Mausehund, L., Skard, A. E., Krosshaug, T. (2018). Muscle Activation in Unilateral Barbell Exercises: Implications for Strength Training and Rehabilitation. *Journal of Strength and Conditioning Research,* under utgivelse. doi:10.1519/JSC.0000000000002617

Muscle activation in unilateral barbell exercises: Implications for strength training and rehabilitation

ABSTRACT

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 six to eight repetition maximum (RM)-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 ($p \leq .05$) higher during the SLS (81.9% MVIC), compared to the RFESS (54.9% MVIC) and SS (46.2% MVIC). The RFESS elicited higher ($p \leq .05$) biceps femoris activity (76.1% MVIC) than the SS (62.3% MVIC), as well as higher ($p \leq .05$) 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 RM 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, while the RFESS should be preferred if high hamstrings co-activation 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, bulgarian lunge

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/or balance. In comparison to 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 (14, 26) and training effects (41) can be achieved with lower external loading. This has important implications for individuals with low back pain, as spinal loading can be reduced substantially (14) 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 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 three 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) for all exercises (4, 6, 14). 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 different relative loads, loading differences between exercises, and not only the exercise characteristics, will determine EMG activity (9, 30). Second, previous research has predominantly used bodyweight or light loads as external resistance (4-6, 18). 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 (20) and Schoenfeld et al. (39) show that relatively heavier loads which approach 100% of 1 repetition maximum (RM) are necessary for maximal strength gains. Although a few studies have utilized the same high relative loading while comparing various unilateral weight-bearing exercise variations (7, 17, 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 (6, 7, 17). 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 co-activation of the hamstrings will reduce ACL loading (28, 33), 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 hamstrings injuries (16, 23). 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 hamstrings co-activation is provided, because many sporting tasks, such as jump landings and cutting movements (10, 34), require substantial hamstrings co-activation.

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 a 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 and front leg would influence the 6 RM load in the three 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 two testing sessions, separated by at least 72 hours. During the first session, the subjects' 6 RM was tested for all three exercises in a randomized order. During the second session, maximum voluntary isometric contractions (MVIC) were performed for each muscle, followed by a 6 - 8 RM-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 (31). To allow for comparisons to be made between exercises and subjects, the same relative load (i.e. 6 - 8 RM) was applied to all exercises. Both sessions were supervised by two accredited strength coaches.

Subjects

Thirteen healthy, moderately strength trained college students, including seven men and six 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 last six 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 eleven subjects were included in this study (Table 1). Subjects were instructed to refrain from any lower body resistance training for 48 hours prior to testing. The Regional Committee for Medical Research Ethics, South-Eastern Norway Regional Health Authority, reviewed the study with no objections and participants signed a written informed consent form before inclusion. The study conformed to the latest revision of the Declaration of Helsinki.

TABLE 1

Procedures

The first session started with a demonstration of the testing criteria and proper execution of each exercise. Prior to RM testing, subjects performed a 5-minute general warm-up on a treadmill, followed by two familiarization sets of the first exercise. Next, two warm-up sets were performed at loads equal to 50% and 80% of the estimated 6 RM, 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 six repetitions. Rest periods of two to four minutes were permitted between trials. The RM protocol was consistent with the guidelines from the National Strength and Conditioning Association (3). At least ten minutes recovery was provided before repeating the test procedure with the next exercise. Exercise sequence was randomized for each subject.

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) (29). Two pre-gelled Ag/AgCl-electrodes (Ambu BlueSensor M; Ambu A/S, Ballerup, Denmark; 10 mm² circular sensor area) were attached to each muscle belly, parallel to the muscle fibers' direction and with an inter-electrode distance of 20 mm (22). The exact positioning and orientation of the electrodes for the biceps femoris, gluteus medius and vastus laterialis were in concordance with the recommendations of the SENIAM (Surface EMG for Non Invasive Assessment of Muscles) project (22). Gluteus maximus electrodes were attached based on the lower gluteus maximus electrode placement of previous research (11). Subsequent to fixating all electrodes and cables, we performed manual muscle function tests to ensure EMG signal validity (22).

