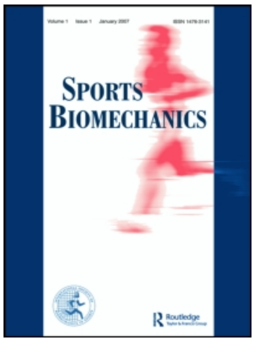

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Effects of barbell load on kinematics, kinetics, and myoelectric activity in back squats

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ABSTRACT

Shortly after beginning the upward phase of a free-weight barbell back squat there is often a deacceleration phase (sticking region) that may lead to repetition failure. The cause for this region is not well understood. Therefore, this study investigated the effects of 90%, 100%, and 102% of 1-RM barbell loads on kinematics, kinetics, and myoelectric activity in back squats. Twelve resistance-trained healthy males (body mass: 83.5 ± 7.8 kg, age: 27.3 ± 3.8 years, height: 180.3 ± 6.7 cm) participated in the study and lifted 134 ± 17 kg at 90% and 149 ± 19 kg at 100%, while they failed at 153 ± 19 kg with 102% load. The main findings were that barbell displacement and barbell velocity in the sticking region decreased with increasing loads. Moreover, the external hip extensor moment increased with heavier loads, whereas the knee extension and ankle plantarflexion moments were similar during the concentric phase. Also, reduced hip and knee extension together with lower myoelectric activity for all hip extensors and vastus lateralis were found for the 102% load compared to the others. Our finding suggests that the increased external hip extensor moment together with lower hip extensor myoelectric activity due to a reduced hip extension and thereby are responsible for lifting failure among resistance-trained males.

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KEYWORDS
Strength; inverse dynamics; sticking region

Introduction

The back squat is a popular multi-joint resistance training exercise used by several different cohorts, such as recreational- and competitive lifters to increase the strength and power of the lower extremity. Previous studies have delineated the squat ascent into three regions: pre-sticking or acceleration region, sticking/failure region, and the post-sticking/strength/deacceleration region (Figure 1) (Escamilla et al., 2001; Larsen et al., 2021b; Maddox & Bennett, 2021; Maddox et al., 2020; van den Tillaar et al., 2014, 2020; van den Tillaar, 2015a, 2019). Several studies have investigated the sticking region, but it is not clear how the body self-organises to overcome external resistance (Bryanton et al., 2012).

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Larsen et al. (2021b) investigated joint moment contributions to the total net joint moment in three repetition-maximum (RM) back squats and reported that the hip moment contribution was approximately 51.5% and 54.4% at the events first peak barbell deacceleration and first minimum barbell velocity during the sticking region. Interestingly, the same investigators (2021) investigated both the effect on stance width and barbell placement upon squat kinetics and reported that the event of peak deacceleration was the event in the squat ascent where the lifters` capability to exert ground reaction force was at its lowest. These findings were similar to what Maddox et al. (2020) reported, but they reported that both submaximal, maximal, and supramaximal squats presented coupling angles of thigh-rising and trunk-falling, resulting in an increased torso forward lean and therefore a large moment arm for the external load for the participants to overcome during supramaximal squat conditions. Moreover, Maddox and Bennett (2021) reported in a follow-up study that vertical acceleration was a greater discriminative measure for successful back squats than velocity, due to larger differences between the successful and unsuccessful squats. Also, submaximal squats had reduced hip and knee moments compared to supramaximal squats, but the knee moments were similar to 1-RM squats, indicating that hip extensor strength is the performance bottle-neck in squats with supramaximal loads.

Interestingly, van den Tillaar et al. (2021) compared maximal dynamic smith-machine squats with maximal isometric contractions at 10 different barbell displacements from the lowest barbell height (v_0) and found that gluteus maximus increased myoelectric activity first at 0.25 m displacement, which is at similar barbell displacement to where the post-sticking region has been reported to start in similar studies. The same researchers speculated that the combination of large hip extensor moment demands together with low myoelectric activity for the gluteus maximus could be an important contributor to the occurrence of the sticking region. However, to our knowledge, no studies have investigated the effect on load upon kinematics, kinetics, and myoelectric activity around the sticking region in back squats. Investigating this could provide detailed information on how increasing barbell load may affect the kinetics and thereby the kinematics and myoelectric activity around the sticking region to overcome it.

Therefore, the purpose of this study was to investigate the effects of 90%, 100%, and 102% of 1-RM barbell loads on kinematics, kinetics, and myoelectric activity in back squats. It was hypothesised that all events except for v_0 would occur at lower barbell displacements from v_0 for the 100% and 102% loads compared to the 90% load based on the findings by Maddox and Bennett (2021). Moreover, it was hypothesised that hip extensor moments would increase with barbell load, but that hip extensor myoelectric activity would decrease due to lower barbell displacement from v_0 with increasing load, putting the hip extensors in a more disadvantageous position to potentially exert force during the sticking region (van den Tillaar et al., 2021).

Methods

To investigate the effect of load on barbell kinematics, kinetics, and myoelectric activity around the sticking region, a within-subjects, repeated measures design was used. Three loads (90%, 100%, and 102%) were used as independent variables. The events analysed were v_0, first maximal barbell velocity (v_{max1}), first peak barbell deacceleration (d_{max1}), and first minimum barbell velocity (v_{min}) in the ascent phase (Larsen et al., 2021b; Madsen & McLaughlin, 1984). Since no post-sticking region could occur at 102% loads, dividing the pre-sticking and sticking region into three regions could be a functional way to analyse the lift based on barbell velocity and barbell acceleration data since Larsen et al. (2021b) reported that d_{max1} was the event in which the lifters` capability to exert force was at its lowest. Therefore, the sticking region was divided into a deacceleration region (v_{max1} to d_{max1}) and a minimum velocity region (d_{max1} to v_{min}). Dependent variables included mean myoelectric activity during the acceleration region, deacceleration region, and minimum velocity region, as well as net joint moments and moment arms, joint angles, barbell velocity, and displacement in the events v_0, v_{max1}, d_{max1}, and v_{min}. Barbell displacement was defined as displacement from v_0. At the 102% load v_{min} was identified as where the barbell velocity were 0 (Figure 1).

