



Comparison of Muscle Activation and Kinematics in 6-RM Squatting With Low and High Barbell Placement

by

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The aim of this study was to compare 6-RM muscle activation and kinematics in back squats with low and high barbell placements. Twelve resistance-trained males (23.5 ± 2.6 years, 86.8 ± 21.3 kg, 1.81 ± 0.08 m) with a minimum of 2 years of squatting experience performed a 6-RM using high and low barbell placements while muscle activation of eight muscles and joint kinematics were measured. During high barbell placement squats, lifting time was longer, with lower average velocity than low barbell placement. This was accompanied by a lesser knee flexion angle at the lowest point of the squat, and larger hip flexion angles during high, compared to low barbell squats. Furthermore, peak angular ankle, knee and hip velocities in the descending phase developed differently between conditions. No significant differences in muscle activation were found between conditions. Thus, our data suggests gross muscular adaptations between barbell placements may be similar over time, and therefore, from a muscular development standpoint, both squat styles are valid. Furthermore, unlike the low barbell placement, fatigue may manifest earlier itself in the high barbell squats during 6-RMs as sets progress toward a lifter's maximal capacity, altering kinematics, especially in the last repetition.

Key words: EMG, resistance exercise, performance.

Introduction

The barbell back squat is arguably the most commonly performed lower body exercise in strength and conditioning settings. With the barbell placed along the back of the shoulders, across the upper trapezius musculature, it is performed by simultaneously flexing the knees, hips and ankles to reach a specific depth (typically the thighs parallel to the floor), followed by extending the hips, knees and ankles to return to a standing position. When using a challenging load, the back squat can effectively train the majority of the body (Glassbrook et al., 2017), as the lifter must isometrically maintain a rigid torso to support the bar, in addition to moving through flexion and extension dynamically at the hip, knee, and ankle. Maximal back squat strength is related to sprinting (McBride et al., 2009) and jumping performance (Nuzzo et al., 2008) and the

back squat is considered an effective tool to both train and assess lower body bilateral strength and power (Escamilla, 2001).

In competitive weightlifting, the back squat is used as a strength building exercise to potentially increase one's snatch, as well as the clean and jerk (the competition lifts of weightlifting), as both lifts require the athlete to move through full, dynamic, flexion and extension of the hips, knees and ankles. Thus, weightlifters use the back squat, with the barbell placed across the upper trapezius, in training to build lower body muscle mass and maximal strength at the hip and knee joints (Wretenberg et al., 1996). Indeed, the snatch and clean and jerk performance are strongly associated with lower limb muscle mass (Siahkouhian and Hedayatneja, 2010) and maximal strength in the back squat

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(Lucero et al., 2019; Stone et al., 2005). Interestingly, the majority of competitive Powerlifters use another variation of the squat, the “low bar” back squat, where instead of the bar being placed across the upper trapezius, it is placed along the mid trapezius using the posterior deltoids as the supportive “shelf” for the bar (Wretenberg et al., 1996). Anecdotally, Powerlifters can lift more weight using this variation of the squat, which has also been observed in previous research comparing the traditional “high bar” back squat placement to the low bar position (Glassbrook et al., 2019). Other unique aspects of the powerlifting squat are that typically wider stances are used (Swinton et al., 2012), and a greater relative degree of hip flexion occurs rather than knee and ankle flexion (Glassbrook et al., 2017); thus, the lifter sits “back and down” reaching the required competition depth (the hip crease traveling below the top of the knee when viewed laterally by a referee (IPF, 2019). This is in contrast to how the back squat is performed by weightlifters, who utilize a high bar position, typically a closer stance width, maintained as upright a torso position as possible, and emphasize greater flexion at the knee and ankle in comparison (Glassbrook et al., 2017) - ostensibly, this technique difference is to better replicate the snatch and clean.

Despite these common differences in back squat bar placements among strength athletes of different disciplines, and subsequent differences in squatting technique, as noted in a 2017 review there are relatively few peer reviewed direct comparisons between high and low back squat bar placements (Glassbrook et al., 2017). Therefore, to add to the body of knowledge in this area, we set out to investigate the muscle activity and kinematic differences between high and low bar placement on the back squat, when using a six-repetition maximum (6-RM) load. Given prior work and anecdotal evidence, we hypothesized there would be differences between squat styles in muscle activity of the posterior chain (hamstrings, glutes, erector spinae) due to different lever arm lengths and hip flexion angles, and in quadriceps muscle activity due to differences in knee flexion angles. Furthermore, that the barbell velocity decreased more and lifting time increased over 6-RM in the high bar placement, compared to the low bar placement due to the different lever arms.

