BIOMECHANICAL DIFFERENCES IN FLYWHEEL SQUAT VS BARBELL BACK SQUAT

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Master`s Thesis in Biomechanics
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Spring 2022
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TIIVISTELMÄ

Eriksson, T. 2022. Biomekaaniset eroavaisuudet vauhtipyörä kyykyssä vs takakyykyssä. Liikuntatieteellinen tiedekunta, Jyväskylän yliopisto, biomekaniikan pro gradu -tutkielma, 62 s., 7 liitettä.

JOHDANTO. Perinteinen painovoimaan perustuva lihasvoima harjoittelu on ollut olemassa jo vuosikausia. Tangolla tehtävä takakyykky on yksi perinteisimmistä ja tunnetuimmista alaraajoihin kohdistuvista liikkeistä ja se kuvastaa erinomaisesti alaraajojen voimantuottoa. Yksi huono puoli perinteisessä painovoimaa vasten tehtävässä harjoittelussa on se, että vastus pysyy muuttumattomana liikkeen aikana ja toistojen välillä. Hitausmomenttiin (kg m^2) perustuva vauhtipyörä harjoittelu on voimaharjoittelu metodi, jonka vastus mukautuu liikkeen aikana ja toistojen välissä käytetyn lihasvoiman perusteella painovoiman sijaan. Tämän tutkimuksen tarkoitus on verrata yhden toiston maksimi takakyykkyä samaiseen vauhtipyörällä tehtävään kyykkyyn lihasaktiivisuuden, voimantuoton ja kinematiikan perusteella.
MENETELMÄT. 14 atleettista voimaharjoittelutaustaista miestä osallistui tähän tutkimukseen. Tutkittavat suorittivat yhden toiston maksimin takakyykyssä ja vauhtipyöräkyykyssä. Huippu- ja keskiarvovoimat mitattiin voimalevyllä takakyykyssä ja rengasanturilla vauhtipyöräkyykyssä. 2D kinematiikka -analyysit tehtiin suurnopeuskameralla polvi- ja lonkkakulmista ja niiden kulmanopeuksista. Lihasaktiivisuutta mitattiin pinta EMG-elektrodeilla viidestä alaraajan lihaksesta (RF, VM, VL, BF, ja GM). Maksimaalinen isometrinen jalkaprässi suoritetiin myös ennen ja jälkeen mittausten. Kaikki mittaukset suoritettiin yhden istunnon aikana.
TULOKSET. Kyykky liike jaettiin eksentriseen ja konsentriseen vaiheeseen viidellä alakohdalla (Ecc 1 – Ecc 5 ja Con 1 – Con 5). Vauhtipyöräkyykky suorituksia verrattiin maksimi takakyykkyyn sekä toiston keston, että keskivoiman perusteella. Takakyykyssä nähtiin suuremmat keskiarvo- ja huippuvoimat sekä eksentrisessä että konsentrisessa vaiheessa. Tilastollisesti merkittäviä löytöjä esiintyi eksentrisessä työssä, jossa nähtiin 28.3 % vähemmän voimantuottoa vauhtipyöräkyykyssä ($p < 0.001$). Suurempia eksentrisiä voimia nähtiin takakyykyssä kaikissa alakohdissa, mutta kahdessa viimeisessä konsentrisessa vaiheessa nähtiin merkittävästi suurempia voimia vauhtipyöräkyykyssä 19,6 % - 42.7 % ($p < 0.05$–0.001). Polvi ja lonkkakulmissa ei nähty merkittäviä eroja. Kulmanopeuksissa nähtiin merkittävästi hitaampia nopeuksia vauhtipyöräkyykyssä Ecc 5 – Con 1 (11.0 % - 68.5 %) ja Con 5 (33.3 % - 34.1 %). Merkittävästi suurempia nopeuksia nähtiin vauhtipyöräkyykyssä Con 2 – Con 4 (37.3 % - 246.1 %) ($p < 0.05$–0.001). Eksentrisen vaiheen lihasaktiivisuus oli suurempaa vauhtipyöräkyykyssä RF (14.8 % - 101.8 %), VL (4.6 % - 45.6 %), VM (2.5 % - 54.4 %) ja BF (16.2 % - 48.4 %), joista RF osoitti myös suurempaa aktiivisuutta konsentrisessa vaiheessa (21.3 % - 54.8 %) ($p < 0.05$). GM lihaksen aktiivisuus oli merkittävästi pienempää vauhtipyöräkyykyssä sekä eksentrisessä (14.3 % - 40.0 %) että konsentrisessa (11.9 % - 58.6 %) vaiheessa ($p < 0.05$–0.001).
POHDINTA. Vauhtipyöräkyykky tuotti vähemmän voimaa mutta suurempaa lihasaktiivisuutta verrattuna takakyykkyyn. Vastustyyppi (vauhtipyörä vs. painovoima) ei välttämättä ole ainoa tekijä, joka on vaikuttanut tämän tutkimuksen tuloksiin. Kinemaattisesti nämä kyykyt eroavat toisistaan painovoiman painopisteen perusteella sillä takakyykyssä käytetään tankoa ja vauhtipyöräkyykyssä käytetään haarniskaa. Tällaista vertailevaa tutkimusta, myös muilla liikkeillä, tarvitaan lisää, jotta tiedetään kuinka vauhtipyörälaite soveltuu maksimaaliseen voimaharjoitteluun.

Avainsanat: takakyykky, painovoimaan perustuva, vauhtipyöräkyykky, isoinertaalinen, muuttuva vastus, yhden toiston maksimi, voima, kinematiikka, EMG

ABSTRACT

Eriksson, T. 2022. Biomechanical differences in flywheel squat vs barbell back squat. Faculty of Sport and Health Sciences, University of Jyväskylä, Master's thesis, 62 pp., 7 appendices.

INTRODUCTION. Conventional gravity-based strength training methods have been around for centuries. Barbell back squat is considered as the golden standard for lower extremity strength training. A major disadvantage of conventional strength training is that the resistance stays constant throughout the movement and between repetitions. Flywheel training is a strength training method that uses moment of inertia (kg m^2) as resistance instead, which varies the external load accordingly throughout the movement and between repetitions based on applied muscle force. The purpose of this study is to compare 1 repetition maximum barbell BS to 1 RM FW squat in terms of muscle activity, force production and kinematics.
METHODS. 14 athletic men participated in the study with previous strength training background. Subjects performed 1RM barbell BS and 1RM FW squat. Peak and average forces were measured with a force plate in BS and with a pulling force meter in FW squat. 2D kinematic analyses were done with a highspeed camera for knee and hip angles and their angular velocities. Muscle activity was measured with sEMG electrodes from RF, VM, VL, BF, and GM muscles. Pre- and post-isometric leg press MVC measurements were also done. All measurements were done in a single session.
RESULTS. Squat movement was divided into eccentric and concentric parts with 5 subsections each (Ecc 1 – Ecc 5 and Con 1 – Con 5). FW squats were compared to BS in two conditions: squat duration and average force. Greater average and peak forces were seen in BS in eccentric and concentric actions. Significant findings were seen in the eccentric actions with 28.3 % greater force in BS ($p < 0.001$). Greater eccentric forces were seen throughout the eccentric subsections in BS, but significantly greater forces were seen in FW squat in the last two sections of the concentric phase by 19,6 % - 42.7 % ($p < 0.05 – 0.001$). No significant differences were seen in knee and hip angles. Knee and hip angular velocities showed significant differences between the two methods. Concentric sections showed lower velocities in FW from Ecc 5 – Con 1 (11.0 % - 68.5 %) and Con 5 (33.3 % - 34.1 %), but greater velocities in FW from Con 2 – Con 4 (37.3 % - 246.1 %) ($p < 0.05 – 0.001$). Muscle activity was significantly greater in FW squats in RF (14.8 % - 101.8 %), VL (4.6 % - 45.6 %), VM (2.5 % - 54.4 %), and BF (16.2 % - 48.4 %) in eccentric sections, with RF showing also significantly greater activity in concentric sections (21.3 % - 54.8 %) ($p < 0.05$). GM activity was significantly lower in FW in eccentric (14.3 % - 40.0 %) and concentric (11.9 % - 58.6 %) sections ($p < 0.05–0.001$).
DISCUSSION. FW squats showed less force, but greater muscle activity compared to barbell BS. Resistance type (moment of inertia vs. gravity) might not be the only factor that influenced the results. Kinematically the squats differ from each other in terms of center of gravity of the barbell in BS vs. harness used in FW squats. Further comparative research like this and with other exercises is needed to determine how FW devices suit for maximal strength training.

Key words: back squat, gravity-based, flywheel squat, isoinertial, variable resistance, one repetition maximum, force, kinematics, EMG

ABBREVIATIONS

BF	biceps femoris muscle
BS	back squat
BW	bodyweight
CON	concentric
GM	gluteus maximus muscle
ECC	eccentric
FW	flywheel
mV	millivolt
MVC	maximal voluntary contraction
N	Newton
RF	rectus femoris muscle
RMS	root mean square
sEMG	surface electromyography
VL	vastus lateralis muscle
VM	vastus medialis muscle
VRT	variable resistance training
1 RM	one repetition maximum

CONTENTS

1 INTRODUCTION

The squat is one of the most frequently used strength exercises. It can be performed with only bodyweight or with added resistance. Commonly used ways to add resistance to the squat is by using a barbell, dumbbells, or kettlebells. The squat is considered a closed chain exercise where the feet are fixed to the ground and the force is expressed through the end by moving the rest of the body and the added resistance (Clark et al., 2012). It can be done in various ways from unilateral to bilateral and by adjusting the squatting position or limiting the range of motion. Squatting is an effective and safe movement when performed correctly. Everyone from novice exercisers to professional athletes are using the squat to improve their quality of life or enhancing their athletic performance (Schoenfeld, 2010; Myer et al., 2014). The squat movement pattern is similar to many daily activities such as sitting and lifting objects of the ground and it has a lot of benefits due to fact that it recruits multiple muscle groups, and it is a multi-joint movement including the ankle, knee, and hip joints. The main muscle groups used in the squat are the glutes, hip extensors, and quadriceps. Abdominal and lower back muscle strength are also crucial for maintaining an upward position while performing the squat to lower the risk of injury (Raske & Norlin, 2002; Siewe et al., 2014).

The barbell back squat is widely recognized as one of the most effective exercise used by athletes to enhance athletic performance since it strengthens the prime movers that are used in explosive athletic movements like sprinting, jumping, and lifting (Myer et al., 2014; Schoenfeld, 2010). In the barbell back squat the barbell is placed behind the neck across the upper back and resistance is adjusted by adding weight plates on both ends of the barbell. The movement starts with eccentric muscle contractions by lowering the bar by flexing the hip and knee joints. The depth of the squat has an effect on the knee and hip angle as well as ankle dorsiflexion angle. Once the desired squat depth has been achieved to upward motion starts which is also known as the concentric phase. In the concentric phase the hip and knee joints are extending, and the ankle is plantar flexing.

Flywheel exercise devices have been around for about 100 years. A.V.Hill is one of the pioneers of studying muscle contractions and one of the first experiments he did with a flywheel device occurred in 1922 (Hill, 1922). The wheel was named after him as the Hill's wheel and the first known study related to flywheel resistance training was conducted in 1924 by Hansen and Lindhard at the University of Copenhagen and they found that the maximum work done by the elbow flexors and the point it was reached was different in different subjects (Hansen & Lindhard, 1924). National aeronautics and Space Administration (NASA) has been utilizing flywheel devices on their space flights since the 1990's. The benefit of using flywheel devices in space flights is the resistance is created through moment of inertia of the spinning flywheel (Berg & Tesch, 1998). Strength training for astronauts is crucial in microgravity since muscle loss occurs at a higher rate than at sea level and so to be able to adjust back to earth's gravity after returning space flights the astronauts have to do strength training regularly. Flywheel training devices have been adopted into rehabilitation processes and into professional sports in the recent years (Worcester et al., 2022). A lot of the same exercises that can be done with free weights can be done with a flywheel. The main difference in resistance between free weights and flywheel is that in free weights the resistance stays constant throughout the repetition and between repetitions while in flywheel the resistance adjusts with the amount of muscle force that is being applied, so the resistance can change drastically within and between repetitions (Bollinger et al., 2020).

There are a few main differences between the barbell back squat and flywheel squat in terms of where the load of the resistance is applied. In the barbell back squat the lower back undergoes high pressures and there is a risk of lower back injury especially in novice squatters. The flywheel squat can be performed with a harness or with a belt, both of which are safer on the lower back since they alleviate the pressure and distributes it on the shoulders and the hips (Sjöberg et al., 2022). This allows for greater flexion at the hip joint with no risk of injuring the lower back. As the barbell back squat, the flywheel squat is a safe exercise that can be performed by novice and professional athletes. Flywheel squats can even be performed by injured people in rehabilitation purposes. Since the resistance adjusts according to the amount of applied muscle force the patient can perform the desired exercise accordingly without pain. When using free weights, it can be hard to find the right amount of resistance needed to make it effective but so that it does not cause pain.

A limitation of using free weights is that the resistance stays constant throughout the repetition meaning that the greatest amount of resistance that can be used is limited to the weakest point of the repetition. There are a few ways that the resistance can be altered throughout the repetition with traditional strength training equipment. Commonly seen methods to achieve variable resistance throughout the repetition are elastic bands and chains. The benefit of using these are that the resistance either progressively increases or decreases depending on the setup of the elastic bands. Chains can only be used so that the resistance gradually increases throughout the concentric phase. The benefit of variable resistance training (VRT) is that the resistance can be adjusted so that it is greater at the stronger parts of the repetition and less in the weaker parts like the sticking point. VRT improves the rate of force development and the recruitment of motor units and it has been found to be especially effective in improving maximal strength in novice and professional athletes (Heelas et al., 2019; Soria-Gila et al., 2015). In the barbell back squat using free weights the resistance stays constant but using elastic bands can either assist or resist the movement. Placing two elastic bands on the end of the barbell and attaching the other ends to the floor or squatting rack so that the elastic bands are stretched at the start of the movement. A study compared back squats with and without elastic bands and found no significant differences in EMG recordings and bar velocity except for higher velocities post sticking regions, meaning that the subjects were able to maintain a higher velocity throughout their sticking point with the variable resistance (Saeterbakken et al., 2016). Another similar study found that elastic band squats encountered for higher muscle activity, especially at the top end of the squats, which is where the resistance of the band is at its highest. Elastic bands seems to be preferrable compared to free weights alone since it will increase the total load and so have an effect on muscle activity as well (Andersen et al., 2016).

Previous cross sectional studies using flywheel devices have focused on comparing multiple repetitions of either squats or leg press exercises. Variables that have been studied are muscle activity with EMG, force production and kinematics. Longitudinal comparison studies have looked at muscle mass gains, rate of force development, change of direction and other specified skills for athletes in a certain sport. Findings in these studies have been diverging. Major findings can be concluded that the flywheel can have similar benefits than conventional free weight training and in more specific tasks where explosive power and eccentric force is needed it can be superior. Differences in muscle activity goes both ways and only significant differences usually occur in one or two muscles (Alkner & Bring, 2019; Berg & Tesch, 1998; Maroto-Izquierdo et al., 2019; Norrbrand et al., 2011; Puustinen et al., 2021; Spudić et al., 2021; Worcester et al., 2022).

The aim and purpose of this study is to compare 1 RM barbell back squats to 1 RM flywheel squat in terms of muscle activity, force production and knee and hip kinematics. This is something that has not been studied before and the results of this study can benefit especially athletes that use maximal loads in their training program but also other people who are looking for ways to train with maximal loads in a safe manner.

2 BARBELL BACK SQUAT

Conventional gravity-based strength training has been around for decades. It is a widely known and used method to increase muscle mass and strength. Regular and progressive strength training stimulates muscle growth and increases muscle activity by the nervous system, which will increase strength over time (Suchomel et al., 2018). In gravity-based training resistance can be either bodyweight or with added external weights. Dumbbells, barbells, kettlebells, weight plates, and weight stacks on machines are all based on gravity and are seen in some form at every gym. The resistance is the gravity pulling the weight down. The total weight is calculated with Newton's second law of motion. $F = m \times a$, where acceleration is replaced with earth's gravity $g = 9.81\ m/s^2$ (Lucas, 2017). An object that is not moving on earth will cause a force that is equal to the mass of the object (in kg) times the gravity of earth. This will lead to force that is expressed in Newtons (N). Greater force can be produced by increasing the mass or acceleration. (Lucas, 2017).

The barbell BS is one of the widely known and used strength training exercises. It is one of the three exercises competed at powerlifting competitions and the other two are bench press and deadlift. BS is also widely regarded as a supreme test of lower-body strength (Schoenfeld, 2010). The barbell BS is suitable for professional athletes and novice and there are many variations to it, making it suitable for everyone. Most of the activities of daily living are involving the same muscles as used in the BS. Multiple muscle groups are used in the BS movement, and it also requires a great amount of coordination and range of motion in the ankle and hip joints (Fry et al., 2003). When performed properly, injuries during squats are uncommon, but as in any exercise, the risk of injury always increases with heavier external loads and poor technique (Watkins, 2010). Most common squat-related injuries are muscle and ligament sprains, spondylolysis, spondylolisthesis, and ruptured intervertebral discs (Vakos et al., 1994). The BS and variations of it are also commonly used in clinical settings in joint-related injuries for rehabilitation purposes. The goal is to strengthen the lower-body and core muscles and connective tissues after injuries. It is most used in ligament lesions, patellofemoral dysfunctions, total joint replacements, and ankle instabilities. Additionally, it is a superior movement for ACL-injury rehabilitation since it is a closed chain movement, which puts the ACL in less strain than performing knee extension exercises (Dahlkvist et al., 1982; Signorile et al., 1994).

2.1 Movement of the back squat

The barbell BS starts in an upright position where the barbell is placed behind the neck, approximately at shoulder level. The squat can be divided into two parts (eccentric and concentric) based on the type of muscle action that is occurring in the main working muscles. A muscle is contracting eccentrically when the muscle tendon unit is lengthening as the muscle is contracting, which means that the external load exceeds the force that the muscle produces at that moment. When the muscle tendon unit is shortening while contracting it is known as concentric muscle contraction. (Brennan, 2021; Giakoumis, 2020.) The muscle can also contract isometrically, which means that the length of the muscle tendon unit stays constant throughout the muscle contraction (Brennan, 2021). The muscle can produce greater force in eccentric muscle contractions, followed by isometric contractions and least amount of force in the concentric phase. (Brennan, 2021; Giakoumis, 2020.) Figure 1 shows the different muscle contractions and how their maximal force is comparable at different velocities.

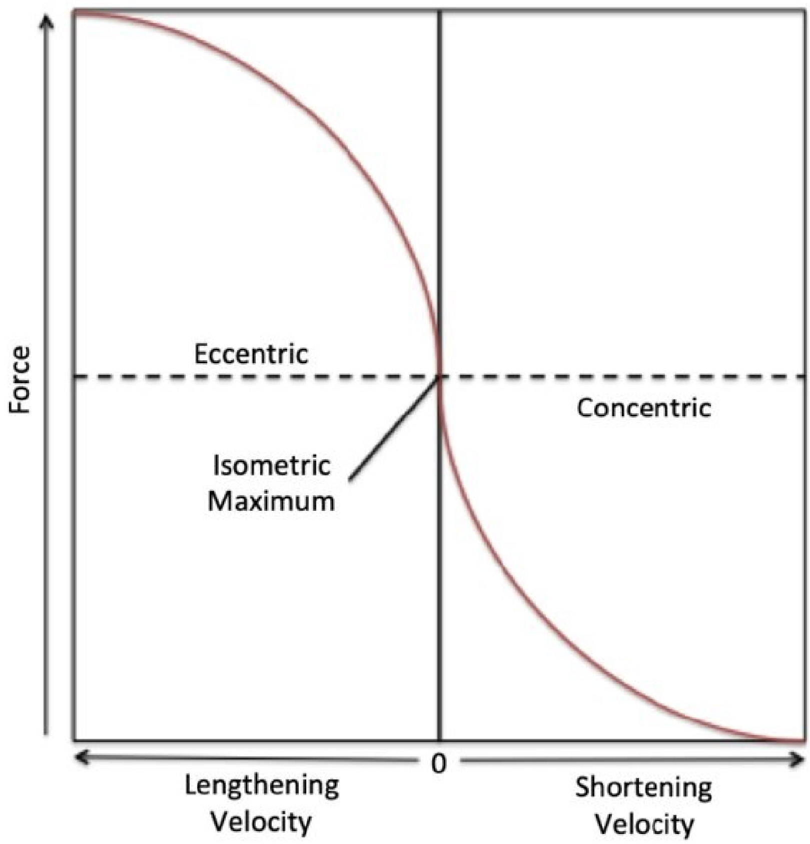

FIGURE 1. The relationship between eccentric, isometric, and concentric muscle contractions in terms of force production at different velocities (Giakoumis, 2020).