Participants

Based on previous studies in the back squat by van den Tillaar et al. (2021), 12 healthy males (body mass: 83.5 ± 7.8 kg, age: 27.3 ± 3.8 years, height: 180.3 ± 6.7 cm) were recruited to the study. Inclusion criteria were: 15–55 years, no injuries at the time of their visit that could reduce maximal performance, and being able to squat 1.5 times own body mass. All participants were informed orally and in writing about study procedures and signed written consent before participation.

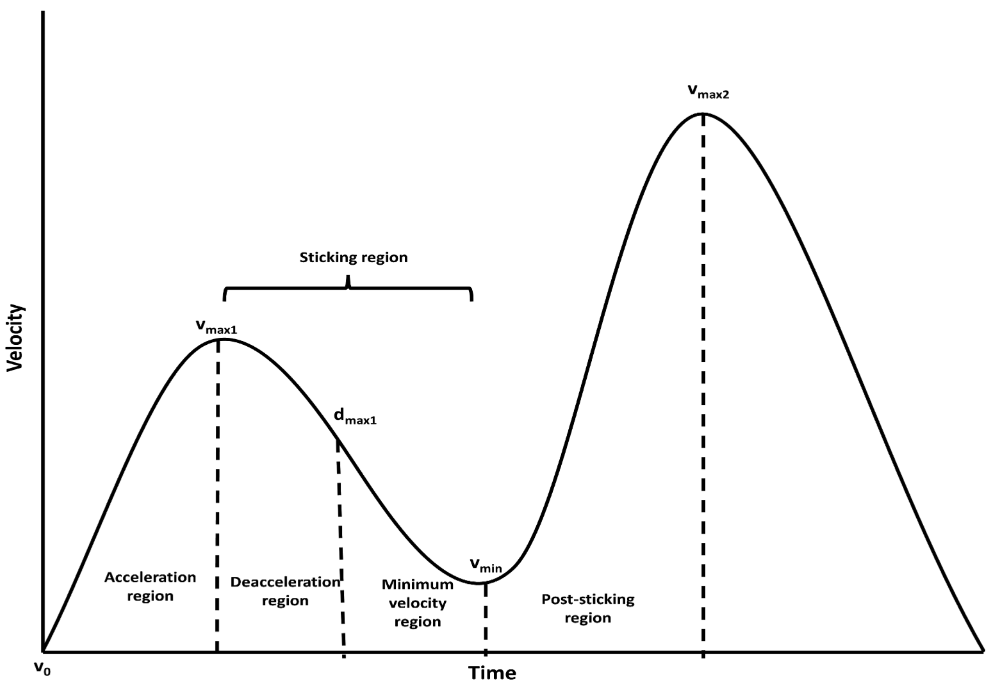

Figure 1. Typical barbell velocity development during the ascending phase of a squat with a sticking region, with different events v_0, v_{max1}, d_{max1}, v_{min}, and v_{max2}.

The study was conducted following the latest revision of the Declaration of Helsinki and current ethical regulations for research and was approved by the Norwegian Center for Research Data (No: 701688).

Protocol

Both stance width, barbell placement, and external rotation of the feet were self-selected by the participants but standardised for each individual throughout all barbell loads. The depth through the end of the eccentric phase was measured and standardised with the depth requirement from International Powerlifting Federation (2019) and marked with a horizontal band behind the participant that needed to touch the proximal part of the hamstring to start the ascent. The test day began with a warm-up, involving three sets of 6–10 repetitions with an Olympic barbell (Rogue, Ohio power bar), three repetitions with 40% and 55% of self-reported 1-RM. Thereafter, one repetition on 70%, 90%, 100%, and 102% of estimated 1-RM was performed. During testing, participants had 180s of rest between warm-ups and 240s between maximal lifting sets. One spotter were placed at each side of the barbell for safety purposes during the 90%, 100%, and 102% squat attempts.

Measurements

Trigno Avanti sensors (DELSYS, USA) were utilised to record myoelectric activity with a sampling rate of 1111 Hz on the side of the participants' dominant leg in 12 different muscles: trapezius ascendens, rectus abdominis, erector spinae iliocostalis, erector spinae longissimus, gluteus maximus, gluteus medius, vastus lateralis, vastus medialis, semitendinosus, biceps femoris, gastrocnemius medialis, and soleus medialis. Placement of electrodes were performed according to SENIAM recommendations (Hermens et al., 2000). To reduce skin impedance before attaching sensors, the skin was shaved, rubbed with alcohol, and dried with paper. The electromyography (EMG) data were recorded and synchronised with body movements using a three-dimensional motion capture system (Qualisys, Gothenburg, Sweden), and converted to a c3d-file, and analysed in Visual 3D v6 software (C-motion, Germantown, USA), where the raw EMG signals were filtered with a high-pass and low-pass (20, 500 Hz) filter, zero meaned. Thereafter, the raw EMG signals were full wave rectified, and mean RMS was calculated for the different regions. To track reflective markers for motion capture data, such as joint angles, Qualisys, with eight cameras at a sampling rate of 500 Hz was utilised. Markers were placed with the same procedures as Larsen et al. (2021b). When referring to an increase in joint angle, for the hip, knee, and ankle, an increase in joint angle means greater flexion angle, whereas a decrease in joint angle means greater extension angles (0 degrees = full extension). For the torso, an increase in angle means greater torso inclination relative to the floor. Moreover, for the hip and knee abduction angles, an increase in angle means greater abduction angles, whereas a decrease means greater hip and knee adduction angles. To track the three-dimensional ground reaction forces and enable inverse dynamics calculation, two force plates (AMTI Multi-axis Force Transducer BP6001200–2000, Lexington, KY, USA; Kistler force plate, type 9260AA6, Winterthur, Switzerland) were integrated into the Qualisys motion capture system. The three-dimensional joint moments for the hip, knee, and ankle were calculated, using inverse dynamics calculations in a resolute coordinate system. The joint moments calculated was external net joint moments, expressed as means and standard deviations at the events v_0, v_{max1}, d_{max1}, and v_{min}, with respect to the distal segments' resolute coordinate system. The reported net joint moments were summed between the right and left segments. Net joint moments were normalised to the participants' mass using default normalisation and expressed as Nm/kg with the same method as Larsen et al. (2021b). The ground reaction force moment arms were calculated as the anterior-posterior distance between the joint centres and centre of pressure. Motion capture data were exported to C3D files for segment modelling and analyses in Visual 3D v6 software. For modelling procedures, see Larsen et al. (2021b).

