Ken Kraft Lund Lien

A biomechanical study on the effect of bouncing in front squats

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Preface

From an early age I was drawn towards sports, where strength was an important aspect in order to succeed. Naturally this led me to strength training, which I really enjoyed, and have ever since. Although I was very curious about the physiology, on how the body adapted to the training, I never thought then about taking an education in sports sciences. Now, years later I can look back at an educational journey, where I followed my interest and curiosity for training. I'm grateful that I can end this journey, by writing a master thesis on a subject that I always had a passion for, namely squats. Which when said out loud, sounds ridiculous to do a master thesis on. There is something fascinating with squats, and how this exercise can challenge the human body. This brings me to another subject which at first, I was intimidated by, biomechanics. Early in my education it seemed very complicated, and sometimes it still does, but it really grew on me, and has become a branch in sports science that I admire. The ability to break down a movement mechanically is for me, one of the most useful tools in sports science.

I would like to thank my supervisor Tron Krosshaug for wanting to create this master thesis with me. This gave me the opportunity, to write a master thesis that combined my interest for both squats and biomechanics, and it further broadened my knowledge on both subjects. Your interest, support, and enthusiasm have been vital for completing this master thesis. It has been uplifting to see your enthusiasm for both the project and the results. I have come to respect you for both your academic knowledge, and as a person. It has also been nice, to have a supervisor that are interested in strength training as well.

I have to give a special thanks to the all the participants in this study. It was an overwhelming interest from people to participate, and I owe this to some key people that helped with recruiting. I especially want to thank the Norwegian weightlifting and powerlifting community, for their curiosity and interest in participating. It has been truly amazing to have so many great lifters take part, and it has lifted this study far beyond expectations.

Ken Lien

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Ken Kraft Lund Lien

Department of Physical Performance

Norwegian School of Sport Sciences, Oslo Norway.

Corresponding Author:

Ken Lien

Department of physical performance,

Norwegian School of Sports Sciences,

Sognsveien 220, Oslo

Email: kenlien@live.no

Abstract

The purpose of this study was to compare performance, and biomechanics between a dynamic front squat, and a paused front squat variation. Specifically, we investigated how removing the bounce affected the execution of the squat, regarding lifting capacity, and the magnitude of net joint moment, including the distribution of the moment between the ankle, knee and hip. Furthermore, we examined how imposing the pause, affected trunk and thigh angels at key phases of the lift, in addition to differences in barbell velocity. Nineteen experienced weightlifters and powerlifters participated in the study. For each participant the one repetition maximum (1RM) in a dynamic front squat was established, before two single repetitions were performed at ninety percent of 1RM. The same protocol was followed for the paused variation. Kinematic data was collected using a ten-camera motion capture system, tracking forty-five skin-markers. Kinetic data was collected using two force plate platforms. Significance level used was $P<0.05$. The bottom bounce, increased the total support moment in the early phases of the dynamic front squat. The difference in 1RM was 4.5 %. This increase was mostly contributed from the knee joint moment 62.5 %. At the minimum moment phase, the total support moment was near identical between the variations. The bounce results in higher performance, by increasing the total support moment early in the concentric phase. This can potentially increase risk of injury. Implementing the pause does not change the technical execution of the squat, except for resulting in a deeper bottom position.

Key words: Net joint moment, paused squat, segment angle, barbell velocity

1. Introduction

The squat is one of the most used exercises for increasing leg strength (McLaughlin, Dillman & Lardner, 1978), and is a vital training tool for many athletes, where leg strength is an important aspect of their sport. Olympic weightlifting and alpine skiing are just some examples of sports where this is important. It has been conducted an ample amount of research on the back squat, studying different variables like technical performance, (Escamilla, Fleisig, Lowry, Barrentine & Andrews, 2001), kinetics McLaughlin et al., 1978) and muscle activity (Bryanton, Kennedy, Carey and Chiu 2012) just to mention some. Although the back squat has gotten a lot of scientific attention, little research have been conducted on the possible effects the counter movement or "bounce" has on squat performance and technical execution. It has been a general consensus that to lift the most amount of weight in a 1 repetition maximum (1RM), counter movement squat "with bounce" is the most effective strategy. And that a squat without this bounce would result in a significant reduction in maximum lifting ability. In some extreme examples a technique with a relative high velocity in the eccentric phase, resulting in a violent bottom bounce is utilized. This technique has been termed "dive bombing or controlled dive bomb" (Miletello, Beam, Zachary, Cooper, 2009). Although this is not a widespread technique, it emphasizes the general belief in the importance of the counter movement in squats. The use of bounce is also evident in Olympic weightlifting. In the clean & jerk it is not uncommon to see weightlifters, fail the first attempt at standing up with the barbell, after caching it in the bottom position, dropping down a second time and then being able to complete the rise. Although this is less favorable, the utilization of the bounce appears to be vital in a maximum lift. Even though, there hasn’t been any research to confirm this assumption in squats. Studies on bodyweight exercises like jumping show that integrating a counter movement, enhances jump height.

There has been multiple studies on counter movement jumps (CMJ) and squat jumps (SJ), where the results have shown a great difference in jump height, in favor of the CMJ (Bobbert, Gerritsen, Litjens, Soest, 1996), (Mackala, Stodolka, Siemienski, Coh, 2013). In the study by Bobbert et al. (1996) the CMJ increased jump height by 5.4 %, which is a substantial increase of performance in sports. In the 2019 weightlifting world championship, there was only 4.8% difference in weight lifted in clean & jerk, between

1st and 9th for men 89kg. In the same world championship, the greatest difference in clean & jerk between 1st and 5th for men, was 4.6%, in five out of ten weight classes.

To make the assumption that the results seen in jumping, also apply to the squat exercise is not unlikely. However there are some significant differences between jumping and squatting that makes these results less applicable. The studies on CMJ vs SJ have naturally focused on the ballistic exercise of jumping. This type of exercise requires a high power output rather than a high force production (Newton, Kreamer, Häkkinen, Humphries, Murphy, 1996). This is an important distinction from a non-ballistic exercise like the squat, where maximum lifting ability (1RM) is usually the measurement of performance. The muscles ability to generate force is depended on the contraction velocity of the movement, described by the force-velocity curve (Hill, 1938). This means that ballistic and non-ballistic exercises require different muscle qualities for optimal performance. Ballistic exercises like jumping require high velocity muscle contractions, which sacrifices the ability to generate maximum force. On the opposite side, non-ballistic high resistant exercises require high force production. Therefore the contraction velocity is low due to the need for high force. Since jumping and heavy resistant squats requires different muscle qualities, results from studies on CMJ and SJ are less applicable to predict how removing the counter movement in squats will affect the performance.

It is uncertain whether the ability to rapidly generate force, in the early stage of the concentric phase, is as crucial for maximum lifting capacity, as for maximum jump height. Removing the bounce in a heavy resistance exercise, might shed light on how the bounce affects performance in exercises like squats.

The purpose of this study was to compare performance and biomechanics between a dynamic front squat, and a paused front squat variation. Specifically, we investigated how removing the bounce affected the execution of the squat, regarding lifting capacity, and the magnitude of net joint moment, including the distribution of the moment between the ankle, knee and hip. Furthermore, we examined how imposing the pause, affected trunk and thigh angels at key phases in the lift, in addition to differences in barbell velocity.

2. Theory

Squats

A barbell squat starts with the lifter standing in an upright position with knees, hip and trunk extended. The descending phase starts with knee, hip and ankle flexion down to desired depth (Schoenfeld, 2010). The trunk is also flexing during the squat, usually referred to as forward lean or trunk flexion. When the desired depth is reached, the lifter starts the ascent towards the upright position again. The prime movers in squat are the ankle flexors (Soleus and Gastrocnemius), knee extensors (Quadriceps), hip extensors (Glute muscles and Hamstrings) as well as the extensor muscle of the trunk (Erector spinae) (McLaughlin, 1978). The extent of the forward lean is dependent on each lifters personal preference (McLaughlin et al, 1978).

Squat mechanics

Most studies on squats have researched the back squat. This squat variation is a competitive lift in powerlifting, and researchers have often used powerlifters in their studies (McLaughlin et al, 1978), (Escamilla et al, 2001), (Miletello et al, 2009). These studies often investigate the joint moment of the knee, hip and ankle as well as the angles of these joints. Previous studies have shown, that the highest joint moment is generated in the hip followed by the knee and then the ankle (McLaughlin et al, 1978), (Farris, Lichtwark, Brown, Cresswell, 2015). The workload put on the hip, knee and ankle also differs, depending on squat depth and barbell load (Bryanton et al, 2012), (Wretenberg, Feng, Lindberg, Arborelius, 1993). Results from a comparison of different squat depths by Wretenberg et al, (1993) showed that the hip moment increased with deeper bottom position in the squat. In their study, the 2nd deepest bottom position was with the thigh parallel to the ground. The deepest position was as far below parallel as the lifters could descent. Although the deepest squat position resulted in the highest knee moment, the hip moment was still larger. The knee moment showed a similar pattern with the largest knee moment reached at the deepest squat position. These findings were supported by results in a study by (Bryanton et al, 2012), which found that the ankle, knee and hip joints were affected differently by barbell load and squat depth. They found that the barbell load had minimal effect on the relative muscular effort (RME) of the knee extensors, but the squat depth increased the RME of the knee extensors. The plantar flexors of the ankle were primarily affected by an increased barbell load. The hip extensors were affected by depth and barbell load (Wretenberg et al, 1993), (Bryanton et al, 2012).

One of the explanations for why the hip and knee -joint moment, increases with squat depth is related to the moment arm. The external moment arm for the, knee and hip joints increase with squat depth (figure 1). Early in the descent, the force vector from the ground reaction force has a short moment arm, to both the knee and hip joint. As the lifter descent further down, the moment arm to the hip and knee increases. The maximum advantage of the external moment arm is reached at parallel. To counteract for the large external moment arm, the joint moment for the hip and knee has to increase.