The start and end position is when knee, and hip joints are fully extended. The movement starts by flexing at the hip, knee, and ankle joints which starts the eccentric part of the squat. (Myer et al., 2014.) The depth of the squat can be anything from just a slight dip to going all the way down to the bottom where the posterior part of the upper leg is in touch with the calves. In the eccentric part of the squat, the lifter squats down and controls the lowering velocity by eccentric braking force (Brennan, 2021; Myer et al., 2014). When the desired depth is achieved a short isometric period occurs before the lifter start to push concentrically upwards by extending the hip and knee joints and by stabilizing the movement with plantar flexion (Myer et al., 2014). The squat movement recruits most of the lower-body musculature, including quadriceps femoris, hip -extensor, -abductor, -adductor, and triceps surae muscles (Nisell & Ekholm, 1986). Throughout the movement, a lot of strong supporting muscles are needed to avoid injury (Myer et al., 2008). Postural stabilization is attained by isometric contractions from the abdominals, erector spinae, trapezius, rhomboids, and many other muscles at different parts of the squat (Myer et al., 2014). During the squatting performance, there is estimated that over 200 muscles are activated in some point of the squat (Solomonow et al., 1987).

Squatting technique is individual, and it depends on the persons anatomy, flexibility, and coordination. The latter two can be improved on and they usually improve with more experienced squatters. When describing the squatting position to beginners, an individual standing position with the feet flat on the floor approximately shoulder width apart, the knees and hips in a neutral, extended anatomical position, and the spine in an upright position with preservation of its natural curves should be taken. (Escamilla, 2001; Pa et al., 2012; Schoenfeld, 2010). In figure 2 below is a demonstration of the BS position at the end of the eccentric phase.

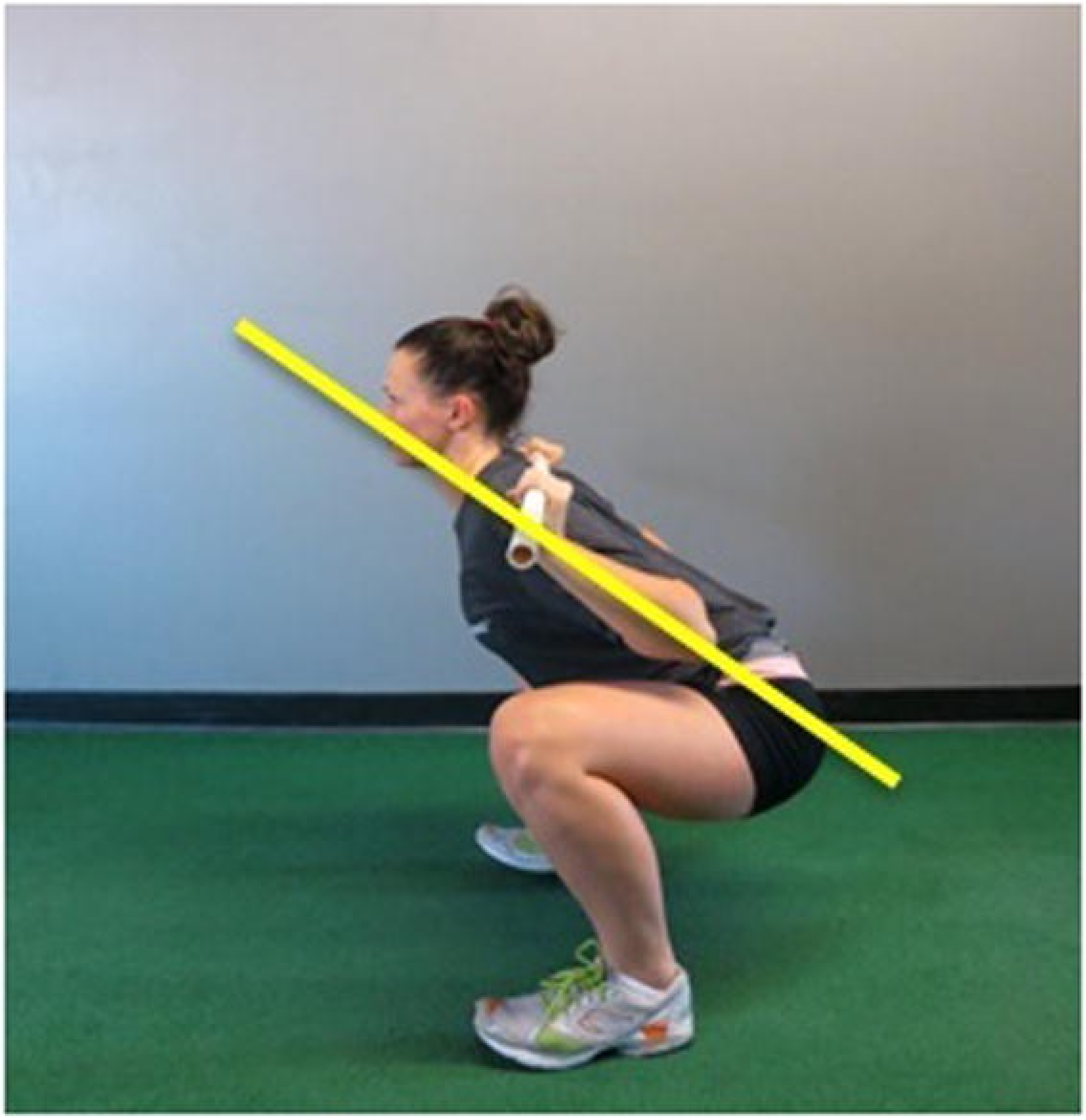

FIGURE 2. Squatting position at the lowest part in a parallel squat. Thighs should line up parallel to the floor. Toes and knees should face forward and back should be kept in a straight line. (Myer et al., 2014.)

Before the start of the eccentric phase, it is recommended to inhale approximately 80 percent of maximal inhalation and hold the breath to increase intra-abdominal pressure which enhances stability of the vertebral column also known as the Valsalva maneuver. By doing this technique it prepares the spine, which is a flexible rod, to bear compressive loads that are created by the load of the barbell (Myer et al., 2014).

2.2 Biomechanical deficits and common mistakes in back squat

The BS movement is considered by many professionals to be a cherished primary physical training exercise since it is a single compound exercise that is highly subtle to highlight biomechanical deficits (Faigenbaum & Myer, 2010; Myer et al., 2008). The deficits that impact performance can be categorized to be either due to inefficient motor unit coordination or recruitment, muscle weakness, strength asymmetry or joint instability, muscle tightness or a combination of these (Schoenfeld, 2010). The BS can be assessed from three different parts: upper body, lower body, and movement mechanics. During the squat, in the upper body, the neck should align perpendicular to the ground and the eyes should look forward and not down into the ground. Chest should be held upward to minimize the pressure in the lower back and the shoulder blades should be retracted for a stabled position. In a parallel squat, the trunk should be parallel to the tibia in the end of the eccentric phase, and the spine should be held as straight as possible and avoid lumbar kyphosis. (Myer et al., 2014.) Figure 3 below demonstrates these key points.

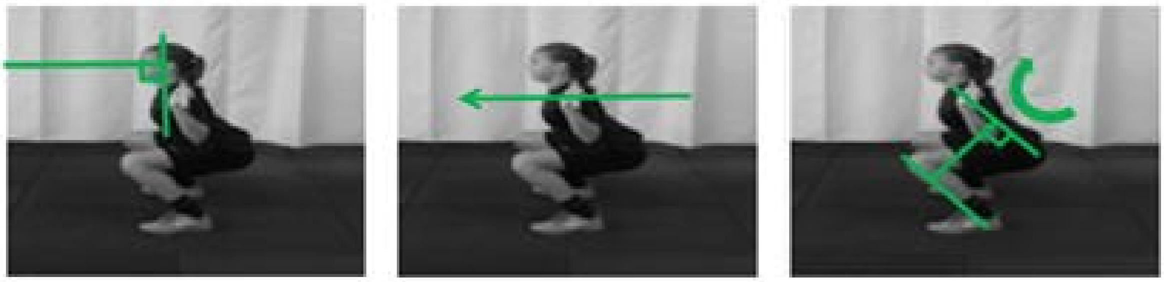

FIGURE 3. Alignment of the head so that the neck is perpendicular to the floor and eyes look straight forward. Chest is held upward, and shoulder blades are retracted. Trunk is parallel to tibia, while maintaining a slight natural curve in the lumbar spine. (Myer et al., 2014.)

In the lower body, the position of the hips should align parallel to the ground in the frontal plane throughout the squat. In the knees, the lateral aspect of the knee should not cross medial malleolus for either leg, this is also known as knock knees. Knees do not excessively pass the front of the foot, however, there are some differences in this, and it depends on ankle dorsiflexion range of motion. Tibias should align parallel to an upright torso and the entire foot should always remain in contact with the ground. (Myer et al., 2014.) Figure 4 below highlights these points.

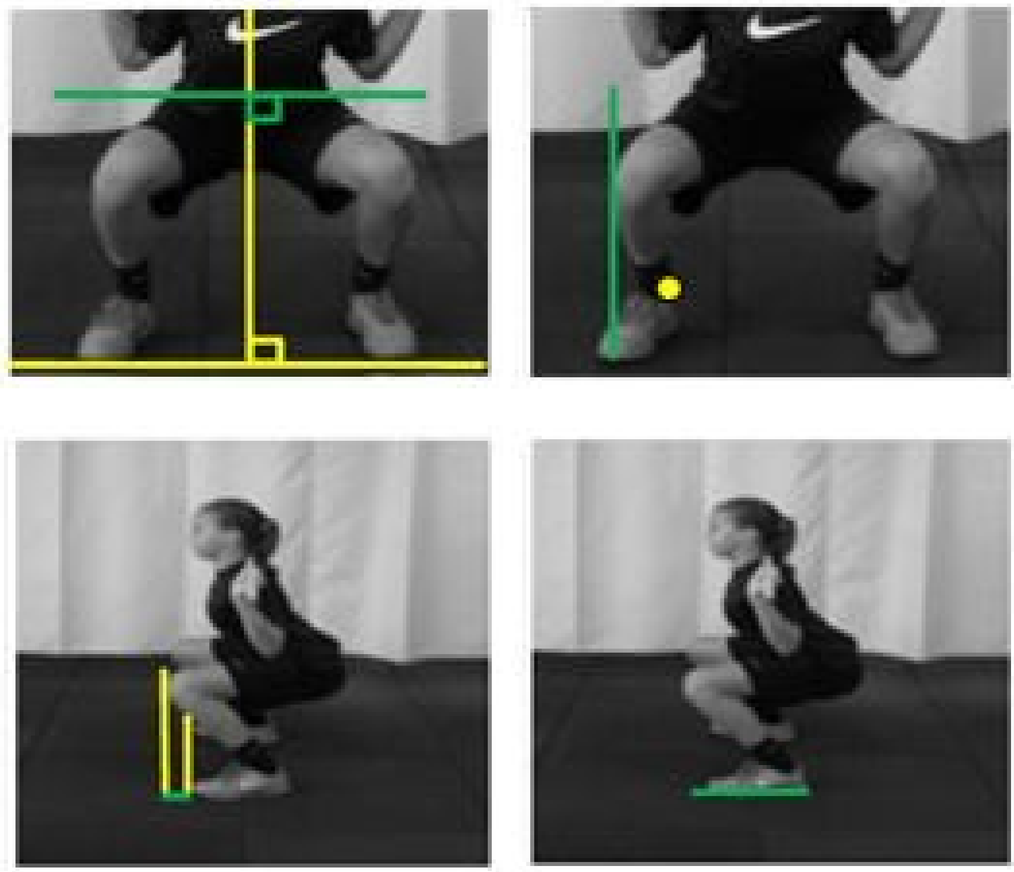

FIGURE 4. Highlighting important aspects in the lower body during BS. Hips should stay aligned and parallel to the floor. Knees should stay in line with the toes and face forward or slightly outwards. Knees should also pass the toe line at the lower parts of the squat. The whole foot should stay on the ground during the whole movement and the weight should be distributed evenly on the entire foot. (Myer et al., 2014.)

The BS movement can be divided into three parts: the descending eccentric part, the ascending concentric part, and the part in between these two which is the isometric part right at the apex of the depth of the squat (Brennan, 2021; Myer et al., 2014). In the descending part a hip-hinge strategy should be used at a controlled, constant speed throughout, and the upper body should remain upright. Depth of the squat should be specified to the needs of the person, but in parallel squat the thighs should align parallel to the floor. In the ascending part, shoulders and hips should rise at the same, constant speed and return to an upright starting position. (Myer et al., 2014.) Figure 5 below demonstrates these three steps of the BS.

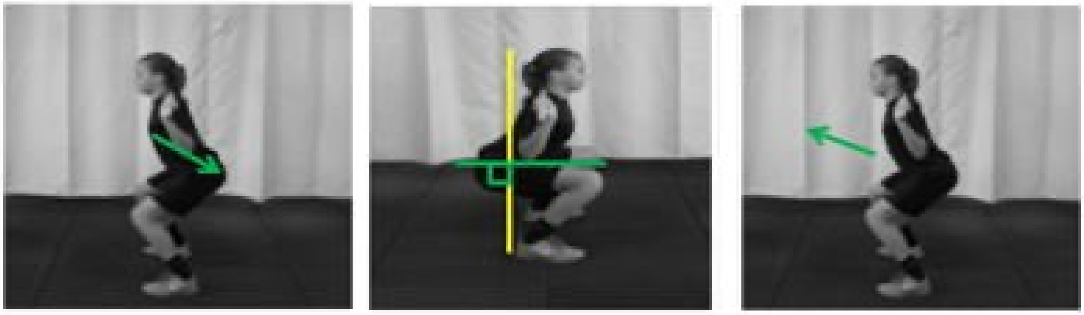

FIGURE 5. In the descending part, the weight should be moved down and slightly backwards. In the parallel BS the line of the thighs should align with the floor. In the ascending part, the hips and shoulders should move upwards at the same pace. (Myer et al., 2014.)

The spine is the most susceptible to injury of the joints during squatting. Since the lumbar spine is better at handling compressive than shear forces, a normal lordotic curve should be sustained in the spinal region, and it should maintain rigid throughout the whole movement (Toutoungi et al., 2000). In the barbell BS the bar is placed so that the spine is constantly under compressive forces from the load of the barbell. Greater barbell loads lead to greater forces. A study found that a half-squat with a barbell load between 0.8 to 1.6 times bodyweight produced compressive forces on the L3-L4 segment of the spine equating to 6 to 10 times bodyweight (Cappozzo et al., 1985). Interestingly another study found that the compressive strength in this region of the spine is 7800 N and this would indicate that many athletes are regularly squatting at or above their threshold for spinal failure (Adams et al., 2000). This is something to take into consideration since spinal injuries usually take a long time to recover from and it can affect the athlete's performance and return to play. However, since failure of the spine does not occur in the vast majority of cases, it can be assumed that a trained athlete's spine adapts to the mechanical stress it undergoes and by so increasing compressive tolerance (Schoenfeld, 2010).

2.3 Muscle activity and force production in back squat

Barbell BS is considered a lower body exercise. Majority of the force produced during the squat is coming from the knee and hip extensors. The ankle complex plays an important role in stabilizing the foot, but it also significantly generates power into the squat performance. However, the role of the ankle complex in power generation is minimal and also less studied than forces in the knee and hip joints (R. F. Escamilla, 2001; Hung & Gross, 1999). The gastrocnemius is the most studied ankle joint muscle during the squat. Its major role is to stabilize the knee and limiting posterior tibial translation. The medial head of the gastrocnemius also plays a major role in preventing valgus knee moments, also known as knock knees (Bell et al., 2008; Nelson, 1976). There appears to be only moderate amount of muscle activity in the gastrocnemius during the squat. The activity progressively increases as the knees flex and decreases with knee extension and this is consisted with the fact that peak forces with the gastrocnemius can be achieved at near maximal dorsiflexion (Donnelly et al., 2006; R. Escamilla, Fleisig, Lowry, et al., 2001). Gastrocnemius and soleus muscle strength is important for stability but so is also ankle flexibility. Squatters with less flexible ankles, especially in the direction of dorsiflexion tend to have worse balance at deeper squats due to heels rising off the ground. A study found that in order to perform a full squat with heels on the ground at all times, dorsiflexion of 38.5° ± 5.9° is needed. (Hemmerich et al., 2006.)

The knee joint consists of the tibiofemoral joint and the patellofemoral joint. They are both supported with a group of ligaments and cartilage which are considered the main stabilizers of the knee in static position. However, in dynamic motion such as BS, the musculature around the knee acts a dominant role in stabilizing the knee. Primary muscles acting around the knee are vastus lateralis, vastus medialis, vastus intermedius, and rectus femoris, all together known as quadriceps femoris. The role of the quadriceps femoris during squat is to eccentrically resist knee flexion and concentrically extend the knee. (Sasaki et al., 2008.)

Biceps femoris, semitendinosus, and semimembranosus make up the hamstring muscles and act as antagonists to the quadriceps muscles. In closed chained exercises like the barbell BS, these two muscle groups act more together and co-contract throughout the movement to exert less force on the ACL ligament (R. F. Escamilla, 2001; Nelson, 1976). Majority of the muscular forces are produced from the quadriceps during squat. Muscle activity in the quadriceps tends to peak at 80° – 90° knee flexion and thereafter maintain relatively constant at lower knee angles. This would suggest that deep squats might not be superior in developing quadricep strength compared to half squats. (R. Escamilla, Fleisig, Lowry, et al., 2001; Walsh et al., 2007.)

When comparing muscle activity between vastus lateralis and medialis, little differences can be seen during the squat movement which suggest that they equally contribute in generating force (Marklof et al., 1990; Sakane et al., 1997). However, when comparing the activity from the vastus muscles to the rectus femoris, studies have shown that the vastus muscles produce 50 % greater muscle force than rectus femoris. The main reason for this drastic difference is that rectus femoris also acts a hip flexor, meaning that during the squat it shortens from the knee end and lengthens at the hip end (R. Escamilla, Fleisig, Lowry, et al., 2001; Watkins, 2010). The hamstring muscles are less active and so play a lesser role in force production during the squat. Studies have found that when comparing muscle activity in hamstring muscles in leg curl and BS, around 50 % less muscle activity is seen in the BS (R. Escamilla, Fleisig, Zheng, et al., 2001; Marklof et al., 1990; Walsh et al., 2007; Wilk et al., 1996). Being bi-articular, hamstring muscles have the same feature as the rectus femoris, meaning that while it shortens from one end it lengthens from the other during squats. Peak muscle activity in the hamstrings has been seen at higher knee angles anywhere from 110° - 170° (R. Escamilla, Fleisig, Zheng, et al., 2001; Senter & Hame, 2006; Walsh et al., 2007). This is since hamstring's role in BS is to extend the hips.

