Roland van den Tillaar [1]

KINEMATICS AND MUSCLE ACTIVATION AROUND THE STICKING REGION IN FREE-WEIGHT BARBELL BACK SQUATS

KINEMATIKA IN MIŠIČNA AKTIVACIJA OKROG OBMOČJA PREVELIKEGA ODPORA PRI POČEPIH Z BREMENOM ZADAJ MED DVIGOVANJEM UTEŽI

ABSTRACT

The purpose of this study was to investigate 3D kinematics and muscle activation 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 squats and the last repetition was taken for further analyses of 3D kinematics and EMG activity around the sticking region. The main findings were that all participants exhibited a sticking region during the last repetition of the 6-RM squatting. The rectus femoris activity decreased in each region from the pre-sticking to the sticking region, the lateral vastus only decreased from the sticking to the post-sticking region, while a significant increase in EMG activity was found for the glutei muscles from the pre-sticking to the sticking region. In addition, the 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 is suggested that the timing and activity between the knee extensors (lateral vastus, rectus femoris) and the gluteus maximus are responsible for the existence of the sticking region together with the large joint moment arms in this region.

Keywords: joint angle, angular velocity, sticking point

IZVLEČEK

Namen te raziskave je bil raziskati 3D kinematiko in mišično aktivacijo v območju prevelikega odpora (najšibkejše območje) pri počepih z bremenom zadaj med dvigovanjem uteži. Enajst moških, ki se ukvarjajo z vadbo z uporom (starost: 23,5 ± 2,6 let, telesna masa: 86,8 ± 21 kg, telesna višina: 1,81 ± 0,08 m) je izvedlo počepe 6-RM, zadnja ponovitev pa je bila upoštevana v nadaljnji analizi 3D kinematike in EMG aktivnosti v območju prevelikega odpora. Glavne ugotovitve so bile, da so vsi merjenci doživeli območje prevelikega odpora pri zadnji ponovitvi počepov 6-RM. Aktivnost mišice rectus femoris se je zmanjšala v vsakem območju pred in po območju prevelikega odpora, aktivnost mišice lateral vastus se je znižala samo od območja prevelikega odpora do območja, ki mu sledi, medtem ko je bilo pomembno zvišanje aktivnosti EMG pri mišicah iz skupine gluteus zabeleženo v območju pred in do območja prevelikega odpora. Poleg tega sta največja in najmanjša kotna hitrost iztegovanja kolka in kolena ter upogibanja stopala sovpadli z dvema največjima hitrostima in najmanjšo hitrostjo uteži. Vse kaže, da sta časovna uskladitev in aktivnost mišic iztegovalk kolena (lateral vastus, rectus femoris) in mišice gluteus maximus odgovorni za pojav območja največjega odpora, skupaj z velikimi ročicami momenta v sklepih v tem območju.

Ključne besede: kot v sklepu, kotna hitrost, točka največjega odpora

[1] ***Nord Trøndelag University College, Department of Teacher Education***

Corresponding author and address:
Roland van den Tillaar PhD
Department of Teacher Education Nord Trøndelag University College
Odins veg 23, 7603 Levanger, Norway
e-mail: roland.tillaar@hint.no

INTRODUCTION

In strength and resistance training, squats are often used as an exercise to strengthen the lower body. A typically successful performance in this exercise is measured when the barbell is lowered first by flexing 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, Bates, Swahill, & Hamill, 1985; Newton et al., 1997; van den Tillaar & Sæterbakken, 2014; van den Tillaar, Andersen, & Sæterbakken, 2014b). 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 (Madsen & McLaughlin, 1984). 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 the bench press (Elliott et al., 1989; Lander et al., 1985; Newton et al., 1997, van den Tillaar & Ettema, 2009, 2010), deadlift (Escamilla et al., 2000) and dumbbell chest press (van den Tillaar & Sæterbakken, 2012), the existence of this sticking region is investigated. However, very little is still known about the causes of this sticking region in these resistance exercises. In the bench press, Elliott et al. (1989), Madsen and McLaughlin (1984), 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. In these studies, the muscle activities were measured in the sticking and surrounding regions to investigate if particular muscles were responsible for enabling the participants to surpass the sticking region (van den Tillaar & Ettema, 2010; van den Tillaar & Ettema, 2013; van den Tillaar et al., 2012).