Statistics

Normality was tested using the Shapiro–Wilks's test. To assess differences in kinetics and kinematics between the barbell loads, a repeated 3 (barbell load: 90%, 100%, and 102%) × 4 (events: lowest barbell height (v_0), first peak velocity (v_{max1}) first peak deacceleration (d_{max1}), and first located minimum barbell velocity (v_{min}) analysis of variance was performed (ANOVA). To access differences in myoelectric activity between the barbell loads, a repeated 3 (barbell load: 90%, 100%, and 102%) × 3 (acceleration region, deacceleration region, and minimum velocity region) was performed. Kinematic variables analysed were: joint angles, moment arms, barbell displacement from v_0, barbell velocity, and time. Of the kinetic variables extension moments were analysed. If main effects were significant, bonferroni post-hoc tests were used to identify where potential differences in kinetics and myoelectric activity occurred. If the assumption of sphericity was violated, the Greenhouse–Geisser adjustments of *p*-values were reported. All results are presented as mean ± standard deviations. Effect sizes were evaluated with η2p (partial eta squared), where <0.01–0.06 constitutes a small effect, <0.06–0.14 a medium effect, and >0.14 a large effect (Cohen, 1988). The alpha level of significance was set at $p < 0.05$. Statistics were analysed in SPSS version 27.0 (IBM Corp., Armonk, NY, USA).

Results

The participants lifted 134 ± 17 and 149 ± 19 kg, respectively, at 90 and 100% of 1RM, and failed at 153 ± 19 kg (102%). A significant effect of load was found for barbell velocity ($F = 65.49$, $p < 0.001$, $\eta^2 = 0.87$), where barbell velocity decreased in all events with increased loads (Figure 2). Also, a significant effect was observed for barbell displacement ($F = 39.91$, $p < 0.001$, $\eta^2 = 0.82$), where post hoc tests showed that barbell displacement for all events (v_{max1} -v_{min}) decreased when increasing loads (Figure 2). Moreover, a condition*event interaction

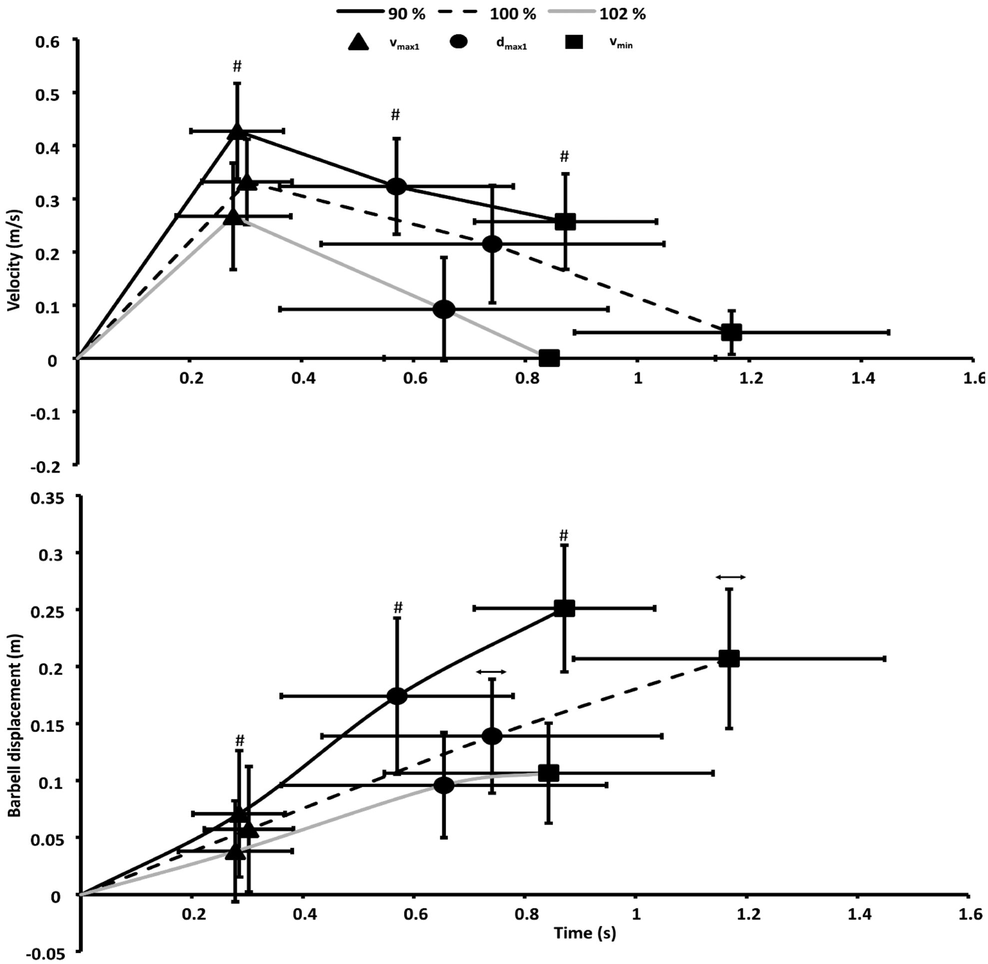

Figure 2. Mean (±SD) velocity and displacement of the events v_{max1}, d_{max1}, and v_{min} from v_0, and their timing.
# Indicates a significant difference between all loads at this event on a $p \leq 0.001$ level.
↔ Indicates a significant difference in timing between the 100% with the 90% and 102% load conditions at this event on a $p \leq 0.05$ level.

was found for lifting time ($F = 3.81$, $p = 0.032$, $\eta^2 = 0.28$). Post hoc tests showed that v_{max1} occurred at similar timings, but that d_{max1} and v_{min} started later for the 100% load compared to the 90% and 102% load (Figure 2).

