A KINEMATIC ANALYSIS OF THE STICKING REGION IN FULL BACK SQUATS

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The purpose of this study was to investigate 3D kinematics around the sticking region (the weakest region) in full back squats. Eleven resistance-training males (age 23.5 ± 2.6 years, body mass 86.8 ± 21 kg, body height 1.81 ± 0.08 m) performed 6-RM full back squats and the last repetition was taken for further analyses of 3D kinematics around the sticking region. The main findings were that all participants exhibited a sticking region during the last repetition of 6-RM squatting. Timing of the peak and minimal angular velocities of the hip extension, knee extension and plantar flexion movements were concomitant with the two peak velocities and minimal velocity of the barbell. It was suggested that timing and activity (power output) between the knee and hip extensors are responsible for the existence of the sticking region.

KEY WORDS: angular velocity, joint angles, strength.

INTRODUCTION: In strength and resistance training squats are often used as exercise to strengthen the lower body. A typically successful performance in this exercise is measured when the barbell is lowered first by bending the knees and hip and then moved upwards again to the extended starting position. However, sometimes the weight cannot be moved all the way upwards again and the lift fails. This often happens in the sticking region (Elliott, Wilson, & Kerr, 1989; Lander, et al, 1985; Newton et al, 1997; van den Tillaar & Ettema, 2010; 2013; van den Tillaar, Andersen, & Sæterbakken, 2014). This sticking region is referred to in the literature as the region from the initial peak upwards velocity (v_{max1}) to the first local minimum velocity (v_{min}) of the barbell. The end of this region occurs when the barbell velocity increases again, which is also called the strength region (Lander et al., 1985). In several strength-training exercises such as bench press (Elliott et al., 1989; Lander et al., 1985; Newton et al., 1997, van den Tillaar & Ettema, 2010, 2013) and dumbbell chest press (van den Tillaar & Sæterbakken, 2012) the existence of this sticking region is investigated. However, very little is known about the causes of this sticking region in these resistance exercises. In the bench press, Elliott et al. (1989), van den Tillaar, Sæterbakken, and Ettema, (2012) and van den Tillaar and Ettema (2013) have suggested that the sticking region is a poor mechanical force position in which the lengths and mechanical advantages of the muscles involved reduce the capacity to exert force in this region.

To the best of our knowledge, only one study has investigated the occurrence of a sticking region in free weight back squats (van den Tillaar et al., 2014). This study found that only two-thirds of the subjects measured showed a sticking region during the last repetition in 6-RM squats. In addition, kinematics was only measured by a linear encoder, which gives information on the barbell position and velocity, but not for the moving body during the lift. Joint angles and velocity of the involved joint movements during the full squat would give more detailed information about the occurrence and causes of the sticking region in squats. When the sticking region occurs at specific joint angles this could indicate a poor mechanical region for vertical force production at these joint angles (Elliott et al., 1989; van den Tillaar & Ettema, 2013).

Therefore, the purpose of this study was to investigate the 3D kinematics around the sticking region (the weakest region) in full back squats. It was hypothesized that the sticking region occurred at specific joint angles indicating a poor mechanical region for vertical force production at these joint angles.

METHODS: Eleven healthy males (age 23.5 ± 2.6 years, body mass 84.4 ± 18.5 kg, body height 1.81 ± 0.08 m) with at least two years of free weight squat training experience (a 6-RM weight of 102 ± 30 kg) participated in the study. The participants conducted no resistance training the last 72 hours before testing and all gave a written consent before testing.
The last repetition of 6-RM free weight squats was used to investigate 3D kinematics around the sticking region in squats. After a standardised warming up, the estimated 6-RM was performed. The load was increased or decreased by 2.5 kg or 5 kg until the real 6-RM was achieved (1–3 attempts). Between each attempt four minutes rest was given. The participants placed their feet in their preferred position, which was then controlled to be identical in every later attempt. Then the lowest position (defined as 80°in the knee joint) was found. The 6-RM squats were performed with an Olympic barbell with one spotter on each side of the barbell for safety. The participants bent from full knee extension in a self-paced, but controlled tempo until the back of their thigh touched the rubber band. They then received a verbal signal from the test leader and returned to the starting position.
A three-dimensional (3D) motion capture system (Qualysis, Gothenburg, Sweden) with six cameras operating with a frequency of 500 Hz was used. The markers were placed, one on each side of the body on the lateral tip of the acromion, the iliac crest and greater trochanter, on the lateral and medial epicondyle of the femur, on the lateral and medial malleolus and on the distal ends of the os metatarsal I and V. Also, two markers were 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 v4 software (C-Motion, Germantown, MD, USA). Barbell position and velocity, joint angles and angular velocity of the hip extension, knee extension and plantar flexion were calculated for the whole lift by Visual 3D software. The events of the lift that were used for further analysis were: the start of the upwards movement (v_0), first peak velocity (v_{max1}), first local minimum velocity (v_{min}) and second peak velocity (v_{max2}) of the barbell (van den Tillaar & Sæterbakken, 2014). These points constituted the start points of the different regions of the lift, v_{max1} being the start of sticking region, v_{min} the start of post-sticking region (and thereby the end of sticking region) and v_{max2} the start of the deceleration phase. In addition to the barbell position, velocity and joint angles of these points and their timing, maximal and minimal angular velocity of the hip and knee extension and the plantar flexion were calculated.
A one-way analysis of variance (ANOVA) with repeated measures was used to investigate the barbell and joint movements velocities at the different events during the lift. All results are presented as means ± standard deviations. Statistical significance was accepted at $p \leq 0.05$.