To the best of our knowledge, only one study has investigated the occurrence of a sticking region in squats (van den Tillaar et al., 2014b). 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, they found that only the biceps femoris EMG activity increased from the pre-sticking to the sticking region, while the rectus femoris decreased in the post-sticking region. However, due to the limitations of the study it was not possible to reach a conclusion regarding the likely causes of the existence of the sticking region. Unfortunately, in the study of van den Tillaar et al. (2014b) the EMG activity of the glutei muscles, which are important in hip extension during squats, was not measured. In addition, kinematics was only measured by a linear encoder, which gives information about the barbell position and velocity, but was not measured for the moving body during the lift. The joint angles and velocity of the joint movements involved during a squat would give more detailed information about the occurrence 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 and muscle activation around the sticking region (the weakest region) in full back squats. It was hypothesised that the sticking region occurred at specific joint angles and that muscle activation of the prime movers was lower in the sticking region than in the pre- and post-sticking regions.

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 prior to testing and who had trained this exercise regularly (2–3 times per week) participated in the study. Inclusion criteria were no recent injuries or pain which could reduce their maximal performance, and being able to lift 1.2 times one's own bodyweight in a full squat with a good full squatting technique, which was evaluated by an experienced weightlifting trainer. The last 72 hours before the testing the participants were not allowed to conduct any resistance training of the legs. All participants were informed verbally and in writing of the possible risks of the test and procedures. Written consent was given by the participants before the test. The study was conducted with approval of the regional Committee for Medical Research Ethics and conformed to the latest revision of the Declaration of Helsinki.

Procedures

The last repetition of the 6-RM free weight back squats was used to investigate the muscle activation and 3D kinematics around the sticking region in squats (van den Tillaar et al., 2014b).

The 6-RM weight was estimated by each participant based upon their training experience (van den Tillaar, Andersen & Saeterbakken, 2014a). After a standardised warming up, the estimated 6-RM was performed. The warming up consisted of, first, 20 repetitions of 25% of the estimated 1-RM, followed by 10 times at 50% and eight repetitions at 70% of the estimated 1-RM (Behm, Leonard, Young, Bonsey, & MacKinnon 2005; van den Tillaar & Sæterbakken, 2014) with three minutes of rest between each warming-up series. Thereafter, the test started with six repetitions at the estimated 6-RM weight. The load was increased or decreased by 2.5 kg or 5 kg until the real 6-RM had been achieved (1–3 attempts). Between each attempt, three to five minutes' rest was given (Goodman, Pearce, Nicholes, Gatt, & Fairweather, 2008).

The participants placed their feet in their preferred position (to avoid extra stress upon the subject and increase the external validity towards training) and the position of the feet was measured. This position was then controlled to be identical in every later attempt. Then the lower position (defined as when the hip crease is lower than the top of the knees, which the International Powerlifting Federation defines as a legal squat depth) was found. A horizontal rubber band was used to identify this lower position during the tests which the participants had to touch with the proximal part of the hamstring before starting the upwards movement (van den Tillaar et al., 2014). The participants wore only shorts and their regular training shoes for this exercise and no weight belt. This was done to avoid their influence on the performance, EMG and marker placement.

The 6-RM squats were performed with an Olympic barbell (2.8 cm diameter, length 1.92 m) with one spotter on each side of the barbell for safety. The barbell was placed on top of the trapezius, also called a high bar back squat. The participants bent from a full knee extension in a self-paced, but controlled tempo until the back of their thigh touched the rubber band, which was controlled by an experienced strength and conditioning expert (van den Tillaar et al., 2014a). They then received a verbal signal from the test leader and returned to the starting position.