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 three seconds), hold the maximal contraction (for three seconds) and gradually reduce force production (over a period of three seconds) (38). Each muscle was tested three times with one minute rest between trials (5). 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 (19). 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 (11). 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. (11). 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 (22).

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

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 split squat 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 (6). 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 (14). 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 utilized during the split squat, and with the toes of the rear foot placed on a box which 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 degrees of knee flexion at the bottom position of the lift (see Figure, Supplemental Digital Content 1, which illustrates knee and hip angles for the three 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.

FIGURE 1

Instrumentation

Raw EMG signals were recorded at a sampling frequency of 1000Hz, with a gain of 220, by two 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) via Bluetooth and recorded and analyzed using a signal-processing application (EMG LommeLab version 1.0; Biomekanikk AS, Oslo, Norway). A digital low-pass filter (Hammond 50 taps) with a cutoff frequency of 500Hz and a digital high-pass filter (4^{th} order Chebychew) set at 10Hz was applied to EMG data. Signals of all repetitions were full-wave rectified and smoothed by a root mean square (RMS) algorithm with a 500 millisecond window. EMG activity was assessed for the entire range of motion (17). EMG 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 three 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. HQ activation ratios were calculated by dividing the normalized EMG peak activation of the biceps femoris by the normalized EMG peak activation of the of the vastus lateralis.

Statistical Analyses

The statistical analyses were performed using IBM SPSS Statistics (Version 23.0; IBM Corp., Armonk, NY, USA). All data were normally distributed, as assessed by Shapiro-Wilk test ($p > .05$). One-way repeated measures analyses of variance (ANOVA) 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 (95% CI) 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 $p \leq .05$ for all statistical tests. All data are reported as means ± standard deviation, unless otherwise stated.

RESULTS

EMG 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 towards greater gluteus medius activity during the RFESS compared to the SS (8.7% MVIC; 95% CI, -0.48, 17.94). Biceps femoris activation was significantly higher during the RFESS compared to 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 - 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 - 67.3). Gluteus maximus activation did not differ significantly from vastus lateralis or biceps femoris activation for any of the exercises ($p > .05$).

FIGURE 2

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 to 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 - 0.41) (Figure 4).

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

TABLE 2

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 of 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 three exercises appear to have a similar effect on these muscle groups. In contrast, biceps femoris activity differed significantly between exercises with higher peak values obtained during the RFESS (76.1% MVIC) compared to 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 hamstrings development is desired. Also, a gradual increase in hamstrings loading can be achieved by progressing from the SLS or SS to the RFESS. This may be relevant during rehabilitation of hamstrings injuries. However, it should be noted that other exercises, such as the Nordic hamstrings (32) will be more effective if the aim is to increase hamstrings strength. In a previous study, Deforest et al. (14) compared RFESSs to SSs while using the same absolute load. However, utilizing 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 (9, 30). Our results show that substantially higher loads can be lifted during the SS than during the RFESS, meaning that subjects in Deforest et al. (14) likely used a higher relative loading during the RFESS. Even though 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 to the two other exercises may have been caused by a more inclined trunk position, as this has been shown to increase biceps femoris activity during the lunge exercise (19). 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, as 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 (31). Our results indicate that if gluteus medius strengthening is desired, the SLS will be the preferred exercise of the three. Although other non-weightbearing exercises may activate the gluteus medius to a greater extent (27), it may be desirable to strengthen the gluteus medius in a weightbearing 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 (24, 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 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 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 (31). However, our study showed no difference in agonist or antagonist muscle activity between the more unstable SLS exercise and the two 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.

FIGURE 3 AND 4

HQ activation ratios below 1.0 illustrate that the three exercises are quadriceps dominant in terms of muscle activation (Figure 4). However, the ratios obtained in the present study (0.6 - 0.8) are substantially higher than what has been reported in previous research (0.1 - 0.5) (4, 7, 18, 25). This can likely be attributed to the use of higher external loads in the present 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 hamstrings co-activation in these exercises may be beneficial for ACL injury prevention and rehabilitation, as co-activation of the hamstrings reduces ACL loading (28, 33). This finding is in agreement with Dedinsky et al. (13), 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 (19). 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 up-regulated 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, as muscle activity may increase in one muscle while it may remain constant in another. As resistance exercises are typically performed close to failure, measuring EMG activity under similar conditions ensures validity.

