Exploring differences in electromyography and force production between front and back squats before and after fatigue and how this differs between the sexes.

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Abstract

Limited research has been conducted to explore sex differences in biomechanical and physiological demands of the front and back squat, especially in response to fatigue where technique may be altered. Therefore, this study investigated differences in electromyography and force production in performance of back and front squats before and after a fatigue protocol and how this differed between males and females. 35 participants (5 female, 30 male) performed a fatigue protocol for back and front squats with measures of maximal performance pre and post. Main findings were that mean and peak activation of the semitendinosus was greater in the back squat than the front squat suggesting that the back squat has greater hamstring activation possibly for hip stabilisation and knee flexion ($p < 0.05$). There were no differences in quadricep activation between back and front squats, disputing the notion that front squats have a greater quadricep focus, however, lending support to the hypothesis that quadricep activation equal to the back squat can be achieved with lighter absolute load in a front squat. There were no differences in electromyography as a result of fatigue however force production decreased for back squats following fatigue ($p < 0.01$). This decrease could result from decreased acceleration out of the bottom position and into the concentric phase. This study also presents preliminary findings of greater mean and peak rectus femoris activation in females compared to males in both front ($p < 0.01$) and back squats ($p < 0.05$). This was suggested to be in order to support the knee and in an attempt to prevent knee valgus and excess hip adduction. These findings have implications in programming for both high performance sport and for rehabilitation of lower limb injuries.

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Abbreviations

ACL – Anterior Cruciate Ligament

ACV – Average Concentric Velocity

ATP – Adenosine Triphosphate

BF – Biceps Femoris

BMI – Body Mass Index

Ca^{2+} - Calcium

CAR – Central Activation Ratio

CMJ – Countermovement Jump

CNS – Central Nervous System

ECG - Electrocardiogram

EMG – Electromyography

ES – Erector Spinae

GM – Gluteus Maximus

GRF – Ground Reaction Force

iEMG – Integrated Electromyography

MVC – Maximal Voluntary Contraction

RF – Rectus Femoris

RM – Repetition Maximum

RPE – Rate of Perceived Exertion

ST – Semitendinosus

vGRF – Vertical Ground Reaction Force

VL – Vastus Lateralis

VM – Vastus Medialis

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Introduction

This thesis explores muscle activation and force production differences between the back squat and its counterpart the front squat. For back squat, the barbell is racked behind the neck across the back of the shoulders on the trapezius. For the front squat, hands are placed just outside shoulder width and the bar is racked across the front of the shoulders approximately at the level of the clavicles, the elbows are fully flexed with palms facing up holding the bar. The front squat is employed much less frequently by the trained general population than the back squat but is still a commonly employed alternative to the back squat compared to other techniques like the Zercher squat or overhead squat (Glassbrook et al., 2019). There is increasing evidence of the benefits of employing front squats for example Waller (2007) discusses how the front squat may reduce lower back strain and Gullet et al. (2009) explored how it may be more optimal for those with lower limb injuries. Hence more research into the use of front squats is required to confirm whether the front squat is a beneficial addition to a training programme. The front and back squat are foundational movements for Olympic weightlifting, performance of these lifts highly correlates with performance of the competition lifts, the snatch and clean and jerk (Lucero et al., 2019). Whilst in powerlifting, the front squat is used as an accessory lift to the back squat to work on decreasing forward lean, keeping the chest up and improving depth (Austin & Mann, 2021). Finally, in sports such as rugby and athletics the front and back squat are important for strength and power development as well as increasing range of motion under load (Durguerian et al., 2019). Including the squat in programming has been demonstrated to have positive impact on counter-movement jump performance (Carlock et al., 2004) as well as other athletic movements (Channel

& Barfield, 2008). In powerlifting and weightlifting, exploring the difference in stresses places on the body by back and front squats may aid in programming pre and post competition, particularly in tapering where load and intensity are modified in the lead up to competition.

Males are biologically stronger than females, this can be argued regardless of bodyweight and training status (Bartolomei et al., 2021; Morrow & Hosler, 1981). These disparities are particularly prominent at an elite level (Renshaw & Mijena, 2016). However, absolute strength may not be the only element to differ between male and female strength sport performance. There may also be differences in force production and muscle activation between males and females as a result of the physiological mechanisms that underpin sex differences in performance, hence it is important to explore these possible differences to highlight any areas that may predispose to injury during learning to squat or at a higher level in programming for optimal performance specific to sex. For example, where females are predisposed to certain injury types such as at the knee (Lin et al., 2018), as discussed later, certain changes in programming may provide injury prevention including the squat type employed, the loads used, the cues given and the depth. For example, earlier research into sex differences in snatch performance highlighted how females require more accessories focusing on strengthening ankle flexors and knee extensors and encouraging faster knee flexion than males (Harbili, 2012).

