts, unilateral weight-bearing exercises may be considered as more functional for daily activities and more sport-specific (37). Also, similar muscle activity (13,25) and training effects (41) can be achieved with lower external loading. This has important implications for individuals with low back pain because spinal loading can be reduced substantially (13) without compromising training stimuli of the lower limbs.

Many variations of unilateral weight-bearing exercises have been developed in the fields of rehabilitation and strength and conditioning, including the commonly used split squat (SS), rear foot elevated split squat (RFESS), and single-leg squat (SLS) (Figure 1). Load distribution between the front leg and rear leg as well as stability and balance requirements vary between these exercises. This may influence muscle activation patterns and the total amount of load lifted.

So far, research comparing different unilateral weight-bearing exercises is scarce. Typically, studies have compared various double-leg exercises with each other, or single-leg exercises with double-leg exercises. In addition, there are 3

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Figure 1. Rear foot elevated split squat (left), single-leg squat (middle), and split squat (right).

important concerns with previous studies comparing muscle activation between different unilateral weight-bearing exercises. First, most studies have not used the same relative load (i.e., % of 1 repetition maximum [1RM]) for all exercises (3,5,13). However, to allow for comparisons of electromyographic (EMG) activity to be made between exercises and subjects, the same relative load should be applied. By using a different relative load for each exercise, loading differences between exercises, and not only the exercise characteristics, will determine EMG activity (8,29). Second, previous research has predominantly used bodyweight or light loads as external resistance (3–5,17). These conditions may be relevant during the early stages of rehabilitation. However, if the resulting muscle activation patterns shall be representative of strength training for healthy individuals or for patients in the later stages of rehabilitation, higher relative loads should be applied. Also, findings from Fry (19) and Schoenfeld et al. (39) show that relatively heavier loads which approach 100% of 1RM are necessary for maximal strength gains. Although a few studies have used the same high relative loading while comparing various unilateral weight-bearing exercise variations (6,16,42), none of these have compared lower-body muscle activity between the SS, SLS, and RFESS. The loaded SLS in particular has not yet been analyzed. As all these exercises are frequently used, a better understanding of differences in muscle activation patterns is important and necessary for appropriate exercise prescription. Third, most studies on unilateral weight-bearing exercises did not measure muscle activity while performing exercises close to failure (5,6,16). For the SLS and RFESS in particular, no such studies have yet been conducted. However, performing sets close to failure will replicate typical strength training conditions and improve ecological validity (2). Also, recent research shows that if sets are performed to failure, even lower loads (<60% 1RM) can elicit similar gains in hypertrophy than heavier loads (>60% 1RM) (39).

Finally, hamstrings-to-quadriceps (HQ) activation ratios have not yet been calculated for the SS, SLS, or RFESS while using external resistance. Knowledge about HQ activation ratios may have importance for rehabilitation, injury prevention, and sport performance. For example, as coactivation of the hamstrings will reduce anterior cruciate ligament (ACL) loading (27,32), exercises with higher HQ activation ratios may be preferred during the early rehabilitation after ACL injury or surgery. It has been suggested that HQ strength ratios should be at least 0.6 to prevent ACL and hamstring injuries (15,22). Choosing exercises with high HQ activation ratios may prevent strength imbalances, and thus injury, to occur. Also, sport specificity may be increased when selecting exercises where high hamstring coactivation is provided, because many sporting tasks, such as jump landings and cutting movements (9,34), require substantial hamstring coactivation.

Therefore, the purpose of the present investigation was to assess lower-body muscle activity and HQ activation ratios during performance of the SS, SLS, and RFESS, while using the same relative load and performing the exercises to muscular failure. Specifically, we wanted to analyze the change in activation of selected muscles in the lower extremity through an RM set, and to determine to what degree peak muscle activation differs between exercises. In addition, we sought to investigate to what extent different stability requirements and load distributions between the rear leg and front leg would influence the 6RM load in the 3 exercises.

METHODS

Experimental Approach to the Problem

A within-subjects design was used to compare muscle activity of the lower extremity during performance of the SS, RFESS, and SLS exercise (Figure 1). All subjects completed 2 testing sessions, separated by at least 72 hours. During the first session, the subjects' 6RM was tested for all 3 exercises in a randomized order. During the second session, maximum voluntary isometric contractions (MVICs) were performed for each muscle, followed by a 6–8RM set of each exercise. At the same time, surface EMG activity of the vastus lateralis, biceps femoris, gluteus maximus, and gluteus medius of the dominant leg was recorded. The dominant leg was used as the lead leg during all exercises and was defined as the leg the subject would use to kick a ball with (30). To allow for comparisons to be made between exercises and subjects, the same relative load (i.e., 6–8RM) was applied to all exercises. Both sessions were supervised by 2 accredited strength coaches.