RESULTS: The lifted 6-RM load was 102 ± 30 kg and a clear sticking region in the last repetition was observed in each participant. The sticking region started at 0.08 m ± 0.02 (11.5 ± 3.1%) from the deepest point of the barbell after 0.31 ± 0.09 s (16.5 ± 5.9%).The sticking region lasted for 0.54 ± 0.30 s and v_{min} occurred on average after around 0.85 ± 0.32 s (43.5 ± 9.4%) at a height of 0.22 ± 0.07 (32.5 ± 8.3%). The first peak velocity was around 0.39 ± 0.15 m/s at v_{max1}, following which it decreased to 0.24 m/s at v_{min}. Thereafter it increased rapidly again to a maximum of 0.83 m/s at v_{max2}. The joint angles were significantly different at each event for each joint during the lift (table 1).

Table 1. Mean (± SD) barbell velocity, height, ankle, knee, hip joint angle and timing at different events during the full squat movement.

Variable	v_0	v_{max1}	v_{min}	v_{max2}
Barbell velocity (m/s)	0	0.39 ± 0.15	0.24 ± 0.11	0.83 ± 0.21
Barbell height (m)	0	0.08 ± 0.02	0.22 ± 0.07	0.55 ± 0.07
Time interval (s)	0	0.31 ± 0.09	0.55 ± 0.30	0.84 ± 0.33
Ankle	58.8 ± 10.1	65.3 ± 8.1	71.2 ± 7.9	79.1 ± 7.4
Knee	67.9 ± 19.0	81.5 ± 17.8	102.7 ± 15.0	138.9 ± 8.1
Hip	78.9 ± 9.9	84.4 ± 11.1	101.4 ± 11.4	151.8 ± 9.5

Plantar flexion and knee extension angular velocity followed the same pattern as the barbell of a two peak velocity during the upward movement, while the hip extension only had one peak angular velocity. Timing of the two peaks in joint angular velocity of the three joints (one peak for the hip extension) occurred at approximately the same time as the timing of the v_{max1} and v_{max2} of the barbell (Figure 1). This was shown likewise for the minimum angular velocity of the plantar flexion and knee extension with the timing of the v_{min} of the barbell (Figure 1).

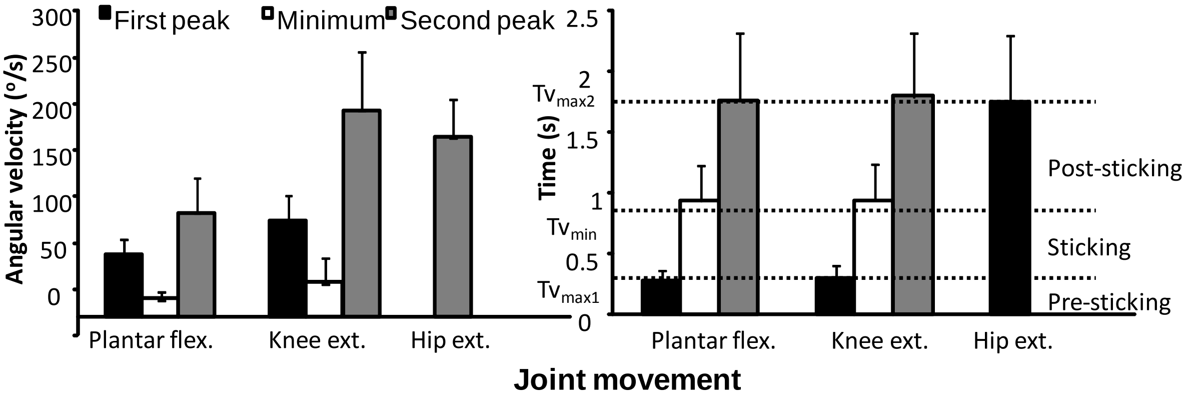

Figure 1. First, second peak and minimal (± SD) angular velocity of plantar flexion, knee extension and hip extension and their timing during the full back squat movement.