Methods

We chose a 6-RM as it is a mid-way point between commonly prescribed loads for both strength/power training, and “hypertrophy” training; thus, our findings should hopefully be informative for practitioners when using various load prescriptions. A repeated-measures crossover design was used to investigate the measurements of the muscle activity and kinematic differences between high and low bar placement on the back squat kinematics when using a six-repetition maximum (6-RM) load. The dependent variables were muscle activation, maximal angular joint velocities and barbell kinematics in the descent and ascend phase.

Participants

Twelve healthy resistance trained males (age 23.5 ± 2.6 years, body mass 86.8 ± 21.3 kg, stature 1.81 ± 0.08 m) with at least 2 years of resistance-training experience in squats participated in the study. Inclusion criteria were being able to lift 1.5 of their own bodyweight in one-repetition maximum (1-RM) squat (femur parallel to the floor) and no injuries or pain during squats which could reduce their maximal performance. The subjects did not conduct any resistance training of the legs 72 hours before testing. Each participant was informed of the testing procedures and possible risks, and written consent was obtained prior to the study. The study complied with the current ethical regulations for research and approved by the National Centre for Research Data, in conformance with the latest revision of the Declaration of Helsinki.

Procedures

Since all subjects were experienced resistance trained athletes they were familiar with their own 6-RM load during squats. Thus, a self-reported 6-RM load was used to start with. Most participants used a high barbell placement during their training, and had little experience (only 4 participants trained regular with the low bar placement) with the low barbell placement; therefore, all warm-up sets were performed with the low barbell placement to familiarise the participants with this condition in addition to training it in the three weeks before the test session. After a general warm-up on a treadmill or cycle ergometer of 5 minutes, warm-up squats were performed with a low barbell placement.

Participants positioned their feet in their preferred position, and then the position of the feet was measured. This position was then controlled and was identical in subsequent attempts. Then, the lowest position in which the hip joint was below the knee (full squat) was found using a protractor. A horizontal rubber band was used to identify this position. The warm-up sets consisted of 20 repetitions at 25%, 10 repetitions at 50% and 8 repetitions at 70% of self-reported 6-RM (Behm et al., 2005; van den Tillaar and Saeterbakken, 2014). A randomized crossover design was used; thus, half of the participants performed their 6-RM with the low barbell placement first, while the other half started with the high barbell placement. The same external load in both conditions was used. The 6-RM squats were performed with an Olympic barbell (2.8 cm diameter, length 1.92 m) in a power rack (Gym 2000, Modum, Norway). The participants performed repetitions in a self-paced but controlled tempo from full knee extension, to the lowest position, marked with a horizontal rubber band. When the back of their thigh touched the rubber band, they received a verbal signal from the test-leader and returned to the starting position as quickly as possible. Up to three attempts were performed to establish their 6-RM for that day. Between each 6-RM attempt, the participants had 3-5 min rest interval (Goodman et al., 2008). After establishing their 6-RM, the participants had 6-10 min rest interval before performing the opposite condition. The barbell was placed across the top of the trapezius just below the spinous process of the C7 vertebra during the high barbell placement, while in the low barbell placement the barbell was placed on the lower trapezius just over the posterior deltoid, along the spine of the scapula.

Measures

Wireless electromyography (EMG) was recorded with a sampling frequency of 1000Hz by using a Musclelab 6000 system and analyzed by Musclelab v10.5.67 software (Ergotest Technology AS, Langesund, Norway). EMG activity was measured for eight muscles: vastus lateralis, vastus medialis, rectus femoris, biceps femoris, gluteus maximus, external oblique and erector spinae (L1, 6 cm lateral to the spinous process). The skin was shaved, abraded and washed with alcohol before placing the gel-coated self-adhesive electrodes (Dri-Stick Silver circular sEMG

Electrodes AE-131, NeuroDyne Medical, USA). The electrodes (11 mm contact diameter and a 2 cm center-to-center distance) were placed on the dominant leg along the presumed direction of the underlying muscle fiber according to the recommendations by SENIAM or similar studies (Hermens et al., 2000; van den Tillaar et al., 2014; van den Tillaar and Saeterbakken, 2014). The EMG signals were converted to root mean square (RMS) EMG signals using a hardware circuit network (frequency response 20–500 kHz, averaging constant 100 ms, total error $\pm 0.5\%$). The mean RMS EMG signals of each muscle during the descending and ascending phases of the lift for every repetition and condition were used for further analysis.