Subjects

Thirteen healthy, moderately strength-trained college students, including 7 men and 6 women, participated in this study. To be included, subjects were required to have been engaged in lower-body resistance training at least once a week for the past 6 months and be familiar with performance of the exercises evaluated. Subjects were excluded if they had acute musculoskeletal injuries or pain, or if they failed to perform the exercises in the prescribed manner. Two men were unable to complete both testing sessions due to muscular soreness in the lower extremity, and thus, data from 11 subjects were included in this study (Table 1). Subjects were instructed to refrain from any lower-body resistance training for 48 hours before testing. The Regional Committee for Medical Research Ethics, South-Eastern Norway Regional Health Authority, reviewed the study with no objections and all participants signed a written informed consent form before inclusion. The study conformed to the latest revision of the Declaration of Helsinki.

Procedures

The first session started with a demonstration of the testing criteria and proper execution of each exercise. Before RM testing, subjects performed a 5-minute general warm-up on a treadmill, followed by 2 familiarization sets of the first exercise. Next, 2 warm-up sets were performed at loads equal to 50 and 80% of the estimated 6RM, respectively, before the first RM trial was conducted. During RM testing, barbell load was adjusted until the maximum load was determined that could be lifted with correct technique for 6 repetitions. Rest periods of 2–4 minutes were permitted between trials. The RM protocol was consistent with the guidelines from the National Strength and Conditioning Association (33). At least 10 minutes of recovery was provided before repeating the test procedure with the next exercise. Exercise sequence was randomized for each subject.

Table 1. Subject characteristics ($n = 11$).

Descriptive	Mean ± *SD*
Age (y)	24.9 ± 2.9
Height (cm)	173.0 ± 10.1
Body mass (kg)	70.5 ± 11.5
Resistance training experience (y)	8.0 ± 3.4
No. of resistance training sessions*	2.5 ± 1.2

*Number of sessions per week during the past 6 months.

The second testing session started with the positioning of the surface electrodes on the dominant lower extremity. The skin was shaved and cleaned with alcohol (2-propanol) (28). Two pre-gelled Ag/AgCl electrodes (Ambu BlueSensor M; Ambu A/S, Ballerup, Denmark; 10 mm^2 circular sensor area) were attached to each muscle belly, parallel to the muscle fibers' direction and with an interelectrode distance of 20 mm (21). The exact positioning and orientation of the electrodes for the biceps femoris, gluteus medius, and vastus lateralis were in concordance with the recommendations of the SENIAM (Surface EMG for Non-Invasive Assessment of Muscles) project (21). Gluteus maximus electrodes were attached based on the lower gluteus maximus electrode placement of previous research (10). Subsequent to fixating all electrodes and cables, we performed manual muscle function tests to ensure EMG signal validity (21).

After electrode attachment, subjects repeated the general warm-up from the first testing session. During MVIC testing, subjects were instructed to gradually increase force production against an immobile resistance (over a period of 3 seconds), hold the maximal contraction (for 3 seconds), and gradually reduce force production (over a period of 3 seconds) (38). Each muscle was tested 3 times with 1-minute rest between trials (4). For the vastus lateralis, subjects were sitting on a leg-extension machine (Selection Leg Extension; Technogym USA Corp., Fairfield, NJ, USA) producing maximal knee extension torque at 60° knee flexion (18). The MVIC for the gluteus maximus was acquired with subjects lying in a prone position with the dominant knee flexed to 90°. One of the researchers applied manual resistance to the distal thigh, while subjects attempted to extend their hip maximally (10). Biceps femoris MVIC was recorded from a prone position with the dominant knee flexed to 45°. The subjects produced maximal knee flexion torque against manual resistance applied to the distal leg. (10). To test the gluteus medius, subjects were lying on their side with their upper, testing leg in an anatomically neutral position. One of the researchers manually provided a downward force applied to the distal leg, while the subjects attempted to abduct their hip maximally (21).