6 RM 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 and the rear leg is likely the reason for the different amount of load that could be lifted in the three exercises. Obviously, during the SLS 100% of the total load is supported by the front leg. In contrast, approximately 85% of the total load is supported by the front leg during the RFESS (31) and 75% during the lunge (21), which is similar to the SS. Therefore, it appears 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 the present study. The SLS was conducted with approximately 10 - 20° less knee flexion compared to the two other exercises (see Figure, Supplemental Digital Content 1, which illustrates knee and hip angles for the three exercises). This may potentially have influenced muscle activation. However, since all exercises were performed with the same relative load and since differences in knee angle were small, only minor differences in muscle activity were expected to occur due to differences in knee angle (12, 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. Further, common error sources of surface electromyography, such as neighboring crosstalk (29), 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 (15), 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 towards 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. Further, during multi-joint 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 (8). Similar effects are likely to be present during unilateral weightbearing 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 to 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 and rear leg allowed 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 appear to be equally effective. The SLS is likely to induce the greatest improvements in gluteus medius strength, while 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, as the high hamstrings co-activation 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.

REFERENCES

1. Andersen LL, Magnusson SP, Nielsen M, Haleem J, Poulsen K, and Aagaard P. Neuromuscular activation in conventional therapeutic exercises and heavy resistance exercises: implications for rehabilitation. Physical therapy 86: 683-697, 2006.
2. Andersen V, Fimland MS, Brennset O, Haslestad LR, Lundteigen MS, Skalleberg K, and Saeterbakken AH. Muscle activation and strength in squat and Bulgarian squat on stable and unstable surface. Int J Sports Med 35: 1196-1202, 2014.
3. Baechle TR and Earle RW. Essentials of strength training and conditioning. Champaign, IL: Human Kinetics, 2008.
4. Begalle RL, Distefano LJ, Blackburn T, and Padua DA. Quadriceps and hamstrings coactivation during common therapeutic exercises. J Athl Train 47: 396-405, 2012.
5. Boren K, Conrey C, Le Coguic J, Paprocki L, Voight M, and Robinson TK. Electromyographic analysis of gluteus medius and gluteus maximus during rehabilitation exercises. Int J Sports Phys Ther 6: 206-223, 2011.
6. Boudreau SN, Dwyer MK, Mattacola CG, Lattermann C, Uhl TL, and McKeon JM. Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. Journal of sport rehabilitation 18: 91-103, 2009.
7. Bruenger AJ, Carruth J, and Tucker WS. Comparison of muscle activity during step ups and single leg squats. International Symposium on Biomechanics in Sports: Conference Proceedings Archive 30: 1-4, 2012.
8. Bryanton MA, Kennedy MD, Carey JP, and Chiu LZ. Effect of squat depth and barbell load on relative muscular effort in squatting. Journal of strength and conditioning research / National Strength & Conditioning Association 26: 2820-2828, 2012.
9. Clark DR, Lambert MI, and Hunter AM. Muscle activation in the loaded free barbell squat: A brief review. Journal of strength and conditioning research / National Strength & Conditioning Association 26: 1169-1178, 2012.
10. Colby S, Francisco A, Yu B, Kirkendall D, Finch M, and Garrett W, Jr. Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. Am J Sports Med 28: 234-240, 2000.
11. Contreras B, Vigotsky AD, Schoenfeld BJ, Beardsley C, and Cronin J. A Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis Electromyographic Activity in the Back Squat and Barbell Hip Thrust Exercises. J Appl Biomech 31: 452-458, 2015.
12. Contreras B, Vigotsky AD, Schoenfeld BJ, Beardsley C, and Cronin J. A Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis Electromyography Amplitude in the Parallel, Full, and Front Squat Variations in Resistance-Trained Females. J Appl Biomech 32: 16-22, 2016.
13. Dedinsky R, Baker L, Imbus S, Bowman M, and Murray L. Exercises that facilitate optimal hamstring and quadriceps co-activation to help decrease ACL injury risk in healthy females: A systematic review of the literature. Int J Sports Phys Ther 12: 3-15, 2017.
14. DeForest BA, Cantrell GS, and Schilling BK. Muscle Activity in Single- vs. Double-Leg Squats. International Journal of Exercise Science 7: 302-310, 2014.
15. Dimitrova NA and Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology 13: 13-36, 2003.
16. Dorgo S, Edupuganti P, Smith DR, and Ortiz M. Comparison of lower body specific resistance training on the hamstring to quadriceps strength ratios in men and women. Research quarterly for exercise and sport 83: 143-151, 2012.
17. Ebben WP, Feldmann CR, Dayne A, Mitsche D, Alexander P, and Knetzger KJ. Muscle activation during lower body resistance training. Int J Sports Med 30: 1-8, 2009.
18. Ekstrom RA, Donatelli RA, and Carp KC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. The Journal of orthopaedic and sports physical therapy 37: 754-762, 2007.

19. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, and Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. The Journal of orthopaedic and sports physical therapy 38: 403-409, 2008.
20. Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. Sports medicine (Auckland, NZ) 34: 663-679, 2004.
21. Hefzy MS, al Khazim M, and Harrison L. Co-activation of the hamstrings and quadriceps during the lunge exercise. Biomedical sciences instrumentation 33: 360-365, 1997.
22. Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, and Hägg G. European recommendations for surface electromyography: Results of the SENIAM Project. Enschede: Roessingh Research and Development, 1999.
23. Holcomb WR, Rubley MD, Lee HJ, and Guadagnoli MA. Effect of hamstring-emphasized resistance training on hamstring:quadriceps strength ratios. Journal of strength and conditioning research / National Strength & Conditioning Association 21: 41-47, 2007.
24. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, and Rayens WS. Hip Abductor Function and Lower Extremity Landing Kinematics: Sex Differences. Journal of Athletic Training 42: 76-83, 2007.
25. Jakobsen MD, Sundstrup E, Andersen CH, Aagaard P, and Andersen LL. Muscle activity during leg strengthening exercise using free weights and elastic resistance: effects of ballistic vs controlled contractions. Human movement science 32: 65-78, 2013.
26. Jones MT, Ambegaonkar JP, Nindl BC, Smith JA, and Headley SA. Effects of unilateral and bilateral lower-body heavy resistance exercise on muscle activity and testosterone responses. Journal of strength and conditioning research / National Strength & Conditioning Association 26: 1094-1100, 2012.
27. Macadam P, Cronin J, and Contreras B. AN EXAMINATION OF THE GLUTEAL MUSCLE ACTIVITY ASSOCIATED WITH DYNAMIC HIP ABDUCTION AND HIP EXTERNAL ROTATION EXERCISE: A SYSTEMATIC REVIEW. Int J Sports Phys Ther 10: 573-591, 2015.
28. MacWilliams BA, Wilson DR, DesJardins JD, Romero J, and Chao EY. Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. Journal of orthopaedic research : official publication of the Orthopaedic Research Society 17: 817-822, 1999.
29. Massó N, Rey F, Romero D, Gual G, Costa L, and Germán A. Surface electromyography applications in the sport. Apunts Med Esport 45: 121-130, 2010.
30. McBride JM, Larkin TR, Dayne AM, Haines TL, and Kirby TJ. Effect of absolute and relative loading on muscle activity during stable and unstable squatting. International journal of sports physiology and performance 5: 177-183, 2010.
31. McCurdy K, O'Kelley E, Kutz M, Langford G, Ernest J, and Torres M. Comparison of lower extremity EMG between the 2-leg squat and modified single-leg squat in female athletes. Journal of sport rehabilitation 19: 57-70, 2010.
32. Mjolsnes R, Arnason A, Osthagen T, Raastad T, and Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. Scandinavian journal of medicine & science in sports 14: 311-317, 2004.
33. More RC, Karras BT, Neiman R, Fritschy D, Woo SL, and Daniel DM. Hamstrings--an anterior cruciate ligament protagonist. An in vitro study. Am J Sports Med 21: 231-237, 1993.
34. Padua DA, Carcia CR, Arnold BL, and Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. Journal of motor behavior 37: 111-125, 2005.
35. Riemann BL, Lapinski S, Smith L, and Davies G. Biomechanical analysis of the anterior lunge during 4 external-load conditions. J Athl Train 47: 372-378, 2012.
36. Saito A and Akima H. Knee joint angle affects EMG-force relationship in the vastus intermedius muscle. Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology 23: 1406-1412, 2013.