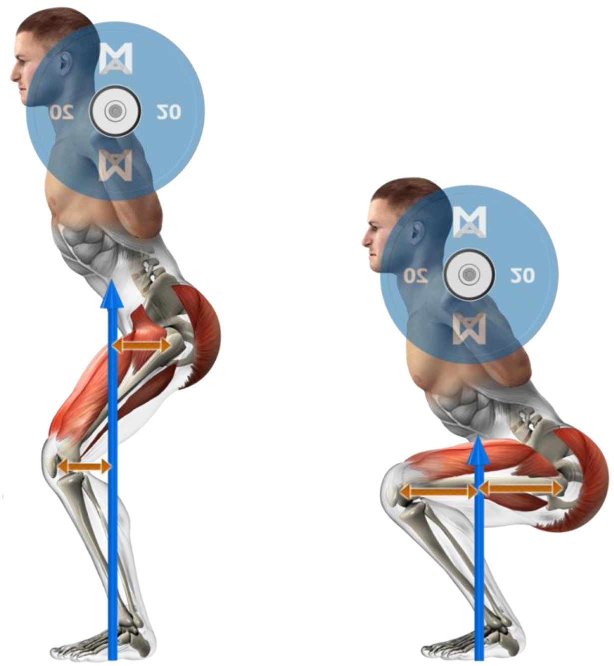

Figure 1*: Show how the moment arm for the knee and hip joint, increase as the lifter descent. This illustration is borrowed with permission from muscleanimations.com.*

The hip moment changes a lot depending on the forward lean, and positioning of the barbell. There are mainly two techniques regarding the placement of the barbell in a back squat. The low-bar places the barbell about 5 cm below the acromion and is often used by powerlifters (Escamilla et al, 2001), (O'Shea, 1985). It enables for a more hip dominant squat, because of increased forward lean resulting in higher hip extensor torque (Escamilla et al, 2001), (McLaughlin et al, 1978). The high-bar which is the variant that weightlifters mostly use, places the barbell across the shoulder just beneath the spinous process of the C7 vertebra (Wretenberg et al, 1993), (Glassbrook, Helms, Brown, Storey, 2017). This results in less forward lean and is more knee joint dominant and reduces the hip extension torque (Schoenfeld, 2010).

Front squat

Most of the biomechanical variables and squat techniques previously mentioned her have its origin from back squat studies. The reason for this is that most squat studies have been conducted on the back squat, and little attention has been given to the front squat variation (Diggin, Regan, Whelan, Daly, McLoughlin, McNamara, Reilly, 2011). Fundamentally, there is little difference in performing a front squat compared to a back squat, except for the placement of the barbell. However this difference in barbell placement, results in some mechanical differences between the back squat and front squat variations (Diggin et al, 2011), (Schoenfeld, 2010), (Gullett, Tillman, Gutierrez, Chow, 2008). In a front squat the barbell is placed on the anterior deltoids and clavicles (Gullett et al, 2008), (Diggin et al, 2011). This affects the external moment arm of the barbell in relations to the ankle, knee and hip (Diggin et al, 2011). An illustration of the different body positions between a front squat, high-bar squat and low-bar squat is shown in figure 2.

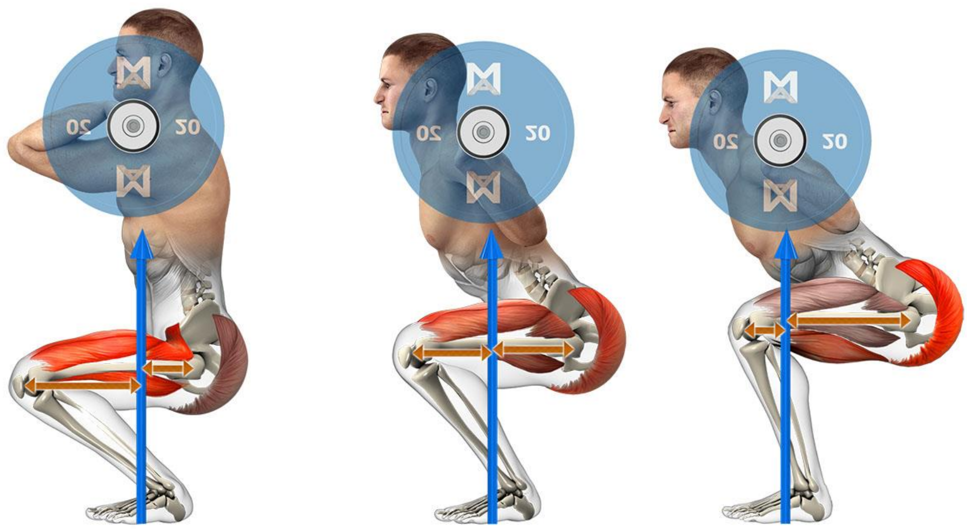

Figure 2: *Show how the moment arms for the hip and knee extensors change between a front squat, high-bar squat and low-bar squat. This illustration is borrowed with permission from muscleanimations.com.*

In a front squat the lifter is required to hold a much more upright trunk position, in order to keep the barbell from dropping. As a result of this upright position, the moment arm for the hip is reduced and the moment arm for the knee extensors is increased. Therefore the front squat increases the workload on the knee joint while decreasing it in the hip joint (Diggin et al, 2011), (Schoenfeld, 2010). This requirement of an upright trunk position also make the front squat well suited for standardizing inter-subject forward lean. In a back squat the extent of forward lean can vary significantly, depending on the lifters preference. By using a front squat this range of forward lean is more limited.

For weightlifters the front squat is an important training exercise because it's an essential part of the clean and jerk exercise (Schoenfeld, 2010). Because of the aforementioned loading pattern between the hip and knee joints, the lifting capability is lower in a front squat compared to a back squat.

Muscle- tendon biomechanics

In order to understand the possible effects of the countermovement in squats it is important to understand the mechanical properties of the Muscle-tendon unit (MTU). The force output capability of a muscle is determined by two factors, the force/velocity relationship and the length/ tension relationship of the sarcomeres. The force/ velocity relationship describes the decay in the force generating ability with increasing contraction velocity (Hill. 1938). This means that the lowest force generation is at high contraction velocities, and the highest force can be achieved during eccentric work, where the muscles are lengthening against a force. This decay in force at higher contraction velocities is due, to the rate limits of the enzymatic process with the actiomyosin cross-bridge cycling, called enzyme Vmax (Robert & Azizi, 2011).

The length/tension relationship describes the changes in force production capabilities at different sarcomere length "muscle length" (Gordon, Huxley, Julian, 1966). The force is proportionate with the number of cross-bridges, between actin and myosin filaments in the sarcomeres (Gordon et al, 1966). These mechanical properties of the muscle are greatly affected by the tendons they connected to, because the tendons have the ability to alter the length and velocity conditions for the muscle. The performance of the muscle-tendon unit (MTU) is affected by compliance of the tendon (Lieber, Brown, Trestik, 1992). The MTU can therefore perform different mechanical functions like force production, force amplification, energy conservation or energy absorption depending on the specific movement task (Robert & Azizi, 2011). These mechanical properties of the MTU have implications for counter movement exercises like squats.

Stretch shortening cycle

A lot of human movements involve muscle actions were the concentric movement is initiated or preceded by an eccentric phase. This eccentric phase is sometimes referred to as a pre-stretch and the entire movement is called a stretch- shortening cycle (SSC). Concentric movements that have been preceded with an eccentric phase increase the force generating capabilities of the MTU, resulting in higher force generation than in concentric movements alone (Cavagna, Dusman, Margaria, 1968). This effect of the SSC is a well-known phenomenon and several studies have been conducted on the SSC

(Schenau, Bobbert, Haan, 1997), (Komi, 2000), (Fukutani, Kurihara, Isaka, 2015). The increased performance by implementing an SSC to the movement has been shown in jumping exercises comparing counter movement jump (CMJ) to squat jumps (SJ) (Mackala et al, 2013) (Bobbert et al, 1996), and resistant exercises like bench press and squats (Wilson, Elliott, Wood, 1991), (Tillar, Ettema, 2013), (Walshe, Wilson, Ettema, 1998). It is important to note that in the study by (Walshe et al, 1998) the squat was performed isokinetically in a smith machine. A possible explanation is that a concentric contraction that has not been initiated with an eccentric or isometric phase, the working muscles will have inadequate time to generate maximal force before the movement starts. Subsequently the MTU starts shortening at submaximal force, resulting in submaximal work. (Schenau et al, 1997), (Bobbert et al, 1996), (Robert & Azizi, 2011), (Fukutani et al, 2015). By implementing a counter movement before the concentric phase, the muscles have more time to generate force, resulting in the ability to start the concentric phase at a higher force output and thereby do more work.

Results from multiple studies have shown that the increased force generating capability from the pre-stretch, decays as time elapses during the concentric contraction (Wilson, Elliott, Wood, 1991), (Fukutani et al, 2015), (Walshe et al, 1998). In the study on isokinetic squats by Walshe et al, (1998), the squat variations that had an isometric preload or eccentric preload generated a significantly higher force the first 300ms of the concentric contraction, than the pure concentric variation. The most significant difference could be seen from 0-100ms. The same trend was reported in the bench press study by Wilson et al, (1991), were the results clearly showed that the largest differences in force generation between rebound bench press and paused bench press variations, was from 0-100ms into the concentric phase and diminished greatly after 300ms.

Imposing a delay between eccentric and concentric contraction

Several studies have shown that the effect of the SSC is decreased by the imposing a delay between the pre-stretch and the concentric shortening. This decay also increases with length of the delay (Thys, Faraggiana, Margaria, 1972), (Wilson et al, 1991). An equation put forward based on the results by Wilson et al, (1991), estimated a quite linear time/ performance decay relationship. They estimated that a delay of 0.35seconds would result in 25% reduction in pre-stretch effect, 0.9s would result in 52% reduction and 1.5s would result in 70%. However they suggested that a delay of 4 seconds would be needed to entirely dissipate the benefits of pre-stretch.

3. Measurement Methods

Defining phases of the squat

The vertical barbell velocity is often studied and reported in squat research. This is because it's the most common way to define and describe different phases and events throughout the lift. The descent is the eccentric part of the squat and is usually reported as one phase. The concentric part of the lift is divided into multiple phases and events. However, in one of the earliest kinematic analysis of the back squat by (McLaughlin, Lardner, Dillman, 1977) the entire squat was divided into 6 phases, were the descent and ascent had 3 phases each. In later studies, dividing the descent into different phases is unusual, and most studies have focused on the ascending part of the squat, since it contains the majority of biomechanical variables if interest. The ascent or concentric part of the lift was first divided into; first peak velocity, lowest velocity (sticking point) and second peak velocity (McLaughlin et al, 1977). Later studies have modified these phases slightly due to other interesting events in the squat such as the sticking region (figure 3).