Maximum voluntary isometric contraction testing was followed by a specific warm-up, comprising 3 sets of the first exercise with 6 repetitions each and gradually increasing resistance (barbell only, 50% of 6RM, and 80% of 6RM). After a 3- to 5-minute rest period, the subject performed his/her first trial with the predetermined 6RM load. If lifting criteria were met and a 6–8RM was accomplished, the subject continued with the next exercise. If the exercise was not performed in the prescribed manner or if the number of repetitions was outside the 6–8RM range, the trial was repeated. To ensure recovery, 3–5 minutes' rest was provided between RM sets and exercises. Electromyographic activity was measured, and synchronized video records were taken during all RM trials.

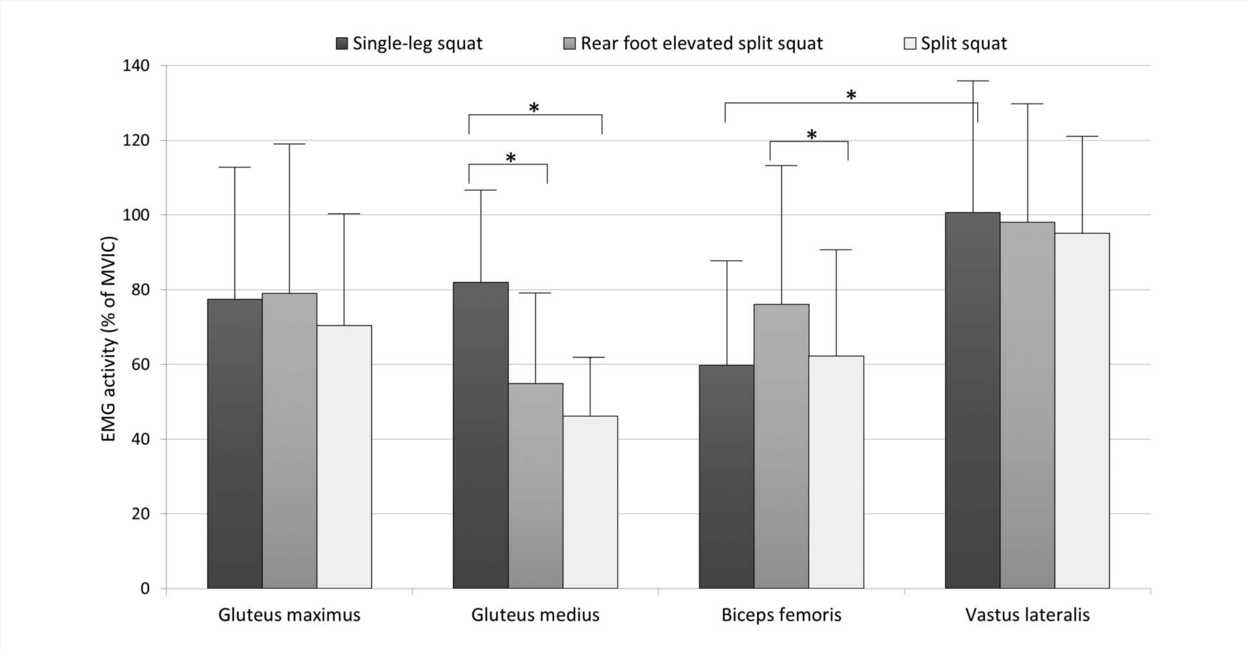

Figure 2. Normalized EMG peak activation for lower-extremity muscles during the single-leg squat, rear foot elevated split squat, and split squat. The EMG values represent the average of the EMG peak values of all analyzed repetitions. *significantly different ($p \leq 0.05$). Mean ± *SD*. EMG = electromyographic; MVIC = maximum voluntary isometric contraction.

Exercise Description. All exercises were performed with the dominant leg in the front and a barbell placed in a high-bar position across the shoulders (Figure 1). Lifting criteria required all repetitions to be performed with a consistent pace through the whole range of motion, and without losing balance. The SS was performed with a step length equal to 100% of leg length, which was defined as the distance from the anterior superior iliac spine (ASIS) to the medial malleolus (5). Step width was set at 75% of hip width, measured as the distance between the right and left ASIS. These standardized distances were perceived as comfortable during pilot testing. Subjects were instructed to lower themselves until the posterior knee touched the floor (13). During performance of the SLS, subjects stood with their dominant leg on top of a box, which had a height equal to tibia length, defined as the distance from the medial knee joint space to the medial malleolus. Subjects descended to the point where the rear foot lightly touched the floor. The RFESS was performed with the same step length and step width used during the SS, and with the toes of the rear foot placed on a box that had the same height as the one used for the SLS. The movement was performed to a depth where the posterior knee touched a balance pad (Airex Balance Pad; Airex AG, Sins, Switzerland). Both the SS and RFESS were standardized to approximately 100–110° of knee flexion at the bottom position of the lift (see Figure, Supplemental Digital Content 1, http://links.lww.com/JSCR/A89, which illustrates knee and hip angles for the 3 exercises). As several subjects experienced difficulties in maintaining good exercise form during the bottom position of the SLS, this exercise was standardized to approximately 90° of knee flexion. Hip flexion angles were similar between lifts.