A significant effect was found for event on torso inclination and ankle dorsiflexion ($F > 24.99$, $p < 0.001$, $\eta^2 > 0.78$), whereas a significant effect on condition was found for hip abduction ($F = 5.73$, $p = 0.024$, $\eta^2 = 0.50$; Figure 3). Also, a significant condition*event interaction effect was found for hip flexion, hip abduction, knee flexion, and abduction angles ($F = 7.74$, $p < 0.001$, $\eta^2 = 0.56$). Post hoc tests showed that torso inclination increased from v_{max1} to d_{max1}, and ankle dorsiflexion decreased from v_{max1} to d_{max1} for all conditions (Figure 3). Hip extension increased from v_{max1} to d_{max1} only for the 90% and 100% loads but

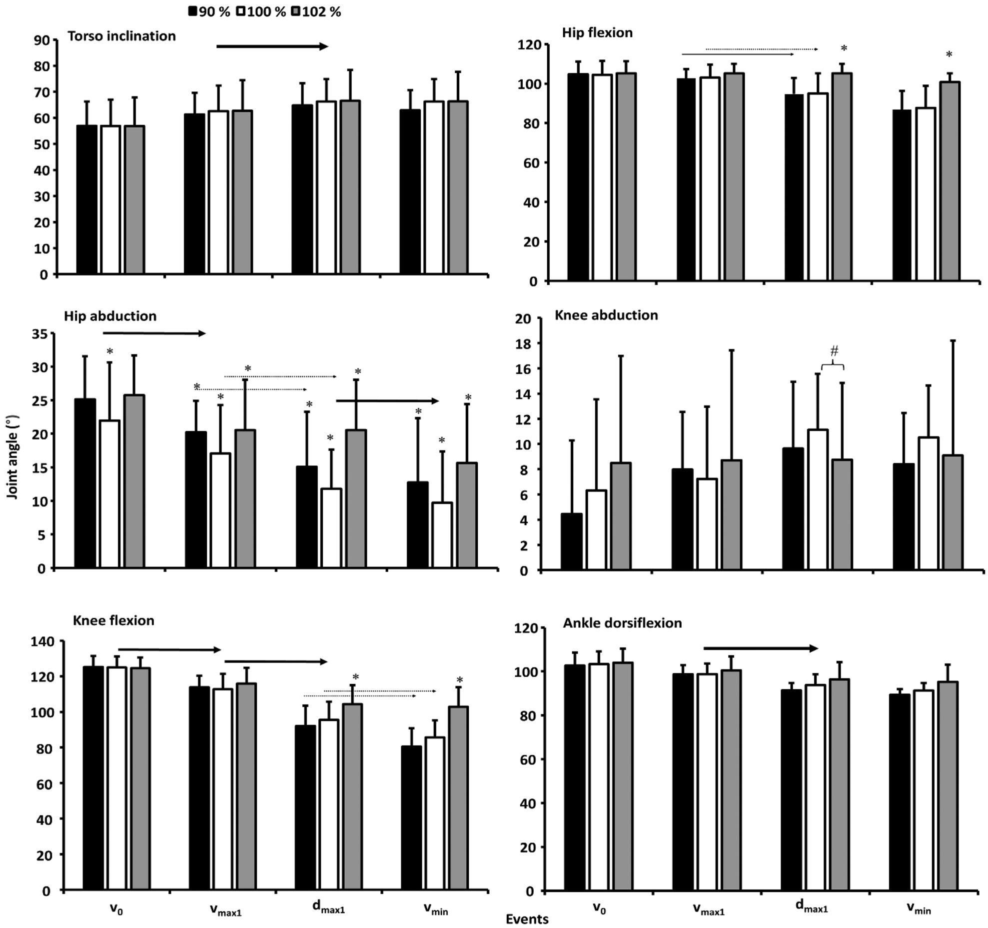

Figure 3. Mean (±SD) torso inclination, hip flexion, hip abduction, knee abduction, knee flexion, and ankle dorsiflexion angle for the 90%, 100%, and 102% load conditions at the events v_0, v_{max1}, d_{max1}, and v_{min}.
* Indicates a significant difference for this load with other conditions at this event on a $p \leq 0.05$ level.
# Indicates a significant difference between these two load conditions on a $p \leq 0.05$ level.
Thick → Indicates a significant change between these two events on a $p \leq 0.05$ level.
Thin → Indicates a significant change between these two events for this condition on a $p \leq 0.05$ level.

not in the 102% load. Furthermore, lower lower hip abduction for the 100% load was observed at each event compared with other loads, while the 102% load caused a greater hip abduction at v_{max1}, d_{max1}, and v_{min}. The hip abduction decreased from v_0 to v_{max1} for all loads, but only for the 90% and 100% loads from v_{max1} to d_{max1}, resulting in an interaction effect. Thereafter, hip abduction decreased from d_{max1} to v_{min} for all loads again (Figure 3). Knee flexion decreased for each event, except from d_{max1} to v_{min} where only the 90% and 100% load decreased, resulting in a greater knee flexion for the 102% at d_{max1} and v_{min} compared to the other load conditions. Post hoc tests showed that knee abduction increased from v_0 to