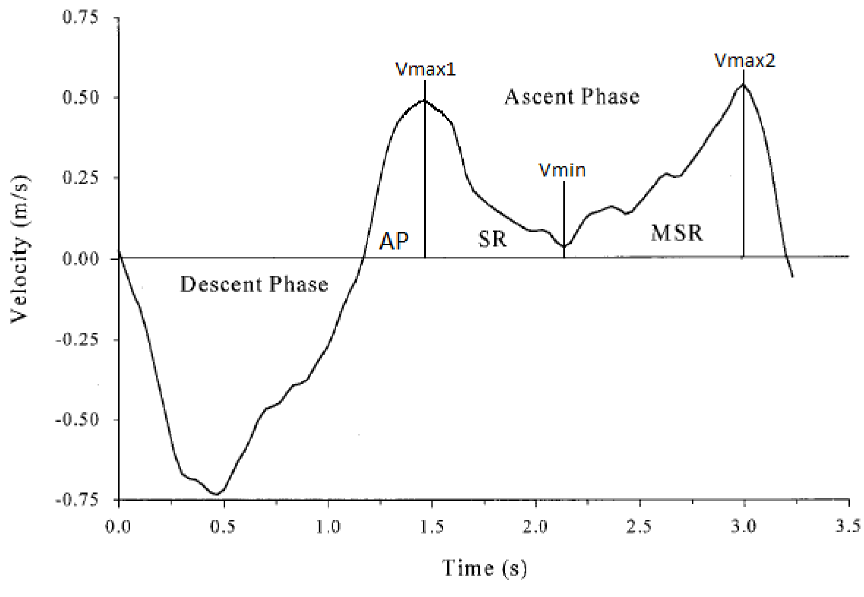

Figure 3: *Definitions of phases and events in a back squat. Adapted from (Escamilla et al, 2001) and (Tillaar et al, 2014) AP: acceleration phase, Vmax: first peak velocity SR: Sticking region, MSR: Maximum strength region, Vmax2: 2nd peak velocity.*

It shows how the changes in barbell velocity during the ascent, are used to define different phases and events during the concentric part of the lift. The phase from first peak velocity to minimum velocity has been investigated in several studies, because it has been identified as the weakest phase where a lifter is most likely to fail a lift (Tillaar, Andersen, Saeterbakken, 2014), (Kompf & Arandjelovic`, 2016).

Inverse dynamics

Inverse dynamics is an important and commonly used computational procedure for calculating joint moment, in biomechanical studies. To calculate the joint moments, the inverse dynamics method uses direct measurements of the external ground reaction force and positional data of the skin markers (Robertson et al, 2014), (Kristianslund et al, 2012). The segmental acceleration is however calculated by numerical differentiation of positional data, using estimates of segment mass and inertial properties (Bisseling, Hof, 2006). These estimates are frequently calculated by implementing Dempster's regression equations Dempster, W.T. (1955) for segment mass and segment geometry based on (Hanavan E. 1964). The adjusted Zatsiorsky-Seluyanov's segment inertia parameters is also commonly used (de Leva, 1996). The joint reaction forces, and net joint moments that are calculated, are 3-D vectors computed into the global positioning system. However in order to give these forces and moments more meaning, they are usually resolved into an anatomical coordinate system (Robertson et al, 2014). There are four representations of the net joint moment and joint reduction that have shown to be robust for 3 D-analysis (Brandon, Deluzio, 2010). The first two options are to resolve the signals into either the distal or proximal segments local coordinate system. For the knee joint moment this would be thigh for proximal or shank for distal. These two options result in the signals being vectors, which is consistent with representations of joint angular velocity, angular acceleration, and joint force. The third option, resolve the signal into the joint coordinate system. It does not treat the signals as vectors and cannot be used to calculate the total support moment described by Winter (1980). This makes the method limited for a kinetic analysis. Option 4 resolves the signal into a plane of progression it is not consistent with any of the kinematic measures and can only compare compatible signals, for example vectors with vectors (Brandon et al, 2010), (Robertson et al, 2014). For a biomechanical analysis of squats where the purpose is to examine and compare support moment and the joint moments, the methods that resolve the signals into to the distal or proximal segments would be most suited.

Analysis of the joint moments are vital in studying human motion, since it reflects the muscle forces and loading of the human body (Kristianslund et al, 2012). In squat related studies the presentation of the net joint moment, as well as the individual joint moments of the ankle, knee and hip important is key variables for a meaningful description. How the net joint moment is presented differs greatly between studies. Some just report the moment or torque as Newton meter (Nm) (McLaughlin et al, 1987), (Wretenberg et al, 1993). Other studies normalizes (scales) the joint kinetics to body mass, Nm/kg or body (Gullet et al, 2008). Normalizing the joint moment has the advantage that it can easier be compared between studies, because it removes the between -subject differences, although not perfectly (Robertson et al, 2014).

When collecting kinematic and kinetic data from human movement, it is recommended to filter the data. In biomechanical research, a low-pass Butterworth filter is often chosen to smooth the data (Robertson, Dowling, 2003). In heavy resistant exercises such as squats, a cutoff frequency between 5hz and 8hz has frequently been used (Escamilla et al, 2001), (Bryanton et al, 2012), (Tillaar et al, 2014). As mentioned earlier, the inverse dynamics method uses both positional and force -data, as input to calculate joint moments (Robertson et al, 2014), (Kristianslund et al, 2012). It is recommended to use the same cut- frequency when filtering. Using different cut-off frequencies between the force and movement- data, can result in artifacts in the joint moment data (Kristianslund et al, 2012).

Because of the input data required for the inverse dynamics calculation, the method is susceptible to a number of sources of error. The primary sources of error are: estimates of body segment parameters, segment angle calculations due to skin artefact, identification of joint center (Reimer, Hsiao-Wecksler, Zhang, 2008). For calculations of joint moments in the ankle, knee and hip the main source of error was identified as, the segment angles which was mainly associated with skin artifact (Reimer et al, 2008). One of the methods for compensate for this skin artifact is to use a cluster of skin markers for each segment.

Skin artifact on marker based motion

When using skin markers to estimate human motion and position of the skeleton, one of the major sources of error is skin artifact. The skin artifact is caused by the movement of the skin in relation to the joint and bones. This affects the estimation of joint center and axis rotation (Cerveri, Pedotti, Ferrigno, 2005). A marker –based analysis system uses a minimum of 3 non-collinear markers per segment, to generate a coordinate system and estimate movement of the bone (Robertson et al, 2014), (Mok et al, 2015). In a foot kinematic study that compared marker methods, skin markers, plate mounted markers and bone pins were investigated (Nester, Jones, Liu, Howard, Lundberg, Arndt, Lundgren, Stacoff, Wolf, 2007). It was found that both the plate mounted and the skin markers differed from the bone pins. The bone pin markers were seen as the golden standard since they were physically attached directly to bones. Although there was a difference between the skin marker methods and the bone pins, the difference was not seen as critical. The kinematic results between the three marker methods, showed that both the plate mounted and the skin marker methods were good and did not have an advantage over the other.

The measurement error between skin-markers and bone pins changes depending on the variables examined. In a walking study the average rotational error ranged from 2.4 - 4.4° and translational error ranged between 3.3mm-13.1mm. In the same study the reported errors of rotation and translation in side cutting movements was 3.3°-13.1° and 5.6mm-16.1mm, respectively (Benoit, Ramsey, Lamontage, Xu, Wretenberg, Renström, 2006). The study concluded that although there was some error, the kinematic results from skin-markers where repeatable, which makes them reliable. This reliability also strengthens the usability in within subject comparisons, where the same potential errors are the same in all conditions. These results are similar results to what was reported in another walking study, they found an absolute difference between bone pins and skin-markers to be 2.28° for the sagittal plane, 2.78° in the frontal plane and 1.88° in the transverse plane. The maximum displacement of skin marker was 14.7mm. They concluded that during the stance phase of a gait cycle, the tracking of the skin-markers were in close agreement with the bone pins, for both the sagittal and frontal plane (Huck, Yack, Cuddeford, 2004). Benoit et al, (2006), reported that the difference in flexion/extension of the knee joint was 2.5° during walking. Considering, that the squat is predominantly a sagittal plane movement, the results from these studies suggest that, the error from skin artifact should be relatively small, and that the magnitude of error will be consistent. It is likely that the displacement of the skin-markers will be greater in deeps squats, considering that the change in joint angles will be far greater than in the walking studies. However, the potential error should be equal in both squat variations and therefore not affect comparative conclusions.

Joint and segment angles

As mentioned the barbell velocity is a common way to define the phases and events of the squat. It gives good platform to interpret results from different studies and compare them to each other. When reporting data such as, joint moment and joint angles these variables are often put in context with the phases defined using the barbell velocity.

When reporting the movements during a squat, both segment angles and joint angles are frequently used (McLaughlin et al, 1977), (Escamilla et al, 2001). The thigh segment is often included since it defines when a squat is performed to parallel. This also makes it an intuitive way of reporting squat depth, since starting position would be reported as 0 degrees. Another advantage with using segment angles instead of joint angles has to do with individual differences. Joint angles are measured as the angle between two segments, like thigh in relation to shank. These joint angles are more susceptible to inter-subject changes, than the segment angles. If we use the knee joint as an example, the knee angles throughout a squat, differs between performing it with or without wedged heels (Charlton, Hammond, Cochrane, Hatfield, Hunt, 2017). This means that the knee joint angles in a squat study can differ between subjects, because they wear shoes with different heel height. In the mentioned study by Charlton et al. (2017) the difference in heel height actually resulted in significant difference in hip angle as well. By using segment angles these potential differences are minimized, because each segments position is individually measured, in relation to a fixed global positioning system.

4. Methods

Experimental approach to the problem

For this study the front squat was the preferred squat exercise, because the front squat limits the magnitude of forward lean, compared to a back squat which sometimes can vary substantially between lifters. This was to ensure that the technical difference between subjects regarding trunk lean was minimized. We also used highly skilled lifters, to ensure that differences registered between the squat variations, was not caused by technical variability within subjects. A two second pause was chosen for the paused variation, to ensure that the bottom position was reached before the concentric phase started. This was also done to minimize potential "dip" before the concentric phase. We chose to have the participants perform the dynamic variation first, because we hypothesized that this variation would require much more effort. We therefore thought it would give the best one repetition maximum in both variations, if the dynamic was performed first.

Participants and test protocol.

A total of 19 experienced lifters from the Norwegian weightlifting and powerlifting community were recruited to participate in the study; 10 women (weight 66.9kg ±5.1kg, height 163.3cm ± 5.1cm) and 9 men (weight 91.4kg ± 11.0kg, height 179.2cm ± 5.7cm). The average age for both groups was (age 28.6 years ± 4.4 years). All of the participants were very familiar with the front squat exercise. Of the 19 participants, 4 had competed at world championships in weightlifting or powerlifting. 1 participant competed in the weightlifting world championship after this study was conducted, and 2 more were associated with the Norwegian national weightlifting team. The participants were recruited through direct contact with coaches, and by participants forwarding the study to other potential candidates. In order to take part in the study the participants had to lift a minimum of 1.3 times their bodyweight in a deep front squat. The participants could not have any injuries that could affect their technique. The study was approved by the ethics committee of the Norwegian School of Sports Sciences. Written and informed consent was obtained from all participants.