Instrumentation. Raw EMG signals were recorded at a sampling frequency of 1,000 Hz, with a gain of 220, using 2 portable EMG units (LommeLab; Biomekanikk AS, Oslo, Norway). Data were sent in real time to a tablet (Samsung Galaxy Tab 3, Android version 4.4.2) through Bluetooth and recorded and analyzed using a signal-processing application (EMG LommeLab version 1.0; Biomekanikk AS). A digital low-pass filter (Hammond 50 taps) with a cutoff frequency of 500 Hz and a digital high-pass filter (fourth order Chebyshev) set at 10 Hz was applied to EMG data. Signals of all repetitions were full-wave rectified and smoothed by a root mean square algorithm with a 500-millisecond window. Electromyographic activity was assessed for the entire range of motion (16). Electromyographic peak values of all but the last repetition were the basis for all analyses and were normalized to the highest EMG signal obtained during the 3 MVIC tests (38). To compare EMG activity between exercises, the peak values of all analyzed repetitions were averaged for each subject. When analyzing changes in muscle activation during the RM set, peak values of all exercises were averaged for each repetition. Hamstrings-to-quadriceps activation ratios were

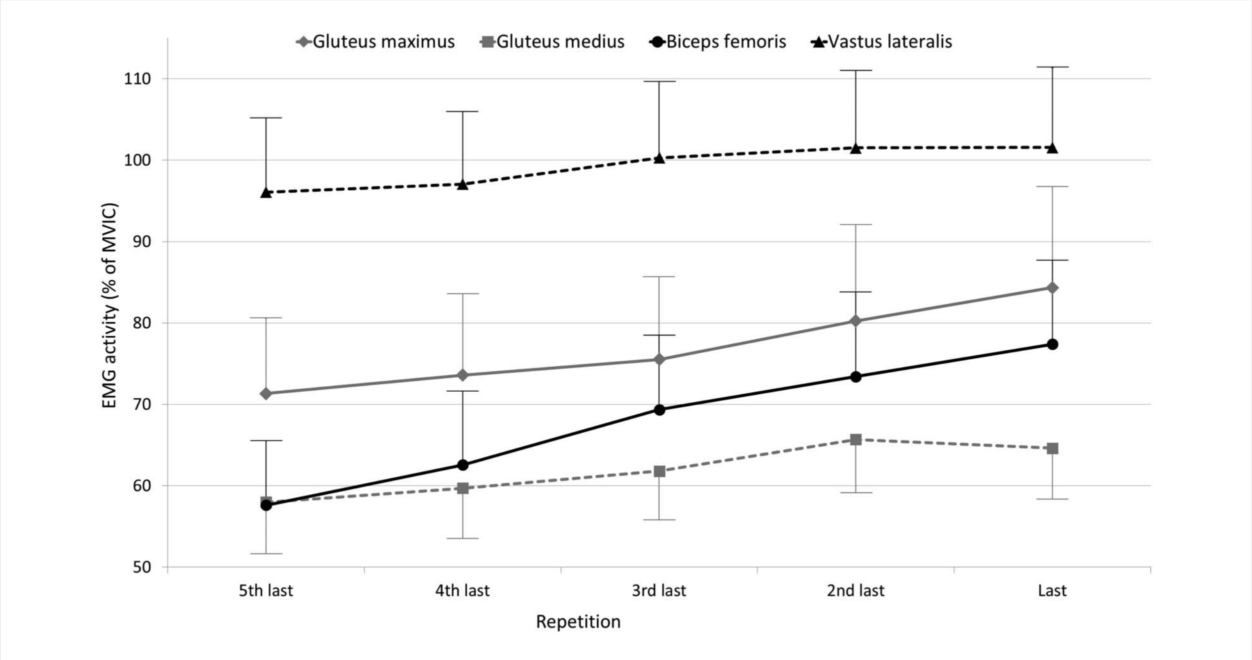

Figure 3. Normalized EMG peak activation for lower-extremity muscles during the last 5 repetitions of the 6–8RM set. Data are collapsed across the 3 exercises for each subject and then averaged for all subjects. Mean ± *SEM*. EMG = electromyographic; MVIC = maximum voluntary isometric contraction; RM = repetition maximum.

calculated by dividing the normalized EMG peak activation of the biceps femoris by the normalized EMG peak activation of the vastus lateralis.