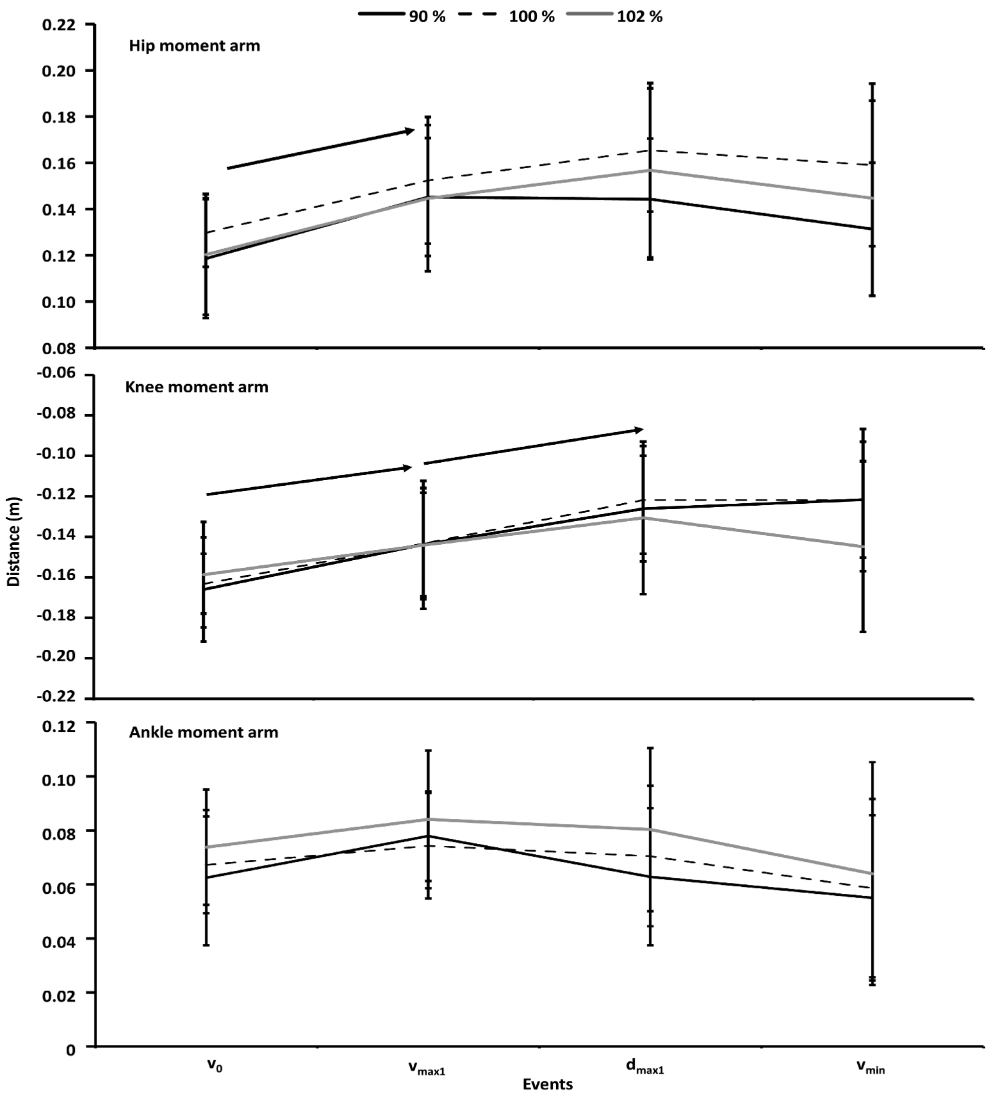

Figure 4. Mean (±SD) hip, knee, and ankle joint moment arm at the events v_0, v_{max1}, d_{max1}, and v_{min}. → Indicates a significant difference in moment arm between these two events on a $p \le 0.05$ level.

v_{max1} for the 90 and 100% loads but not for the 102% load, and greater knee abduction for the 100% load compared to the 102% load condition at d_{max1} (Figure 3).

For hip and knee moment arm, only a significant effect was found for event ($F \ge 8.98$, $p \le 0.001$, $\eta^2 \ge 0.60$). Post hoc tests showed that the hip moment arm increased from v_0 to v_{max1}, whereafter it is stable, whereas the knee moment arm decreased from v_0 to v_{max1}, to d_{max1} (Figure 4). For ankle moment arm, no differences were found between the load conditions or events ($F \le 1.85$, $p \ge 0.21$, $\eta^2 \le 0.24$).