The beginning, lowest point and end of each lift were identified by using a linear encoder (ET-Enc-02, Ergotest Technology AS, Langesund, Norway) attached at the inside of the weights to the barbell. The encoder measures the upward phase duration of the barbell to the nearest 0.075 mm and counts the pulses with 10-ms intervals (Bosquet et al., 2010). Total descending and ascending times and total barbell distances were measured per repetition and condition. Peak and average velocity of the barbell during the descending and ascending phases were calculated by using a 5-point differential filter with Musclelab v10.73 software (Ergotest Technology AS, Langesund, Norway). Furthermore, absolute and relative timing of the peak velocity in descending and ascending phases per repetition and condition were used for additional analysis.

A three-dimensional (3D) motion capture system (Qualysis, Gothenburg, Sweden) with eight cameras operating at a frequency of 500Hz was used to track reflective markers, creating a 3D positional measurement. The markers were placed, one on each side of the body, on the lateral tip of the acromion, the iliac crest, greater trochanter, the lateral and medial condyle of the knee, the lateral and medial malleolus, and the distal ends of the first and fifth os metatarsal. There were also two markers placed on the middle of the barbell between the hands and shoulders 80 cm apart, to track barbell displacement. Segments of the feet, lower and upper leg, pelvis and trunk were made in Visual 3D v5 software (C-Motion, Germantown, MD, USA). Barbell position and velocity, joint angles

and angular velocity of hip extension, knee extension and plantar flexion were calculated for the whole lift by Visual 3D software. Joint angles were estimates of the anatomical angles calculated from lines formed between the centres of the reflective markers. The joint angles at the deepest point of the lift at each repetition and condition, together with the peak angular velocities of hip extension/flexion, knee extension/flexion and ankle plantar/dorsal flexion were calculated during the descending and ascending phases. The 3D motion capture system was synchronized with the linear encoder and EMG recordings using a Muscledab 6000 system (Ergotest Technology AS, Langesund, Norway).

Statistical Analysis

To assess differences in kinematics and EMG activity during the descending and ascending phases between high and low barbell squat conditions, a two-way (low and high barbell \times 6 repetitions) analysis of variance (ANOVA) with repeated measures was used. If significant differences were found for the variable repetition, a One-way ANOVA with repeated measures for the low and high barbell was performed with Holm-Bonferroni post-hoc tests. In cases where the sphericity assumption was violated, the Greenhouse-Geisser adjustment of p -values was reported. The level of significance was set at $p \leq 0.05$. For statistical analysis, the SPSS version 25.0 (SPSS, Inc., Chicago, IL) was applied. All results are presented as means \pm standard deviations and effect sizes were calculated with η^2_p (Eta partial squared) where $0.01 < \eta^2 < 0.06$ constitutes a small effect, a medium effect when $0.06 < \eta^2 < 0.14$ and a large effect when $\eta^2 > 0.14$ (Cohen, 1988).

Results

The 6-RM load lifted was 102 ± 30 kg. A significant effect of barbell placement was found during the ascending phase in lifting time, average velocity and time to peak velocity ($F \geq 7.9$, $p \leq 0.017$, $\eta^2 \geq 0.42$), while for all other barbell kinematics, including the descending phase, no significant effect of barbell placement was found ($F \leq 7.9$, $p \geq 0.11$, $\eta^2 \geq 0.02$). A significant effect of repetitions for all barbell kinematic variables was found, except for the relative time of peak barbell velocity in the descending and ascending phase and peak barbell velocity during the ascending phase ($F \leq 2.2$, $p \geq 0.113$, $\eta^2 \geq 0.13$). Furthermore, a