In addition to the hamstring, a main hip muscle involved in the squat is gluteus maximus. The role of gluteus maximus during the squat is to control the eccentric part and overcoming the resistance in the concentric part of the squat. Gluteus maximus plays also a crucial role in stabilizing the pelvis and knees during the squat (Nelson, 1976). Peak hip extension force has been shown to be at 90 ° hip flexion (R. Escamilla, Fleisig, Lowry, et al., 2001). Gluteus maximus muscle activity varies tremendously with different squat depths. A study that compared half squats, parallel squats and full squats reported that average muscle activity was greater the deeper the squat was. Compared to half squats, parallel squats showed an increase of 11.1 % and deep squats an increase of 18.6 % in gluteus maximus muscle activity (Caterisano et al., 2002). Similar trends were also seen in peak values, where also significant differences were seen between these three squat depths.

Muscle activity during squats can be measured with EMG electrodes. In this study, muscle activity was measured from 5 muscles (RF, VL, VM, BF, and GM) with surface electrodes and the signal is demonstrated in figure 6 below. Quadriceps muscles are relatively evenly active in eccentric and concentric parts, but BF and GM show greater activation at the end of the concentric part where the hips start to extend.

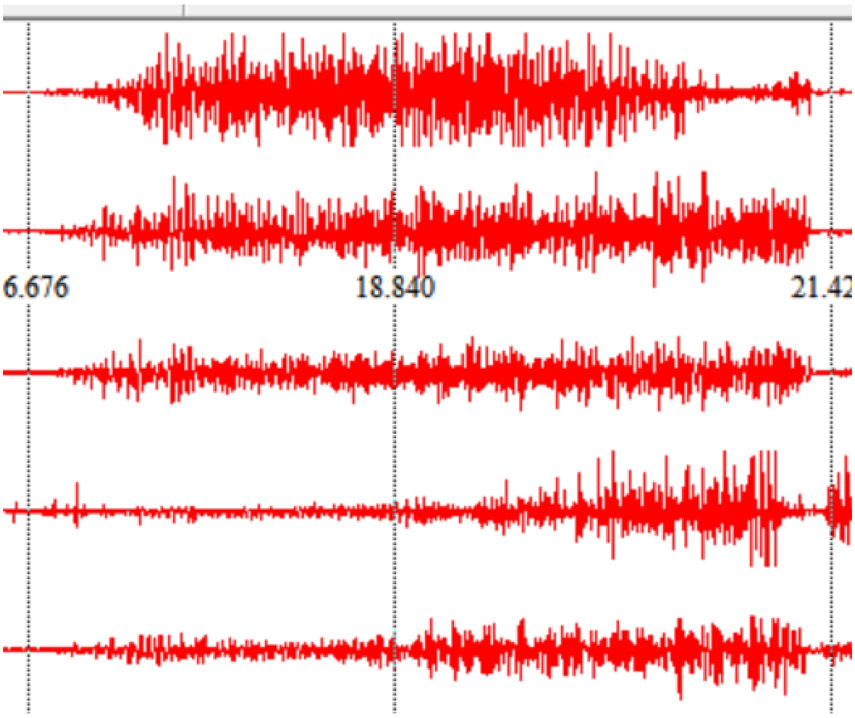

FIGURE 6. Muscle activity (from top to bottom) in RF, VL, VM, BF, and GM muscles during barbell BS in this study. The eccentric part of the squat starts from 16.676 and ends at 18.840. The time from 18.840 to 21.420 is the concentric part of the squat.

3 FLYWHEEL ISOINERTIAL EXERCISE DEVICE

Flywheel devices have been around for decades, but in the last few years their use has exponentially grown especially among athletes. The use of flywheels as resistance dates back to 1796 when a device called Gymnasticon was introduced by Francis Lowndes. Gymnasticon was designed to be used as a full body exercise device (Bakewell, 1997). A.V Hill was one of the pioneers to study the effects of flywheel resistance training in the beginning of the 20^{th} century (Hill, 1920). By the end of the 20^{th} century, first commercially available flywheel exercise devices were introduced. Flywheel exercise devices have been used during spaceflights to prevent astronauts' skeletal muscle loss in space (Berg & Tesch, 1998). Since flywheel exercise devices can fit into smaller space than conventional gravity-based strength training equipment the benefit of using flywheel exercise devices in space is substantial. Another important factor is that the flywheel device is not dependent on gravity unlike conventional gravity-based strength training equipment. Within the last decade, flywheel exercise devices have been used in improving athletic performance, preventing injuries, and rehabilitation purposes. There are strong evidence that flywheel training improves muscle strength, power and hypertrophy in healthy subjects and athletes of different sports (Tesch et al., 2017).

In flywheel training the resistance created through moment of inertia of the flywheel (kg m^2). The flywheel is accelerated and decelerated with muscle force so the harder the athlete is able to push on the concentric phase, the harder the flywheel pulls back in the eccentric phase. The flywheel exercise device is a relatively simple equipment. The device consists of one or more flywheels connected to a rotating shaft. The flywheels start to rotate around its axel by pulling on a rope that is attached to it. In the concentric action, kinetic energy is transferred to the flywheel. When the rope is pulled to its maximum length, the flywheel continues to spin and winds the rope back on the shaft again which then requires eccentric muscle action to try to slow down the flywheel and its kinetic energy. Using larger or additional flywheels creates more inertia, which requires more force to increase the speed of the flywheel (Norrbrand et al., 2008).

The biggest difference between flywheel resistance and gravity-based resistance is that in gravity-based resistance the resistance stays constant throughout the movement, while in flywheel, the resistance alters throughout the movement and between repetitions based on the amount of muscle force used. Figure 7 below demonstrates the difference in resistance training between these two methods.

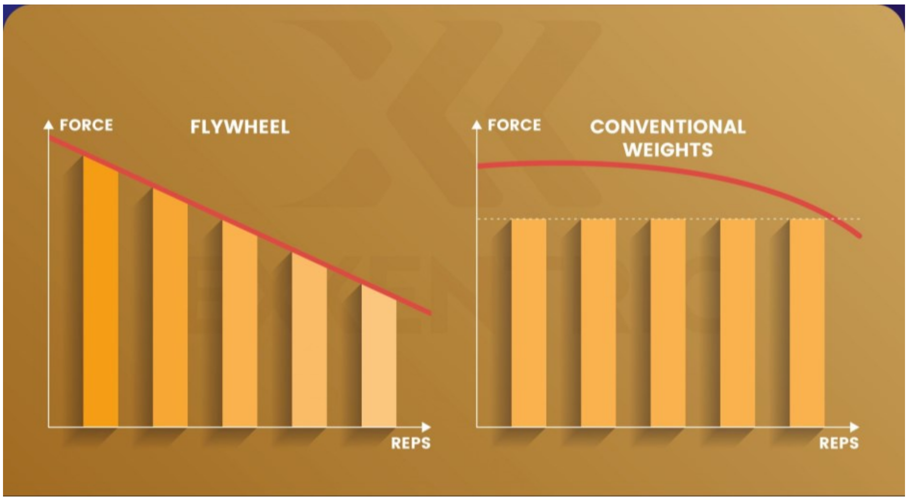

FIGURE 7. The major difference between flywheel and conventional weights throughout multiple repetitions. In this example, throughout five repetitions the resistance is relatively easy in the first few repetitions in with conventional weights and only the last repetition is maximal. Flywheel resistance adapts to the muscle force and each repetition can be performed with maximal resistance for the available muscle force that is left (Exxentric AB, n.d.).

3.1 Flywheel squat

In conventional gravity-based squat, the range of motion has different phases that requires different amount of force. Squatting, as well as any other exercise is limited to the weakest point in the range of motion, also known as the sticking point (Petré et al., 2018). The highest momentum will be achieved at the strongest point of the movement. Flywheel training does not have this limitation since the movement is isoinertial, meaning that the inertia stays constant throughout the range of motion, facilitating a constant resistance and maximal muscle force in every angle (Puustinen et al., 2021). In flywheel training there is no sticking points and maximal force can be produced throughout the entire range of motion which can increase muscle strength more effectively. Another benefit with flywheel training is that it is easy and safe to achieve eccentric overload compared to conventional strength training where it can be dangerous due to high risk of injury. (Petré et al., 2018.)

FW squats can be performed with belts or holding on to a bar but are usually performed with a harness. The benefit of using a harness is that it puts less stress on the lower back than conventional barbell BS. Squatting with a harness distributes the centre of gravity throughout the movement by decreasing the length of the moment arm which leads to less strain on the lower back. Figure 8 below demonstrates a FW squat with a harness. The squat movement can also be easier to execute with a harness than compared to having a barbell behind the neck (Petré et al., 2018).

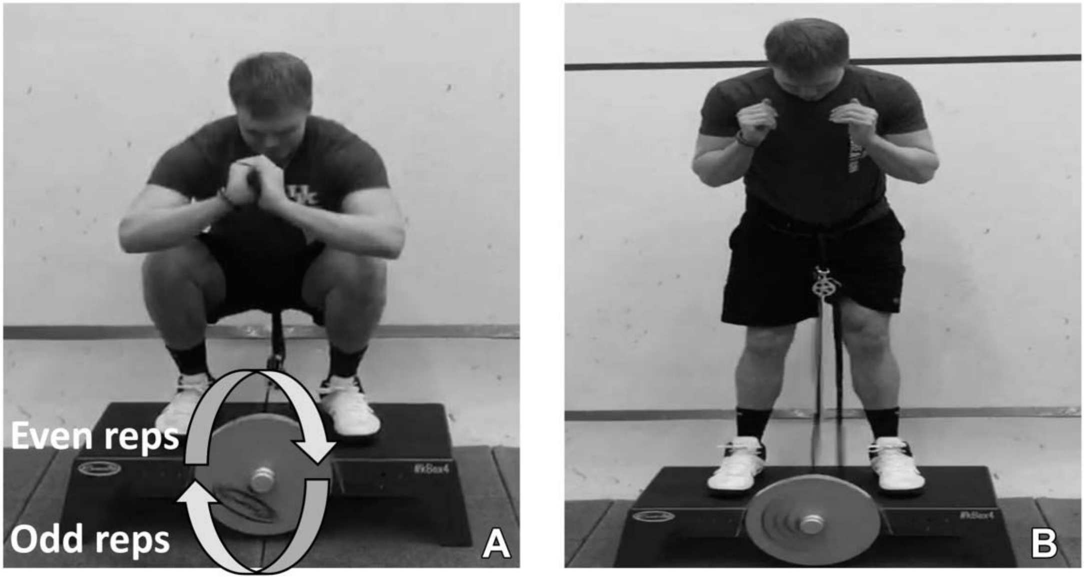

FIGURE 8. FW squats performed with a harness. The direction of rotation of the flywheel changes every time at the bottom of the squat (Worcester et al., 2022).

3.1.1 Lower body kinematics of the FW squat

Same lower body kinematical guidelines apply to the FW squat as barbell BS. The only kinematical difference is that since the loading of the external load is distributed differently the FW squat can be performed with greater hip flexion without the risk of injuring the lower back (Sjöberg et al., 2022). No previous studies have compared kinematics of the FW squat and the barbell BS to each other. Studies have been made by comparing how inertial load affects the kinematics of the FW squat. Increasing the inertial load decreases average power and average vertical velocity whereas average force increased. This did however not have a significant effect on knee and hip angles but did affect joint angular velocities. (Worcester et al., 2022.) In the FW squat, the hands are free to move as well, which can help in maintaining balance with some people at lower knee angles. There is no such freedom in barbell BS since the arms are grabbing the bar.

3.1.2 Muscle activity and force production in FW squat

In previous studies FW squats have been compared to barbell BS, front squats, leg press, and knee extension. The results in regards of muscle activity vary between studies. Quadriceps muscle activity was similar in barbell BS and FW squat, however greater exercise induced T_2 relaxation times were seen in magnetic resonance imaging (MRI) scans after FW squats compared to barbell BS (Norrbrand et al., 2011). They concluded that quadriceps muscle use is comparable with these two squatting methods if not greater with FW squats. Another study compared FW squats to front squats, leg press and knee extensions and found that FW squats were superior in both eccentric and concentric phases in terms of muscle activity in vastus lateralis, vastus medialis, and rectus femoris (Alkner & Bring, 2019). Greater muscle activity can be achieved with FW squats throughout the whole squat movement since the load varies and the muscles are under maximal tension during the whole range of motion. Greater muscle activity was seen at specific knee angles in a study that compared FW unilateral knee extensions to unilateral weight stack knee extensions and concluded that higher muscle activity noted with FW exercise compared to conventional gravity-based could be attributed to its unique iso-inertial loading features. Therefore, the resulting greater mechanical stress can explain greater muscle hypertrophy reported earlier in response to FW training (Norrbrand et al., 2010).

FW squats and FW leg press was compared in a study were ground reaction forces, net joint moments, and muscle activity were measured. They found that forces were significantly greater in squat than in leg press, however depth was 11° greater in leg press. Muscle activity was similar between the two settings and the authors concluded that leg press is superior to squat since there is a greater range of motion and smaller chance for injury (Sjöberg et al., 2021).

3.1.3 Effects of FW training on sport performance

There have not been many studies made with comparisons between free weights and FW exercises and the majority of the FW studies have been longitudinal intervention studies either comparing physical changes in muscle mass or by looking at how it affects sport performance. Sports like ice-hockey, soccer, track and field amongst others rely heavily on explosive power and change of direction. A superior ability of quickly slowing the eccentric motion contributes to an increased amount of elastic energy build up in the tissues and consequently an increased effect of the stretch-shortening cycle can be utilized. This provides to an increase in force in the concentric phase of the motion and leads to greater performance (Hoyo et al., 2015; Komi, 1986). Flywheel training permits for, not only maximal muscle activity in the concentric phase but also for increased resistance for short periods in the eccentric phase compared to the concentric phase, also known as eccentric overload. For example, overload can be generated by assisting the concentric phase with more external force which then transfers into the eccentric phase or by resisting the eccentric force later in the eccentric range of motion. Eccentric overload can be achieved even with conventional load alternatives, like dumbbell and barbell exercises, but the setup can be tricky to achieve and the risk of injury is very high (Norrbrand et al., 2008, 2010).

Eccentric overload training has been found extremely effective in developing muscle hypertrophy and maximal strength (English et al., 2014; Friedmann-Bette et al., 2010; Hedayatpour & Falla, 2015; Roig et al., 2009; Schoenfeld et al., 2017). Training studies have found that eccentric overload training is superior to traditional weight training in developing muscle hypertrophy, maximal strength and power which of the latter two are in key importance in most sports (Maroto-Izquierdo et al., 2017). Eccentric overload training with conventional gravity-based methods have been compared to flywheel isoinertial training. In this study the eccentric overload group showed greater increases in maximal force production. However, no significant differences were found in muscle cross-sectional area in either group (Walker et al., 2016). Eccentric overload training could be superior to conventional strength training at it should be utilized, especially in sports that require strength, power, and speed.

Many studies have found superior results in muscle hypertrophy, maximal strength and power in FW training compared to conventional strength training (Fernandez-Gonzalo et al., 2014; Naczk et al., 2014; Norrbrand et al., 2010, 2011; Seynnes et al., 2007). FW training have also been found to yield superior results compared to conventional training methods in functional tests like vertical jumps, running sprints and change of direction (Cuenca-Fernández et al., 2015; de Hoyo et al., 2015; Hoyo et al., 2015). However, there is no consistency in these studies since all used very different protocols and executions in their training studies regarding the inertial load, measuring tools, exercises used, age and previous training experience of the participants amongst others. Especially in the last few years, FW training has made it into a lot of different sports and is being utilized on daily basis in athletes training and there are a lot of studies that justifies its use (de Hoyo et al., 2015; English et al., 2014; Faigenbaum & Myer, 2010; Friedmann-Bette et al., 2010; Hoyo et al., 2015; Naczk et al., 2014; Puustinen et al., 2021; Roig et al., 2009; Walker et al., 2016). Some smaller teams or individual athletes may not afford to purchase a FW device, although they are relatively inexpensive compared to conventional training equipment. Luckily there are a few other methods to achieve variable resistance training.

3.2 Other methods for variable resistance training

Altering the resistance throughout the movement can be done with resistance bands, chains or by using machines that alters the resistance based on a certain velocity for example. Most commonly used and easily available are elastic bands and metal chains. Both methods work in a similar way. In VRT the resistance varies throughout the range of motion and with elastic bands can either be set so that the resistance increases towards the end of the movement or decreases. Metallic chains can only be utilized in a way that resistance increases towards the end of the movement. When using a barbell for example, the elastic bands or the chains are attached to both ends and the other ends of the elastic bands are attached either below the bar to the ground or above the bar in a squatting rack for example. (Ebben & Jensen, 2002; Fox, 2020; Godwin et al., 2018.) Figure 9 below demonstrates the use of elastic bands on a barbell.

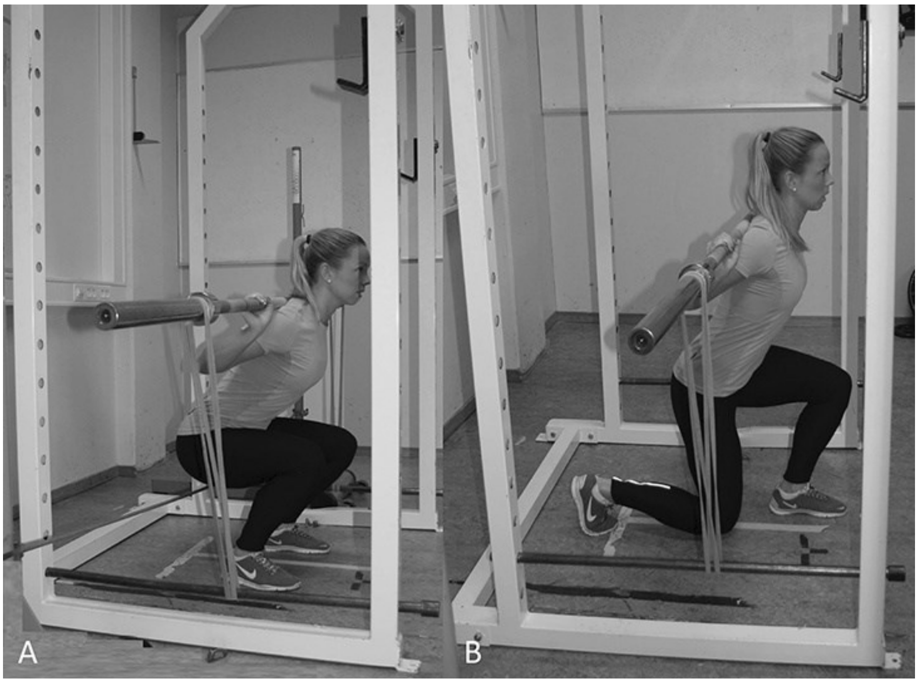

FIGURE 9. Elastic bands used for VRT in BS (A) and split squat (B) movements. Resistance increases towards the end of the concentric phase (Andersen et al., 2015).

Studies have found that variable resistance with elastic bands has no effect on muscle activity compared to free weights in training studies or in cross sectional studies with BS exercises (Andersen et al., 2015; Saeterbakken et al., 2016), however less muscle activity has been seen in elastic band deadlifts compared to free weight deadlifts in some muscles (Heelas et al., 2019). Barbell velocity has been found to vary significantly in BS and deadlifts in a way that velocity is higher at the lowest point with elastic bands but slowly decreases compared to the free weight. This makes sense since the resistance keeps increasing as the movement progresses. Greater improvements in MVC and countermovement jump as well as 6RM squat performance was seen in free weights than with added elastic bands after a 10 week training period (Andersen et al., 2015).

Metal chains are used in a similar way, but the other end is not attached to the floor. The chain lies on the ground or on a box, and the resistance increases the more chain is hanging in the air. (Fox, 2020; Godwin et al., 2018.) Figure 10 demonstrates the setup of barbell BS with metal chains used as variable resistance.