Finally, there is evidence to suggest that males and females fatigue differently. However, these differences have not yet been explored in strength sports as most study focuses on endurance. The biological mechanisms behind this difference are explored and this study aimed to investigate how sexes respond differently to a strength endurance protocol.

This study aimed to explore the differences between back squats and front squats by investigating whether they produce different muscle activation, force production and whether they elicit fatigue differently.

Literature review

The front squat and the back squat both require the lower back, hip, and leg muscles to perform the movement and are regarded as very similar, however the change in bar positioning produces variations in technique and different mechanical positions as well as possibly different muscle activation (Gullet et al. 2009). This can be seen in Figure 1. The front squat (Figure 1e.) must be performed with a more upright torso as the bar is supported in front whereas the back squat creates space for significant forward lean while still being able to complete the lift (Figure 1d.), particularly in low bar (Figure 1c). This distinction may produce differences in depth and muscle activation during the squat (Yavuz et al. 2015).

Each variation of the squat serves its own purpose such as training rate of force development, power production, strength development and arguably different muscle activation. Muscle activation is most commonly studied using electromyography (EMG) where electrodes are applied to the skin above the muscle, the amplitude of the signal may provide a measure of the muscle force generation. A larger EMG amplitude may signal greater force generation, increased fatigue or simply greater activation (Royer, 2005). However, EMG amplitude is also dependent on electrode application including distance from the muscle area, the quality of contact with the skin and the properties of the electrode as well as anatomical and physiological differences such as muscle fibre composition and amount of tissue between electrode and muscle (Raez et al. 2006). These factors can all interfere with the signal meaning a greater EMG amplitude does not always indicate greater muscle activation.

The front squat has been argued to have similar muscle activation to back squats despite a lower absolute load (Gullet et al., 2009; Contreras et al., 2015; Hammond et al., 2016; Erdag and Yavuz, 2020; Korak, 2018) despite the more upright posture of the front squat. However, there is also evidence to suggests that activation of the Semitendinosus, Biceps Femoris and Gluteus Maximus is greater in the back squat than the front squat (Yavuz et al., 2015; Boylett-Long, 2019) and Vastus Medialis activation is greater in the front squat (Boylett-Long, 2019). Therefore, whilst the majority of research suggests that there are no differences in muscle activation between squat types, there are still contrasting results.