Measurements

A three-dimensional (3D) motion capture system (Qualysis, Gothenburg, Sweden) with six cameras operating at a frequency of 500 Hz 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 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. In addition, 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 v5 software (C-Motion, Germantown, MD, USA). The 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 the Visual 3D software. Joint angles were estimates of the anatomical angles calculated from lines formed between the centres of the reflective markers. The points 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 starting points of the different regions of the lift, v_{max1} being the start of sticking region, v_{min} the start of the post-sticking region (and thereby also the end of the sticking region) and v_{max2} the start of the deceleration phase. In addition to the barbell position, the relative 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 also calculated.

The 3D motion capture system was synchronised with wireless EMG recordings using a Musclelab 6000 system and analysed by Musclelab10.73 software (Ergotest Technology AS, Langesund, Norway). EMG activity of the lateral vastus, vastus medialis, rectus femoris, biceps femoris, gluteus maximus and erector spinae was measured. Before placing the gel-coated self-adhesive electrodes (Dri-Stick Silver circular sEMG Electrodes AE-131, NeuroDyne Medical, USA), the skin was shaved, abraded and washed with alcohol. The electrodes (11 mm contact diameter and 2 cm centre-to-centre distance) were placed along the presumed direction of the underlying muscle fibre according to the recommendations of SENIAM (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). The electrodes were placed on the right leg (Sæterbakken & Fimland, 2013). To minimise noise from the surroundings, the raw EMG signal was amplified and filtered using a preamplifier located close to the sampling point. The preamplifier had a common mode rejection ratio of 100 dB, high cut frequency at the level of 600 Hz and low cut frequency at the level of 8 Hz. The EMG signals were converted to root mean square (RMS) EMG signals using a hardware circuit network (frequency response 0–600 kHz, averaging constant 100 ms, total error ± 0.5%). Finally, the RMS converted signal was sampled at 100 Hz using a 16 bit A/D converter. In order to compare EMG activity during the upward back squat movement, three regions were assigned. The first region (pre-sticking region) was from the lowest barbell point (v_0) to the maximal barbell velocity (v_{max1}); the next region (sticking region) was from the maximal barbell velocity to the first located lowest vertical barbell velocity, also called the sticking point (v_{min}); the last region, the post-sticking region, started at the first located lowest barbell velocity to the second maximal barbell peak velocity (v_{max2}), which is also called the strength region (Lander et al., 1985; van den Tillaar & Sæterbakken, 2012, 2014). Only the root mean square (RMS) EMG of each region for each subject was calculated and used for further analysis.

Statistical analysis

A one-way analysis of variance (ANOVA) with repeated measures was used to investigate the barbell and joint movement velocities at the different events (v_0, v_{max1}, v_{min} and v_{max2}) during the lift.

A one-way analysis of variance (ANOVA) with repeated measures (pre-sticking, sticking and post sticking region) was used with Holm-Bonferroni post hoc tests to assess differences in the EMG activity for each of the muscles in the different regions. In case the sphericity assumption was violated, the Greenhouse-Geisser adjustments of the p-values were reported. Statistical analyses were performed with SPSS version 21.0 (SPSS, Inc., Chicago, IL). 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%; Table 1). 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} (see Table 1).

Table 1. Mean (± SD) barbell velocity, height and time interval at first maximal barbell velocity (v_{max1}), minimal vertical barbell velocity (v_{min}) and second peak barbell velocity (v_{max2}) during the full back squat movement

Variable	v_{max1}	v_{min}	v_{max2}
Barbell velocity (m/s)	0.390 ± 0.152	0.240 ± 0.108	0.830 ± 0.214
Barbell height (m)	0.077 ± 0.023	0.221 ± 0.072	0.548 ± 0.069
% of total lift height	11.5 ± 3	32.5 ± 8%	81.7 ± 5%
Time interval (s)	0.305 ± 0.091	0.545 ± 0.298	0.838 ± 0.329

A one-way ANOVA for repeated measures performed on the EMG of the different muscles indicated significant main effects for the rectus femoris (F = 9.6; p = 0.001), lateral vastus (F = 11.7; p < 0.001; Figure 1), and gluteus (F = 8.9; p = 0.002; Figure 3) EMG activity in the three regions. Post hoc comparisons revealed that for the rectus femoris the activity significantly decreased in each region from the pre- to the post-sticking region (Figure 3), while the lateral vastus activity significantly decreased in the post-sticking region. The gluteus muscles activity was significantly lower in the pre-sticking region compared to the other two regions (Figure 2). No significant differences were found for the biceps femoris (F = 0.84; p = 0.446), erector spinae (F = 2.5; p = 0.104) and medial vastus medial (F = 0.95; p = 0.40) EMG activity between the three regions (Figures 1 and 2).