37. Santana JC. Single-Leg Training for 2-Legged Sports: Efficacy of Strength Development in Athletic Performance. Strength & Conditioning Journal 23: 35, 2001.
38. Schoenfeld BJ, Contreras B, Tiryaki-Sonmez G, Wilson JM, Kolber MJ, and Peterson MD. Regional differences in muscle activation during hamstrings exercise. Journal of strength and conditioning research / National Strength & Conditioning Association 29: 159-164, 2015.
39. Schoenfeld BJ, Grgic J, Ogborn D, and Krieger JW. Strength and Hypertrophy Adaptations Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. Journal of strength and conditioning research / National Strength & Conditioning Association 31: 3508-3523, 2017.
40. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, and Andersen TE. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ (Clinical research ed) 337: a2469, 2008.
41. Speirs DE, Bennett MA, Finn CV, and Turner AP. Unilateral vs. Bilateral Squat Training for Strength, Sprints, and Agility in Academy Rugby Players. Journal of strength and conditioning research / National Strength & Conditioning Association 30: 386-392, 2016.
42. Stastny P, Lehnert M, Zaatar AM, Svoboda Z, and Xaverova Z. Does the Dumbbell-Carrying Position Change the Muscle Activity in Split Squats and Walking Lunges? Journal of strength and conditioning research / National Strength & Conditioning Association 29: 3177-3187, 2015.
43. Stearns KM and Powers CM. Improvements in hip muscle performance result in increased use of the hip extensors and abductors during a landing task. Am J Sports Med 42: 602-609, 2014.
44. Stensrud S, Risberg MA, and Roos EM. Effect of exercise therapy compared with arthroscopic surgery on knee muscle strength and functional performance in middle-aged patients with degenerative meniscus tears: a 3-mo follow-up of a randomized controlled trial. American journal of physical medicine & rehabilitation / Association of Academic Physiatrists 94: 460-473, 2015.
45. Turner AN and Stewart PF. Strength and Conditioning for Soccer Players. Strength & Conditioning Journal 36: 1-13, 2014.
46. Ward SR, Winters TM, and Blemker SS. The architectural design of the gluteal muscle group: implications for movement and rehabilitation. The Journal of orthopaedic and sports physical therapy 40: 95-102, 2010.

ACKNOWLEDGEMENTS

We would like to thank all participants for their commitment and participation in the study. This study was conducted without any funding from manufacturers or outside companies and the authors report no conflicts of interest. The results of this study do not constitute endorsement by the National Strength and Conditioning Association.