FIGURE 10. Metal chains attached to each end of the barbell. Resistance increases towards the end of the concentric phase (Fox, 2020).

A study that compared conventional barbell BS to barbell BS with metal chains and barbell BS with elastic bands found no differences in muscle activity in eccentric and concentric phases. No differences were also found in ground reaction forces. The authors stated that, based on their results they question the usefulness of performing squats with added chains or elastic bands as variable resistance (Ebben & Jensen, 2002). Similar results were found in a study that compared conventional barbell bench press to barbell bench press with added metal chains. No significant differences were found in force, however peak barbell velocities and peak power were higher in the chained barbell bench press which can be explained with variable resistance throughout the movement (Godwin et al., 2018). Although it seems that there are no superior benefits of doing VRT in muscle activity or force production, it can still be extremely beneficial for athletes to use in daily training to develop power and to challenge the nervous system which can lead to improvements in the long run.

Electric motors can also be utilized to add more resistance in to a specific phase or a specific knee angle in squats. An electric motor can quickly change the velocity of the movement or the resistance. A study compared the effects of eccentric overload training in three conditions: Flywheel (FW) training, electric motor with 1:1 ratio in resistance in eccentric and concentric phases, and electric motor with 1.5:1 ratio in resistance in eccentric and concentric phases which means eccentric overload. The subjects performed unilateral single leg squats in their designated group. (Maroto-Izquierdo et al., 2019.) Figure 11 below demonstrates the training setup.

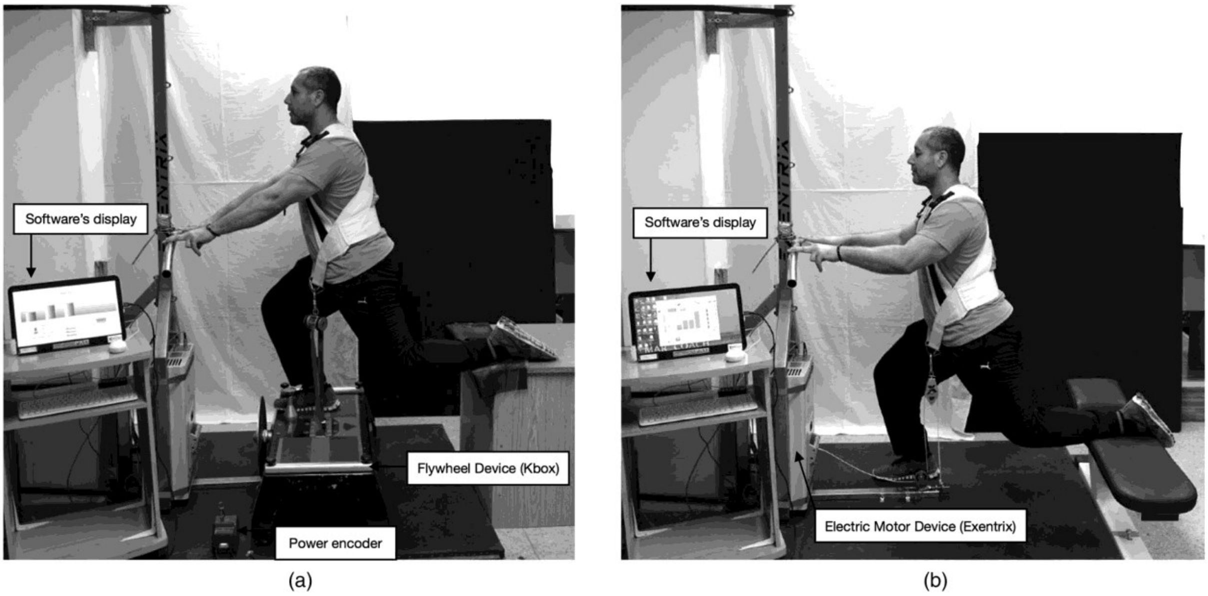

FIGURE 11. Single leg squats performed on a FW device (A) and with an electric motor (B) (Maroto-Izquierdo et al., 2019).

During the 6-weeks training period significant improvements were seen in 1RM, vertical jump performance, muscle power, and muscle cross-sectional area. However, no significant differences were seen between groups, except for significantly greater improvements were seen in the electric motor group with greater eccentric overload in eccentric average peak power. (Maroto-Izquierdo et al., 2019.)

4 AIM AND PURPOSE OF THE STUDY

Previous FW studies have shown varying results. As stated before, no 1 RM studies with FW devices have been done before, so there are no clear comparisons. In previous studies FW squats have been compared to BS, front squat, and leg press with sub-maximal loads and higher repetitions (Maroto-Izquierdo et al., 2019; Sjöberg et al., 2021). Greater muscle activity in FW squats were seen throughout the full repetition but greater differences were seen in the eccentric actions (Alkner & Bring, 2019; Norrbrand et al., 2010). Another study found no difference in muscle activity but stated that FW squats are comparable if not greater compared to BS in terms of muscle activity in the quadriceps (Norrbrand et al., 2011)

Differing from previous studies, this study focused on heavy loads (1RM) and the aim and purpose of the study was to find out how conventional gravity-based strength training (in this case barbell BS) compared to FW squats in terms of muscle activity and concentric and eccentric force production in maximal one repetition performance. This is something that has not been studied before and the results of this study can benefit especially athletes that use maximal loads in their training program.

The main research questions and their subsequent hypothesis for this study are stated below:

Research question: How does FW squat differ from barbell BS in terms of muscle activity, force production, knee and hip angles and angular velocities?

Hypothesis: Greater muscle activity and force production in the eccentric phase should be seen in the FW squat than the barbell BS since the flywheel is actively pulling the subject in the eccentric phase due to moment of inertia in the FW (Petré et al., 2018). Concentric phase should be similar between the two methods in terms of muscle activity and force production since the subject is maximally trying to extend the knees and hips in both scenarios.
Since the FW squat uses a harness, the weight is more evenly distributed and there is no pressure in the lower back like in the barbell BS. This should lead to greater hip flexion at the bottom of the squat. Knee angles should be similar between the squatting methods since the depth of the squat instructed to be thighs parallel to the floor in both settings.

5 METHODS

The purpose of the study was to compare the conventional barbell back squat to the flywheel squat in terms of force production, muscle activity, knee and hip angles and angular velocities in 1RM performances. There are no previous similar studies prior to this that would compare 1RM performances in both settings. The following chapters describes the characteristics in detail about the participants, study design, measurement methods, data analysis, and statistical analysis.

5.1 Participants

14 healthy athletic male subjects (age 25.6 ± 3.3 years, height 187.6 ± 7.3 cm, mass 91.4 ± 8.7 kg, 1RM barbell back squat 135.4 ± 19.9 kg) participated in the study. Most of the participants were athletes or previous athletes. All participants had to have at least two years of experience of heavy strength training, especially in squatting. The subjects did not have any ongoing injuries or neuromuscular disorders that would prevent or hinder them from performing maximal squats. The participants had to be between 18 and 35 years old and the reason for including only male participants was because of surface EMG electrode usage in the gluteus maximus where women tend to have more fat tissue which could interfere with the signal. All the procedures were carried out in agreement with the Helsinki Declaration on research with human subjects and ethical statement was given by the ethics committee of the University of Jyväskylä in the spring of 2021. Recruitment of the subjects was arranged via email to the students and faculty of sports and health science in the early fall of 2021. The aim and purpose of the study was clearly explained to the subjects prior to the study and the participants were participating voluntarily and had the right to stop the measurements at any moment. Due to the ongoing Covid-19 pandemic, all safety measures and recommendations set by the regional state administrative agency (AVI) and the university were followed.

5.2 Study design

The study was conducted as a cross-sectional study, so all the measurements for one subject were collected in the same session. The subjects performed squats in two settings: barbell back squat and flywheel squat with harness. The order of the squats was randomized so that half (n

= 7) of the participants started with the barbell back squat, and the other half (n = 7) started with the flywheel squat.

After the recruiting process, the participants came in to do a familiarization session that lasted for 30 minutes. The majority of the familiarization session was to get the subjects familiarized on how to squat with the flywheel device. Since the participants had previous experience of the barbell back squat, no separate familiarization was needed for that. Only a few had some previous experience of flywheel exercise devices, but every subject got comfortable at doing maximal squats on the flywheel device during the familiarization session. For each participant, there was at least five days between the familiarization session and the actual data collection session. Full protocol of the data collection session was also explained to the participants during the familiarization session.

The data collection session lasted for two hours per participant. The subject was instructed through a standardized warmup that consisted of 5 minutes on a stationary bike at their own desired pace and after that they performed four different warmup exercises on the lower limbs containing bodyweight squats and lunges. In total the warmup took about 15 minutes. After the warmup, EMG electrodes and reflective markers were placed on the subject. The next chapter will go into more detail about the placement of the electrodes and markers and all the other equipment used.

The participants did pre and post isometric MVC leg press tests. The purpose of these tests was to see if the FW squats and BS caused muscle fatigue, which could affect the results in this study. In the pretest the participants performed a total of five trials of which the first two was considered as warmup with 50% and 80% of their maximum. Each participant performed three maximal trials with three minutes of rest between sets. The highest peak force was considered as their maximal. The isometric leg press device was set so that knee angle was at 90 degrees. In the post test there was no warmup trials, so the subjects only performed three maximal trials. One repetition lasted for about 3-5 seconds.

5.2.1 Barbell back squat

The order of the barbell back squat and the flywheel squat were randomized. In the barbell back squat the subject had to give an approximate estimation of their 1RM back squat. The first load was at 40% of their estimated value and they performed five repetitions with that load. After this the subject only had to perform one repetition with each load. The loads progressively increased from 50% to 100% depending on how the subject was feeling. In the lighter loads (< 80% of their estimated maximum) the participant were given about three minutes of rest and once they started to get closer to their maximum, five minutes of rest between sets were given. The participants performed in total between 5 and 8 sets of the barbell back squat depending on how long it took to reach their maximum. The participants were instructed to squat so that their thighs would lie parallel to the floor, and this was supervised from the frontal plane. The squat rack had safety bars placed so that when the participant was not able to lift the weight, they would lower it on the safety bars and a spotter was standing right behind them at all times in the heavier squats.

5.2.2 Flywheel squat

In the flywheel squat, the protocol was the same for each participant. Since the load in the flywheel squat depends on effort and force production the subject is performing, each participant is capable to squat on the device. The difference will be seen in the velocity that they are able to squat at. The subjects squatted on the flywheel device with a total of five different moments of inertia. The total moment of inertia in each trial can be seen in table 1 below.

TABLE 1. Each subject performed the FW squats with the same amount of moment of inertia and a total of five sets as described in the table.

Trial number	Flywheel moment of inertia (kg m^2)
1	0.070
2	0.140
3	0.210
4	0.280
5	0.355

The participants were given 3-5 minutes rest between each trial. Since the flywheel needs to wind up to achieve high forces, one repetition maximum was obtained the following way. The starting position was thighs parallel to the floor. Then the subject was asked to stand up with approximately 80% effort to get momentum into the flywheel. In the following repetition the subjects were asked to push maximally in the concentric direction and to let the flywheel pull them down about a third in the eccentric part before they start to apply breaking force and try to change the direction of the flywheel as quickly and forcefully as possible into the last maximal concentric action. The participants were asked to perform the squats down to thighs parallel to the floor, so same as in the barbell back squat.

A major difference in FW squats and barbell BS is the placement of the external load. In FW squats a harness was used as seen in figure 12 below. The harness puts less stress on the lower back by distributing the force lower on the hips. This takes away the lever arm that puts stress on the lower back in BS. The two metal rings at the end of the harness were attached to the pulling force meter and FW setup as seen in figure 13 below.

FIGURE 12. The harness made by Exxentric was used in this study. Picture retrieved from https://exxentric.com.

FIGURE 13. Flywheel setting. Exxentric kBox 4 Pro and their flywheels were used in this study. Elevated platforms had to be placed on top of the kBox since the pulling force meter would have otherwise gotten tangled with the flywheels. White tape marks are placed on top of the platform at the subjects desired stance width.

The participant had the freedom to choose the footwear for their squats as long as they performed both the barbell back squat and the flywheel squat with the same shoes. Lifting belts were allowed in the barbell back squat. The participants had also freedom to choose the width of the squatting stance, but the once they settled on the stance width, tape markers were placed on the floor so that they would use the same stance width in all trials in both settings.

5.3 Measurement methods

In the barbell back squat setting, Leoko barbell and weight plates (Leoko Oy, Tampere, Finland) were used. For the flywheel squat, Exxentric kBox4 Pro with their flywheels and harnesses (Exxentric AB, Bromma, Sweden) was used in this study. Forces were obtained from a force plate (University of Jyväskylä, Jyväskylä, Finland) in the barbell back squat and with a pulling force meter (University of Jyväskylä, Jyväskylä, Finland) in the flywheel squat. All back squats were performed on the force plate and the pulling force meter was placed between the harness and the cable that is attached to the flywheel. A custom-made force signal amplifier ForAmps was used as well (University of Jyväskylä, Jyväskylä, Finland). Force data was sampled at 1000 Hz. Data of average force and peak force in eccentric and concentric contractions as well as five sub sections in both eccentric and concentric actions was as obtained from the force measurements.

Muscle activity was measured with Ambu BlueSensor N silver – silver chloride bipolar surface EMG electrodes (Ambu A/S Ballerup, Denmark). The skin was prepared by shaving, sand papering and rubbing alcohol. The measured muscles were rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), and gluteus maximus (GM). The electrodes were placed on the muscles according to the SENIAM guidelines (Hermens et al., 2000). Figure 14 below shows the electrode placements for all measured muscles as well as a reference electrode. The sEMG electrodes were attached to a wireless Noraxon TeleMyo 2400R transmitter (Noraxon U.S.A Inc, Arizona, USA). Hardware filters were set as following: No notch 50/60 Hz filters, 1^{St} order high pass filters set to 10 Hz +/- 10 % cutoff and 8^{th} order Butterworth / Bessells low pass anti-alias filters set to 1000 Hz +/- 2 % cutoff. Sample rate was set at 1000 Hz.

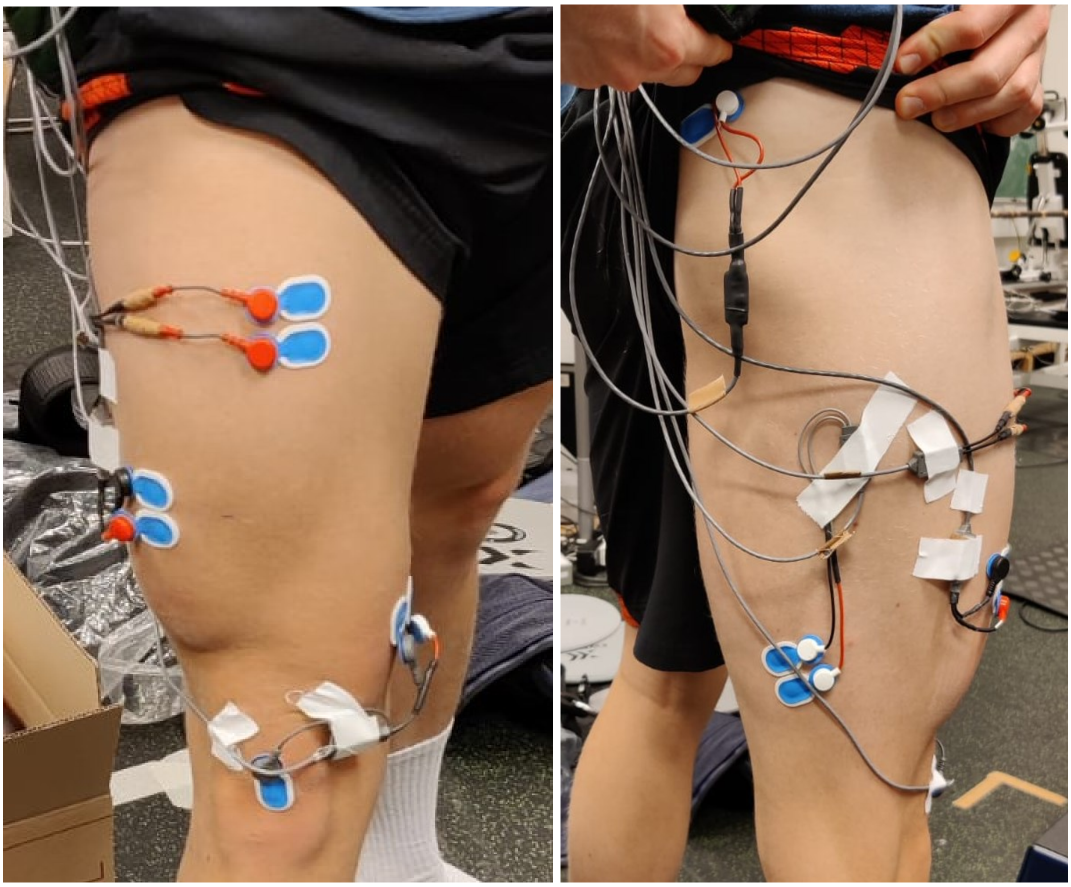

FIGURE 14. sEMG eletrodes placed on a subject's right leg on RF, VL, VM, BF, and GM following Seniam guidelines. A reference electrode was placed on the patella.

All force and sEMG data were collected using Signal software (Signal 4.11, Cambridge Electronic Design, Cambridge, UK). A trigger light connected to the Signal software enabled the data to be synchronized between the kinematics, force, and sEMG.

Each trial was recorded with a Sony RX0 II high speed camera (Sony Group Corporation, Tokyo, Japan) from the sagittal plane at 100 Hz. Reflective markers were placed on the right lower limb at the lateral malleolus, lateral femoral epicondyle, and on the thigh on the line between lateral femoral epicondyle and greater trochanter. In the barbell back squat setting a marker was placed at the end of the barbell and in the flywheel setting on the acromion for hip angle analysis. Knee- and hip angles as well as knee and hip angular velocities were obtained using Kinovea motion analysis software (Kinovea version 0.9.5 for Windows, Kinovea open-source project).

5.4 Data analysis

For each subject a successful 1RM barbell back squat was used as the reference repetition. In that repetition the eccentric and concentric parts were timed using a timer and frame by frame analysis in Kinovea. Then for each participant each flywheel trial was timed in using the same method and the one that was closest to the barbell back squat in terms of full repetition total time, was chosen as their 1RM flywheel squat. For a few participants, a separate comparison was also made by finding full repetition average force to be as close in the flywheel squat as to the barbell back squat. After the timed matches were found the full repetition was further divided into a total of 10 sections (5 eccentric and 5 concentric). This was done by dividing the eccentric and concentric times into five parts. This allows for side-by-side comparison between the barbell back squat and flywheel squat in smaller sections within each participant as seen in figure 15 and figure 16.