Before testing the participants did a 5 minute warmup on a Monark Ergomedic 828 E (Monark, Vansbro, Sweden) stationary bike followed by a stretching routine of their own choosing, for as long as they needed. The height of each participant was measured without shoes, while their weight was measured with shoes. The reason for this had to do with the modeling of the anthropometrics used to calculate the kinetic and kinematic data, which will be explained further on. The first part of the test protocol, was to determine 1rm in the dynamic front squat, and then having the participants performing 2 single repetitions at 90% of their 1rm. This was repeated for the paused squat as well. The length of the pause was 2 seconds. To ensure that the duration of the pause at the bottom was the same, an oral que was given when the participant could start the concentric phase of the squat. An important criterion for when the 2 second count could start, was that the downward movement had stopped, and the participant was sitting still at the bottom position. To determine the specific load increments up to the 1rm we used the participants self-expected 1 rep max, since we used very advanced lifters. The warm up consisted of 8 reps at around 30% of 1rm, 5 reps at 55%, 3 reps at 70%, 1 rep at 90% and 95% and then the 1 rep maximum. This protocol was used as a general guideline, and individual adjustments were done, to ensure the optimal load increments for each participant. In the cases where the estimated 1rm did not seem to be a maximum effort lift, we increased the load until the 1rm was established. The increments for this were decided from the collective opinion of the participant and test leader. If however the participant wasn't able to lift the anticipated 1rm, the load would be decreased to the closest weight that the participant and test leader thought would be the 1rm. After the 1rm was established, the 2 single repetitions at 90% were performed. The same load increments were used for the paused squat. For all participants the dynamic front squat was performed before the paused variation.

Lifting equipment

For this study, a simple squat stand without safety arms was used. Since all of the participants where highly experienced lifters, we used a custom made wooden platform that the participants could drop the barbell on to if necessary, without hitting the force platforms they were standing on figure 4.

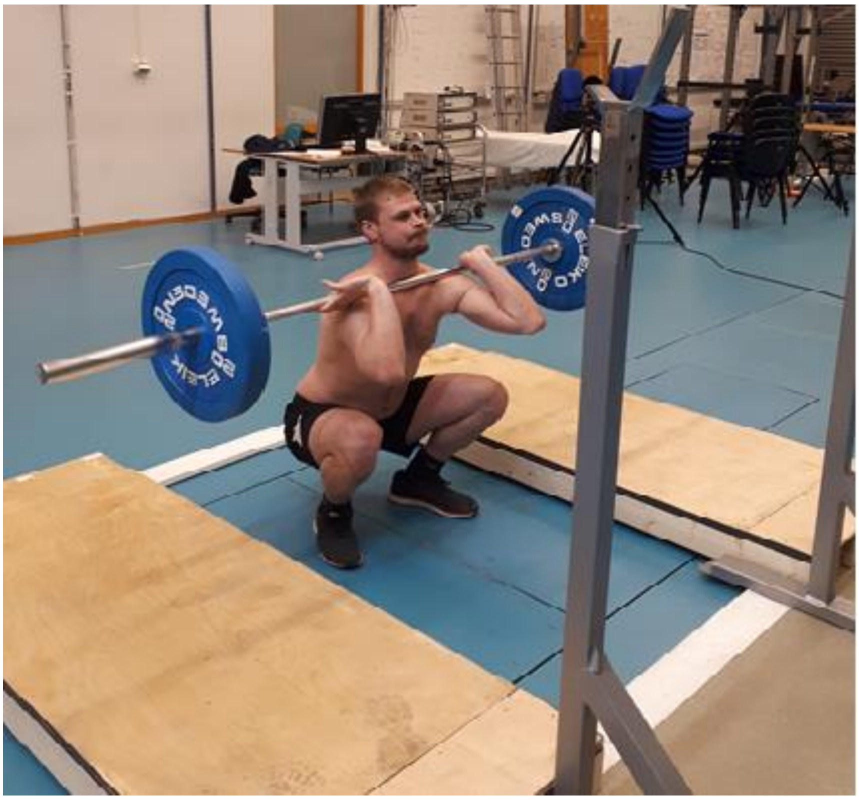

Figure 4: *Shows the set- up around the force plates, with the custom made platform and squat stand.*

This minimized the chances of equipment blocking the view of the 3d cameras to an absolute minimum, while maintaining the safety of the participants. For the data collection a male competition weightlifting barbell was used for both male and female participants. The participants were not allowed to use a belt, knee wraps or sleeves. We made no restrictions on shoes, but all participants used weightlifting shoes.

Data collection and trajectory editing

A ten-camera motion capture system sampling at 300Hz, was used to record the three-dimensional positional data (Oqus 400 and 700, Qualisys Medical AB, Gothenburg, Sweden). The cameras were positioned at different height and angles around the test area. 43 reflective markers were placed on anatomical landmarks on the upper and lower body of the participants figure 5, as well as 2 reflective markers attached to each end of the barbell.

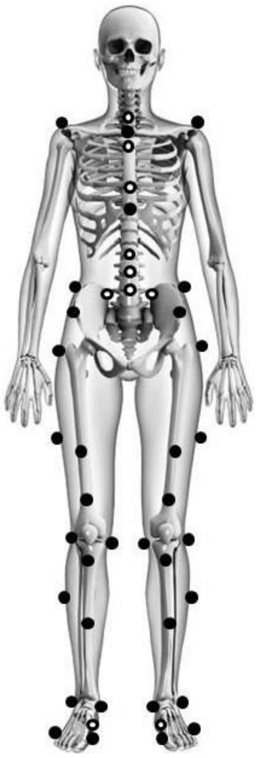

Figure 5*: Marker setup.*
Adapted from Kristianslund et al (2012) and Mok et al (2015).

We used the marker setup previously used by (Kristianslund, Krosshaug, Bogert, 2012), without the arm markers, as a base for the marker model. It was however modified using a thigh marker setup from (Mok, Kristianslund, Krosshaug, 2015) and some additional markers from the c-motion.com/v3dwiki website. This website is a guideline tool for Visual 3D users. The marker setups were modified because the two mentioned studies used customized Matlab scripts for their study. We on the other hand used Visual 3D, which is a more rigid command based program. Visual 3d have specific data requirements for specific tasks. An example would be marker placement, in order to model a segment and track the movements.

For the thigh segment we applied the marker placements from (Mok et.al. 2015), however we added an additional marker on the medial epicondyle. This was crucial, because both the medial and lateral epicondyles are used to define the thigh and shank segments in Visual 3d. For the foot segment we utilized the same skin marker placement as (Kristianslund et.al. 2012), but added a marker on the calcaneus, to be used as a tracking maker for the foot segment. To define the pelvis segment, we used the same marker set up as (Kristianslund et.al, 2012), but added markers on the iliac crest. These were used as tracking markers along with the PSIS. To model and track the thorax, Visual 3D also needed to include markers on the Spinal process of the 1st and 8th thoracic vertebra, Xiphoid process, and 3 markers on the lumbar vertebras.

The model used to analyze the front squats in visual 3D was calibrated using a static trial. The participants stood still in a T-pose position, with feet straight forward and approximately shoulder width apart. This calibrated model was later applied to every squat trial for each participant. The marker positions on the participants were used to generate the kinematics for an eight-segment 6 degrees of freedom rigid body model for feet, shanks, thighs, pelvis and thorax. To measure ground reaction force and center of pressure on each foot, two AMTI LG6-4-1 force plate platforms measuring 120cm x 60cm and an AMTI MCA6 amplifier with gain set to 2000 (AMTI, Watertown, MA, USA) was used. The sampling frequency was set at 1500Hz. Before each trial the area around the force plates was calibrated using a calibration wand with a width of 749.2mm (Qualisys, Gothenburg, Sweden.). The system was considered to be calibrated as long as the measured wand width was within 0.10mm of true width. To convert the analog force plate signals to digital a USB-2533 converter (Measurement Computing Corporation, MA, USA) were used. Both motion and force data where simultaneously collected using a computer with Qualisys Track Manager (QTM, version 2.16, Qualisys). The marker trajectories were calculated and tracked using the same software. If markers were missing in a frame it was gap filled using equations in Qualisys that could estimate the trajectory during the missing frames. The limit for gap filling was set to 20 frames, before the data would be discarded. This was only the case with 3 lifts, due to loss of Metatarsal markers, and not all data needed to be discarded. However, all data from 1 participant was discarded, due to technical difficulties with the squat.

Segment modeling

Both the kinetic and kinematic data were further processed and analyzed in Visual 3D software (v6, C-Motion, Germantown, MD, USA) using 3D rigid body linked segment modeling procedures. Segments were treated as geometrical objects that have inertial properties based on their shape. Visual 3D models segments as cones, cylinders, spheres and ellipsoids based on the shape of a particular segment. The dimensions of these geometrical objects are calculated using the marker placement on specific anatomical landmarks for each segment. Segment mass were based on Dempster's regression equations (Dempster, W.T. 1955), and segment geometry were based on (Hanavan E. 1964).

The pelvis segment was defined using a model in Visual 3D called CODA pelvis, which uses the anatomical landmarks of anterior superior iliac spine and posterior superior iliac spine bilaterally as proposed by Bell et al. (1990). The coordinate system of the pelvis follow the right hand rule using the X, Y, Z Cardan sequence, with the global positioning system in the lab as reference. The hip joint center was calculated in Visual 3D using the same anatomical landmarks, using the regression equations adapted from (Bell, Brand, 1989) and (Bell, Pedersen, Brand, 1990), Hip Joint Center = (0.36*ASIS_Distance,-0.19*ASIS_Distance,-0.3*ASIS_ Distance). This equation is used on both left and right side.
The shank and foot segment coordinate systems were defined by, placing markers at anatomical landmarks lateral and medial at both the proximal and distal end of the segments. The "Segments Endpoint" was defined as the midpoint between the lateral and medial markers at both the distal and proximal end. The thigh coordinate system uses almost the same method, but instead of the medial marker at the proximal end, the hip joint center is used as a medial reference. The knee joint center was defined using, the Endpoint between the lateral epicondyle and the medial epicondyle. The local coordinate system of the shank is used as reference system. The ankle joint center was defined using, the Endpoint between the lateral- and medial -malleolus, with the local coordinate system of the foot as reference.