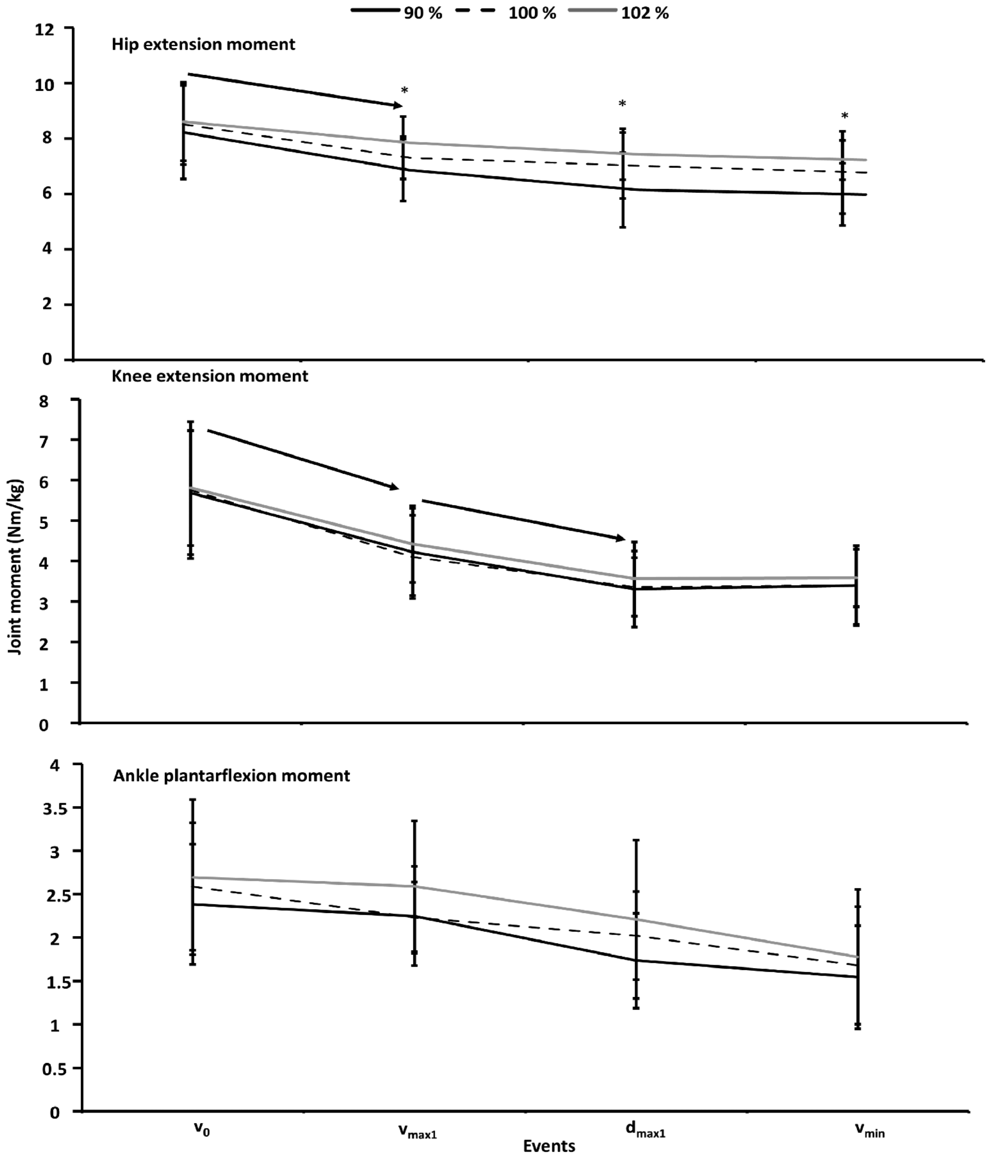

Figure 5. Mean (±SD) normalised net hip extension, knee extension, and ankle plantarflexion moments at the events v_0, v_{max1}, d_{max1}, and v_{min}.
* Indicates a significant difference in net hip extension moment between the 90%, 100%, and 102% at this event on a $p \leq 0.001$ level.
→ Indicates a significant decrease in net joint moment between these two events on a $p \leq 0.05$ level.

A significant effect of event and load was found for net hip extension moment ($F \geq 15.05$, $p \leq 0.001$, $\eta^2 \geq 0.68$). Post hoc tests revealed that net hip extension moment increased with loads and that the hip moment decreased from v_0 to v_{max1} (Figure 5). Moreover, a significant effect was found for event on net knee extension moment ($F = 27.89$, $p < 0.001$, $\eta^2 > 0.80$), but not load ($F = 0.49$, $p = 0.498$, $\eta^2 > 0.075$). Post hoc tests

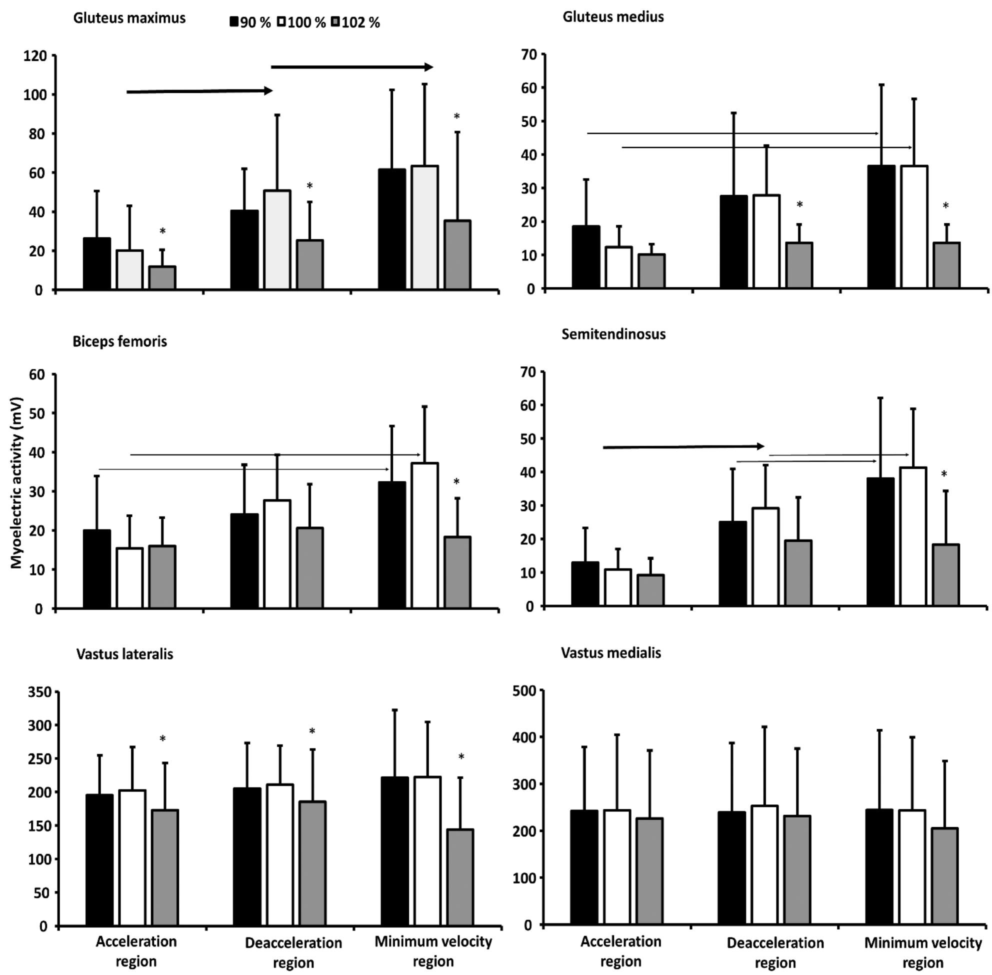

Figure 6. Mean ± SD myoelectric activity in the acceleration region, deacceleration region, and minimum velocity region for the gluteus maximus, gluteus medius, biceps femoris, semitendinosus, vastus lateralis, and vastus medialis.
* Indicates a significant difference between this load and all other load conditions in this region on a $p \leq 0.05$ level.
Thick → Indicates a significant change between these two regions on a $p \leq 0.05$ level.
Thin → Indicates a significant change between these two regions for this condition on a $p \leq 0.05$ level.

showed that the net knee extension moment decreased from v_0 and v_{max1} to all other events (Figure 5). No significant differences were found for load or event on ankle plantarflexion moment ($F \leq 3.33$, $p \geq 0.053$, $\eta^2 \leq 0.021$).