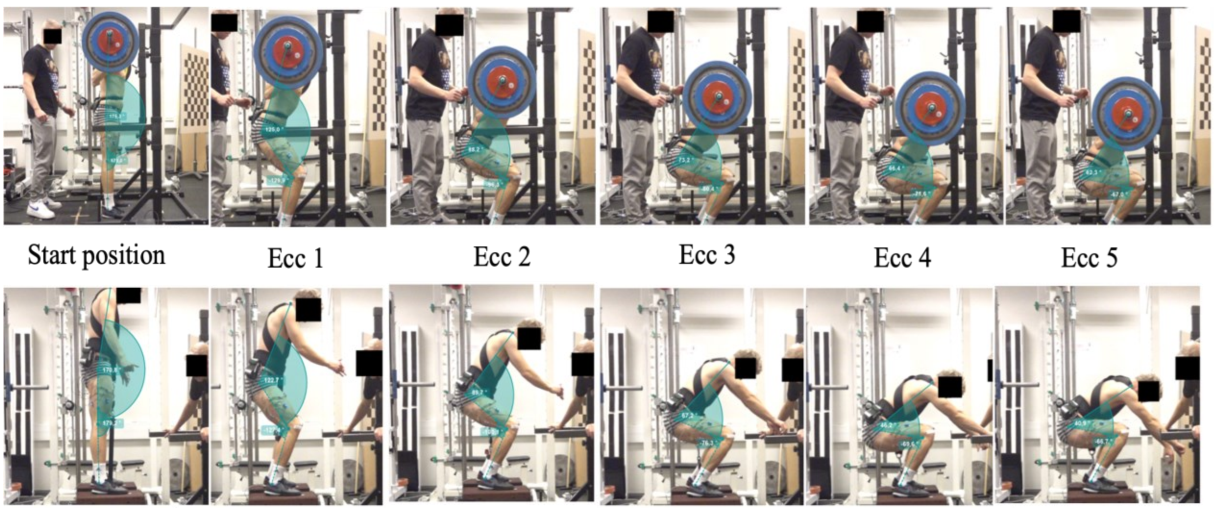

FIGURE 15. Side-by-side comparison of a subject BS and FW squat divided into starting position and 5 eccentric parts. Top pictures are BS and lower are FW.

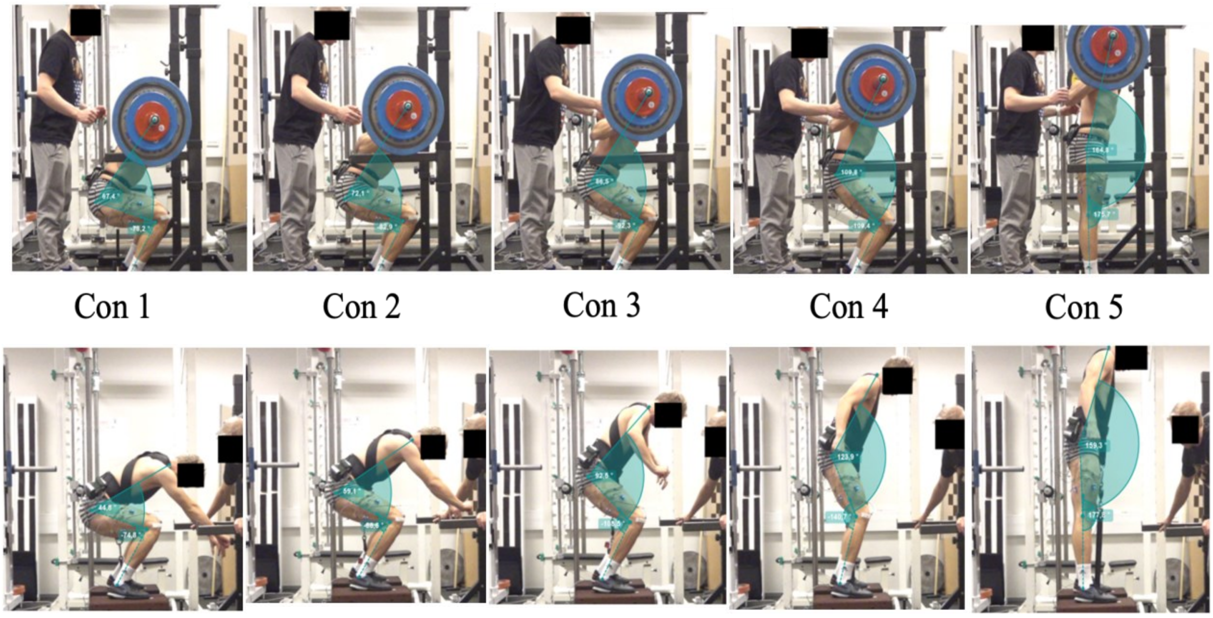

FIGURE 16. Side-by-side comparison of a subject BS and FW squat divided into 5 concentric parts. Top pictures are BS and lower are FW.

In the back squat force signal, the subject's bodyweight was subtracted from the total force to make it comparable to data given by the pulling force meter in the flywheel squat. Average and peak forces were obtained and reported for the full repetition, eccentric part, concentric part, and all 10 sub sections described above. Force values are presented in Newtons. The force signal data and EMG data was gathered and analyzed with Signal software. Figure 17 below shows EMG- and force signals in Signal software in barbell BS and FW squat and the analyzed subsections.

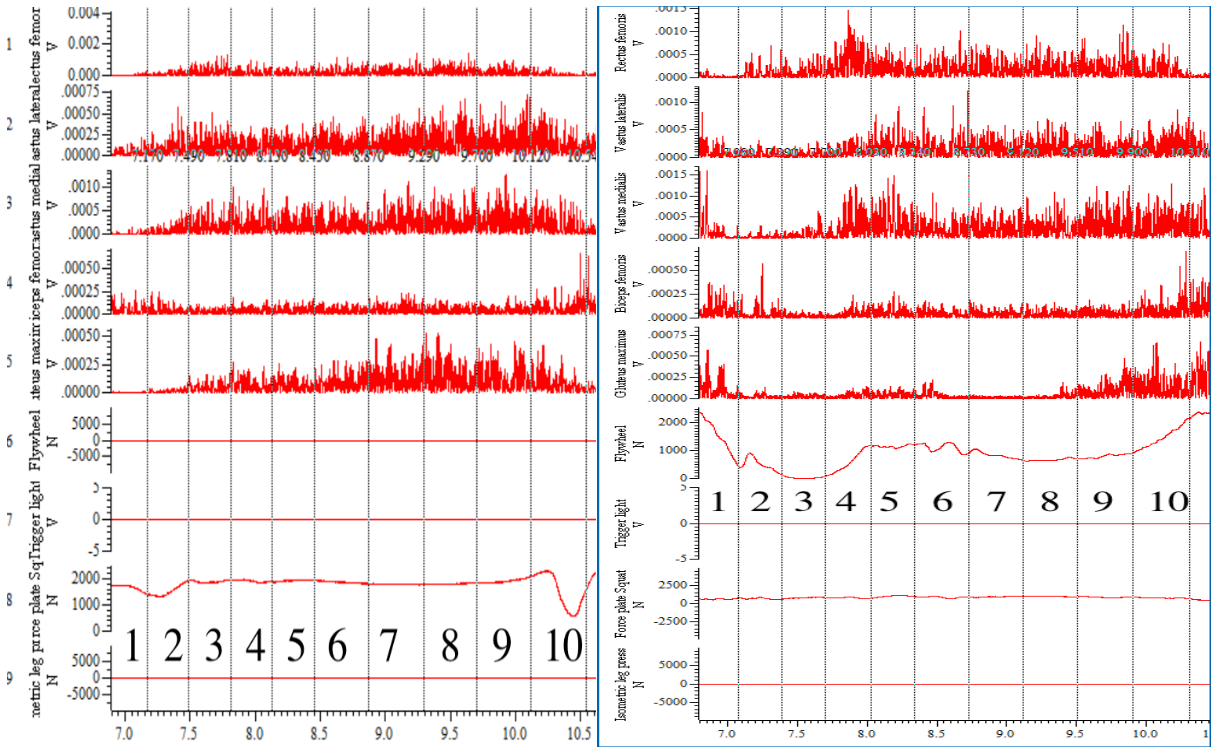

FIGURE 17. Muscle activity in (from top to bottom) RF, VL, VM, BF, and GM. Left picture shows a force signal from the force plate in BS and the right picture shows a force signal from the force pulling meter in FW squat. Under the respective force signals are the subsections for eccentric (1-5) and concentric (6-10) parts of the squats.

EMG data was rectified and reported as RMS amplitude within each sub section. Averages were also calculated for full repetition, eccentric and concentric parts. EMG data is presented in Volts but was later converted to mV during the analysis.

For kinematic analysis, joint angles were analyzed using Kinovea. Since the videos were recorded at 100 frames per second, each frame represents 1/100 of a second. At the start of each sub section, knee- and hip angles were obtained. Knee and hip angular velocities were calculated by dividing the change in the angle between two sub sections with the change in time. Angular velocity is reported as degrees / seconds, where negative values represent eccentric actions.

In pre- and post-isometric leg press, force signal data and EMG data was gathered and analyzed with Signal software. Attempt with the highest peak force was taken for each subject in both pre and post tests and compared with each other.

5.5 Statistical analysis

All imported data from Signal and Kinovea was processed in Microsoft Excel spreadsheet version 16.58 for Mac OS. The data was later analyzed with SPSS statistical analysis software (IBM SPSS Statistics, version 26 for Mac OS). The results are reported as mean and standard deviation. Graphs are presented with mean values and with error bars of 95% confidence interval. The data was analyzed for normal distribution which led to using paired samples T-test in all variables and all settings for statistical significance. Percent differences were calculated as $\frac{(\mathrm{FW}-\mathrm{BS})}{|\mathrm{BS}|} \times 100$, where BS is the variable value for back squat and FW is the value for flywheel respectively. The significance level was set to $P \leq 0.05$ in all conditions.

6 RESULTS

For each subject a performance time of individual flywheel squat that was as close as possible to their 1RM barbell back squat was selected for the analysis. For most of the subjects (n = 9) the same performance in FW squat repetition was also the one where they produced the most amount of average and peak force. Another comparison was also made where the average force in a FW squat repetition was closest to the 1RM BS.

6.1 Peak and average force

Table 2 below shows average and peak forces at different time points in the BS and FW squat in the squats where the duration of the squat performance was similar. Average repetition time in BS was 4.15 s ± 1.10 s and 3.84 s ± 0.55 s in FW squats. The eccentric parts were much closer to each other (1.90 s ± 0.51 s BS and 1.95 s ± 0.37 s FW) than the concentric parts (2.25 s ± 0.70 s BS and 1.89 s ± 0.29 s FW). Figures 18 and 19 below demonstrates the results in terms of average and peak forces in duration matched squats in BS and FW settings.

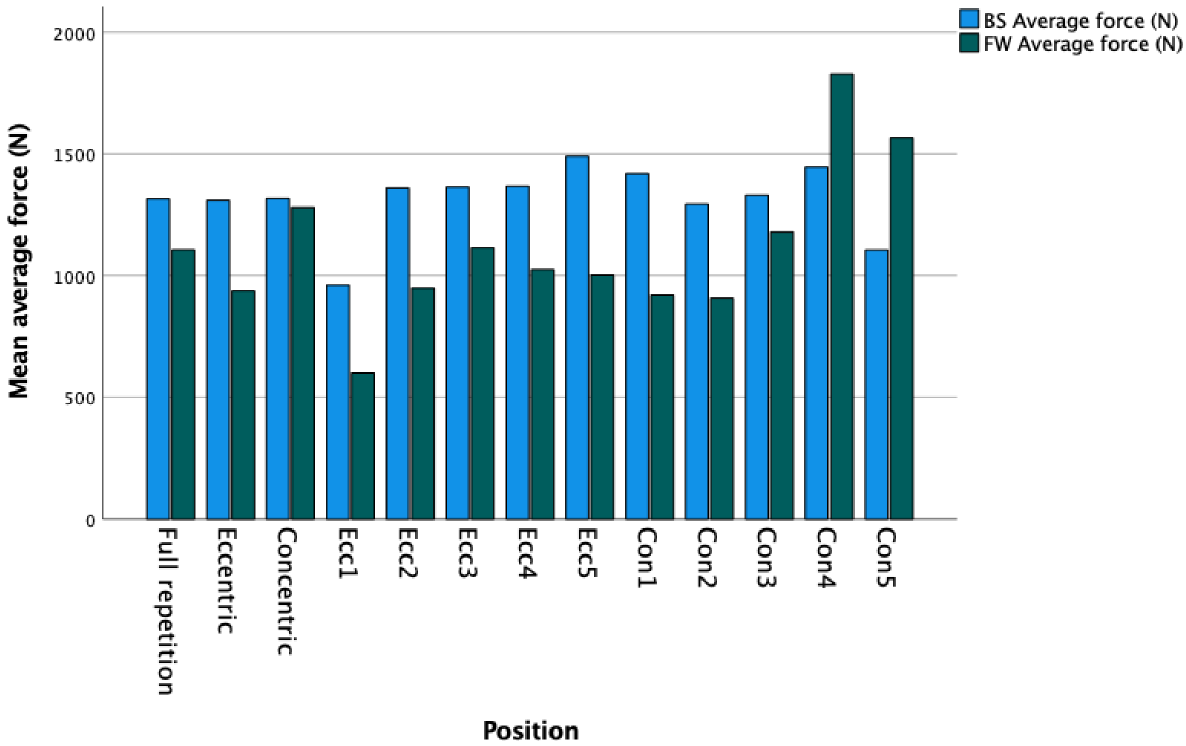

FIGURE 18. Mean average force in duration matched squats in BS and FW performances.

In terms of average force, significant differences were seen in full repetition and eccentric part with 16.4 % ($p < 0.05$) and 28.3 % ($p < 0.001$) lower values respectively in FW compared to BS. In peak force values significant differences were only seen in the eccentric part where FW showed 19.6 % lower peak forces ($p < 0.05$). Dividing the eccentric and concentric phases down to smaller sections, significant differences are more noticeable. FW showed lower average forces throughout the whole eccentric part and the first three sections of the concentric part with greatest differences seen at the bottom of the squat (Ecc 5 32.8 %, $p < 0.001$ and Con 1 35.2 %, $p < 0.001$). At the end of the of the concentric phase, FW produced significantly higher values in Con 4 by 24.8 % and Con 5 by 34.4 % ($p < 0.05$).

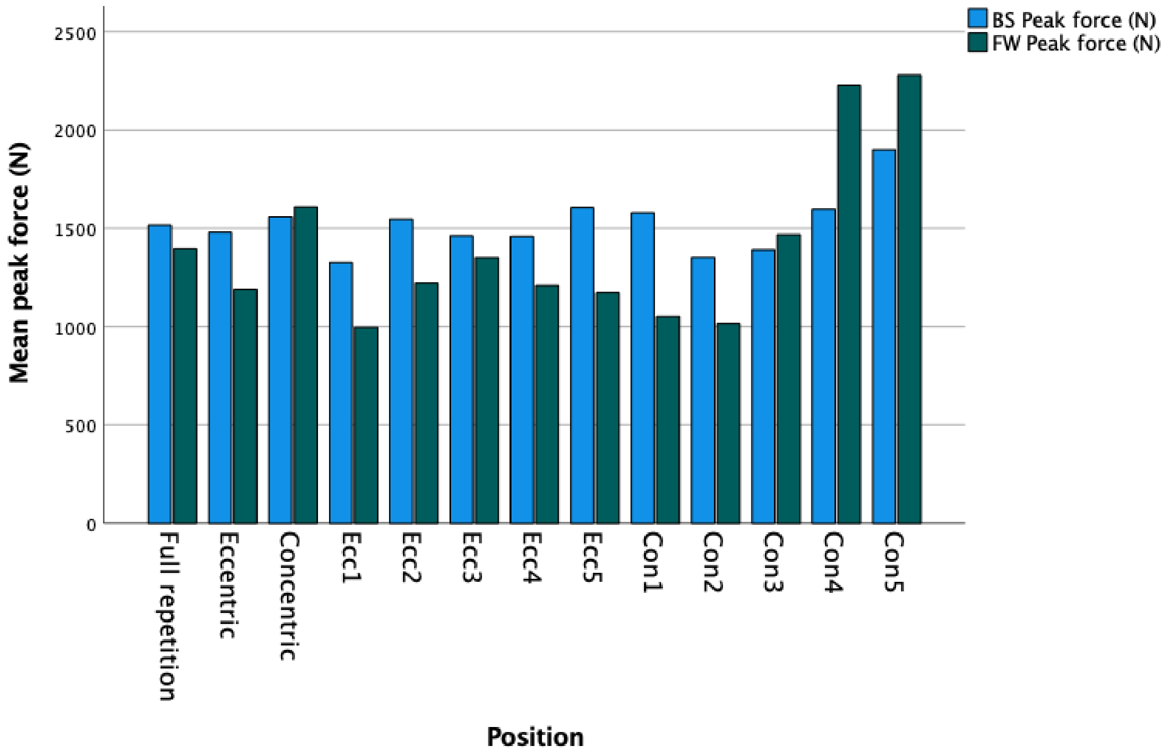

FIGURE 19. Mean average force in duration matched squats in BS and FW performances.

Similar results can be seen in peak force values as well. Greatest differences can be seen in Ecc 5 and Con 1, where FW showed 26.9 % ($p < 0.05$) and 33.4 % ($p < 0.001$) lower forces respectively. Greater peak forces in FW could be seen in the last three parts of the concentric phase with the last two being significant (Con 4 37.2 %, $p < 0.001$, Con 5 19.6 %, $p < 0.05$). All data for time, average and peak force at the different parts of the barbell BS and FW squat in duration matched performances are presented in table Appendix 1.

The same 1 RM BS was also compared with a FW squat performance that produced greater average forces. Most of the subjects were able to produce greatest average forces in the duration matched performances but with certain subjects this was not the case.

Even with highest peak force values in FW squats, average force was lower during full repetition and eccentric phase by 13.4 % ($p < 0.05$) and 25.0 % ($p < 0.001$) respectively. In peak force values, FW showed significantly lower forces in the eccentric phase by 18.3 % ($p < 0.05$). Similar findings are seen in eccentric and concentric subsections, with greater average and peak forces in sections from Ecc 1 to Con 2. Again, significantly greater average and peak forces can be seen in FW squat in the last two sections of the squat (Con 4 average 26.3 %, $p < 0.05$ and peak 40.2 %, $p < 0.001$) (Con 5 average 42.7 % and peak 20.5 %, $p < 0.05$). All data with comparisons of FW squats to the 1RM BS where the average force of the FW squat was closest to the 1RM BS can be seen in table Appendix 2.

6.2 Muscle activity

Muscle activity was measured in five muscles with sEMGs. In general, greater muscle activity was seen in the eccentric phases of FW squats especially in the quadriceps muscles. More muscle activity in the GM occurred in BS. A more detailed comparison will be shown later. The first graph below (figure 20) shows mean muscle activity in the three measured quadriceps muscles in the eccentric and concentric phases as well as full performance. Figure 21 shows the same thing for the hamstring muscle biceps femoris and hip muscle gluteus maximus. Figures 22, 23, 24, 25 & 26 demonstrates the differences in muscle activity in each of the muscles in the 10 subsections of the squat.

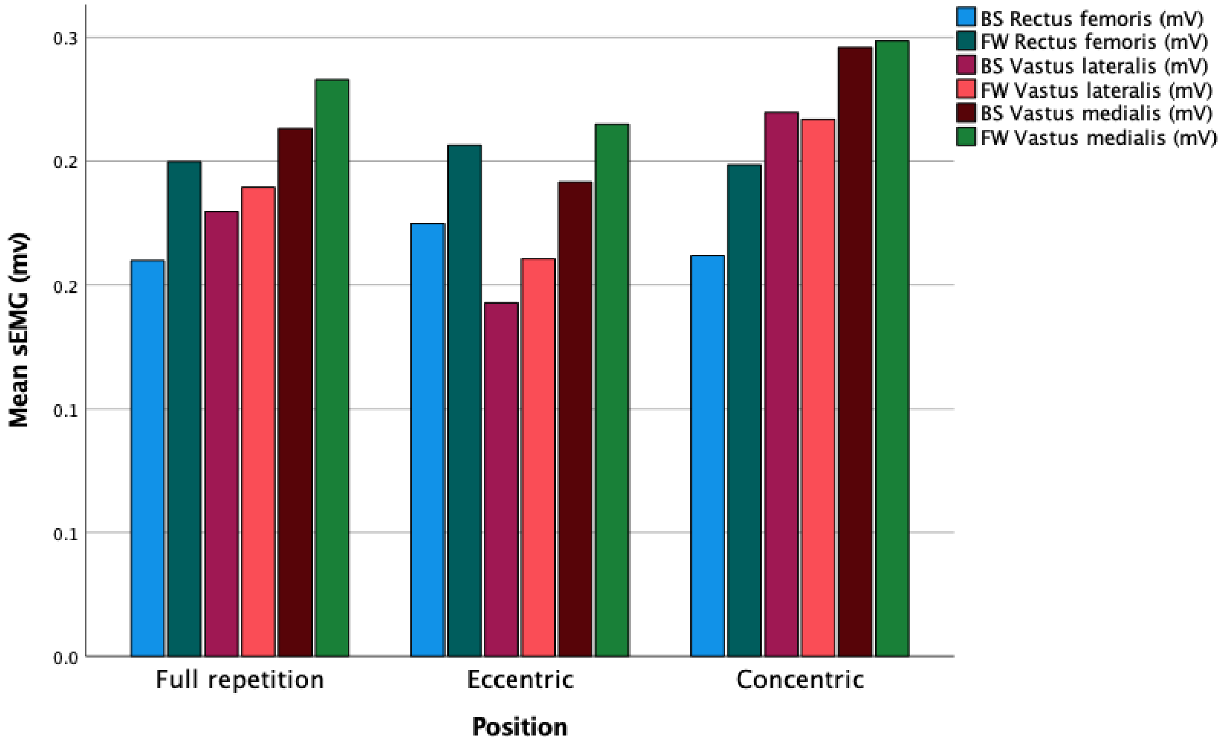

FIGURE 20. RMS amplitude values in RF, VL, and VM muscles in BS and FW squat at different phases of the squat.