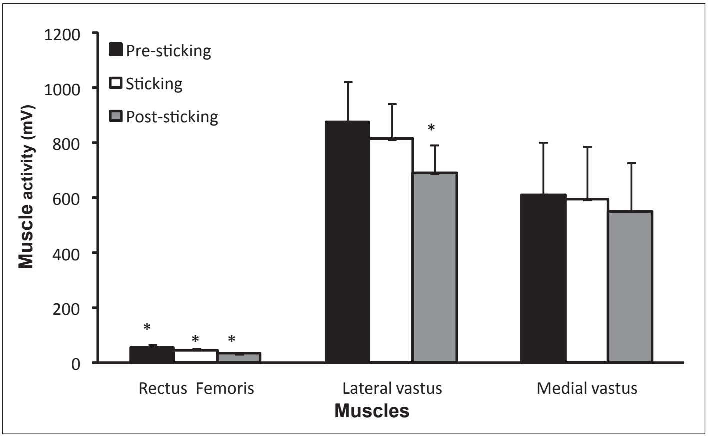

Figure 1. Mean (± SEM) root mean square (RMS) EMG activity of pre-sticking, sticking and post-sticking region in rectus femoris, lateral and medial vastus during the last repetition of the 6-RM squatting
* indicates a significant difference with all other regions at $p \leq 0.05$.

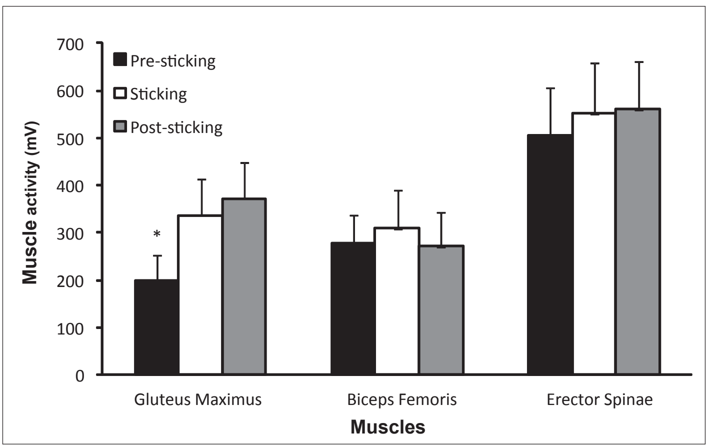

Figure 2. Mean (± SEM) root mean square (RMS) EMG activity of the pre-sticking, sticking and post-sticking region in biceps femoris, gluteus maximus and erector spinae during the last repetition of the 6-RM squatting
* indicates a significant difference with all other regions at $p \leq 0.05$.

Table 2 shows the different joint angles in the different events during the lift. The joint angles were significantly different in each event for each joint during the lift. 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 (Figure 3). Timing of the two peaks in the 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 3). 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 4).

Table 2. Mean (± SD) joint angle of ankle, knee and hip at lowest barbell height (v_0), first maximal barbell velocity (v_{max1}), minimal vertical barbell velocity (v_{min}) and second peak barbell velocity (v_{max2}) during the full squat movement

Variable	v_0	v_{max1}	v_{min}	v_{max2}
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