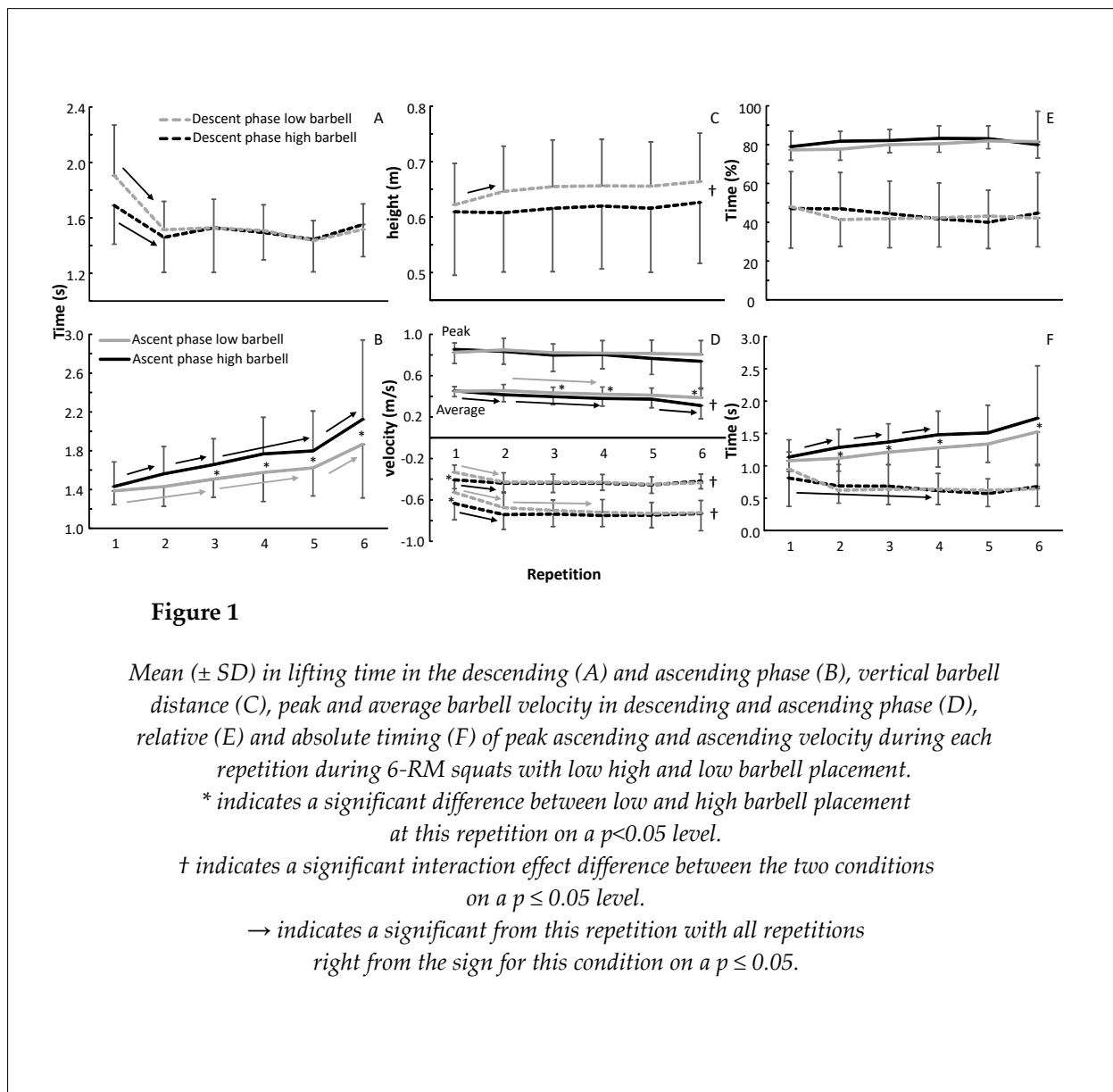
significant interaction was found for the position of the barbell, and peak and average velocity during the descending phase ($F \geq 3.1$, $p \leq 0.035$, $\eta^2 \geq 0.22$). Post hoc comparison revealed that the ascending phase took longer in the high barbell than the low barbell squat, especially from repetition 3 onward. This was accompanied by a lower average ascending barbell velocity and a later absolute timing of peak ascending barbell with the low barbell position (Fig. 1A, C, D and F). During the descending phase, repetition one differed from all subsequent repetitions, having a longer total time, and lower peak and average velocity. This was more apparent with the low barbell placement as the kinematics of how repetitions developed (interaction effect) significantly differed from the high barbell placement. Specifically, barbell position descended to a greater degree following the initial repetition in the low barbell condition, while in the high barbell condition no change in barbell position occurred as the repetitions progressed (Fig. 1 C).