The Visual 3D thorax/Ab model was applied for modeling the upper body segment. This thorax model is constructed by using a combination of palpated anatomical landmarks and virtual landmarks. The positioning of the virtual landmarks is estimated by using the placement of the anatomical landmarks, and applying mathematical constants from the Terry database (kepple, Sommer, Siegel, Standhope, 1998) to identify their position. The Virtual landmarks that are created for the thorax/Ab model are lateral superior borders of the Iliac Crest bilaterally, which uses the anatomical landmark of the anterior superior iliac spine to estimate its location. MID_ IJCV7, which is estimated as a location that is the midpoint between the Incisura Jugularis and spinal process of the 7th cervical vertebra. MID_ PXTV8, which is estimated as the midpoint between Xiphoid process and the spinal process of the 8th cervical vertebra. The last virtual landmark is Thorax_X, which is used as a lateral landmark of the thorax model and defines the mediolateral axis. This virtual landmark is made by applying the anatomical landmarks of the Incisura Jugularis, spinal process of the 7th cervical vertebra and the virtual landmark previously created called MID_ PXTV8.

Kinetic and kinematic calculations

Force platform data were digitally low-pass filtered, using a Butterworth filter with a 6Hz cutoff frequency. Joint angles were defined as proximal segment relative to the distal segment, shank relative to the foot (ankle) thigh relative to the shank (knee), and pelvis relative to the thigh (hip) bilaterally, using a standard XYZ Cardan sequence X-flexion/extension, Y- abduction/adduction and Z- longitudinal rotation (Yeadon,1990), (Davis, Õunpuu, Tyburski, Gage, 1991), (Kadaba, Ramakrishnan,1991). The segment angles for the thighs and thorax are based on each segments orientation in relation to the global positioning system in the lab. The segments uses the same Cardan sequence as mentioned for the joints. For calculating the Net joint moment, we used the Inverse dynamics analysis in the Visual 3D software. This analysis combines the kinematic data with the ground reactions force, to calculate the net internal forces, using the Newton-Euler equations. The joint moment was resolved into the distal segment, so for the net joint moment the reference coordinate system is, (hip to thigh, knee to shank and ankle to foot). For lifting velocity, we used the displacement of the two markers on each side of the barbell relative to the global positioning system, to calculate the velocity and acceleration. We averaged each marker displacement, and divided by two to get the average barbell displacement. To get velocity, we used the first derivative and the second derivative for acceleration.

Data reduction

The analysis for this study was done on the two single repetitions at 90% of 1rm and the one repetition maximum lift. The variables of interest between the two front squat variations was maximum lifting ability (1RM), barbell velocity, upper body position, peak moment and minimum moment, squat depth and work distribution between the ankle, knee and hip muscles.

For analyzing purposes, we divided the concentric part of the squat into 5 phases of interest, bottom position (1), peak moment (2), start sticking region (3), minimum moment (4) and end sticking region (5) figure 6.

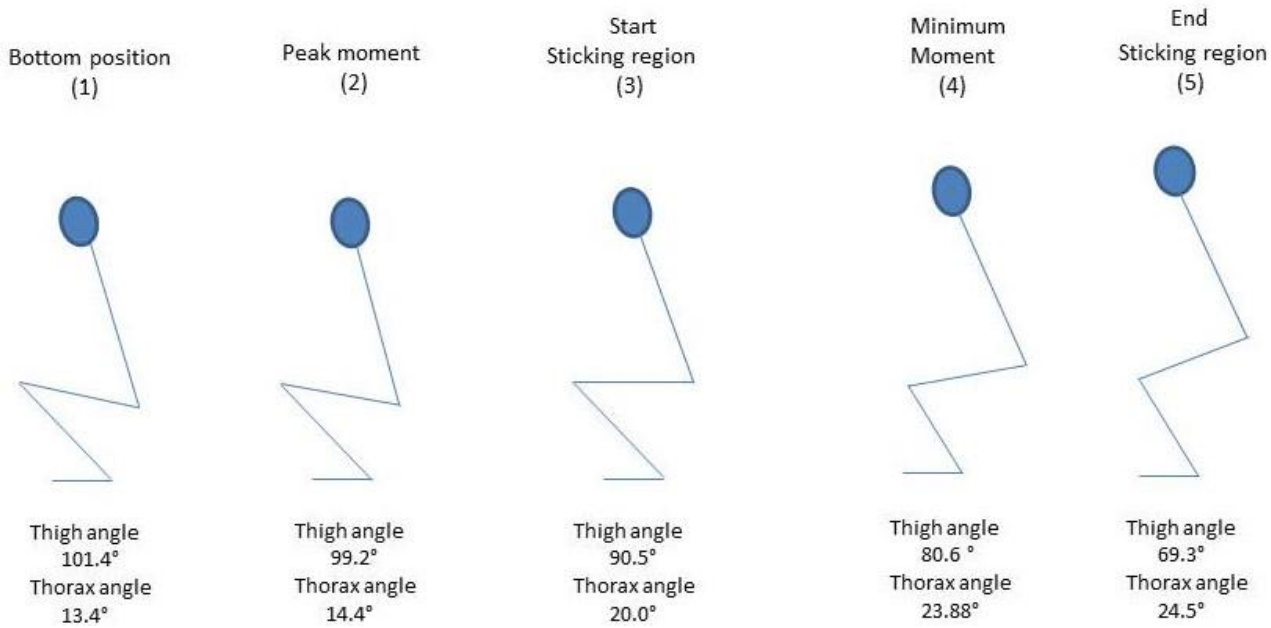

Figure 6: *The 5 defined phases of a front squat, using kinematic and moment data. The figure shows the average thigh and thorax angles in a paused front squat.*

These phases were defined using kinematic data and moment data figure 7. The kinematic data was used to define the bottom position, which was defined as the deepest position of the squat, measured using the thigh angle. The peak moment, was defined as the point where the total support moment reached maximum. The total support moment is defined as, the sum of the internal net joint moment in the ankle, knee and hip joint, in the sagittal plane (Winter. 1980). This distribution of moment between the joints, is also how each joints contribution to the total support moment, was calculated. The minimum moment phase was defined as the phase where the total support moment was at its lowest.

The start and end of the sticking region was defined by the barbell velocity. The start of the sticking region was defined as, the point where the barbell velocity continuously decreased, after reaching first peak velocity. When the barbell velocity reached its lowest point, it was defined as the end of sticking region. The upper body position was defined as the angle of the thorax, in the sagittal plane.

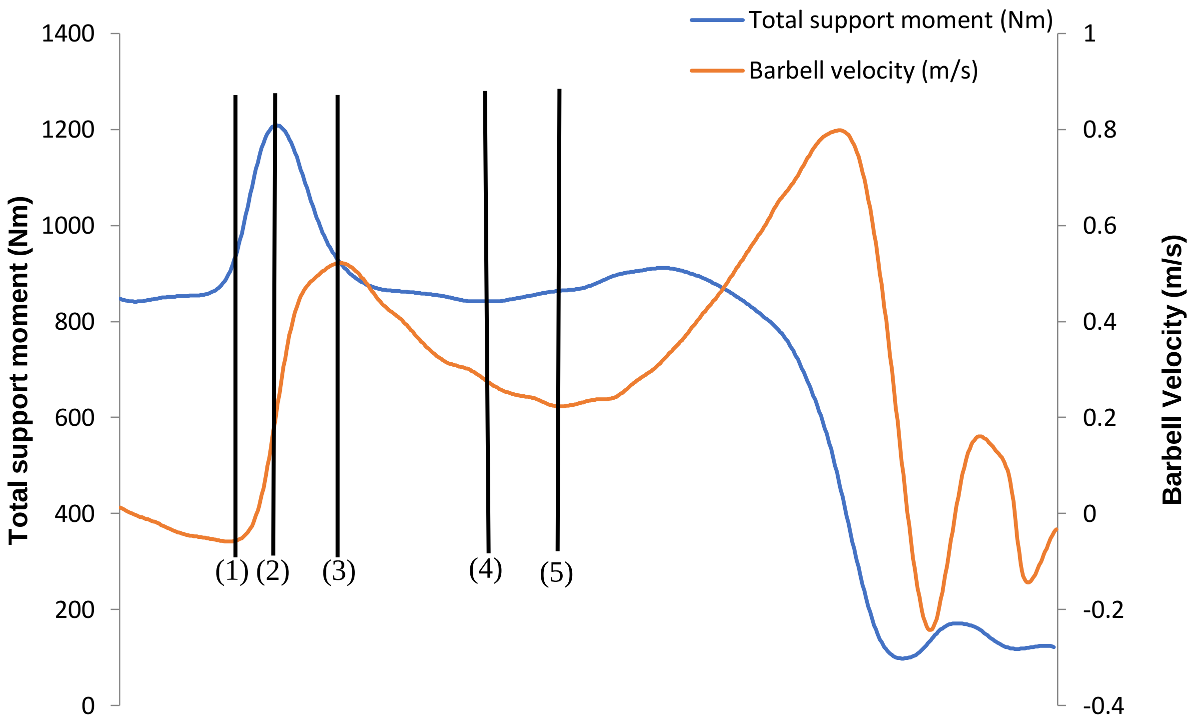

Figure 7: *Bottom position (1), Peak moment (2), start sticking region (3), Minimum moment (4), end sticking region (5). The figure shows a typical graph of total support moment and barbell velocity. Taken from a paused squat at 90% of 1RM.*

Statistical analysis

A paired two tailed t-test was applied to analyze the data and statistically compare the two front squat variations. If the t-test marked for possible outliers, a Wilcoxon signed – rank test was used to confirm the statistical significance. Statistical significance was set to $P < 0.05$, unless specified otherwise. The results are presented as mean ± standard deviation (SD).

5. Results

The average dynamic front squat 1RM was 120.9kg ± 39.6kg and 115.5kg ± 37.8kg for the front squat, performed with a stop at the bottom. The average difference for each participant between the two front squat variations was 5.39kg ± 6.7kg in favor of the dynamic squat ($P<0.001$).

The barbell velocity was very similar between the dynamic front squat and the paused front squat variations Table 1. The only exception was the barbell velocity at the start of sticking region (SR Start), at 90 % of 1RM, where the barbell velocity was higher for the dynamic squat ($P<0.05$)

Table 1: *Barbell velocity at the start and end of the sticking region at 90% and 1 repetition max, for both dynamic and paused front squat.*

	Dynamic (m/s)		**W. Stop (m/s)**		**Difference (m/s)**	
	SR start	SR end	SR start	SR end	SR start	SR end
90 %	0.47 ± 0.1	0.25 ± 0.06	0.43 ± 0.09	0.23 ± 0.04	0.04 ± 0.32*	0.01 ± 0.05
1RM	0.42 ± 0.11	0.08 ± 0.08	0.39 ± 0.1	0.10 ± 0.1	0.03 ± 0.06	0.02 ± 0.08

* Significantly difference in barbell velocity $P<0.05$

There were no significant differences in thorax angle or thigh angle between the dynamic and the paused front squat variations, at the 5 defined phases of the lift Table 2. The only exception was the thigh angle at bottom position. The paused front squat had a 3.3° deeper bottom position, which was statistically significant ($P<0.001$).