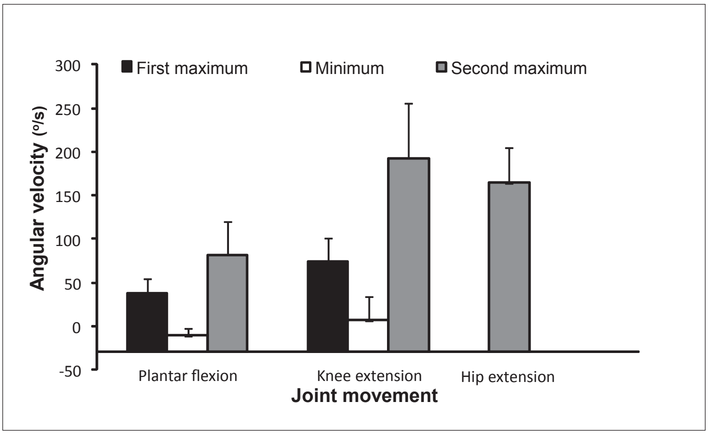

Figure 3. Maximal (± SD) first and second peak angular velocity of the plantar flexion, knee and hip extension, together with the minimal plantar flexion and knee extension during the last repetition of the 6-RM squatting averaged over all participants

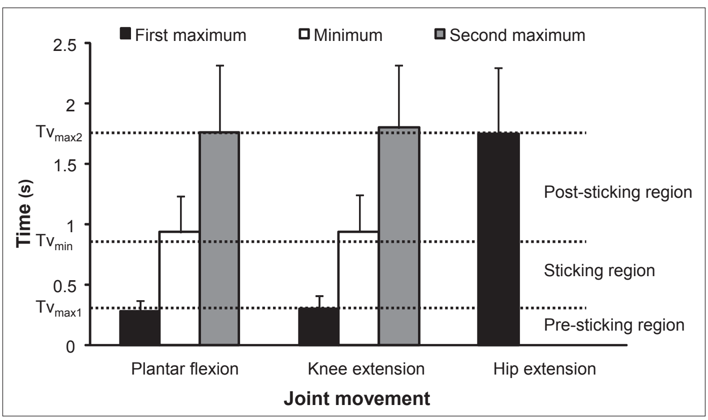

Figure 4. Timing of the maximal (± SD) first and second peak angular velocity of the plantar flexion, knee and hip extension, together with timing of the minimal plantar flexion and knee extension during the last repetition of the 6-RM squatting averaged over all participants

DISCUSSION

The purpose of this study was to investigate the 3D kinematics and muscle activation 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 the 6-RM squatting. The rectus femoris activity decreased in each region from the pre- to the sticking region, the lateral vastus only decreased from the sticking to the post-sticking region, while a significant increase in EMG activity was found for the glutei muscles from the pre-sticking to the sticking region (Figures 1 and 2). In addition, the 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. (2014b) who observed that only two-thirds of the subjects showed a sticking region. The reasons for this difference could be the lifted weight and the knee angle at the deepest point. The knee angle at v_0 in the study of van den Tillaar et al. (2014b) was around 89°, which was much larger than in the present study (67°) implying that those subjects only performed a parallel squat and not a full back squat. Therefore, more barbell weight could be lifted (130 kg vs. 102 kg) by the same type of subjects (experience, height and body mass), which could influence the existence of the sticking region. However, when comparing the other kinematic parameters between the two studies many similarities were also found. The sticking region in both studies started after approximately 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 m) with the same knee angle at v_{min} (102°: the end of the sticking region). In addition, the post-sticking regions in both studies were approximately of a similar duration (0.71 ± 0.15 vs. 0.84 ± 0.33 s), velocity (0.72 ± 0.16 and 0.83 ± 0.21 m/s), vertical position (0.54 ± 0.10 vs. 0.548 ± 0.07 m) and knee extension angles (136 ± 12 and 139 ± 8°) at v_{max2}. These similar findings of the start and end of the sticking region in both studies indicated 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; Madsen & McLaughlin, 1984; van den Tillaar et al., 2012). This less force production is probably caused by the large external moments of the ankle, knee and hip joint around the lifting trajectory of the barbell in the pre- and sticking phase. During the upwards movement these moments could exert less and more force, as shown in the post-sticking region. That the sticking region started after approximately 0.3 s in the upwards movement and not straight at the lowest barbell position (v_0) with larger external moments of the joints involved can be explained by potentiation of the contractile system which is caused by a stretch–shortening contraction movement. This makes it possible to perform better for a short time in the upward part, that is, to produce more force during the early shortening period. It results in higher absolute force at the beginning of the shortening. This potentiation effect seems to disappear completely after about 300 ms in these types of strength tasks (van den Tillaar & Ettema, 2009, 2010; van den Tillaar et al., 2012; Walshe, Wilson, & Ettema, 1998), as also shown in our study.