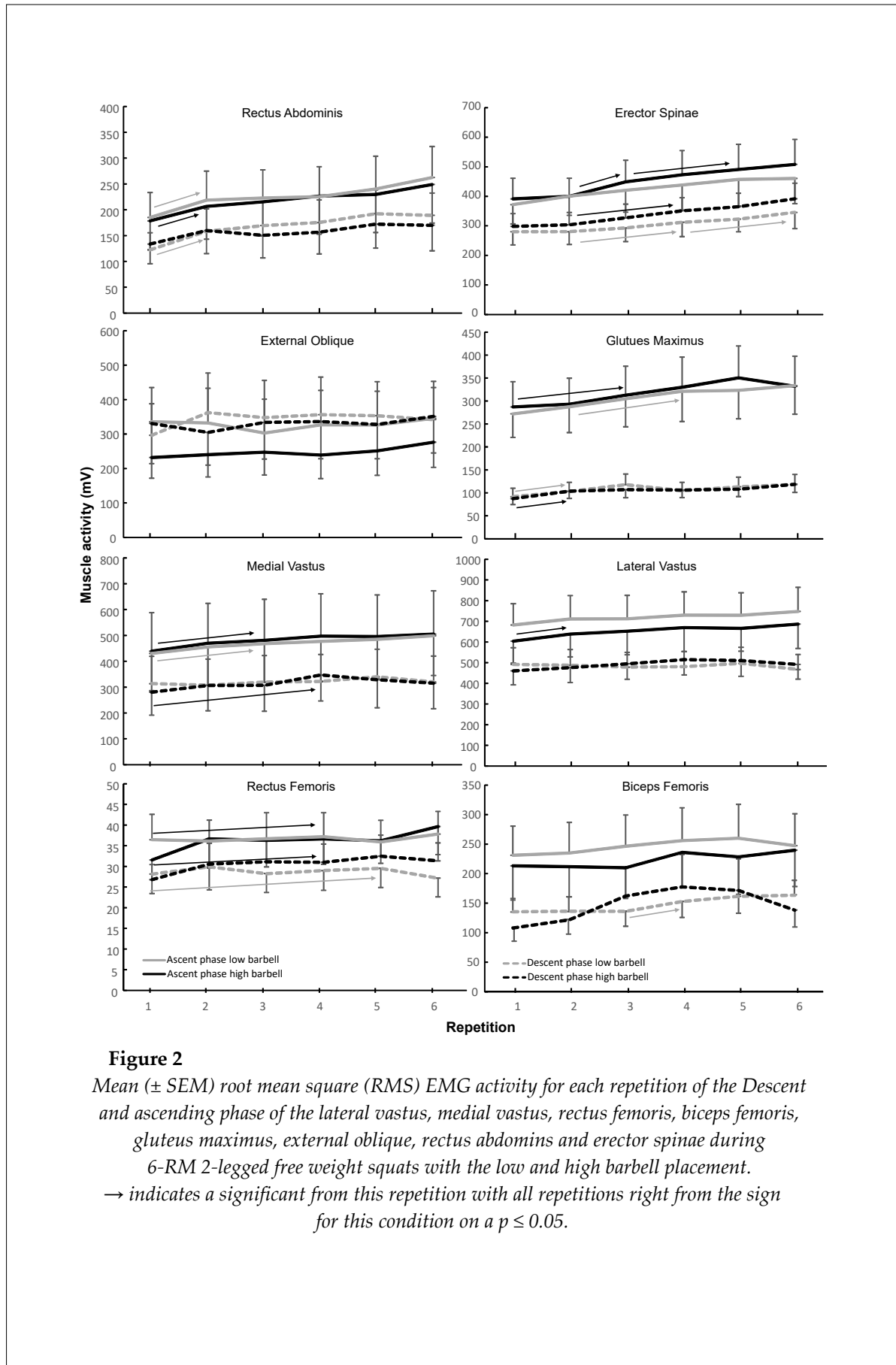
No significant differences in muscle activity were found between the low and high barbell squats for any of the muscles during the descending or ascending phases ($F \leq 3.1$, $p \geq 0.11$, $\eta^2 \leq 0.22$). However, a significant effect of repetitions was found in both phases for the gluteus maximus, erector spinae, rectus abdominis and medial vastus ($F \geq 3.8$, $p \leq 0.021$, $\eta^2 \geq 0.26$). For the vastus lateralis only, the ascending phase showed a significant effect ($p = 0.036$). The biceps femoris, rectus femoris, external oblique and vastus lateralis during the descending phase did not show a significant effect of repetitions ($F \leq 2.3$, $p \geq 0.055$, $\eta^2 \leq 0.17$). Furthermore, no significant interaction effects were found for any of the muscles ($F \leq 2.4$, $p \geq 0.138$, $\eta^2 \leq 0.18$). In muscles, in which a significant effect of repetitions was observed, the post hoc comparison revealed that muscle activation increased from repetition to repetition as more were performed. Specifically, muscle activity differed when comparing repetition one with repetition 2, 3 and 4 and subsequent repetitions (Fig. 2).