Table 1: *Thigh and thorax angles for the dynamic front squat, at the 5 defined phases*

		Bottom position	**Peak Moment**	**Start SR**	**Minimum Moment**	**End SR**
Dynamic	Thigh	98.1° ± 4.8°	97.6° ± 5.3°	89.6° ± 4.6°	79.5° ± 5.9°	68.4° ± 4.0°
	Thorax	12.6° ± 5.6°	12.8° ± 5.7°	18.5° ± 5.6°	22.0° ± 5.4°	23.2° ± 4.3°
W. Stop	Thigh	101.4° ± 4.6°*	99.2° ± 4.6°	90.5° ± 4.3°	80.6° ± 5.6°	69.3° ± 5.8°
	Thorax	13.4° ± 5.8°	14.4° ± 5.8°	20.0° ± 5.0°	23.9° ± 4.8°	24.5° ± 4.8°

* Significantly difference in thigh angle at bottom position P<0.001

The difference in thigh angle between peak moment (phase 2) and the start of sticking region (phase 3) was 8 degrees for the dynamic squat and 8.7 degrees for the paused squat variation.

The dynamic front squat variation has a larger total support moment at the peak moment phase, with 15.2 Nm/kg ± 2.5 Nm/kg against the paused variation 13.8 Nm/kg ± 2.2 Nm/kg. The greatest difference was seen in knee joint moment, between the dynamic and paused variation, 7.5 Nm/kg ± 1.6 Nm/kg and 6.6 Nm/kg ± 1.3 Nm/kg, respectively. However the reduction in total support moment for the dynamic variation is so large, that at the minimum moment phase there is no statistical difference, between the dynamic and paused -front squat variation, 10.7 Nm/kg ± 1.5 and 10.5 Nm/kg ± 1.5, respectively. When examining the changes in net joint moment for the ankle, knee and hip, between peak moment (phase 2) and minimum moment (phase 4) Figure 8, the results show some further distinctions between the dynamic and paused squat variation.

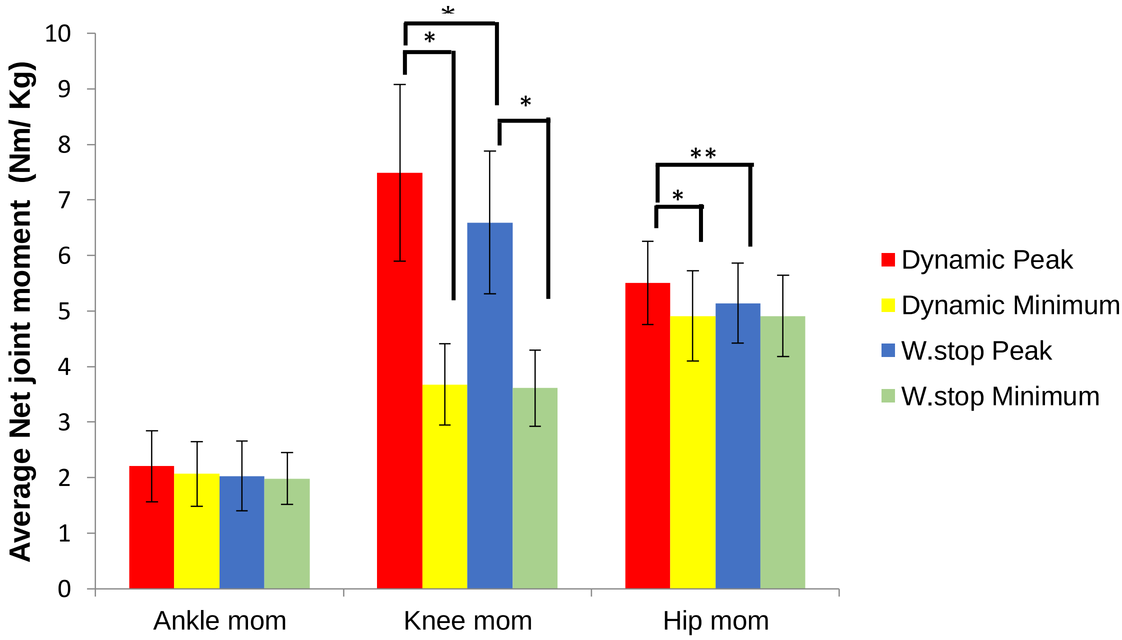

Figure 8: *Show the average net joint moment for all participants, at the dynamic peak and start sticking region phase, at 1RM. * indicates significant reduction in joint moment between peak moment and minimum moment.*

In the dynamic front squat, both the knee and hip joints have a significant reduction in moment, between peak moment and minimum moment- phase with ($P<0.001$) for both joints. The paused squat however, has only a significant reduction in moment in the knee joint ($P<0.001$), between these two phases. The reduction in knee and hip joint moment for the dynamic front squat was 3.8 Nm/kg ±1.7 Nm/kg and 0.6 Nm/kg ± 0.7 Nm/kg respectively. For the paused front squat the reduction in knee and hip joint moment was 3.0 Nm/kg ± 1.2 Nm/kg and 0.2 Nm/kg ± 0.5 Nm/kg respectively. When we compare the extent of the reduction in moment, between peak moment and minimum moment -phase, the dynamic front squat has a statistically greater decrease in moment than the paused variation, with $P<0.001$ for the knee and $P<0.005$ for the hip. For both the dynamic and paused squat variation the reduction in ankle moment was not statistically significant.

If we see the net joint moment for each joint as a percentage of contribution to the total support moment, we found the knee to be the only joint to decrease its contribution between peak moment and the start of sticking region phase. The ankle and hip actually has an increased contribution percentage to the total support moment, although both these joints decrease their joint moment. This applies to both the dynamic and paused squat variation.

Both the dynamic- and paused -front squat variations had a very similar joint moment contribution from the ankle, knee and hip joints, at both the peak moment and minimum moment phase. At peak moment in the dynamic front squat, the contribution from the ankle, knee and hip were (15% ± 2.9%), (49% ± 3.9%) and (36% ± 4.3%), respectively. For the paused front squat the distribution at peak moment was (15% ± 2.6%), (48% ± 4.5%) and (38% ± 4.0%), respectively.

At the low moment phase in the dynamic variation the distribution between ankle, knee and hip were (19% ± 3.1%), (35% ± 4.5%) and (46% ± 3.5%), respectively. For the paused variation the distribution was (18% ± 3.4%), (35% ± 4.1%) and (47% ± 3.6%), respectively.

When comparing the percentage of joint moment reduction, between the peak moment and low moment phase at 1RM Table 3. The dynamic front squat has a higher percentage of moment reduction between the two phases. The total joint moment reduction is, (29.3% ± 7.87%) for the dynamic- and (23.0% ± 8.90%) for the paused squat, which is a significant difference (P<0.001). When looking at the moment reduction for each joint, the dynamic front squat had a significantly greater decrease in moment in both the knee and hip.

Table 2: *The percentage of reduction in joint moment, between the peak moment- and minimum moment -phase at 1RM.*

	Ankle (%)	**Knee (%)**	**Hip (%)**	**Total (%)**
Dynamic	1.5 ± 32.4	49.3 ± 11.6	10.5 ± 11.9	29.3 ± 7.9
W.stop	-3.6 ± 29.4†	44.1 ± 11.3	4.6 ± 8.9	23.0 ± 8.9
Average diff	5.1 ± 37.5	5.3 ± 6.9*	6.3 ± 9.6**	6.3 ± 6.2*

* Significantly difference P<0.005

** Significantly difference P<0.05

† Negative number indicates increase in joint moment

6. Discussion

The purpose of this study was to compare performance and biomechanics between a dynamic front squat, and a paused front squat variation. We investigated how removing the bounce affected magnitude of net joint moment, as well as the distribution of the moment between the ankle, knee and hip. Furthermore, we examined how the pause effected the technical execution of the squat.

The main findings in this study, reveal that the highest 1RM was achieved in the dynamic front squat ($P<0.001$).The bottom bounce increased the total support moment in the early phases of the lift. Furthermore, the increased support moment was predominantly contributed from the knee joint moment, which also resulted in the knee having the greatest reduction in joint moment, as the effect decayed. At the minimum moment phase, the total support moment was near identical, between the dynamic and paused –front squat. This indicates that the majority of the effect from the bounce had diminished before this phase. The bounce does not change the distribution of the support moment between the ankle, knee and hip. Furthermore, the pause resulted in a deeper bottom position.

As we expected, the dynamic front squat variation had the highest average 1RM, however we were surprised that the average difference was relatively small. The difference in 1RM between these squat variations was smaller than what has been reported in studies, comparing counter movement jumps (CMJ) to squat jumps (SJ). In the study by Bobbert et al. (1991) the CMJ increased jump height by 5.4 % and Mackala et al. (2013) reported 8.97 % difference. In the present study, the difference between the dynamic and paused -front squat variation was 4.46 %.

In contrast to our relative small difference in 1RM, other studies have found greater differences, when comparing counter movement exercises to pure concentric variations. In a bench press study comparing counter movement to pure concentric lifts, the reported average difference was 20kg in favor of the counter movement bench press (Tillaar, Ettema, 2013). This is very dissimilar to the results in this present study, were the difference is only 5.39kg ± 6.7kg. They also found a statistical difference in barbell velocity in 1RM bench press, at both the start and the end of the sticking region. This is in contrast with the findings in the present study, where we only found a difference in barbell velocity at the start of sticking region, in the 90 % of 1RM lift. There was no statistical difference in barbell velocity at 1RM. This was unexpected since there was a significant difference in force generation, in the early phases between the front squat variations. An important difference between the bench press study and our study is that, in the bench press study, the participants started with the barbell already at the lowest height, in the pure concentric lift, and therefore had no eccentric phase. This is a distinct difference to our protocol, where they performed the eccentric part of the lift and then paused.