Figures/tables

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

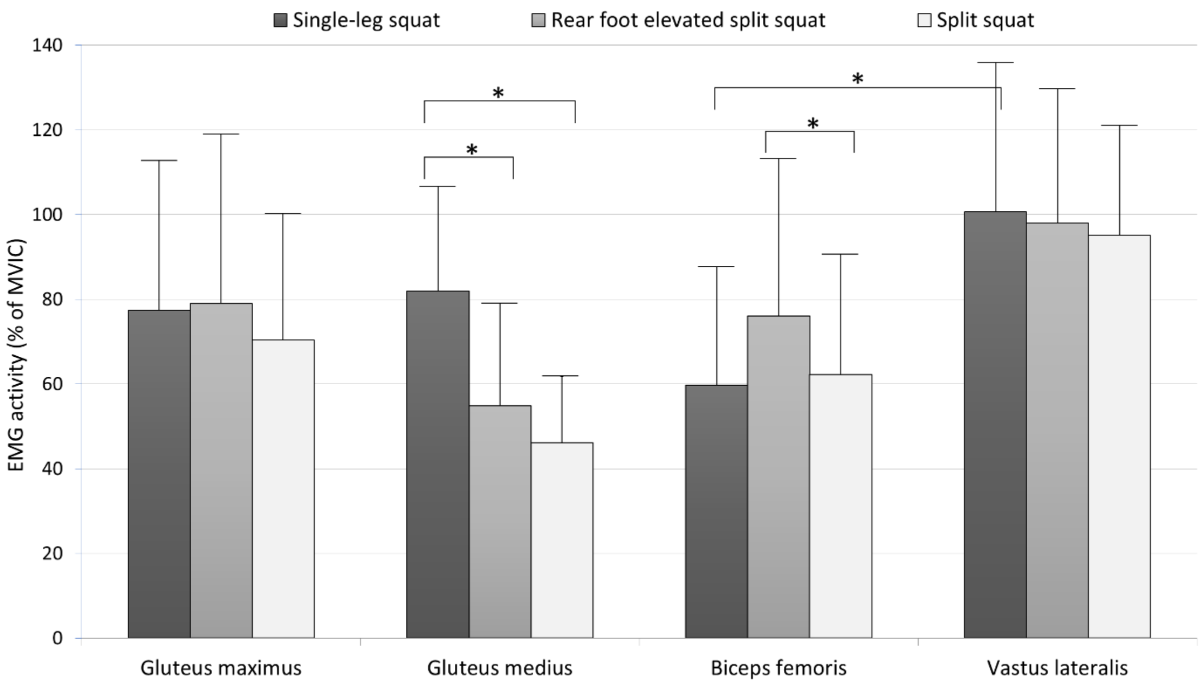

Figure 2. Normalized EMG peak activation for lower extremity muscles during the single-leg squat, rear foot elevated split squat and split squat. The EMG values represent the average of the EMG peak values of all analyzed repetitions. *Significantly different ($p \leq .05$). Mean ± SD.

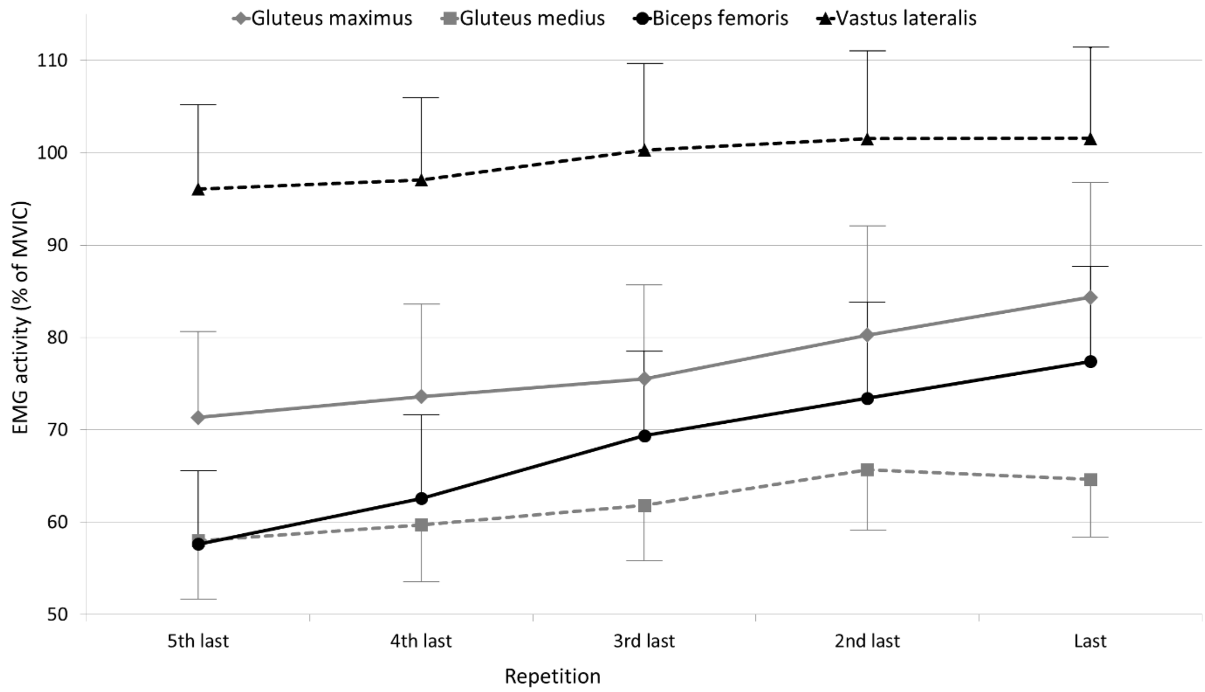

Figure 3. Normalized EMG peak activation for lower extremity muscles during the last five repetitions of the 6 - 8 RM set. Data are collapsed across the three exercises for each subject and then averaged for all subjects. Mean ± SEM.