The barbell placement had a significant effect on the hip and knee angles at the deepest point of the lift and peak hip flexion velocity during the descending phase ($F \geq 7.8$, $p \leq 0.019$, $\eta^2 \geq 0.43$,

Figure 3). Furthermore, a significant effect of repetitions was only found during the descending phase of hip, knee and ankle peak angular velocity when the hip angle was at the lowest point ($F \geq 3.7$, $p \leq 0.045$, $\eta^2 \geq 0.29$). Also, an interaction effect was found during the descending phase of the peak hip, knee and ankle movements ($F \geq 3.1$, $p \leq 0.017$, $\eta^2 \geq 0.24$). Post hoc comparison revealed that at the lowest point of the lift, the knee flexion angle was less and the hip flexion angle was larger in the high barbell condition than in the low barbell condition. Furthermore, hip flexion angle decreased as repetitions in the set progressed in the low barbell condition, while this angle only decreased during the last repetition in

the high barbell condition (Figure 3). During the descending phase, the development of the peak angular velocities of the hip, knee and ankle behaved differently as repetitions were performed (interaction effect). In the low barbell condition, the peak angular velocity significantly increased (became more negative) from repetition 1 to 2 in all three joint movements and then stabilised or increased to a greater extent from repetition 5 to 6 for knee flexion, while the high barbell condition generally maintained the same pattern as the first repetition during subsequent repetitions, except in the final repetition where peak angular velocities in each joint decreased significantly compared to the previous repetitions (Figure 4).





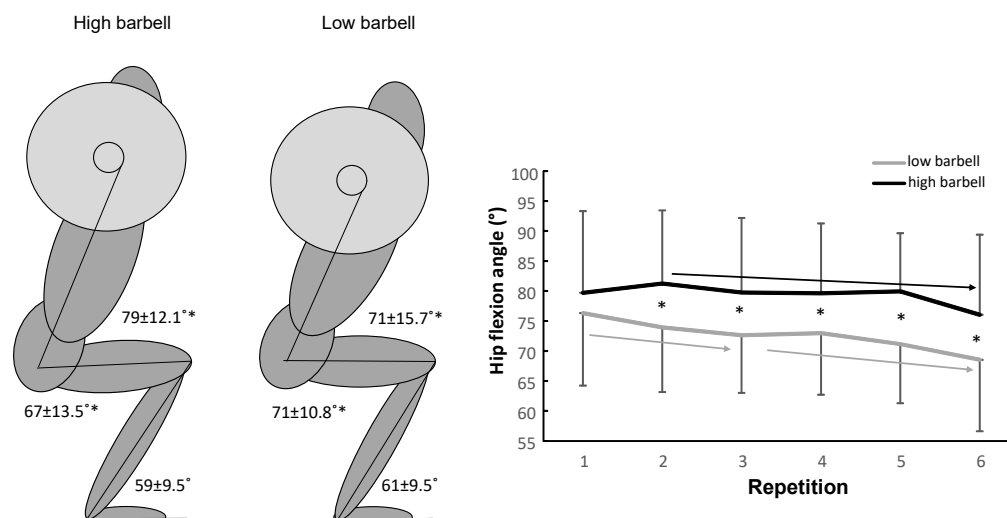


Figure 3

Mean (\pm SD) ankle plantar flexion, knee flexion and hip extension at the lowest barbell point during squats with low and high barbell placement, together with hip angle at lowest barbell point per repetition and condition.

* indicates a significant difference between low and high barbell placement at this repetition on a $p < 0.05$ level.

→ indicates a significant from this repetition with all repetitions right from the sign for this condition on a $p \leq 0.05$.