The greatest difference between the dynamic front squat and the paused front squat was the increased total support moment, in the early phase of the lift. At the peak moment phase, the difference in total support moment was 11.2 % between the squat variations, and the difference in barbell load was only 4.5 %. It is apparent that the bounce facilitates for increased force generation. The knee joint was most affected by the bounce, and had the largest difference in joint moment, at peak moment phase, between the front squat variations 7.5 Nm/kg ± 1.6 Nm/kg in the dynamic, and 6.6 Nm/kg ± 1.3 Nm/kg in the paused. The knee joint also had the largest decrease in joint moment, from peak to minimum moment phase. The reason why the knee joint was so affected compared to the hip joint, could perhaps be explained by the moment arms in the front squat. Because of the upright trunk position, the moment arm for the hip joint is considerably shorter than for the knee joint (Diggin et al, 2011), (Schoenfeld, 2010). Consequently, a lot of the workload is put on the knee, which would also explain why most of the effect of the bounce is seen in the knee joint. In a back squat, where the moment arm is more equal between the hip and knee, the hip joint might have been more affected by the bounce. The decay of support moment was so large in the dynamic front squat that, at the minimum moment phase, there was no longer a statistical difference in support moment between the squat variations. The majority of this reduction was a result of decreased knee joint moment, which was 3.8 Nm/kg ±1.7 Nm/kg, the reduction in hip joint moment was only 0.6 Nm/kg ± 0.7 Nm/kg. In comparison, the paused variation had a significantly smaller reduction in knee joint moment Nm/kg and 3.0 Nm/kg ± 1.2 Nm/kg and the reduction in the hip was insignificant. It is evident that some sort of force contributing effect had diminished, between the peak and minimum moment -phase in the dynamic variation.

Our results showing that, the increased force generation ability diminishes during the concentric phase, coincides with results from similar studies. In a back squat study by Walshe et al. (1998), they compared counter movement squats, purely concentric squats and concentric squats preceded with an isometric load. Their results showed that the squat variation with a stretch shortening cycle had a significantly larger force production capability early in the concentric part of the lift, compared to the pure concentric variation. However this increased force production capability from the pre-stretch, was greatly reduced later in the lift. In their study, the biggest difference in mechanical work was seen from 0-100ms in the concentric part of the lifts. After 300ms, the force production was almost equal. Some important differences between the present study, and the one by Walshe et al (1998), are that our paused front squat variation was performed with an eccentric phase. In their study the squat was also performed isokinetically in a smith machine. This could make the present results, more relevant for other external loaded exercises involving counter movements. This early peak in knee and hip moment was also found, in a back squat study by Wretenberg et al. (1993). They found the peak moment in knee and hip, to occur within 80ms into the concentric phase. Also McLaughlin et al. (1978) reported that the highest net joint moment occurred in the early phases of the back squat.

The dynamic front squat might have some advantages in the early stages of the concentric phase, which results in a greater decay of support moment compared to the paused variation. Concentric movements that have been preceded with an eccentric phase, increase the force generating capabilities of the muscle tendon unit (MTU), resulting in higher force generation than in concentric movements alone (Cavagna et al, 1968). This is a well-known phenomenon and implementing a stretch shortening cycle

(SSC), has shown to increase performance in resistant exercises like bench press and squats (Wilson et al, 1991), (Tillaar et al, 2013), (Walshe et al, 1998). The pre-stretch during the eccentric phase enables the working muscles to develop a higher level of force, before the concentric phase starts (Schenau et al, 1997), (Bobbert et al, 1996), (Robert & Azizi, 2011), (Fukutani et al, 2015). In the present study both front squat variations have an eccentric phase, and should benefit from the pre-stretch. However, for the paused variation, the delay drastically affects the early force generating ability

Several studies have shown that, the effect of the SSC is decreased by imposing a delay between the pre-stretch and the concentric shortening. This decay also increases with duration of the delay (Thys et al, 1972), (Wilson et al, 1991). In the present study, the paused front squat had a 2 second delay between the eccentric and concentric phase. This delay makes the paused front squat more similar to a pure concentric lift, in terms of utilizing the eccentric phase. By estimates from Wilson et al. (1991) the delay could result in a 70 % reduction in pre-stretch effect. Compared to the dynamic front squat, the paused variation could potentially start the concentric phase at a more submaximal force, because it is not able to utilize the pre-stretch to the same extent. Consequently, the paused front squat has less potential for force reduction, because it relies more on the pure concentric strength of the muscles, already in the early phase.

It seems very likely that the mechanisms behind the difference between CMJ and SJ, plays a role in the difference between dynamic and paused – front squats. However, there are two potential reasons for why the difference is smaller in the present study, than in studies comparing jumps. The first reason is the time for force generation. In a ballistic exercise like jumping, the time to generate force once the acceleration of the body begins is limited (Robert & Azizi, 2011). Therefore, the pre-stretch is vital for jump performance, because it facilitates for a higher force output before the push-off phase starts (Schenau et al, 1997), (Bobbert et al, 1996), (Robert & Azizi, 2011). In a non-ballistic exercise like squats, the ascending phase can only start once the force generated is large enough, to accelerate the center of mass. The time to generate this force is theoretically unlimited. Although the pre-stretch increases the force output in the early phase of the lift and results in a higher 1RM, the muscles still have time to generate a near maximum force, which makes the pre-stretch less vital. The second reason, for the smaller difference in performance is because of the aforementioned relationship, between imposed delay and decay of pre-stretch effect. It is possible that the paused front squat had benefits of the pre-stretch, even after the 2 second pause. Wilson et al. (1991) estimated that it would take about 4 seconds of delay between eccentric and concentric contraction before the effect was totally diminished.

The most distinct difference between the dynamic and paused -front squat variation regarding technical execution, was the thigh angle at bottom position. The thigh angle was larger in the paused squat variation, resulting in a deeper squat. This was to a certain extent expected, since the participants were instructed to hold the bottom position for 2 seconds. During this pause it would be most energy efficient to sit as far down as possible, and let the muscles work isometrically against the tension of the quadriceps/patellar tendon (Robert & Azizi, 2011). Most of the participants had the flexibility to "rest" in the bottom position, by having the backside of the thigh lean on the calf, which would be the most energy conserving position.

For both squat variations, the peak and minimum moment -phase were at the same thigh angles, and more surprisingly, there was no difference in thigh angle at the start and end for the sticking region. These results are in dispute with what Tillaar et al. (2013) reported in their bench press study, were they compared pure concentric lifts to dynamic lifts. In their study the barbell traveled further, before the sticking region (Vmax) occurred in the pure concentric bench press. Suggesting that the sticking region started earlier in the dynamic variation. The result in our present study indicates that, the bounce doesn’t affect the timing of neither sticking region nor the peak and minimum moment phases. The sticking region affects both front squat variations the same, despite the fact that their force generating capabilities are different in the early stage. Therefore it seems less likely that the sticking region originates from factors preceding the concentric contraction, which diminishes during the ascent.

The result from the present study, suggests that the risk of injury is potentially smaller in the paused squat variation. The bottom bounce in the dynamic variation resulted in significantly higher peak in total support moment, especially the knee joint moment. Previous studies have shown that these increased peak forces associated with bounce, are potential risk factors for injury, due to increased shear and compression forces (Schoenfeld, 2010). This increased force, comes from the deceleration when transitioning from eccentric to concentric work, and results in high peak of joint moments (Hartmann, Wirth, Klusemann, 2013), Schoenfeld, 2010). Although the bounce increases performance, it comes with the cost of increased injury potential. In both weightlifting and powerlifting the most common injuries are related to the spine, knee and shoulder (Aasa, Svartholm, Andersson, Berglund, 2017). For weightlifters, the reason for why the knee is particularly susceptible to injuries could be related to the catch phase in clean & jerk, as well as the snatch. In both these lifts, the lifter catches the barbell while sitting in a deep squat position (Gourgoulis, aggelousis, Mavromatis, Garas, 2000). This results in a bottom bounce, where the lifter is required to decelerate the barbell, and transition from eccentric to concentric work.

Although the dynamic front squat variation with bounce, increase performance, it might be beneficial to implement the paused squat variation in day to day training. The results from this study show, that although the bounce increase performance, the difference is relative small, and is associated with increased injury risk. Therefore the paused squat might be better suited, as the main squat variation, and the bounce could be implemented when the athlete wanted to increase performance. The paused squat might also stimulate for increased muscle strength, in the early phase of the lift, because of the reduced pre-stretch effect forces the muscles to rely more on contraction force.

One of the limitations to the present study, are the order of which the front squat variations were performed. The dynamic variation was, systematically performed before the paused variation. We hypothesized, that the paused variation would result in a much larger reduction in lifting ability, compared to the dynamic variation. We therefore thought it would optimize the conditions for maximum performance, if the dynamic lifts were performed first. When considering the result, that the average reduction in barbell weight was only 4.5% for 1RM, there is a possibility that the order of the squat variations had a minor effect on the result. Although there was no restriction in the length of rest before each lift, it cannot be dismissed that muscle fatigue played a role.

Another variable is the length of the pause, as mentioned earlier the decay of pre-stretch effects increases with duration of the pause (Walshe et al, 1998), (Thys et al, 1972), (Wilson et al, 1991). In the present study, the main objective with implementing the 2 second pause was to eliminate the bounce, and ensure that the bottom position was reached, before the participants initiated the concentric phase. Hence, it is possible that the difference between the front squat variations, would have been increased, if the duration of the pause was longer, or decreased if shorter. However, considering the results in this present study, it seems unlikely that these variables would affect the conclusions. The two second countdown was also performed verbally, and could be a potential source of inconsistency, regarding the duration of the pauses.

The kinematic data from skin-markers is also a potential source of error in this study. It has been shown that marker displacement during walking can be as much as 16.1mm (Benoit et al, 2006). Considering that participants in this study have squatted into a deep position, with average thigh angle exciding 100 degrees. It is possible that marker-displacement is greater, than reported by Benoit et al, (2006). The placement of markers is another source, some anatomical landmarks are difficult to palpate and it is likely that some markers are not places correctly. However, since this is a comparative study, these errors would have been the same during both squat variations, and would therefore not affect the conclusions in this study.

In conclusion, this study revealed that the bottom bounce, increased the total support moment in the early phases of the dynamic front squat, which resulted in a higher 1RM. This increase in total support moment is primarily a result of increased knee joint moment. Compared to the paused front squat, the dynamic variation had a significantly greater decrease in total support moment, between peak moment phase and minimum moment phase. At the minimum moment phase, the advantage of the bounce had almost entirely diminished, and there was no longer a statistical difference in total support moment, between the front squat variations. The bounce does not change the distribution of support moment between ankle, knee and hip. Furthermore, there was no difference in technical execution, between the front squat variations, except for the deeper thigh angel in the paused variation.

Practical Applications

The dynamic front squat with bounce, results in a higher 1RM. However, the difference is relatively small, and because of the high peak in joint moments, it can potentially increase the risk of injury, due to increased shear and comression forces. Implementing the paused squat, could reduce the risk of injury, because the peak moment is significantly reduced, with little sacrifice of maximum lifting ability. Consequently, the paused squat might be better suited as the main squat variation, and the bounce can be implemented as a means for increases performance when needed. The deeper bottom position in the paused front squat variation, might be beneficial for weightlifters who want to increase the depth of the catch position. The paused squat might also stimulate for increased muscle strength in the early phase of the lift, because of the reduced pre-stretch effect.