The 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. (2014b) have already speculated. They stated that first the knee extended, followed by the hip extension. In our study, we were able to exactly confirm this. The first peak velocity (v_{max1}) is caused by the 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 a 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 (Figure 3) together with the occurrence of the maximal hip extension at that time (Figure 4) (Roberton, Wilson, & St Pierre 2008).

Muscle activation during the full squat was comparable with the studies of van den Tillaar et al. (2014b) and Roberton et al. (2008). Roberton et al. (2008) measured the muscle function and inverse dynamics during a full squat at 80% of 1-RM. In their study, they did not find a sticking region. However, they found the same muscle activation as in the present study by which the gluteus activity increased and the lateral vastus and rectus femoris decreased during the upwards movement. As the first upwards movement of the barbell is caused by the knee extension and plantar flexion, this has to be effected by the quadriceps muscles (Figure 1). The glutei muscles are not so active at the start of the upwards movement as shown by the decreased muscle activity in the pre-sticking region (Figure 2). The cause of this lower EMG activity is probably due to the low hip angle at the deepest position (78°). This low hip angle resulted in a large gluteus muscle length that gives a mechanical disadvantage such that the capacity to exert force was reduced (Roberton et al. 2008). As a result, the hip does not extend much in this part of the upward movement (Figure 4). In addition, this gives the barbell weight position high up on the back a large moment arm around the hip joint that also has a negative influence (extra stretch) upon the erector spinae and gluteus maximus muscle activity (Roberton et al. 2008). The knee extension and plantar flexion that happens in the pre-sticking region changes the gluteus muscle length and the moment around the hip joint (Roberton et al. 2008), which makes it possible to use the gluteus more during the rest of the lift (Figure 2).

None of the measured muscles' EMG activity was lower during the sticking region compared to the other regions (Figures 1 and 2), which was at variance with our hypothesis. However, the quadriceps muscle activity decreased from the pre- to the sticking region and from the sticking region to the post-sticking region (Figure 1). At the same time, the gluteus EMG activity increased from the pre-sticking to the sticking region, but probably not fast enough to compensate for the lost muscle activity of the quadriceps. In addition, of the quadriceps muscles only the vastii muscles contributed with positive work in the pre- and sticking region (Roberton et al., 2008). The rectus femoris, a bi-articular muscle that is a knee extensor and hip flexor, could not produce much positive work as it acted eccentrically through the pre-sticking region during which most of the external work of the knee extensors was carried out, as shown by Roberton et al. (2008). They showed that the muscle lengths of the rectus femoris did not vary much (< 2%) during the lift and that they may have acted to prevent unwarranted hip extension.

In the present study, no kinetics or inverse dynamics were conducted due to insufficient equipment (the absence of a 3D force platform). Fortunately, Roberton et al. (2008) performed full squats at 80% of 1-RM and performed an inverse dynamics analysis that resulted in calculation of the net internal moment of force and their associated powers at the ankle, knee and hip joints. 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. In a 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 again coincides 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 (the post-sticking region in the present study). The moment around the knee was at 75% of the cycle (v_{max2} in our study) around zero, which resulted in no positive work of the knee extensors at this point, as shown in the lower EMG activity of the lateral vastus and rectus femoris in the present study.

In summary, it can be concluded that the timing and activity between the knee extensors (lateral vastus, rectus femoris) and the gluteus maximus are responsible for the existence of the sticking region together with the large moment arms of the ankle, knee and hip joint during the pre- and sticking phases. Since in the present study no inverse dynamics could be performed and the results were compared with Roberton et al. (2008) who did not show a sticking region, future studies should be performed in which EMG, 3D kinematics and kinetics are included to investigate whether the joint moment arms in combination with the EMG activity of the prime movers are the cause of the existence of the sticking region in full back squats. Further, by changing the barbell position lower on the back or performing a front squat this interaction between the joint moment arms, torques, muscle activity and force production can increase our knowledge about the limitations during lifting in free-weight squats. This gained information could help researchers, coaches and athletes in their understanding of overcoming the sticking region (weakest region) and enhance lifting performance in squats.