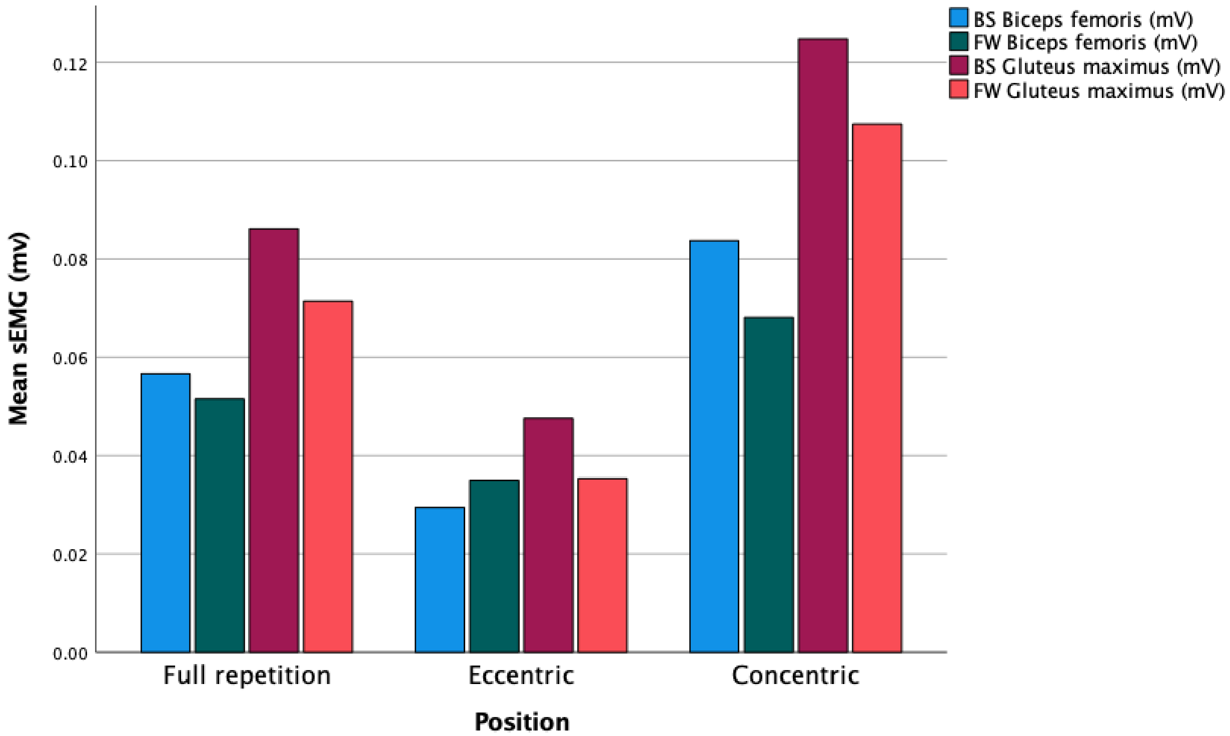

FIGURE 21. RMS amplitude values in BF and GM muscles in BS and FW squat at different phases of the squat.

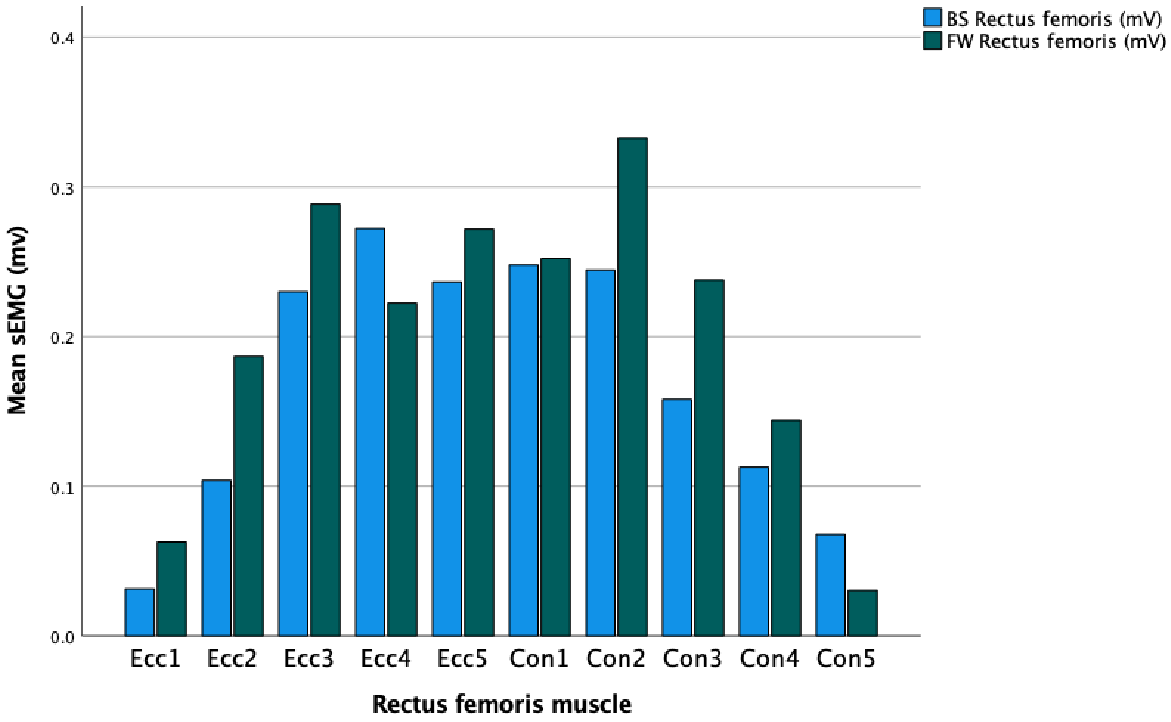

FIGURE 22. Mean RMS amplitude values in RF muscle at different sections of the squat.

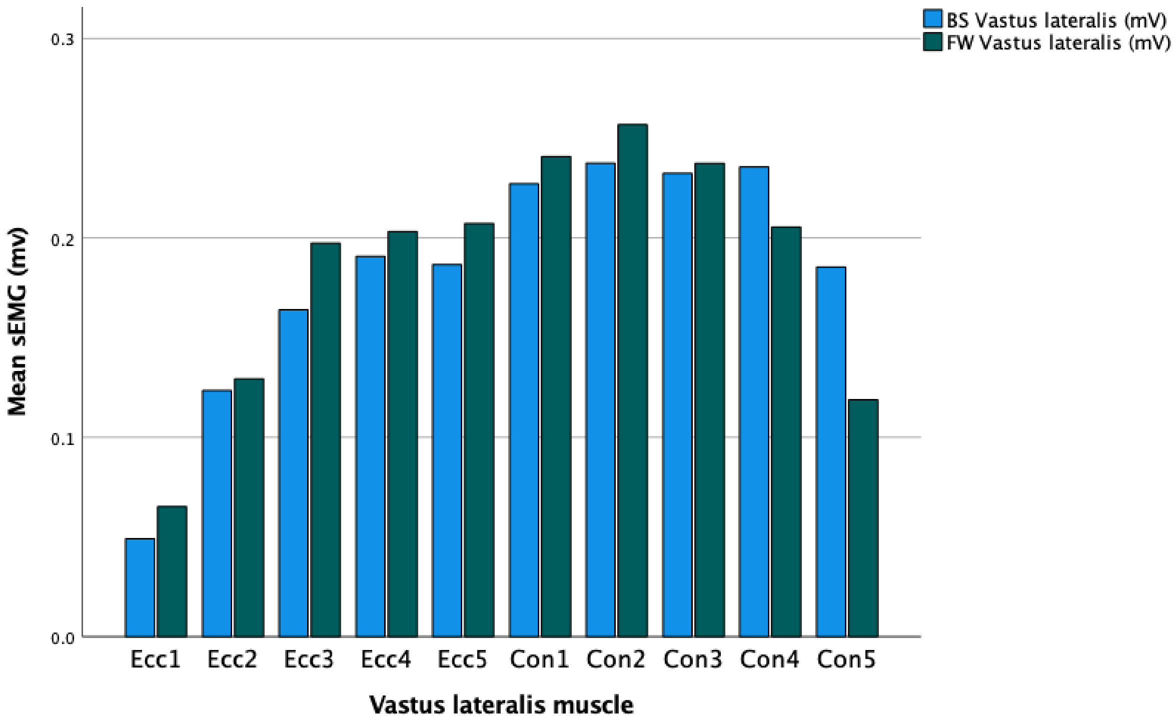

FIGURE 23. Mean RMS amplitude values in VL muscle at different sections of the squat.

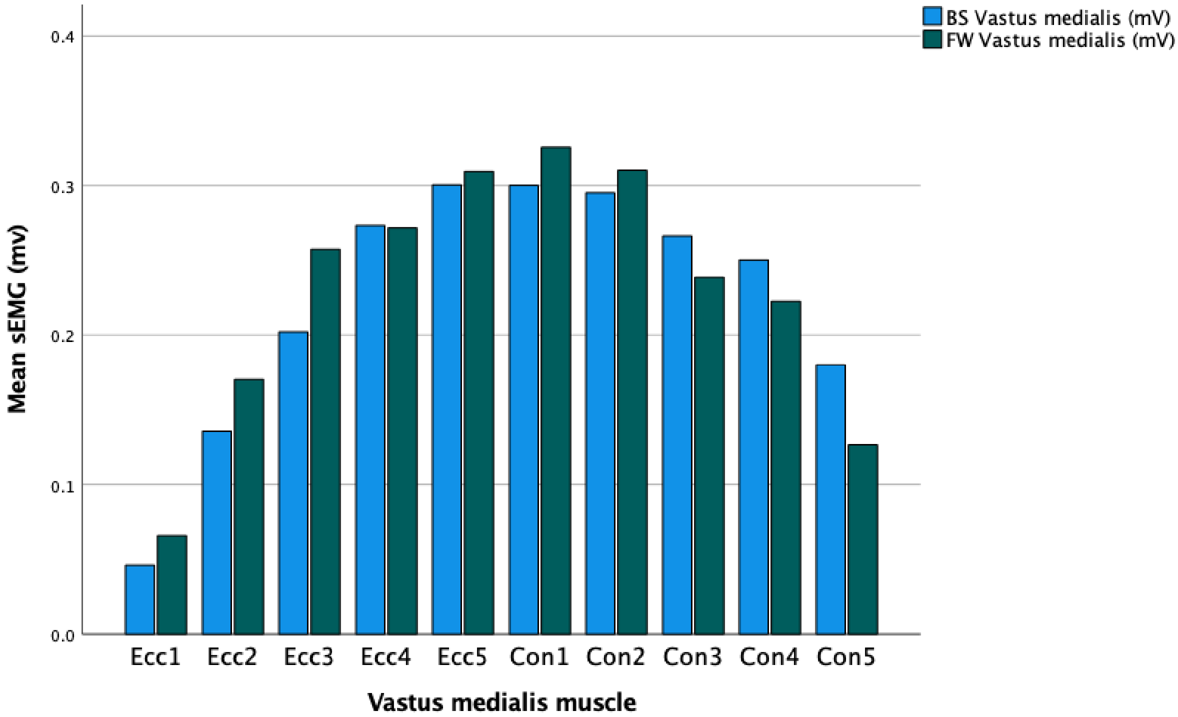

FIGURE 24. Mean RMS amplitude values in VM muscle at different sections of the squat.

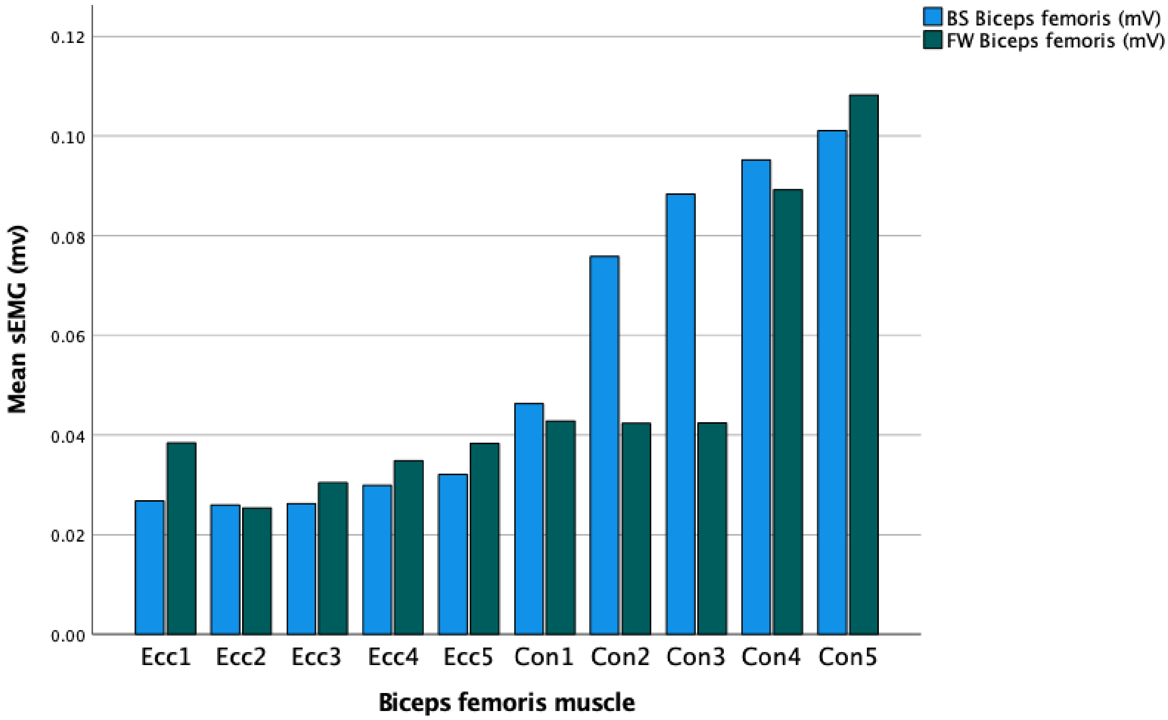

FIGURE 25. Mean RMS amplitude values in BF muscle at different sections of the squat.

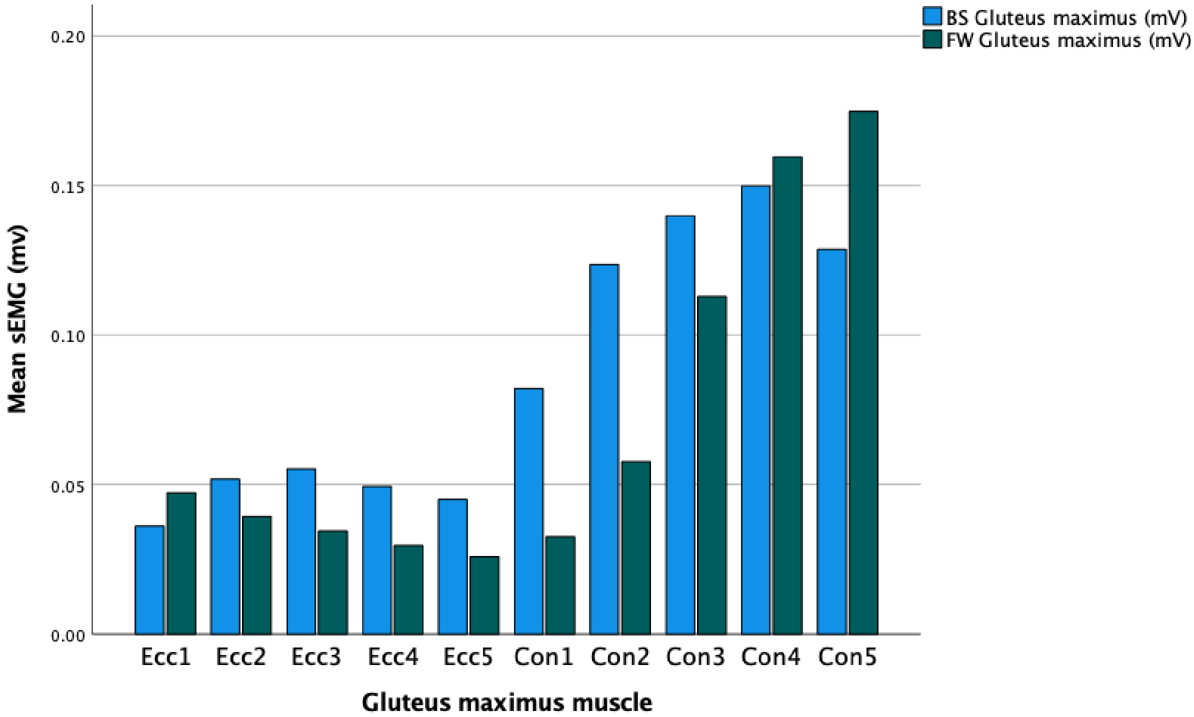

FIGURE 26. Mean RMS amplitude values in GM muscle at different sections of the squat.

During the full repetition, significantly greater muscle activity was seen in force matched squats in FW in RF by 37.9 % ($p < 0.05$), and in duration matched squats FW showed significantly lower activity in GM by 14.1 % ($p < 0.05$). In the eccentric phase, higher muscle activity was seen in FW squats in force matched squats in VL by 17.8 % and in BF by 19.0 % ($p < 0.05$). In BF higher activity was also seen in time matched squat in FW by almost the same amount (18.8 %, $p < 0.05$). GM showed lower activity in the eccentric phase in FW in both duration matched (23.1 %, $p < 0.001$), and force matched (18.0 %, $p < 0.05$) squats. During the concentric phase, significant differences could only be seen in force matched squats in VL that showed 6.6 % less activity in FW ($p < 0.05$).