Statistical Analyses

The statistical analyses were performed using IBM SPSS Statistics (Version 23.0; IBM Corp., Armonk, NY, USA). All

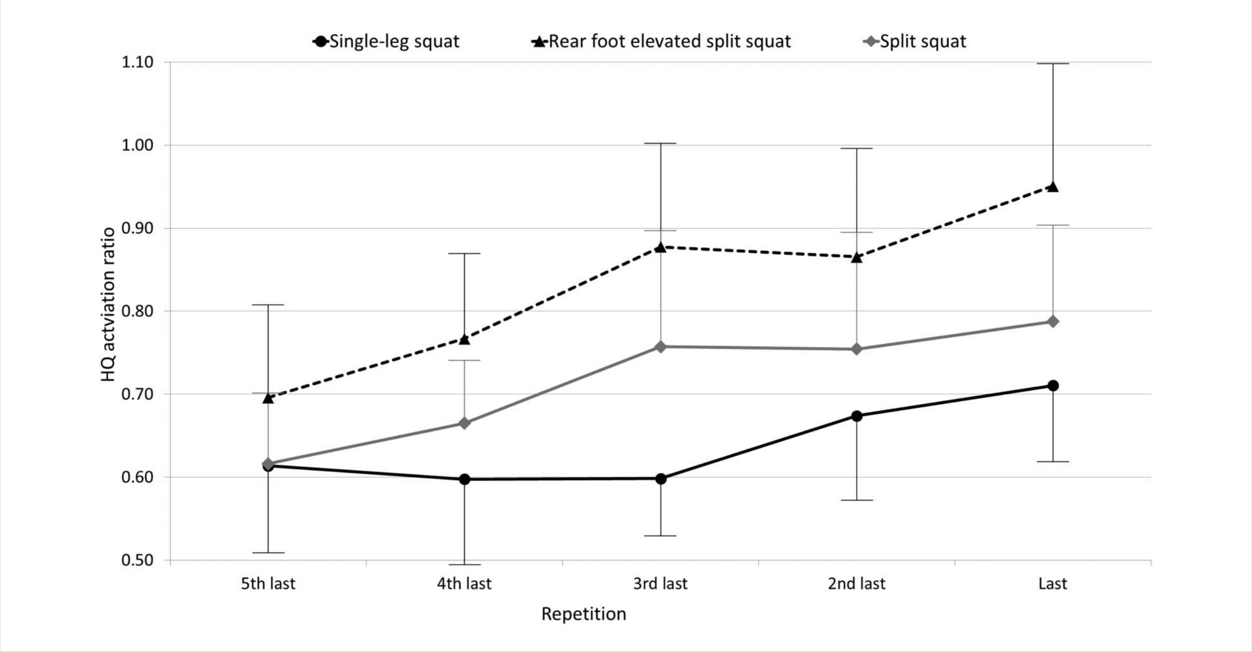

Figure 4. Hamstrings-to-quadriceps (HQ) activation ratios during performance of the single-leg squat, rear foot elevated split squat, and split squat. The last 5 repetitions of the 6–8 repetition maximum set are presented. Data are averaged for all subjects. Mean ± *SEM*.

TABLE 2. Six repetition maximum load (kg) for the test exercises.*

	Mean ± *SD* (range)
SLS	48.2 ± 10.7 (30–65)†
RFESS	57.3 ± 14.3 (40–90)†
SS	70.9 ± 19.1 (50–110)†

*SLS = single-leg squat; RFESS = rear foot elevated split squat; SS = split squat.
†All exercises differed significantly ($p \leq 0.05$).

data were normally distributed, as assessed by Shapiro-Wilk test ($p > 0.05$). One-way repeated-measures analyses of variance were conducted to determine whether there were statistically significant differences in EMG activity, HQ activation ratios, and RM loads between exercises and between muscles. In cases where the assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, a Greenhouse-Geisser correction was applied. If significant main effects were achieved, post hoc analysis with Bonferroni corrections was conducted. Mean differences in percent of MVIC and 95% confidence intervals (CIs) are reported. Paired-samples *t*-tests were used to assess whether there were significant changes in EMG activity and HQ activation ratio between the first and the last repetition. The level of significance was set at $p \leq 0.05$ for all statistical tests. All data are reported as mean ± *SD*, unless otherwise stated.