REFERENCES

Behm, D. G., Leonard, A. M., Young, W. B., Bonsey, W. A. C., & MacKinnon, S. N. (2005). Trunk muscle electromyographic activity with unstable and unilateral exercises. *Journal of Strength & Conditioning Research, 19*, 193–201.

Elliot, B. C., Wilson, G. J., & Kerr, G. K. (1989). A biomechanical analysis of the sticking region in the bench press. *Medicine and Science in Sports and Exercise, 21*, 450–462.

Escamilla, R. F., Fransisco, A. C., Fleisig, G. S., Barrentine, S. W., Welch, C. M., Kayes, A. V., Speer, K. P., & Andrews, J. R. (2000). A three-dimensional biomechanical analysis of sumo and conventional style deadlifts. *Medicine and Science in Sports and Exercise, 32*, 1265–1275.

Goodman, C. A., Pearce, A. J., Nicholes, C. J., Gatt, B. M., & Fairweather, I. H. (2008). No difference in 1RM strength and muscle activation during the barbell chest press on a stable and unstable surface. *Journal of Strength & Conditioning Research*, *22*, 88–94.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography & Kinesiology, 10*, 361–374.

Lander, J. E., Bates, B. T., Swahill, J. A., & Hamill, J. (1985). A comparison between free-weight and isokinetic bench pressing. *Medicine and Science in Sports and Exercise, 17*, 344–353.

Madsen, N., & McLaughlin, T. (1984). Kinematic factors influencing performance and injury risk in the bench press exercise. *Medicine and Science in Sports and Exercise*, *16*, 376–381.

Newton, R., Murphy, A. J., Humphries, B., Wilson, G., Kraemer, W., & Häkkinen, K. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occur during explosive upper body movements. *European Journal of Applied Physiology, 75*, 333–342.

Roberton, D., Wilson J., & St Pierre T. (2008) Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics*, *24*, 333–339.

Sæterbakken, A., & Fimland, M. (2013). Muscle force output and electromyographic activity in squats with various unstable surfaces. *Journal of Strength & Conditioning Research, 27*, 130–136.

van den Tillaar, R., Andersen, V., & Saeterbakken, A. (2014a) A comparison of muscle patterning and performance in 6-RM 2 legged free weight squatting. *Kinesiologia Slovenica* 20, 2, 5–16.

van den Tillaar, R., Andersen, V., & Sæterbakken, A. (2014b). The existence of a sticking region in free weight squats. *Journal of Human Kinetics, 42*, 7–20.

van den Tillaar, R., & Ettema, G. (2009). A comparison of kinematics and muscle activity between successful and un-successful attempts in bench press. *Medicine and Science in Sports and Exercise, 41,* 2056–2063.

van den Tillaar, R., & Ettema, G. (2010). The "sticking period" in bench press. *Journal of Sports Sciences, 28*, 529–535.

van den Tillaar, R., & Ettema, G. (2013). A comparison of muscle activity in concentric and counter movement maximum bench press. *Journal of Human Kinetics, 38*, 63–71.

van den Tillaar, R., & Sæterbakken, A. (2012). The sticking region in three chest-press exercises with increasing degrees of freedom. *Journal of Strength & Conditioning Research, 26*, 2962–2969.

van den Tillaar, R., & Sæterbakken, A. (2014) Effect of fatigue upon performance and EMG activity in 6 RM bench press. *Journal of Human Kinetics, 40*, 57–65.

van den Tillaar, R., Sæterbakken, A. H., & Ettema, G. (2012). Is the occurrence of the sticking region the result of diminishing potentiation in bench press? *Journal of Sports Sciences, 30*, 591–599.

Walshe, A. D., Wilson, G. J., & Ettema, G. J. (1998). Stretch-shorten cycle compared with isometric preload: Contributions to enhanced muscular performance. *Journal of Applied Physiology*, *84*, 97–106.