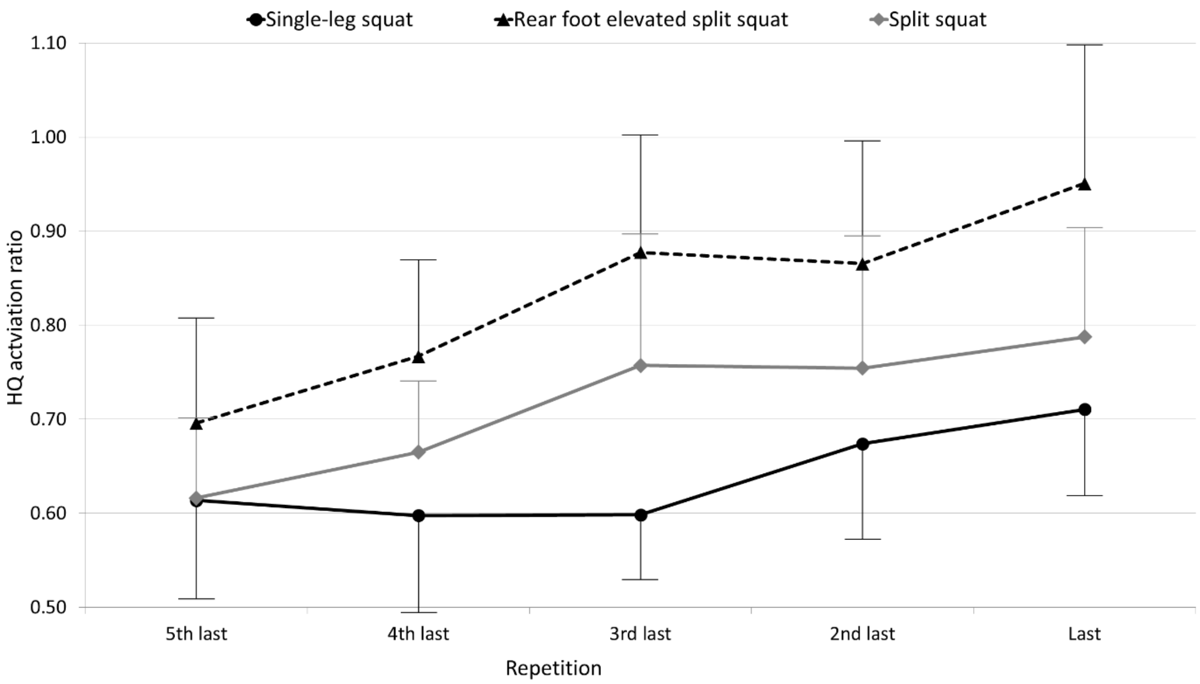

Figure 4. Hamstrings-to-quadriceps activation ratios during performance of the single-leg squat, rear foot elevated split squat and split squat. The last five repetitions of the 6 - 8 RM set are presented. Data are averaged for all subjects. Mean ± SEM.

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
Number of resistance training sessions*	2.5 ± 1.2

*Number of sessions per week during the last six months

Table 2. 6 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] *

*All exercises differed significantly ($p \leq .05$).

†SLS = Single-leg squat; RFESS = Rear foot elevated split squat; SS = Split squat

List of Supplemental Digital Content

Supplemental Digital Content 1. Comparison of knee and hip flexion angles between the three exercises, illustrated for one subject. The knee flexion angle for the single-leg squat was typically 10 - 20° smaller compared to the two other exercises. Hip flexion angles were similar between exercises.