DISCUSSION: The purpose of this study was to investigate the 3D kinematics around the sticking region (the weakest region) in full squats. The main finding was that all participants exhibited a sticking region during the last repetition of 6-RM squatting. Timing of the peak and minimal angular velocities of the hip extension, knee extension and plantar flexion movements were concomitant with the v_{max1}, v_{min} and v_{max2} events of the barbell.

All participants showed a sticking region, compared to the study of van den Tillaar et al. (2014) who observed that only two-thirds of the subjects showed a sticking region, which was probably due the difference in knee angle at the deepest point (67º vs. 89°). However, when comparing the other kinematic parameters between the two studies many similarities were also found. So, the sticking region in both studies started after around 0.3 s and 0.07 m in the upwards movement, and ended at approximately the same vertical height (0.17 ± 0.077 vs. 0.221 ± 0.072) with the same knee angle at v_{min} (102º: the end of the sticking region). In addition, the post-sticking regions in both studies were approximately of similar duration (0.71 ± 0.15 vs. 0.84 ± 0.33 s), velocity (0.72 ± 0.16 and 0.83 ± 0.21), vertical position (0.54 ± 0.10 vs. 0.548 ± 0.07 m) and knee extension angles (136 ± 12 and 139 ± 8°) at v_{max2}. In both our study and van den Tillaar et al. (2014) the sticking region started after around 0.3 s, which can be explained by potentiation of the contractile system that is caused by stretch–shortening contraction movement (van den Tillaar & Ettema, 2010; 2013; Walshe, Wilson, & Ettema, 1998). In both studies, the sticking region ends at approximately the same vertical height and similar knee angles at v_{min}, which indicates that the sticking region could be angle-specific in that less force can be produced, also called a poor mechanical force production region (Elliott et al., 1989; van den Tillaar et al., 2012). This sticking region, which gives two peak velocities on each side of the sticking region, was probably caused by the timing of the different joint movements, as van den Tillaar et al. (2014) have already speculated. They stated that first the knee extended, followed by the hip extension. In our study, we were able to confirm this. The first peak velocity (v_{max1}) is caused by timing of the first peak angular velocity of the plantar flexion and knee extension, while the timing of v_{min} was at around the same time as the minimal plantar flexion and knee extension angular velocity. The time of occurrence of the second peak velocity of the barbell coincided with the peak angular velocity of the hip extension and the second peak of the plantar flexion and knee extension. The v_{max1} (0.39 m/s) was significantly lower than the second peak due to the fact that only knee extension and plantar flexion occurred. The second peak velocity (0.83 m/s) was much higher, because the second maximal angular velocities of the knee extension and plantar flexion were higher at that time together with the occurrence of the maximal hip extension at that time (Figure 1) (Roberton, Wilson, & St Pierre 2008).

Although no kinetics or inverse dynamics were conducted in our study, our findings can be explained by Roberton et al. (2008) who performed an inverse dynamics analysis in full back squats. They showed that the hip extensors had the largest peak moments (> 300 N·m at the start of the upwards movement) and peak power (> 300 N·m at 75% of the upwards lift). The ankle plantar flexors also produce a peak power of around 150 N·m at 75% of the upward lift, while the knee extensors produced the lowest powers (around 56 N·m) at 15% of the upwards cycle. These peak powers coincided with the occurrences of v_{max1}, and v_{max2} in our study, which could explain these occurrences here. At 15% upwards cycle (v_{max1}), Roberton et al. (2008) also showed a local maximal hip angular velocity and peak power of the hip, after which the angular velocity of the knee and hip extensors and power of the hip extensors kept quite constant until around 50% of the cycle. This coincided again with the occurrence of v_{min} in the present study. During this period, Roberton et al. (2008) showed that the power of the knee extensors decreased, which could be the cause of the sticking region. After 50% (v_{min}), the angular velocity of all three joints and power of the hip and ankle increased rapidly again, while the moments around the different joints decreased in this region (post-sticking region in the present study).

CONCLUSION: It was concluded that sticking region is caused by a decrease in knee extension and plantar flexion angular velocity during this region. Possible timing and activity (power output) between the knee and the hip extensors are responsible for the existence of the sticking region. Future studies should be performed in which EMG, 3D kinematics and kinetics are included to gain more information about the causes of the existence of the sticking region in full squats. The gained information can help researchers, coaches and athletes in their understanding of the sticking region and limitations during full squats.

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