For myoelectric activity, a significant effects of load and region were found for the gluteus maximus ($F \geq 6.2$, $p \leq 0.012$, $\eta^2 \geq 0.47$), where myoelectric activity increased from region to region. Furthermore, myoelectric activity was lower for the 102% load compared to the other conditions in all regions. For the gluteus medius, biceps femoris, and semitendinosus, significant effects were found for region, load, and load*region interaction effect ($F > 4.34$, $p < 0.034$, $\eta^2 > 0.38$). Post hoc tests showed that myoelectric activity increased for the gluteus

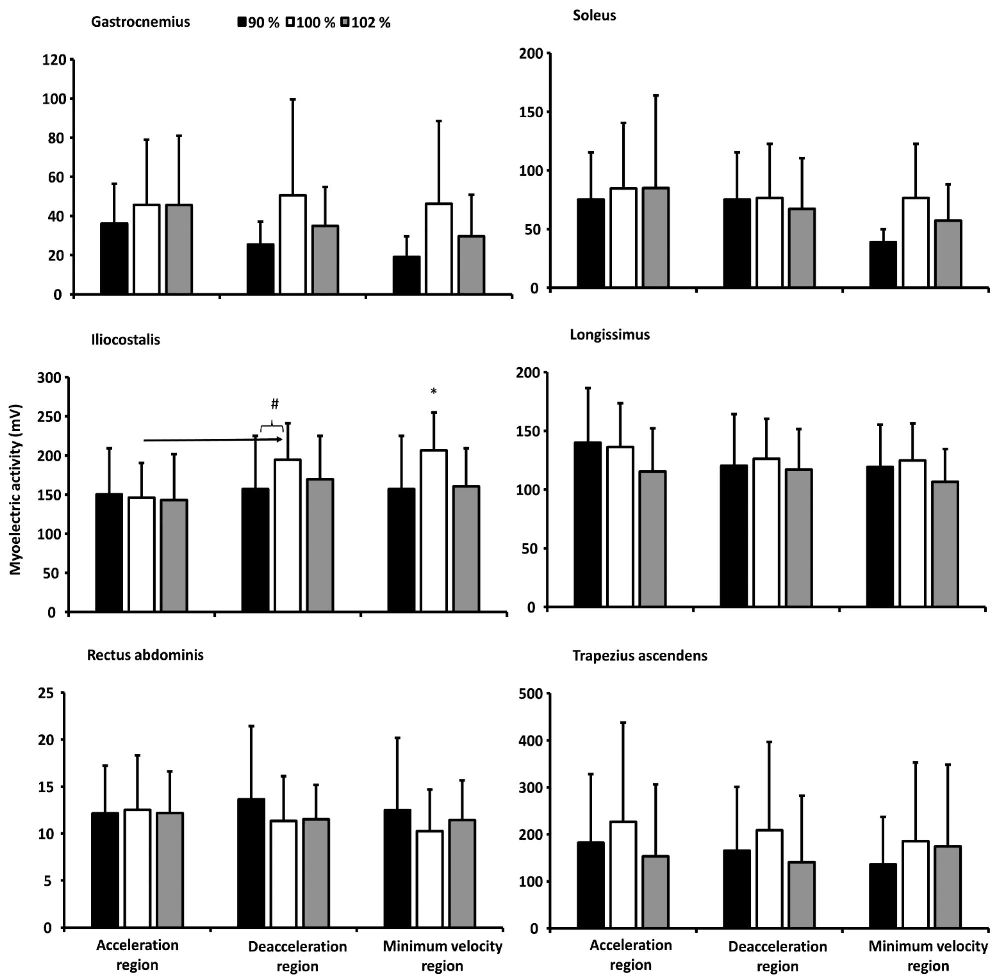

Figure 7. Mean (±SD) myoelectric activity in the acceleration region, deacceleration region, and minimum velocity region for gastrocnemius, soleus, erector spinae iliocostalis, erector spinae longissimus, rectus abdominis, and trapezius ascendens.
* Indicates a significant difference between this load and all other conditions for this region on a $p \leq 0.05$ level.
# Indicates a significant difference between these two loads on a $p \leq 0.05$ level.
→ Indicates a significant difference in myoelectric activity between these two regions for this condition on a $p \leq 0.05$ level.

medius and biceps femoris from the acceleration region to the minimum velocity region for the 90% and 100% loads but not the 102% load. Moreover, the semitendinosus increased myoelectric activity from acceleration region to deacceleration region for all loads, but only for the 90% and 100% loads from deacceleration to minimum velocity region (Figure 6). For the vastus lateralis, only a significant effect of load was found ($F = 4.38$, $p = 0.033$, $\eta^2 = 0.39$), where the 102% load had lower myoelectric activity in all regions than the other loads.

For the erector spinae iliocostalis significant load and load*region interaction effects were found ($F \geq 3.29$, $p \leq 0.025$, $\eta^2 \geq 0.32$). Post hoc tests showed that myoelectric activity increased from the acceleration region to next region for the 100%

load but not the other load conditions, resulting in higher myoelectric activity for the 100% load compared to the 90% load in the deacceleration region, whereas the 100% load had higher myoelectric activity than both the 90% and 102% loads in the minimum velocity region (Figure 7). No significant differences in event or load were found for the vastus medialis, gastrocnemius, soleus, erector spinae longissimus, rectus abdominis or trapezius ascendens ($F \leq 3.1$, $p \geq 0.12$, $\eta^2 \leq 0.31$, Figures 6 and 7.

Discussion and implications

This study investigated the effects of 90%, 100%, and 102% of 1-RM barbell loads on kinematics, kinetics, and myoelectric activity in back squats. The main findings were that barbell displacement and barbell velocity decreased in the sticking region when increasing barbell load. Moreover, torso inclination increased during the deacceleration and minimum velocity regions for all loads, whereas the hip and knees were more extended at 90 and 100% compared to the 102% load in the minimum velocity region. Furthermore, the hip moment arm increased, and the knee moment arm decreased, whereas the ankle moment arm was stable during the events. Also, the external hip extension moments increased with increasing barbell load, whereas the external knee extension and plantar flexion moments were similar. Moreover, all hip extensors and vastus lateralis showed lower myoelectric activity in the minimum velocity region for the 102% load compared to the other loads.