RESULTS

Electromyographic activity differed significantly between exercises for the gluteus medius ($F_{2,20} = 37.2$, $p < 0.001$) and biceps femoris ($F_{2,20} = 7.4$, $p = 0.004$), but not for the gluteus maximus ($F_{2,20} = 2.2$, $p = 0.136$) or vastus lateralis ($F_{2,20} = 0.74$, $p = 0.491$) (Figure 2). Post hoc analysis revealed that the SLS elicited significant greater gluteus medius activity than the RFESS (mean difference, 27.0% MVIC; 95% CI, 14.9–39.1) and the SS (35.7% MVIC; 95% CI, 20.5–50.9). There was a trend toward greater gluteus medius activity during the RFESS compared with the SS (8.7% MVIC; 95% CI, −0.48 to 17.94). Biceps femoris activation was significantly higher during the RFESS compared with the SS (13.8% MVIC; 95% CI, 3.3–24.4) and the same trend was observed between the RFESS and the SLS (16.4% MVIC; 95% CI, −0.2 to 32.9).

For all exercises, muscle activation was highest for the vastus lateralis, followed by the gluteus maximus and biceps femoris (Figure 2). The vastus lateralis elicited significantly higher muscle activation than the biceps femoris during the SLS (40.9% MVIC; 95% CI, 5.5–76.3), and the same trend was found during the SS (32.8% MVIC; 95% CI, −1.7 to 67.3). Gluteus maximus activation did not differ significantly from vastus lateralis or biceps femoris activation for any of the exercises ($p > 0.05$).

The HQ activation ratio was highest during the RFESS (mean, 0.83; *SD*, 0.39), followed by the SS (0.69 ± 0.35) and SLS (0.63 ± 0.30). Post hoc comparisons showed that the HQ ratio was significantly higher during the RFESS compared with the SLS (mean difference, 0.20; 95% CI, 0.03–0.38) and the SS (0.14; 95% CI, 0.05–0.23).

In the combined analysis for all exercises, each muscle's EMG activity increased in the course of the RM set (Figure 3). From the first to the last repetition, muscle activity increased significantly by 16.3% MVIC for the gluteus maximus (95% CI, 5.9–26.7), by 8.3% MVIC for the gluteus medius (95% CI, 3.6–13.1), by 23.8% MVIC for the biceps femoris (95% CI, 13.5–34.0), and by 9.6% MVIC for the vastus lateralis (95% CI, 3.5–15.6). Similar results were found in separate analyses of each exercise. Between the first and the last repetition, HQ activation ratios increased significantly for the SLS (mean difference, 0.15; 95% CI, 0.02–0.29) and the SS (0.25; 95% CI, 0.13–0.37), and the same trend was found for the RFESS (0.19; 95% CI, −0.03 to 0.41) (Figure 4).

Six repetition maximum load was significantly higher for the SS compared with the RFESS (13.6 kg; 95% CI, 7.7–19.6) and the SLS (22.7 kg; 95% CI, 12.7–32.8) (Table 2). Also, a significantly higher load could be lifted during the RFESS than during the SLS (9.1 kg; 95% CI, 0.70–17.5).

DISCUSSION

This is the first study to assess lower-body muscle activity during performance of unilateral barbell exercises, while using the same relative load and performing the exercises to muscular failure. All exercises elicited similar muscle activation of the primary movers, i.e., the gluteus maximus and vastus lateralis. The main difference was observed in gluteus medius and biceps femoris activation, which were highest during the SLS and RFESS, respectively.

Relatively high EMG activities (≥40% of MVIC) indicate that all the measured muscles can be strengthened effectively by using the exercises evaluated (1). This is especially true for the quadriceps (95–101% MVIC) and the gluteus maximus (71–79% MVIC) during all exercises, but also for the gluteus medius during the SLS (82% MVIC) and for the hamstrings during the RFESS (76% MVIC).

No differences in vastus lateralis or gluteus maximus activity were identified between any of the exercises (Figure 2). Thus, all 3 exercises seem to have a similar effect on these muscle groups. By contrast, biceps femoris activity differed significantly between exercises with higher peak values obtained during the RFESS (76.1% MVIC) compared with the SS (62.3% MVIC) and SLS (59.7% MVIC; trend only) (Figure 2). This implies that the RFESS may entail a slight advantage if hamstring development is desired. Also, a gradual increase in hamstring loading can be achieved by progressing from the SLS or SS to the RFESS. This may be relevant during rehabilitation of hamstring injuries. However, it should be noted that other exercises, such as the Nordic hamstrings, (31) will be more effective if the aim is to increase hamstring strength.