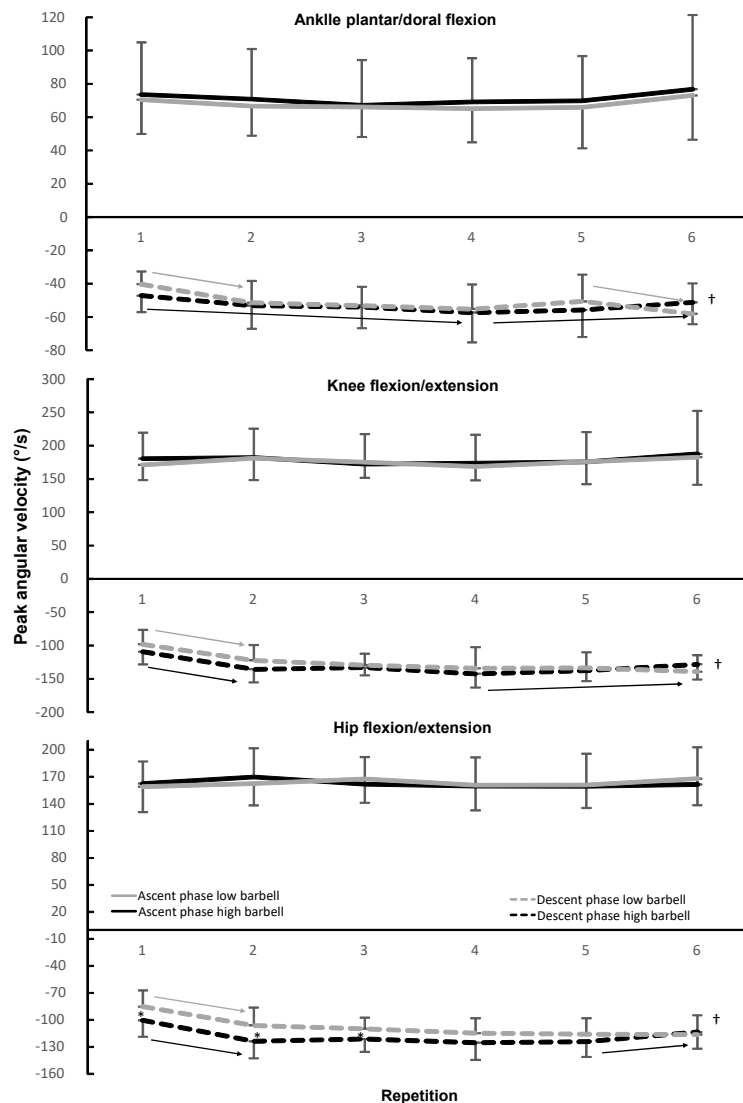


Figure 4

Mean (\pm SD) peak angular joint velocity of ankle plantar/dorsal flexion, knee flexion/extension and hip flexion/extension during descending and ascending phase per repetition of 6-RM squats with low and high barbell placement.

* indicates a significant difference between low and high barbell placement at this repetition on a $p < 0.05$ level.

† indicates a significant interaction effect difference between the two conditions on a $p \leq 0.05$ level.

→ indicates a significant from this repetition with all repetitions right from the sign for this condition on a $p \leq 0.05$.

Discussion

The aim of this study was to compare the kinematics and muscle activity during a 6-RM free weight back squat with low and high barbell placement in experienced resistance-trained athletes. We hypothesized that differences would primarily manifest in the EMG outcomes; however, contrary to our hypothesis only kinematic differences were observed. Specifically, the main findings were with the high barbell placement lifting time, which was longer, with a lower average velocity than the low barbell placement. This was accompanied by a knee flexion angle at the lowest point of the lift, which was less, and a hip flexion angle that was larger in the high barbell condition than in the low barbell condition (Fig. 3). Furthermore, the development of the peak angular velocities in the descending phase developed differently between the two conditions. Finally, no significant differences in muscle activity were found between the two conditions for any muscle during the descending and ascending phase.

In line with the greater body of research comparing the high and low bar back squat (Glassbrook et al., 2017), we observed significantly less knee flexion and greater hip flexion angles at the lowest point in the lifts comparing the high bar to the low bar position. However, to our knowledge we are the first to demonstrate that unique changes manifest in these joint angles over the course of a 6-RM set. Specifically, while Glassbrook and colleagues (2019) were the first to compare high load, maximal back squats with differing bar positions by assessing kinetic and kinematic differences between power and Olympic weightlifters performing a 1-RM, this is the first kinematic investigation of differences in joint angles during a high load, multiple-repetition set. We observed a slower time to peak velocity during the ascent of the high bar back squat, which became slower throughout the course of the set after the initial repetition, and during the final two repetitions.

Not only did squats slow to a greater extent during the high bar condition as the 6-RM set progressed, but the peak angular ankle dorsiflexion, knee flexion and hip flexion in the descent phase concomitantly decreased in the last repetition (Fig. 4). Collectively, these outcomes indicate that as the lifters approached their

maximal strength capacity during the 6-RM set (van den Tillaar, 2015; van den Tillaar et al., 2014), fatigue manifested in a slower concentric phase and increased muscle activation (Fig. 2). In both conditions, the first repetition differed from the following repetitions indicated by a slower descent velocity and peak angular joint velocities (Fig. 1 and 4), which is in accordance with earlier studies on 6-RM squats (van den Tillaar, 2015; van den Tillaar et al., 2014). However, these kinematic changes developed differently between conditions as repetitions were performed; peak descent velocity and forward lean (Fig. 3) seemed to increase (Fig. 1) in low bar condition as repetitions continued, while it remained stable in the high bar condition. Furthermore, fatigue manifested clearly in the high bar condition, indicated by an increase in lifting time for each subsequent repetition, and a lower average ascending velocity compared to the low bar condition (Fig. 1), and a decrease in peak angular velocities during the descent phase in the last repetitions. Most notably, in the last repetition of the high bar condition, the kinematics changed significantly compared to previous repetitions, while in the low bar condition no change occurred. Indeed, uniquely, an increased peak ankle dorsal flexion velocity in the descent phase was observed in the final repetition.