Our findings showed that external peak moments were produced at v_0 (Figure 4), whereas the deacceleration region started at around 0.04–0.07 m barbell displacement and 0.3 s (Figure 2). This could be explained by potentiation of the quadriceps, caused by the stretch-shortening cycle, which enables larger force production during the acceleration region, as observed by van den Tillaar et al. (2021). This effect has been reported to diminish after approximately 0.3 s, which is where the deacceleration region started for all loads. Moreover, our data showed that when increasing load, all events (v_{max1}-v_{min}) started at lower barbell displacement with lower velocities, which is logical because greater barbell loads have greater inertia, and when the force output is maximal, acceleration and velocity decreases.

The lower barbell velocity at the different events resulted in a lower barbell displacement, especially at v_{min} for 102% (0.11 m vs 0.20 m barbell displacement from v_0). However, from v_0 to v_{min} the hip flexion only decreased with five degrees while the knee flexion decreased with 22 degrees. This is explainable by the fact that the squat lift starts with knee extension and plantar flexion as van den Tillaar (2015a) found that knee extension and plantar flexion movements had a first peak in angular velocity which was concomitant with v_{max1}, whereas hip extension only had a second peak which was concomitant with second peak velocity. This resulted in greater torso inclination for all loads and therefore an increase in hip moment arm from v_0 to v_{max1} events (Larsen et al., 2021, 2021b). The increased inertia from the barbell lead to an increase in hip extension moment because the hip is responsible for extending the hip and thereby the trunk and barbell (Larsen et al., 2021b). Therefore, hip angular acceleration decreased with increased load to keep the joint moment similar, resulting in only 5 degrees hip extension from v_0 to v_{min}.

Since the hip moment increased with 102% load with lower barbell displacement and a reduced hip extension at d_{max1} and v_{min} (Figure 3), the subjects are at a height at which the possible force output is lower (van den Tillaar et al., 2021). At this height, the hip extension is so low (≈70°) that the large gluteus and hamstring (biceps femoris and semitendinos) muscle lengths together with a small moment arm of the muscle around the joint gives a mechanical disadvantage such that the capacity to exert force was reduced (Robertson et al., 2008; van den Tillaar, 2015a). Due to this incapacity of the gluteus and hamstring muscles at this height the subject, as indicated by the lower myoelectrical activities (Figure 6) get stuck at this height. This has also been found in bench press at specific heights and joint angles, thus it is speculated that less force can be produced due to lower myoelectric activation at these heights (van den Tillaar et al., 2012). However, this remains a speculation because myoeletric activity may not reflect the state of the muscle (Vigotsky et al., 2022).

In addition, with the 102% load, lower vastus lateralis activity was observed in all regions compared to the other loads, which also could be a factor that the lift was not successful (Figure 6), since the external knee moment increases over the first two phases. When in the first ascending region lateral vastus activity was less this results in lower knee extension at different events (Figure 3), thereby sticking at heights with less force capacity (van den Tillaar et al., 2021). Another surprising observation was greater erector spinae iliocostalis activity for 100% compared to other loads (Figure 7), as the erector spinae is responsible for maintaining a rigid torso during lifts (Schoenfeld, 2010). Its activity was expected to be the same or higher between the 100 and 102% load due to the increasing load on the trunk. However, This finding can be explained by an intricate coordinating mechanism as suggested by Toussaint et al. (1995) who found that the thoracic part of the erector spinae takes over activity of the lumbar part when demand of erector spinae increases during lifts. The thoraral part of the erector spinae has through the aponeurosis attachement at L5S1 more posterior than lumbar part of the erector spinae. Thereby it has a longer moment arm around the lumbar sacral joint and in that way it is more effective to use this part of the erector spinae to withstand the extra load (Potvin et al., 1991; Toussaint et al., 1995).

Interestingly, with the 100% load a lower hip abduction at all events and larger knee abduction at d_{max1} compared to the other load conditions was observed (Figure 3). Meaning that knee valgus was greater for the 100% load condition. A modelling study by Vigotsky and Bryanton (2016) reported that the adductor magnus was the main hip extensor at lower barbell heights. However, the adductor magnus is also a hip adductor, which means that the participants in our study may have recruited the adductor magnus to a greater extent for the 100% load compared to the other condition due to larger hip adduction in all events (Figure 3). However, this remains speculative in the absence of musculoskeletal modelling data of the adductor magnus.

A limitation of this study was that the participants were resistance-trained lifters and not advanced powerlifters. Therefore, our findings may not be generalisable to powerlifters. Moreover, our study reported resultant forces and joint moments from inverse dynamics analyses. This method neglects muscle forces and potentially extra knee flexor moments created by the biarticular hamstrings (Bryanton et al., 2015; Vigotsky et al., 2019). Therefore, further studies should use musculoskeletal modelling to quantify these muscle forces. Also, we only used men and no women. Therefore, further studies should investigate how increasing load may affect kinematics, kinetics and myoelectric activity among women. Lastly, we used EMG, which may not reflect the neuromuscular excitation of the muscles, because EMG amplitude may be affected by the muscles length even if he neuromuscular excitation is identical (Vieira et al., 2017; Vigotsky et al., 2022)

Conclusion

In conclusion, this study suggests that failure to lift the 102% load occurred because of an increased moment of inertia from the barbell lead to an increased external hip extensor moment for this load compared to the 90% and 100% loads. This resulted in a reduced hip extension at d_{nax1} and v_{min}, and may have contributed to lower myoelectric activity for all hip extensor muscles in the minimum velocity region for the 102% load compared to the 90% and 100% loads. Therefore, our findings suggest that the large external hip extension moment together with an inefficient force-length tension relationship of the gluteus and hamstring muscles may be a limiting factor in the back squat. Based on the principle of specificity together with our findings, we suggest training with almost maximal loads of 1-RM when targeting maximal strength in the hip extensors, whereas training stimulus on knee extensors may be achieved on slighty lower loads in the back squat.

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