Again, looking at the subsections, more noticeable differences can be seen. In RF, significant difference was found in time matched squats in Con 2 by 32.3 % greater activity in FW ($p < 0.05$), however less activity can be seen in FW in time and force matched squats in Con 5 (55,0 % and 50,0 %) respectively ($p < 0.05$). In VL, in Ecc 1 and Ecc 3 showed greater activity levels in force matched squats in FW (45.6 % and 26.1 %) respectively ($p < 0.05$). In the last two sections VL muscle activity was lesser in FW in both duration and force matched squats (Con 4 12.8 % and 13.2 %, $p < 0.05$ and Con 5 35.9 % and 36.4 %, $p < 0.001$). VM showed greater activity in FW in Ecc 1 (42.7 % and 54.4 %) and in force matched Ecc 5 (13.1 %), however lower values were again seen in Con 5 (29.6 % - 32.0 %) ($p < 0.05$). BF showed greater activity in force matched Ecc 1 (48.4 %) and duration matched Ecc 5 (19.4 %) in FW ($p < 0.05$). In Con 2 and Con 3 lower activity levels were seen in FW in both conditions (Con 2 44.1 % and 46.4 %, $p < 0.001$, and Con 3 51.9 %, $p < 0.001$ and 45.7 %, $p < 0.05$). Greatest amount of significant difference occurred in GM with higher muscle activity in BS. Significantly lower activity levels were seen in FW in time matched Ecc 2 (21.5 %), Ecc 3 (35.7 % and 28.1 %), Ecc 4 (37.4 % and 35.7 %, $p < 0.001$), Ecc 5 (39.9 % and 40.0 %), Con 1 (58.6 % - 56.9 %), Con 2 (51.3 % and 48.0 %), and force matched Con 3 (11.9 %) ($p < 0.05$). Con 4 showed greater activity in FW in force matched by 15.8 % ($p < 0.05$). All percent differences in muscle activity between BS and FW squat at different phases of the squat in both duration and force matched performances can be seen in table Appendix 3.

6.3 Kinematics

Knee and hip angles were similar and followed a similar pattern between BS and FW squat. Squat depth was instructed to be so that thighs are parallel to the floor. On average in BS knee angles went down to 76.2 ° ± 10.3 ° and in FW squat 72.2 ° ± 12.6 °. Lowest hip angle values were 66.7 ° ± 12.3 ° in BS and 46.9 ° ± 13.1 ° in FW squat. Knee and hip angles are demonstrated in figure 27 and figure 28 below.

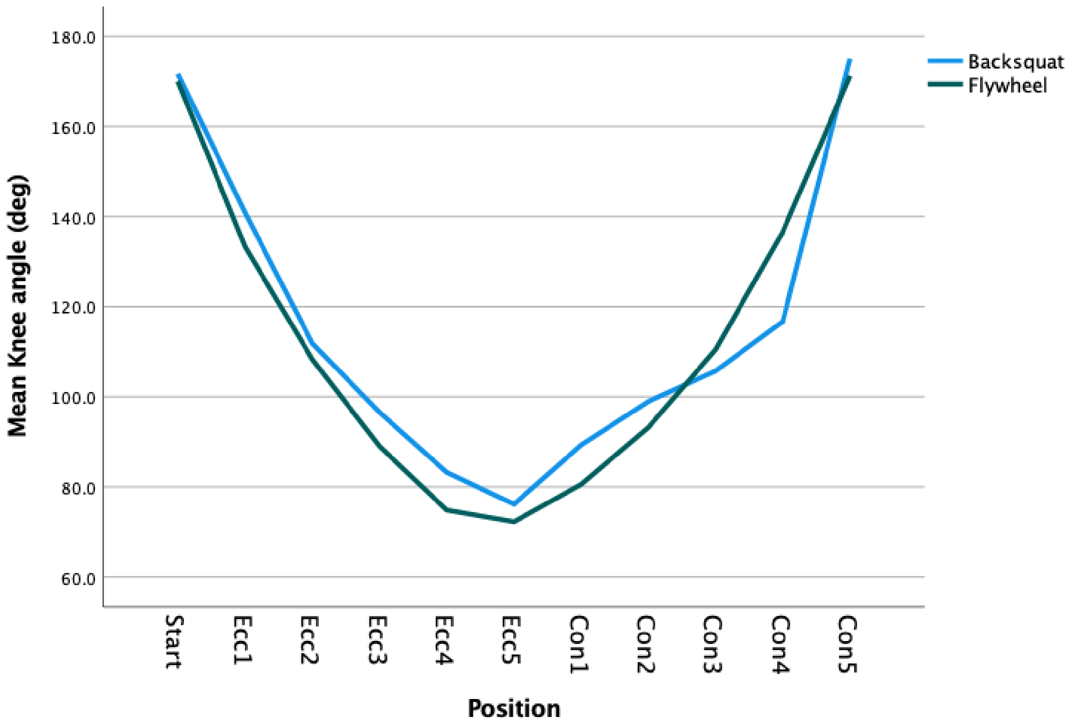

FIGURE 27. Mean knee angles at different time points in the BS and FW squat.

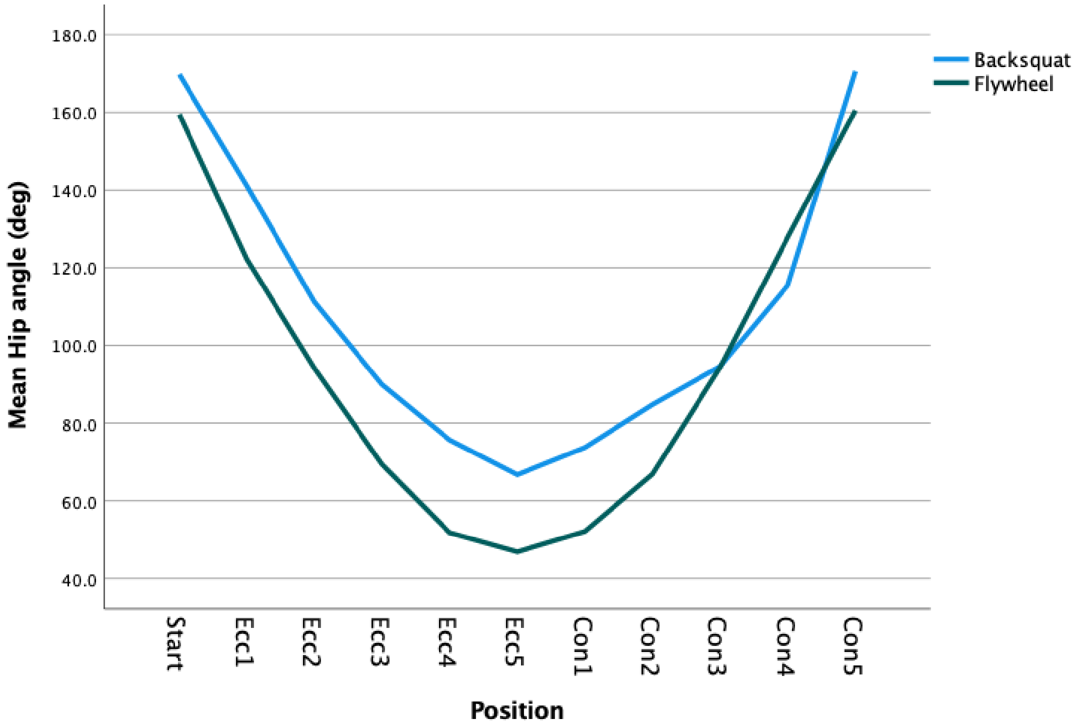

FIGURE 28. Mean hip angles at different time points in the BS and FW squat.

Slightly greater, but still minor differences can be seen in angular velocities. The eccentric phase was almost identical in regards of knee and hip angular velocities. Some differences can be seen in the concentric phase, but only significantly greater hip angular velocities were seen in FW squat by 23.2 % ($p < 0.05$). Looking at the subsections, more noticeable differences can be seen. In knee angular velocities, significant differences can be seen in Ecc 2 with 19.6 % lower velocity in FW ($p < 0.05$). Significantly lower knee angular velocities in FW were also seen in Ecc 5 (68.5 %, $p < 0.05$), Con 1 (27.4 %, $p < 0.05$), and Con 5 (33.3 %, $p < 0.001$). Significantly higher knee angular velocities were seen in FW squat in Con 3 (199.7 %, $p < 0.001$) and Con 4 (156.3 %, $p < 0.001$).

Hip angular velocities showed similar findings in sub sections. Significantly lower hip angular velocities were seen in FW in Ecc 5 by 49.4 % and Con 5 by 34.1 % ($p < 0.05$). Higher hip angular velocities in FW squats were seen in Ecc 1 (26.3 %, $p < 0.05$), Con 2 (49.4 %, $p < 0.05$), Con 3 (246.1 %, $p < 0.001$) and Con 4 (70.2 %, $p < 0.001$). All knee and hip angular velocities are demonstrated in table Appendix 4.

6.4 Pre and post isometric leg press

Pre and post isometric MVC leg press was measured as part of the study to see that the study protocol does not have a fatiguing affect, and so would affect the results in the latter exercise. In the pretest, mean peak force was 4401 ± 859 N and in the post test 4229 ± 815 N. The subjects were able to produce on average 3.9 % less force in the post test but this reduction was not statistically significant, $t(13) = 1.91$, $p = 0.08$.

7 DISCUSSION

FW training has emerged as an alternative strength training method, especially amongst athletes within the last few years. The aim and purpose of this study was to compare 1 RM barbell BS to FW squats in terms of force production, muscle activity, and kinematics in eccentric and concentric phases. No previous studies have made cross-sectional studies with these comparisons and with maximal loads. Based on the current literature, hypothesis of the study was that greater muscle activity and force production in the eccentric phase in the FW squat should be seen (Norrbrand et al., 2010). The concentric phase should be more similar between the two methods in terms of muscle activity and force production with slightly greater activity in FW squats (Alkner & Bring, 2019; Norrbrand et al., 2011). Greater hip flexion should occur in FW squats since the harness alleviates pressure from the lower back. Knee angles should be similar between the squatting methods since the depth of the squat was instructed to be thighs parallel to the floor in both settings.

Major findings include that, subjects were able to generate in general more force in BS than in FW squats, especially greater forces were seen in BS in the eccentric phases. In the last two concentric subsections, subjects were able to generate greater forces in FW than in BS. No major differences were seen in squat depth in terms of knee angles, but greater hip flexion was seen in FW squats. Greater knee and hip angular velocities were seen in FW squats in the middle of the concentric phase, which is where a sticking point occurs in BS. In general, muscle activity was greater in FW squats in the quadricep muscles in the eccentric phase, however most of these findings were not statistically significant. Dorsal muscles of the lower extremities also referred to as posterior chain muscles, especially GM, were significantly more active in BS than FW squats throughout majority of the movement.

7.1 Average- and peak forces

Average and peak forces were in general greater in BS than in FW squats. Greatest differences in average force were seen at the start of the squat (Ecc 1 and Ecc 2) and at the bottom part of the squat on the way down (Ecc 4 and Ecc 5) and on the way up (Con 1 and Con 2). In these eccentric parts, average forces were from 23.1 % up to 37.6 % lower in FW squat than BS ($p < 0.05$). In barbell BS, average force stayed almost constant throughout the movement and the force was the amount of weight of the barbell in Newtons. This is due to the slow movement in the squat due to maximal external load for each participant. The weight of the barbell does not change so the external force is constant throughout the movement and it can only be altered by greater acceleration since $F = m \times a$. In FW squats, the force varied much more than in BS throughout the movement. Instead of constant load, moment of inertia of the FW and acceleration determines the force that is needed. With less acceleration or less moment of inertia, there will be less force. Greatest eccentric forces in FW squats occurred in Ecc 4, which is where the subjects started to absorb the kinetic energy from the FW and tried to change direction of the FW into the concentric part. Significantly greater average forces were seen in FW squats in the last two sections of the concentric part (Con 4 and Con 5). This part of the squat produced 24.8 % - 42.7 % higher average forces in FW squats than BS ($p < 0.05$). In the concentric phase, the weakest spot is at the bottom of the squat and gradually increases as the knees and hips extend and comes closer to their resting length where they can produce most active force. However, a sticking point occurs at approximately halfway through the concentric phase. At this point, passive strength, which is created by stretching the muscle tendon unit, is decreasing as the muscles get closer to their resting length. (Bryanton et al., 2012.) Greater forces at the end of the FW squat could also be explained by the fact that there was no sticking point like in BS which requires the maximum amount of active force to overcome. The absence of a sticking point in FW squat is due to the mechanics of inertia. As the FW is already rotating, a decrease in muscle force will not affect its rotational velocity negatively. When the weakest point has been overcome, an increase in active muscle force will accelerate the FW and thus create more force since $F = m \times a$. (McErlain-Naylor & Beato, 2021.)

Similar results can be seen in peak forces. Subjects produced lower peak forces in FW squats in the eccentric phases by 17.2 % to 28.6 % ($p < 0.05$). Again, greatest differences were seen in the start of the squat and at the bottom part of the squat. The start of the squat can be explained by a brief moment off zero pulling force right before the FW starts to wind the rope in and pulling the subject down. Also, higher peak forces in FW can be seen in the strongest section of the squat (Con 4 and Con 5) where 19.6 % – 40.2 % more force was produced ($p < 0.05$). No previous studies have made comparisons like this before, so the results in force production cannot be compared to any previous data. Previous studies have used multiple repetitions and it favors the FW squat since the subject can produce much higher forces in the first few repetitions and then slowly fatigue but still maintain the average force above what BS can produce since there the load is again constant in each repetition (Petré et al., 2018).

7.2 Muscle activity

Muscle activity was measured from three quadricep muscles (RF, VL, and VM) and two posterior chain muscles (BF and GM) with sEMG electrodes. In RF, greater muscle activity was seen in FW squats throughout the movement except for the last section (Ecc 5), where muscle activity was greater in BS. VL and VM behaved in a similar fashion and greater activity levels were seen in FW in all eccentric phases and concentric phases up until the last 2 - 3 phases where BS showed greater activity. BF showed greater activity in FW in the eccentric phase and greater activity in BS in concentric phases. The biggest difference in favor of BS can be seen in Con 2 and Con 3 which is right around the sticking point in BS but again, significantly greater activity levels were seen in FW in Ecc 1 and Ecc 5. GM muscle activity was greater almost through all sections in BS. Greatest differences can be seen from Ecc 2 to Con 3. For the last two sections (Con 4 and Con 5), muscle activity turned greater in FW.

At the beginning of the squat (Ecc 1) showed greater muscle activity in all muscles in FW. This might be because of the initial pull of the FW. Although forces were significantly lower in FW squats in the eccentric phase, muscle activity seems to be higher. In FW squats, the subjects need to actively decelerate the FW and they must adapt to the pulling force and velocity whereas in barbell BS the subject is more in charge of the velocity and the load is constant at all times. The initial pull activates the muscles in the eccentric phase due stretch reflex also known as myotatic reflex. This reflex causes the muscles to rapidly activate to prevent the muscle for lengthening too fast. (Muraoka & Kurtzer, 2020.) These findings agree with previous studies that also found that greater muscle activity can be seen in FW squats, especially in eccentric actions (Alkner & Bring, 2019; Norrbrand et al., 2010). Even though greater activity could be seen in FW squat in the concentric phases in quadriceps muscles less force was still produced than in BS (except Con 4 and Con 5, that produced greater forces in FW). FW squatting position and the use of harness might influence this. Since the subjects did not have to worry about their lower back in FW squat, so they had their hips more flexed. A major advantage of the harness in FW squats lies in the concentric phase. Being able to push more with the quadriceps to extend the knee without worrying of lifting the hips so high that it injures the lower back is a major safety advantage. Lifting the hips up in barbell BS increases the lever arm to a point that risk of injury the lower back is high. This forward lean position starts to look more like a leg press position, which is a quadriceps dominant exercise.

GM was significantly more active in BS than FW squat almost throughout the whole movement. In squatting, GM is in charge of extending the hips with the hamstring muscles. As stated before, FW squats were slightly deeper in terms of knee angle which would suggest more activity from GM, however results show the opposite. An explanation for this might be that the greater muscle activity in BS in GM might not be to generate force into the squat, but to maintain a more upright body position to minimize pressure in the lower back. Greater force in the eccentric phase could also be explained by more activity in the GM muscle since the position is more upright, which is more optimal in terms of active force production in the GM. (Bryanton et al., 2012.) GM muscle assists during the squat in force production but its role is also to isometrically contract to keep the lower back safe. BF muscle use showed a big increase in BS around the sticking point and since its role is also to extend the hips it may have been more active at this stage to aid in maintaining an upright position.

Interestingly, in the concentric phases the roles switched between quadriceps muscles and posterior chain muscles. Majority of the concentric phase, muscle activity was greater in FW in quadriceps and in BS in posterior chain muscles, however, roughly for the last two sections (Con 4 and Con 5), quadriceps were more active in BS and posterior chain muscles more active in FW. A reason for why posterior chain muscles were more active in FW in the last sections of the squat might be that at this stage the upper body is already in a fairly upright position so less isometric muscle force is needed from the hip extensors (BF and GM) and so the difference is now only how much muscle work these muscles contribute to the squatting force, which at this stage was significantly higher in FW squats.

7.3 Knee and hip angles

Knee and hip angles followed similar patterns between BS and FW squat, especially knee angels were almost identical with slightly lower squats in FW than in BS (72.2 ° ± 12.6 ° vs. 76.2 ° ± 10.3 °). The participants were given the instruction to aim for parallel squats in both scenarios. Parallel squats are usually around 70 ° knee angle, depending on how much dorsiflexion occurs in the ankle (Cotter et al., 2013). More dorsiflexion leads to knees passing the toes further, which then require smaller knee angles to reach parallel. Greater differences were seen in hip angles. In FW squat, at the bottom of the squat the hip angle was on average 19.8 ° smaller than in BS (46.9 ° ± 13.1 ° vs. 66.7 ° ± 12.3 °). A major contributor to this difference is the fact that in FW squat a harness was used. The harness allows for greater hip flexion since it puts less stress on the lower back than conventional barbell BS. Squatting with a harness distributes the pressure on the hips and shoulders throughout the movement which leads to less strain on the lower back (Petré et al., 2018). Another factor is that since the pulling force is coming from underneath the subject slightly in front of their body and centre of gravity, so a natural way to act against this pull is in a slightly forward lean. The difference in hip angles stays constant throughout the eccentric phase then starts to catch up so that hip angles are almost identical in the last three sections of the squat (Con 3, Con 4, and Con 5). This allows for greater muscle use from the hip extensors (BF and GM) to extend the hips a longer distance, which could also explain the greater force in the last sections of the squat.

7.4 Knee and hip angular velocities

Knee and hip angular velocities showed greater differences than their respective angles. Greater knee angular velocities could be seen in BS in the eccentric phases especially at the bottom of the squat (Ecc 5). Moving upwards from the bottom of the squat FW had still lower knee angular velocity by 27.4 % ($p < 0.05$). In BS it might be easier to obtain a stretch shortening cycle by doing a little bounce from the bottom of the squat to maintain momentum in the movement. This is not possible in FW squat since the FW needs to be decelerated, come to a complete stop, and then accelerate again in the opposite direction. This could explain the slower parts in FW squat at the bottom of the movement. Suddenly in Con 3 and Con 4, FW squats had 199.7 % and 156.3 % higher knee angular velocities respectively ($p < 0.001$). This is the spot where the sticking point occurs in BS, and it is usually the weakest point of the squat since the passive force starts to decrease as the muscles get closer to their resting length (Bryanton et al., 2012). At this point the movement gets very slow or even stops for a moment. In FW squats there is no sticking points since the resistance adapts throughout the range of motion and maximal force can be produced with continuous movement (Petré et al., 2018). Then again in the last section of the squat (Ecc 5) where acceleration occurs after the sticking point, more active force can be produced, and BS knee angular velocity exceeds FW squats velocity which leaves FW squats knee angular velocities 33.3 % slower than BS ($p < 0.001$). In conventional gravity-based exercises the total maximum load that can be lifted is the amount that can be overcome at the weakest point. At the end of the concentric phase is the strongest part in terms of active force, and subjects can perform this part of the BS at much higher velocities since the external load stays constant. (Bryanton et al., 2012.) In FW, the resistance is variable and much greater at the end, which leads to slower knee angular velocities, but greater force as was seen above.