While the low bar back squat is characterized by greater forward lean due to beginning with a smaller hip flexion angle (as the bar is further down the spine), lifting performance (indicated by velocity) was not negatively impacted compared to the high bar condition as the set progressed towards maximal capacity. Thus, it may be that the leverage provided by the lower barbell position to the hip joint prevents the development of fatigue from impacting certain kinematic elements of performance. Specifically, in the high bar condition the forward lean increased in the last repetition (Fig. 3), and resultantly had a larger influence upon lifting performance, demonstrated by lower ascending velocity and lifting time compared to the low bar condition.

Also, our assessment of EMG is unique to the current literature. While the EMG profile of high and low bar back squats was previously reviewed (Glassbrook et al., 2017), to our knowledge only Wretenberg and colleagues

(1996) directly compared muscle activity between bar positions. Wretenberg et al. (1996) found higher rectus femoris EMG activity in powerlifters performing the low bar back squat compared to Olympic weightlifters performing the high bar variation. However, it is important to note Wretenberg et al. (1996) did not have the Olympic lifters and Powerlifters perform both styles of squats. Rather, only the Powerlifters performed low bar back squat and weightlifters only the high bar back squat, and each was allowed to self-select their stance width and overall style of squatting. Thus, EMG differences reported by Wretenberg et al. (1996) may not be specifically caused by bar placement *per se* but possibly by secondary aspects of the techniques used by powerlifters and weightlifters; specifically, powerlifters not only use a low bar position but also a wider stance width, different cues (sitting back vs down), and slightly different depths (Swinton et al., 2012). With that said, previous research on squat stance width has repeatedly found a lack of significant differences in quadriceps muscle activity (Escamilla et al., 2001; Paoli et al., 2009); however, some data suggest it may influence glute and adductor EMG (McCaw and Melrose, 1999). Furthermore, Wretenberg et al. (1996) only examined single repetition sets with 65% of 1-RM. Thus, while it is unknown why there are discordant EMG outcomes in the present study and the examination by Wretenberg et al. (1996), it may be that these differences are not present when squatting with higher loads or when performing sets to maximal strength capacity, as was done presently.

To summarize our findings, in contrast to our hypothesis it seems bar placement does not significantly influence EMG of the measured musculature when performing squats during 6-RM sets. Our kinematic findings align with prior research showing the low bar back squat is characterized by a smaller hip flexion angle and larger knee flexion angle than the high barbell placement. However, uniquely, the high bar back squat concentric phase took longer to complete, and had a slower peak velocity, and resulted in a significantly different development of peak angular joint velocities in the descent phase over the course of multiple repetitions compared to the low barbell placement. With that said, there are limitations to our observations. Specifically, the

subjects in our study were more familiar with the high barbell placement, and while they were familiarized with the low barbell placement, it is possible our findings would have differed had we compared highly experienced high and low barbell placement squatters such as Olympic weightlifters and Powerlifters as has been performed in previous research (Glassbrook et al., 2017; Wretenberg et al., 1996). Furthermore, contrary to our hypothesis we did not observe EMG differences between conditions; however, the gluteus maximus body region is typically high in body fat specifically; thus, it is possible that differences in muscular activity did occur, but body fat prevented the signal from being clear enough to observe (Baniqued et al., 2016; Bartuzi et al., 2010). Further research with larger samples and both more varied, and more specific cohorts is required to confirm if our findings are accurate, and if so, applicable to different populations.

Conclusion

In conclusion, both the high and low barbell placements are valid applications of the barbell back squat. Our EMG data suggests gross muscular adaptations between barbell placements may likely be similar over time when squatting with either style. However, due to kinematic differences between bar placements, certain individuals with greater range of motion capacities or who experience discomfort at the knee, hip and ankle joint when squatting may be better suited to one style of back squat than the other. For example, a squatter with poor ankle mobility who cannot accommodate greater forward knee travel and reach depth while staying upright (a smaller knee flexion angle and larger hip flexion angle) might be better suited to a low bar placement. Likewise, a lifter who has hip discomfort squatting with a more “hip dominant”, forward-leaning position (greater knee flexion angle and smaller hip flexion angle), but who has adequate ankle mobility might be better suited to a high barbell placement. Finally, fatigue may manifest earlier during the high barbell back squat when performing 6-RM sets as the set progresses toward a lifter’s maximal strength capacity, altering the kinematics of the lift, especially in the last repetition, while during a low bar back squat, fatigue is less likely to impact kinematics.

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