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Attachments

Tron Krosshaug
Seksjon for idrettsmedisin OSLO 21. november 2017

Søknad 30 -141117 – Hva forårsaker "sticking region" i frontknebøy? En biomekanisk sammenligning av plyometriske og rene konsentriske løft

Vi viser til søknad, prosjektbeskrivelse, informasjonsskriv og innsendt søknad til NSD.

I henhold til retningslinjer for behandling av søknad til etisk komite for idrettsvitenskapelig forskning på mennesker, ble det i komiteens møte av 14. november 2017 konkludert med følgende:

Vedtak

På bakgrunn av forelagte dokumentasjon finner komiteen at prosjektet er forsvarlig og at det kan gjennomføres innenfor rammene av anerkjente etiske forskningsetiske normer nedfelt i NIHs retningslinjer. Til vedtaket har komiteen lagt følgende forutsetning til grunn:

- *At NSD godkjenner prosjektet og at eventuelle vilkår fra NSD følges*
- *At det utarbeides samarbeidsavtaler og databehandleravtaler med eventuelle samarbeidene institusjoner*

Komiteen gjør oppmerksom på at vedtaket er avgrenset i tråd med fremlagte dokumentasjon. Dersom det gjøres vesentlige endringer i prosjektet som kan ha betydning for deltakernes helse og sikkerhet, skal dette legges fram for komiteen før eventuelle endringer kan iverksettes.

Med vennlig hilsen
Professor Sigmund Loland
Leder, Etisk komite, Norges idrettshøgskole

Tron Krosshaug
Postboks 4014
0806 OSLO

Vår dato: 12.10.2017 Vår ref: 55872 / 3 / EPA Deres dato: Deres ref:

Tilrådning fra NSD Personvernombudet for forskning § 7-27

Personvernombudet for forskning viser til meldeskjema mottatt 12.09.2017 for prosjektet:

55872	*Hvorfor oppstår det en "sticking region" i knebøy*
Behandlingsansvarlig	*Norges idrettshøgskole, ved institusjonens øverste leder*
Daglig ansvarlig	*Tron Krosshaug*
Student	*Ken Lien*

Vurdering

Etter gjennomgang av opplysningene i meldeskjemaet og øvrig dokumentasjon finner vi at prosjektet er unntatt konsesjonsplikt og at personopplysningene som blir samlet inn i dette prosjektet er regulert av § 7-27 i personopplysningsforskriften. På den neste siden er vår vurdering av prosjektopplegget slik det er meldt til oss. Du kan nå gå i gang med å behandle personopplysninger.

Vilkår for vår anbefaling

Vår anbefaling forutsetter at du gjennomfører prosjektet i tråd med:
- opplysningene gitt i meldeskjemaet og øvrig dokumentasjon
- vår prosjektvurdering, se side 2
- eventuell korrespondanse med oss

Meld fra hvis du gjør vesentlige endringer i prosjektet

Dersom prosjektet endrer seg, kan det være nødvendig å sende inn endringsmelding. På våre nettsider finner du svar på hvilke endringer du må melde, samt endringsskjema.

Opplysninger om prosjektet blir lagt ut på våre nettsider og i Meldingsarkivet

Vi har lagt ut opplysninger om prosjektet på nettsidene våre. Alle våre institusjoner har også tilgang til egne prosjekter i Meldingsarkivet.

Vi tar kontakt om status for behandling av personopplysninger ved prosjektslutt

Ved prosjektslutt 28.10.2018 vil vi ta kontakt for å avklare status for behandlingen av personopplysninger.

Se våre nettsider eller ta kontakt dersom du har spørsmål. Vi ønsker lykke til med prosjektet!

Vennlig hilsen

Katrine Utaaker Segadal

Eva J. B. Payne

Kontaktperson: Eva J. B. Payne tlf: 55 58 27 97 / eva.payne@nsd.no
Vedlegg: Prosjektvurdering
Kopi: Ken Lien, kenlien@live.no

Personvernombudet for forskning

Prosjektvurdering - Kommentar

Prosjektnr: 55872

FORMÅL
Formålet med prosjektet er å øke vår forståelse for hvilke faktorer som bestemmer knebøy prestasjon. Spesielt skal forskeren studere de biomekaniske faktorene som ligger til grunn for hvorfor sticking point oppstår og snevre inn mulige årsaker til sticking region ved å sammenligne ulike knebøy variasjoner.

Personvernombudet legger til grunn at studentene innehar kompetansen som er nødvendig for å sikre forsvarlig gjennomføring av treningsopplegget og testene, eventuelt at en studielege er tilknyttet prosjektet.

INFORMASJON OG SAMTYKKE
Utvalget informeres skriftlig og muntlig om prosjektet og samtykker til deltakelse. Informasjonsskrivet er godt utformet, men vi ber om at følgende endres/tilføyes:
- legg til at Norges idrettshøgskole er behandlingsansvarlig institusjon
- legg til kontaktopplysninger til daglig ansvarlig (veileder)
- legg til prosjektslutt 28.10.2018
- ifølge meldeskjemaet skal datamaterialet anonymiseres ved prosjektslutt, men i informasjonsskrivet er det skrevet at datamaterialet skal anonymiseres senest fem år etter prosjektslutt. Vi ber om at informasjonsskrivet redigeres, jf. informasjonen i meldeskjemaet.

SENSITIVE OPPLYSNINGER
Det behandles sensitive personopplysninger om helseforhold.

INFORMASJONSSIKKERHET
Personvernombudet legger til grunn at student/forsker etterfølger Norges idrettshøgskole sine interne rutiner for datasikkerhet. Dersom personopplysninger skal lagres på privat pc/mobile enheter, bør opplysningene krypteres tilstrekkelig.

PROSJEKTSLUTT OG ANONYMISERING
Forventet prosjektslutt er 28.10.2018. Ifølge prosjektmeldingen skal innsamlede opplysninger da anonymiseres. Anonymisering innebærer å bearbeide datamaterialet slik at ingen enkeltpersoner kan gjenkjennes. Det gjøres ved å:
- slette direkte personopplysninger (som navn/koblingsnøkkel)
- slette/omskrive indirekte personopplysninger (identifiserende sammenstilling av bakgrunnsopplysninger som f.eks. bosted/arbeidssted, alder og kjønn)

FORESPØRSEL OM DELTAKELSE I FORSKNINGSPROSJEKTET

HVORFOR OPPSTÅR STICKING REGION I KNEBØY?

I utførelsen av en knebøy kan vi observere en nedgang i stangas hastighet midtveis i løftet. Dette kalles "sticking region". Det er uklart hvorfor vi har denne «svakhetsfasen».

Vi ønsker å undersøke mulige årsaker til at sticking region oppstår. Ved å studere forskjellen mellom en eksentrisk -konsentrisk frontbøy (vanlig frontbøy) og en frontbøy som kun gjøres konsentrisk (fra bunnposisjon og opp) kan vi få svar på hvordan muskelaktivering samt elastisitet i muskel-senekomplekset påvirker sticking region.

For å kunne delta i denne studien må du være i stand til å løfte 1.3 ganger din egen kroppsvekt i dyp frontbøy. Du må også være 18 år eller eldre og ha trent frontbøy og knebøy på jevnlig basis i mer enn 3 år. Både jenter og gutter kan delta. Du kan ikke ha skader som kan påvirke knebøyprestasjonen din.

HVA INNEBÆRER PROSJEKTET?

Du trenger kun å møte opp én gang på Norges idrettshøgskole. Data innsamlingen tar ca 2 timer.

Vi vil feste små refleksmarkører med dobbeltsidig teip på bein og overkropp. Vi vil også feste elektroder på enkelte muskler for å registrere hvor aktive de er. Etter oppvarming på ergometersykkel gjennomføres en frontbøy-protokoll hvor hensikten er å finne 1 repetisjon maksimum (1RM) i frontbøy. Når dette er gjort vil du gjennomføre 2 single repetisjoner på 90 % av 1RM.

Etter vanlig frontbøy gjennomføres en ny protokoll for å finne 1RM i en ren konsentrisk frontbøy. Deretter gjennomføres igjen 2 single repetisjoner på 90 % av 1RM.

MULIGE FORDELER OG ULEMPER

Som alltid vil det være en liten risiko for skade ved maksimale løft, men sikkerhet vil ha høy prioritet i laboratoriet. Begge frontbøy-variantene skal gjennomføres i et "power rack" hvor det er sikringer som forhindrer vektstangen i å falle i gulvet hvis du ikke kan fullføre løftet. Du vil til enhver tid kunne trekke deg om du ikke er komfortabel med løftet som skal gjennomføres. Hvis en skade skulle oppstå under testing vil Norges idrettshøgskole være den behandlingsansvarlige institusjonen.

Som deltaker i dette studiet vil du få innsyn i biomekanisk måleutstyr og forskning. Kamerasystemet som benyttes er det samme som benyttes ved animerte bevegelses i Hollywood-filmer. I tillegg vil du få en omfattende analyse av din frontbøy teknikk.

FRIVILLIG DELTAKELSE OG MULIGHET FOR Å TREKKE SITT SAMTYKKE

Det er frivillig å delta i prosjektet. Dersom du ønsker å delta, undertegner du samtykkeerklæringen på siste side. Du kan når som helst og uten å oppgi noen grunn trekke ditt samtykke. Dersom du trekker deg fra prosjektet, kan du kreve å få slettet innsamlede prøver og opplysninger, med mindre opplysningene allerede er inngått i analyser eller brukt i vitenskapelige publikasjoner. Dersom du har spørsmål til prosjektet, kan du kontakte:

Ken Lien (Masterstudent); 97169776/ kenlien@live.no Tron Krosshaug (Prosjektansvarlig); 456 60 046/ tron.krosshaug@nih.no

HVA SKJER MED INFORMASJONEN OM DEG?

Informasjonen som registreres om deg skal kun brukes slik som beskrevet i hensikten med studien. Du har rett til innsyn i hvilke opplysninger som er registrert om deg og rett til å få korrigert eventuelle feil i de opplysningene som er registrert.

Alle opplysningene vil bli behandlet uten navn og fødselsnummer eller andre direkte gjenkjennende opplysninger. En kode knytter deg til dine opplysninger gjennom en navneliste.

Prosjektleder har ansvar for den daglige driften av forskningsprosjektet og at opplysninger om deg blir behandlet på en sikker måte. Informasjon om deg vil bli anonymisert etter prosjektslutt 28.10.2018.

SAMTYKKE TIL DELTAKELSE I PROSJEKTET

JEG ER VILLIG TIL Å DELTA I PROSJEKTET

Sted og dato

Deltakers signatur

Deltakers navn med trykte bokstaver

Jeg bekrefter å ha gitt informasjon om prosjektet

Sted og dato

Signatur

Rolle i prosjektet