Similar results can be found in hip angular velocities. Greater differences can be seen in the concentric phases starting from the bottom of the movement (Ecc 5). BS had greater hip angular velocity than FW. This is the spot where in FW squats the subjects were trying to decelerate the FW and change its direction. Again, around the sticking point in BS (Con 3 and Con 4), greater velocity can be seen in FW since there is no sticking point, like was seen in knee angular velocities. 246.1% (Con 3) and 70.2 % (Con 4) differences were seen around the sticking point in hip angular velocities in favor of FW ($p < 0.05$). Then again, like seen in knee angular velocities, the hip angular velocity in BS exceeds FW in the last section of the squat (Con 5). Subjects were able to accelerate at this stage since they overcame the sticking point into a stronger phase of the squat.

7.5 Limitations and strengths of the study

One major factor that might influence the results is that most of the participants had no previous training experience with a FW device. Every subject had years of experience of the barbell BS but only a familiarization session with the FW device. Each subject said that they felt comfortable and were able to push maximally in the FW squats, but previous studies have found that there are significant differences in novice and expert FW squatters, even though they all have an athletic background. Experienced FW squatters were able to produce greater peak and average forces and they tended to do deeper squats than novice FW squatters (Galiano, 2021).

Some other limitations in the study are that subjects only performed one maximal repetition in BS. However, adding more maximal attempts with their maximal load would have most likely caused significant fatigue that could have affected the results in both squats in latter performances. Knee angles were instructed and controlled in the study, but it would be interesting to see if some changes would be seen in the results if hip angles were tried to maintain as identical as possible. Due to the use of harness, it might not be easily done especially with maximal forces since the weight is differently distributed compared to barbell BS.

A substantial strength of this study design is that all the measurements were done in a single session for each subject. This gives precision in the kinematic and muscle activity results since the markers and sEMG electrodes remained untouched throughout the whole session. Collecting all the data in a single session also eliminates the fact that there usually is some alteration in one's daily maximum. This would have been an issue if measurements were done on separate days.

8 CONCLUSION

The main purpose of this study was to find out how does these two squatting methods differ from each other in terms of kinematics, force production and muscle activity. Barbell BS and FW squat are both bilateral squatting methods that can be performed with maximal external loads and forces and they do look similar in outline. However, looking at the kinematics, it is safe to say that there are some major differences that can explain some of the differences in force production and muscle activity. Greater average and peak forces in BS might be due to inexperienced subjects in regards of FW squatting and that the external load stays always constant whereas in FW squat there is a big range in terms of force throughout the squat motion due to inertia of the FW. Muscle activity tended to be greater in FW squats, especially in the eccentric phase. This might be due to active pulling of the FW that activates the stretch reflex, creating more activity in the muscles. The biggest difference in hip angles were seen in the concentric phase, where greater angles were seen in BS. This is due to the external load. The back needs to be more upright in BS since the barbell creates greater tension in the lower back. In FW squat, where a harness is used, no external tension is created on the lower back which allows for a more forward lean in the concentric phase causing a smaller hip angle. The biggest difference in hip and angular velocities were seen around the sticking point in the concentric phase. In BS the motion almost stopped for a moment in the sticking point and after overcoming that accelerated again towards the end of the motion. In FW squat the angular velocities gradually increased throughout the concentric phase with no sticking point.

The biggest difference is still that barbell BS uses conventional gravity-based loading and FW squats uses moment of inertia in a FW as resistance, which most likely explains the majority of the findings. This study compared squat movements and lower limb muscle activity, but FW devices are versatile, and a lot of different movements can be done using it. More research needs to be done with comparisons like in this study to find out what the role of FW resistance and gravity-based resistance is truly and how they differ.

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APPENDIX 1

Position	Statistics	BS Time (s)	FW Time (s)	BS Average force (N)	FW Average force (N)	% - Difference	BS Peak force (N)	FW Peak force (N)	% - Difference
Full repetition	Mean	**4.15**	**3.84**	**1322**	**1106**	**-16.4 % ***	**1525**	**1396**	**-8.5 %**
	Std. Deviation	1.10	0.55	196	255	-	224	312	-
Eccentric	Mean	**1.90**	**1.95**	**1310**	**939**	**-28.3 % ****	**1480**	**1190**	**-19.6 % ***
	Std. Deviation	0.51	0.37	196	241	-	234	270	-
Concentric	Mean	**2.25**	**1.89**	**1335**	**1281**	**-4.1 %**	**1570**	**1608**	**2.5 %**
	Std. Deviation	0.70	0.29	204	276	-	220	364	-
Position	Statistics	BS Cumulative Time (s)	FW Cumulative Time (s)	BS Average force (N)	FW Average force (N)	% - Difference	BS Peak force (N)	FW Peak force (N)	% - Difference
Ecc1	Mean	**0.38**	**0.39**	**963**	**601**	**-37.6 % ***	**1326**	**997**	**-24.8 % ***
	Std. Deviation	-	-	202	461	-	193	580	-
Ecc2	Mean	**0.76**	**0.78**	**1361**	**950**	**-30.2 % ***	**1546**	**1221**	**-21.0 %**
	Std. Deviation	-	-	290	585	-	300	668	-
Ecc3	Mean	**1.14**	**1.17**	**1366**	**1115**	**-18.3 %**	**1462**	**1351**	**-7.6 %**
	Std. Deviation	-	-	232	353	-	241	328	-
Ecc4	Mean	**1.52**	**1.56**	**1369**	**1025**	**-25.1 % ***	**1459**	**1209**	**-17.2 % ***
	Std. Deviation	-	-	215	294	-	227	349	-
Ecc5	Mean	**1.9**	**1.95**	**1491**	**1002**	**-32.8 % ****	**1605**	**1173**	**-26.9 % ***
	Std. Deviation	-	-	271	387	-	313	441	-
Con1	Mean	**2.35**	**2.33**	**1420**	**920**	**-35.2 % ****	**1578**	**1051**	**-33.4 % ****
	Std. Deviation	-	-	213	192	-	292	309	-
Con2	Mean	**2.8**	**2.71**	**1294**	**908**	**-29.8 % ****	**1352**	**1017**	**-24.8 % ****
	Std. Deviation	-	-	192	213	-	199	268	-
Con3	Mean	**3.25**	**3.08**	**1331**	**1179**	**-11.4 %**	**1390**	**1468**	**5.6 %**
	Std. Deviation	-	-	194	370	-	203	469	-
Con4	Mean	**3.7**	**3.46**	**1465**	**1828**	**24.8 % ***	**1623**	**2227**	**37.2 % ****
	Std. Deviation	-	-	217	534	-	246	586	-
Con5	Mean	**4.15**	**3.84**	**1166**	**1567**	**34.4 % ***	**1905**	**2279**	**19.6 % ***
	Std. Deviation	-	-	321	559	-	267	563	-

* Significance $p < 0.05$ — Greater force in BS (-)

** Significance $p < 0.001$ — Greater force in FW (+)

APPENDIX 2

Position	Statistics	BS Average force (N)	FW Average force (N)	% - Difference	BS Peak force (N)	FW Peak force (N)	% - Difference
Full repetition	Mean	**1322**	**1145**	**-13.4 % ***	**1525**	**1417**	**-7.1 %**
	Std. Deviation	196	255	-	224	312	-
Eccentric	Mean	**1310**	**983**	**-25.0 % ****	**1480**	**1209**	**-18.3 % ***
	Std. Deviation	196	241	-	234	270	-
Concentric	Mean	**1335**	**1311**	**-1.8 %**	**1570**	**1632**	**3.9 %**
	Std. Deviation	204	276	-	220	364	-
Position	Statistics	BS Average force (N)	FW Average force (N)	% - Difference	BS Peak force (N)	FW Peak force (N)	% - Difference
Ecc1	Mean	**963**	**699**	**-27.4 %**	**1326**	**1056**	**-20.4 %**
	Std. Deviation	202	461	-	193	580	-
Ecc2	Mean	**1361**	**1046**	**-23.1 % ***	**1546**	**1306**	**-15.5 %**
	Std. Deviation	290	585	-	300	668	-
Ecc3	Mean	**1366**	**1124**	**-17.7 % ***	**1462**	**1351**	**-7.6 %**
	Std. Deviation	232	353	-	241	328	-
Ecc4	Mean	**1369**	**1026**	**-25.1 % ***	**1459**	**1187**	**-18.6 % ***
	Std. Deviation	215	294	-	227	349	-
Ecc5	Mean	**1491**	**1021**	**-31.5 % ****	**1605**	**1146**	**-28.6 % ****
	Std. Deviation	271	387	-	313	441	-
Con1	Mean	**1420**	**929**	**-34.1 % ****	**1578**	**1067**	**-32.4 % ****
	Std. Deviation	213	192	-	292	309	-
Con2	Mean	**1294**	**909**	**-29.8 % ****	**1352**	**1030**	**-23.8 % ****
	Std. Deviation	192	213	-	199	268	-
Con3	Mean	**1331**	**1197**	**-10.1 %**	**1390**	**1484**	**6.8 %**
	Std. Deviation	194	370	-	203	469	-
Con4	Mean	**1465**	**1851**	**26.3 % ***	**1623**	**2276**	**40.2 % ****
	Std. Deviation	217	534	-	246	586	-
Con5	Mean	**1166**	**1664**	**42.7 % ***	**1905**	**2296**	**20.5 % ***
	Std. Deviation	321	559	-	267	563	-
	* Significance p < 0.05		Greater force in BS (-)				
	** Significance p < 0.001		Greater force in FW (+)				

APPENDIX 3

Position	Rectus femoris	Vastus lateralis	Vastus medialis	Biceps femoris	Gluteus maximus
Full repetition	29.2 % 37.9 % *	1.6 % 2.9 %	2.2 % 7.0 %	-10.0 % -8.6 %	-14.1 % * -9.4 %
Eccentric	18.1 % 27.9 %	12.4 % 17.8 % *	12.2 % 19.4 %	18.8 % * 19.0 % *	-23.1 % ** -18.0 % *
Concentric	27.5 % 34.2 %	-5.2 % -6.6 % *	-5.3 % -2.2 %	-20.0 % -18.2 %	-10.7 % -6.1 %
Position	**Rectus femoris**	**Vastus lateralis**	**Vastus medialis**	**Biceps femoris**	**Gluteus maximus**
Ecc1	98.6 % 101.8 %	32.6 % 45.6 % *	42.7 % * 54.4 % *	43.4 % 48.4 % *	33.7 % 42.9 %
Ecc2	79.8 % 90.5 %	4.6 % 14.9 %	25.5 % 32.8 %	-2.3 % -6.1 %	-21.5 % * -14.3 %
Ecc3	25.5 % 31.4 %	20.5 % 26.1% *	27.2 % 34.4 %	16.2 % 16.5 %	-35.7 % * -28.1 % *
Ecc4	-18.3 % -16.5 %	6.6 % 10.0 %	-0.6 % 2.5 %	16.6 % 20.0 %	-37.4 % ** -35.7 % **
Ecc5	14.8 % 38.1 %	11.0 % 13.2 %	2.9 % 13.1 % *	19.4 % * 15.8 %	-39.9 % * -40.0 % *
Con1	21.3 % 35.1 %	6.0 % 1.7 %	8.5 % 14.3 %	-7.4 % -9.9 %	-58.6 % * -56.9 % *
Con2	32.3 % * 30.3 %	8.2 % 6.5 %	5.1 % 9.5 %	-44.1 % ** -46.4 % **	-51.3 % * -48.0 % *
Con3	47.4 % 54.8 %	2.1 % 2.5 %	-10.4 % -5.3 %	-51.9 % ** -45.7 % *	-16.7 % -11.9 % *
Con4	27.5 % 36.5 %	-12.8 % * -13.2 % *	-11.0 % -11.1 %	-6.3 % -8.0 %	8.3 % 15.8 % *
Con5	-55.0 % * -50.0 % *	-35.9 % ** -36.4 % **	-29.6 % * -32.0 % *	7.1 % 13.6 %	43.7 % 48.1 %

Top value = Duration matched squats
Bottom value = Force matched squats
Greater activity in BS (-)
Greater activity in FW (+)

* Significance $p < 0.05$

** Significance $p < 0.001$

APPENDIX 4

Position	Statistics	BS Knee angular velocity (deg/s)	FW Knee angular velocity (deg/s)	% - Difference	BS Hip angular velocity (deg/s)	FW Hip angular velocity (deg/s)	% - Difference
Eccentric	Mean	**-54.0**	**-52.3**	**-3.2 %**	**-58.0**	**-59.4**	**2.3 %**
	Std. Deviation	17.3	15.1	-	18.1	12.7	-
Concentric	Mean	**47.2**	**53.1**	**12.4 %**	**49.6**	**61.0**	**23.2 % ***
	Std. Deviation	14.1	9.3	-	15.9	9.5	-
Ecc1	Mean	**-84.7**	**-98.1**	**15.9 %**	**-77.6**	**-98.0**	**26.3 % ***
	Std. Deviation	35.5	39.1	-	27.0	30.8	-
Ecc2	Mean	**-81.9**	**-65.9**	**-19.6 % ***	**-84.6**	**-74.0**	**-12.6 %**
	Std. Deviation	27.5	16.9	-	26.7	18.9	-
Ecc3	Mean	**-43.3**	**-51.2**	**18.5 %**	**-61.7**	**-64.1**	**3.9 %**
	Std. Deviation	21.6	17.2	-	30.2	21.1	-
Ecc4	Mean	**-40.0**	**-39.9**	**-0.4 %**	**-40.8**	**-47.8**	**17.4 %**
	Std. Deviation	31.9	27.8	-	28.7	23.0	-
Ecc5	Mean	**-20.1**	**-6.3**	**-68.5 % ***	**-25.6**	**-13.0**	**-49.4 % ***
	Std. Deviation	18.0	7.6	-	16.0	8.8	-
Con1	Mean	**31.0**	**22.5**	**-27.4 % ***	**16.0**	**14.2**	**-11.0 %**
	Std. Deviation	16.5	10.2	-	15.2	9.8	-
Con2	Mean	**24.6**	**33.8**	**37.3 %**	**26.7**	**39.9**	**49.4% ***
	Std. Deviation	17.8	11.8	-	13.2	14.3	-
Con3	Mean	**15.7**	**47.0**	**199.7 % ****	**21.7**	**75.0**	**246.1 % ****
	Std. Deviation	7.1	14.8	-	21.8	22.7	-
Con4	Mean	**27.5**	**70.5**	**156.3 % ****	**52.9**	**90.1**	**70.2 % ****
	Std. Deviation	16.0	21.6	-	28.0	23.6	-
Con5	Mean	**137.3**	**91.6**	**-33.3 % ****	**130.5**	**85.9**	**-34.1 % ***
	Std. Deviation	37.6	17.3	-	43.2	18.4	-
* Significance p < 0.05		Greater velocity in BS (-)					
** Significance p < 0.001		Greater velocity in FW (+)					

APPENDIX 5

Etsitään osallistujia Gradu tutkimukseen

Force Production and Muscle Activation in Flywheel Squat vs Gravity-Based Squat

Tutkimuksen tarkoitus on selvittää miten vauhtipyörällä tehtävä kyykky eroaa vapailla painoilla tehtävään kyykkyyn voimantuotollisesti ja lihasaktivoinnin kannalta.

Mikäli täytät seuraavat kriteerit voit osallistua tutkimukseen:

- Olet mies
- Olet 18 – 35 vuotias
- Teet voimaharjoittelua säännöllisesti (etenkin alaraajoilla)
- Sinulla ei ole vammoja jotka estävät sinua tekemästä maksimaalista kyykkyä
- Et sairasta hermostollista sairautta tai ota lääkkeitä, jotka vaikuttavat hermostoon

Mitä osallistuminen vaatii:

- Yksi tutustumiskerta (noin 30 minuuttia). Tutustutaan lähinnä vauhtipyörän käyttöön.
- Yksi tutkimuskerta (noin 1,5–2 tuntia). Suoritetaan maksimaalinen yhden toiston takakyykky tangolla ja yhden toiston maksimi vauhtipyöräkyykky.

Mitä mitataan:

- Voimantuottoa voimalevyillä konsentrisessa ja eksentrisessä vaiheessa.
- Lihasaktivaatiota kaksinapaisilla pintaelektrodeilla (EMG) viidestä eri alaraajan lihaksesta
- Kinematiikkaa nivelkulmista suurinopeuskameroilla

Missä ja milloin:

- Tutkimus suoritetaan Jyväskylän yliopiston liikuntalaboratoriossa.

Mikäli kiinnostuit tai tiedät jonkun, joka voisi olla kiinnostunut, ota yhteyttä.

APPENDIX 6

LIITE 7 SUOSTUMUSLOMAKE

JYVÄSKYLÄN YLIOPISTO

SUOSTUMUS OSALLISTUA TIETEELLISEEN TUTKIMUKSEEN

Minua on pyydetty osallistumaan tutkimukseen ” **Force Production and Muscle Activity in Flywheel Squat vs Gravity-Based Squat**” ”**Voimantuotto ja Lihasaktivaatio Vauhtipyörä Kyykyssä vs Painovoimaa Vasten Tehtävässä Kyykyssä** ”

Olen perehtynyt tutkimusta koskevaan tiedotteeseen ja saanut riittävästi tietoa tutkimuksesta sekä henkilötietojeni käsittelystä. Minulla on ollut riittävästi aikaa harkita tutkimukseen osallistumista.

Olen ymmärtänyt, että tutkimukseen osallistuminen on vapaaehtoista ja voin milloin tahansa ilmoittaa, etten enää halua osallistua tutkimukseen. Tutkimuksen keskeyttämisestä ei aiheudu minulle kielteisiä seuraamuksia. Kieltäytyminen tai keskeyttäminen tutkimuksesta ei aiheuta ongelmia omassa urheiluyhteisössä. Keskeyttämiseen asti minusta kerättyjä tutkimusaineistoja voidaan edelleen hyödyntää tutkimuksessa.

Erittely :

Allekirjoittamalla suostumuslomakkeen hyväksyn tietojeni käytön tiedotteessa kuvattuun tutkimukseen

Kyllä ☐

Ymmärrän, että minusta voidaan ottaa valokuvia tutkimustarkoitusta varten. Tutkimuksessa otetaan myös videoita alaraajoista suurinopeuksisella kameralla kinematiikka analyysejä varten. Kuvia ja videoita säilytetään, kunnes aineiston analyysi on saatu päätökseen. Näitä ei julkisteta muodossa, mistä koehenkilöt voisi tunnistaa.

Kyllä ☐

En osallistu mittauksiin flunssaisena, kuumeisena, toipilaana tai muuten huonovointisena.

Kyllä ☐

Olen ymmärtänyt saamani tiedot ja haluan osallistua tutkimukseen.

Allekirjoittamalla suostumuslomakkeen hyväksyn tietojeni käytön tiedotteessa kuvattuun tutkimukseen tutkittavaksi sekä annan luvan kohtiin, joiden kohdalla olen merkinnyt kohdan ”Kyllä”. Jos en ole merkinnyt jotakin kohtaa, se tarkoittaa, että en anna lupaa henkilötietojeni käyttämiseen kyseiseen tarkoitukseen.

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Tutkimukseen osallistuvan allekirjoitus, nimenselvennys ja päivämäärä

APPENDIX 7

LIITE 8: TUTKITTAVILLE ANNETTAVA MATERIAALI

Tutkimus:

”Force Production and Muscle Activation in Flywheel Squat vs Gravity-Based Squat”

”Voimantuotto ja Lihasaktivaatio Vauhtipyörä Kyykyssä vs Painovoimaa Vasten Tehtävässä Kyykyssä ”

Sukupuoli:______________________

Ikä:____________________________

Pituus:__________________________

Kuuluuko voimaharjoittelu viikoittaiseen harjoitusohjelmaasi?

- Kyllä
- Ei

Oletko tehnyt voimaharjoittelua säännöllisesti vähintään viimeisen kahden vuoden ajan?

- Kyllä
- En

Onko sinulla jokin vamma tai muu rajoite, joka estää sinua suorittamasta maksimaalista kyykkyä?

- Ei
- Kyllä, mikä?____

Onko sinulle todettu jokin hermolihas sairaus?

- Ei
- Kyllä, mikä?____