In a previous study, DeForest et al. (13) compared RFESSs with SSs while using the same absolute load. However, using the same absolute load, rather than the same relative load, can be methodologically inaccurate and yield invalid results, especially when comparing exercises that are characterized by large loading differences (8,29). Our results show that substantially higher loads can be lifted during the SS than during the RFESS, meaning that subjects in the study by DeForest et al. (13) likely used a higher relative loading during the RFESS. Although our studies revealed similar results, this may explain why the difference in biceps femoris activity between the RFESS and SS was considerably greater in their study (Cohen's *d* effect size of 2.1 vs. 0.4). The higher biceps femoris activation during the RFESS compared with the 2 other exercises may have been caused by a more inclined trunk position because this has been shown to increase biceps femoris activity during the lunge exercise (18). However, trunk angles have not yet been compared between these exercises.

We observed a significantly higher gluteus medius activation during the SLS (81.9% MVIC) than during the RFESS (54.9% MVIC) and SS (46.2% MVIC) (Figure 2). This is not surprising because increased load bearing on one leg means that the systems' center of mass projection on the ground needs to be positioned closer to this leg. Hence, the external hip adduction moment arm will increase. In agreement with our findings, previous research has shown that RFESSs and lunges produce higher gluteus medius activity than bilateral squats (30). Our results indicate that if gluteus medius strengthening is desired, the SLS will be the preferred exercise of the 3. Although other non–weight-bearing exercises may activate the gluteus medius to a greater extent (26), it may be desirable to strengthen the gluteus medius in a weight-bearing condition, to replicate muscle loading during daily activities and sports. Being able to activate the gluteus medius and exert a hip abduction force in a weight-bearing position is believed to be important for preventing excessive knee valgus during pivoting or cutting maneuvers and may lower the risk of ACL injuries (23,43). Interestingly, we observed that the gluteus medius activity reached its peak near the top position, i.e., close to full hip extension, during all exercises. This finding is consistent with that of Ward et al. (46) and implies that large knee and hip flexion angles are not necessary to activate the gluteus medius during unilateral weight-bearing exercises. As a matter of fact, a reduced range of motion allows for heavier loads to be lifted and may yield even higher gluteus medius activation.

Unstable exercises, such as the SLS, have been criticized for being difficult to perform with high external loading, thereby preventing high levels of muscle activation and optimal training adaptations (30). However, our study showed no difference in agonist or antagonist muscle activity between the more unstable SLS exercise and the 2 other exercises. As previous research has reported lower, greater, or similar muscle activation when comparing exercises with different requirements to stability while using the same relative loading, we agree with Andersen et al. (2), suggesting that there are no universal effects of instability on EMG activation.

Hamstrings-to-quadriceps activation ratios below 1.0 illustrate that the 3 exercises are quadriceps dominant in terms of muscle activation (Figure 4). However, the ratios obtained in this study (0.6–0.8) are substantially higher than what has been reported in previous research (0.1–0.5) (3,6,17,24). This can likely be attributed to the use of higher external loads in this study, as Riemann et al. (35) showed that adding load increases hip joint extensor impulse more than knee joint extensor impulse during the lunge exercise. The high hamstring coactivation in these exercises may be beneficial for ACL injury prevention and rehabilitation because coactivation of the hamstrings reduces ACL loading (27,32). This finding is in agreement with that of Dedinsky et al. (12), stating that single-leg exercises produce adequate HQ ratios, which may reduce ACL injury risk.

Interestingly, biceps femoris activity increased more than vastus lateralis activity in the course of the RM set in all exercises (Figure 3). Accordingly, HQ activation ratios increased as well (Figure 4). Increasing external loading during the lunge exercise has been shown to increase hip dominance (35). Probably, the same occurs when increasing exercise demands by performing sets to failure. A more hip-dominant strategy may have involved that subjects increased trunk forward lean as fatigue increased, thereby increasing biceps femoris activity (18). Both gluteus maximus and biceps femoris activity increased more than vastus lateralis activity, at the same time as vastus lateralis activity was near 100% of MVIC. This implies that the quadriceps muscle group was working close to its maximal capacity and that the hip extensor loading is upregulated when exercise demands are increased further. Hence, the quadriceps muscle group seems to be the limiting factor during performance of the SS, RFESS, and SLS. Moreover, this finding underlines the importance of performing sets close to failure when studying EMG activity during strength training exercises because muscle activity may increase in one muscle, whereas it may remain constant in another. Because resistance exercises are typically performed close to failure, measuring EMG activity under similar conditions ensures validity.

Six repetition maximum load was highest during the SS, followed by the RFESS and SLS, in that order (Table 2). This may imply that SLSs should be chosen if one wants to reduce spinal loading, while obtaining similar activation of the lower-extremity musculature. The difference in load distribution between the front leg and the rear leg is likely the reason for the different amount of load that could be lifted in the 3 exercises. Obviously, during the SLS, 100% of the total load is supported by the front leg. By contrast, approximately 85% of the total load is supported by the front leg during the RFESS (30) and 75% during the lunge (20), which is similar to the SS. Therefore, it seems that the higher the relative loading on the front leg, the lower the absolute load lifted.

There are some limitations that should be considered in this study. The SLS was conducted with approximately 10–20° less knee flexion compared with the 2 other exercises (see Figure, Supplemental Digital Content 1, http://links.lww.com/JSCR/A89, which illustrates knee and hip angles for the 3 exercises). This may potentially have influenced muscle activation. However, because all exercises were performed with the same relative load and because differences in knee angle were small, only minor differences in muscle activity were expected to occur due to differences in knee angle (11,36). Importantly, we believe that the current standardization will replicate typical training conditions and would therefore be the preferred choice even if EMG signals would be affected by the differences in knee angle. Furthermore, common error sources of surface electromyography, such as neighboring crosstalk (28), may have influenced EMG activity. If the MVIC tests failed to generate maximal muscle activation, EMG activity will be overestimated during the following measurements. However, this will only affect the EMG comparisons made between different muscle groups, but not the comparisons between exercises. Previous studies have suggested that fatigue may affect the maximal EMG amplitude (14), making it difficult to establish the true relative muscle activation throughout a series to failure. In the current study, we observed the highest EMG changes in the muscle with lowest relative activation, i.e., the biceps femoris. Due to its low relative activation, the biceps femoris is likely less affected by fatigue than the vastus lateralis. In other words, it seems likely that the observed EMG changes of the biceps femoris reflect a true change in loading distribution, i.e., a more hip-dominant exercise execution toward the last repetitions. In the present investigation, only peak values of the EMG signal were considered. Integrated EMG can potentially provide a more complete picture of the muscular demands of an exercise. Furthermore, during multijoint tasks, there can be an uneven distribution of relative muscular efforts. During squatting, for instance, hip, knee, and ankle relative muscular efforts vary depending on squatting depth and loading (7). Similar effects are likely to be present during unilateral weight-bearing exercises (35). Therefore, alterations from the range of motions and loads used for the exercises in this investigation may change moment distribution and subsequent muscle loading and training adaptations. Finally, our study cannot determine whether the higher gluteus medius activation during the SLS and the higher biceps femoris activation during the RFESS will translate into improved training adaptations in terms of hypertrophy and strength, compared with the other exercises.

In conclusion, all exercises elicited similar activation of the primary movers, i.e., the gluteus maximus and vastus lateralis. The main differences were observed in gluteus medius and biceps femoris activation, which were highest during the SLS and RFESS, respectively. During all exercises, HQ activation ratios increased in the course of the RM set, meaning that these exercises become more hip dominant when being performed to failure. Differences in load distribution between the front leg and rear leg allowed for the highest loads to be lifted during the SS, followed by the RFESS and SLS. To improve validity in EMG studies, strength training exercises should be performed close to failure while using the same relative loading.

PRACTICAL APPLICATIONS

The results of the current investigation allow practitioners to make informed decisions when selecting unilateral weight-bearing exercises for strength training and rehabilitation purposes and can help to adjust training programs to meet the needs of the individual. The SS, RFESS, and SLS can be used effectively to strengthen all muscle groups evaluated, particularly the quadriceps femoris and gluteus maximus. For targeting the gluteus maximus and quadriceps femoris, all exercises seem to be equally effective. The SLS is likely to induce the greatest improvements in gluteus medius strength, whereas the RFESS seems to be the preferred choice for training the hamstrings. During performance of all exercises, the quadriceps muscle group seems to be the limiting factor and when exercise demands are increased further, the hip extensors need to compensate for its failure. The SS, SLS, and especially the RFESS can be recommended during the early rehabilitation after ACL injury or ACL reconstruction because the high hamstring coactivation observed will reduce ACL loading. The SLS necessitates a lower absolute loading for providing the same amount of leg muscle activation. This reduces spinal loading and may have importance for individuals with low back pain.

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