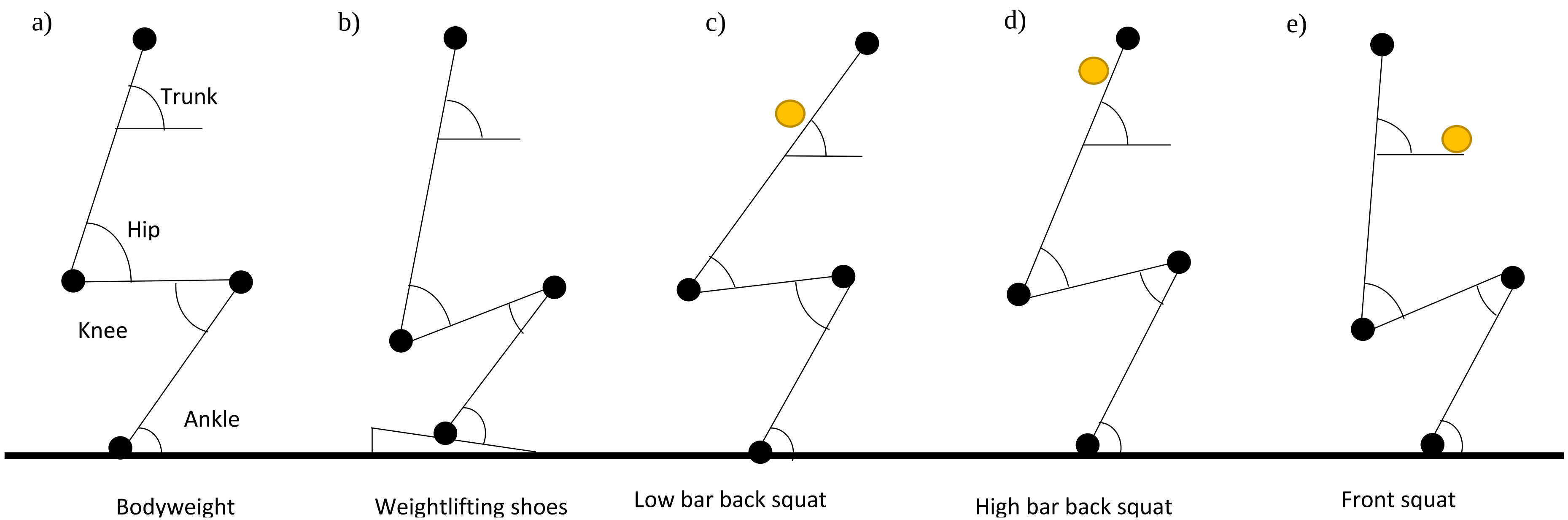

***Figure 1: Difference between some of the squat types discussed**. Bar positioning is indicated by a yellow dot where necessary.*

1. Electromyography in squats.

There is a volume of literature exploring the back squat (Table 1.). These studies explore muscle activation differences between the back squat and front squat (Contreras et al., 2015; Gullet et al., 2008), how utilising different equipment, depths and loads affect electromyography (EMG). Most studies focus on at least one of the following muscles Vastus Lateralis (VL), Vastus Medialis (VM) and Rectus Femoris (RF) of the quadriceps, Biceps Femoris (BF) and Semitendinosus (ST) of the hamstrings, Gluteus Maximus (GM), and/or Erector Spinae (ES).

These studies give insight into the use of the back squat in producing optimal muscle activation of target muscle groups, for example whether the back squat is always the most appropriate exercise depending on the objectives of the individual. Limited studies have explored sex differences in squat performance (Mehls et al, 2020; Amdi et al., 2021).

To perform both squat types, the individual must have a certain level of movement competency in order to reach full range of motion, have safe mechanical positions throughout the squat regardless of muscle dominance and finally to stay balanced throughout the movement. The individual must also demonstrate a degree of uniformity in performance of squats with limited variation of stance, depth and cadence between repetitions. A large amount of variation in technique may indicate a lack of proficiency. Alternatively, if an individual demonstrates excessive movement of the feet during squats, heels coming off the ground excessively or inability to adequately distribute weight, inward or external rotation of the feet during the squat, or finally unsteadiness in descent, this may also evidence a lack of experience. There are some factors that can affect muscle activation during squats such depth (Contreras et al., 2015; Hammond et al., 2016), stability and bar positioning (Yavuz et al. 2015) or equipment used (Glassbrook et al., 2019). These factors contribute to differing activation in back squats and could contribute to differing activation in front and back squats and hence must be considered when interpreting the results of this study.

1.1. Front squats

Contreras et al. (2015) studied the difference between front and back squats, finding that there was similar mean muscle activation in the GM, BF and VL between front and back squats but that a parallel back squat elicited slightly greater VL activation than front squats. Erdag & Yavuz (2020) also found that there were no differences in EMG between back and front squats at submaximal weights. Participants performed 6 squats at 60% of their pre-determined 1RM to study the electromyography signal of the back squat, front squat, hack squat and Zercher squat. Although absolute loads were heavier in the back squat in relation to the other squat types, backs squats were not shown to elicit significantly more muscle activation than any other squat type. Like many studies, this study only involved experienced male participants, a further analysis of the kinematic differences between these squat types could have important implications for injury recovery, rehabilitation and avoidance.

Gullett et al. (2009) utilised video recording and reflective markers for kinematic analysis of net compressive, shear forces at the knee and extensor moments. In this study investigating front and back squats, there was a mixed sex sample of 9 males and 6 females however sex was not considered as an influential variable. Whilst this makes the study more generalisable, it ignores the biomechanical and performance differences that may exist between sexes. As expected loads lifted were heavier in the back squat than the front squat. Whilst this had no effect on the shear forces at the knee, there were significantly greater compressive forces in the back squat and increased knee extensor moments. Increases in load have been correlated with increases in activity in VM, GM and BF when performing squats over 80%1RM (Yavuz & Erdag, 2017). If this is the case, back squats could be expected to produce more activation than front squats as the maximal load for a back squat is generally higher than front squat. Yavuz & Erdag (2017) also report that as load increases so does erector spinae activity in order to stabilise and control trunk musculature.

Despite this, there were no muscle activation differences between front and back squat in any of the muscles studied despite popular social media belief that front squats are more quadricep focused and back squats more glutes and lower back (Otey, 2018). Consequently, it is not always an increased load that elicits greater muscle activation. However, it was reported that muscle activation differed greatly between descending and ascending phases, more specifically that activation in the ascending phase was near maximal and descending was significantly lower for all muscle groups.

The only muscle group to elicit higher average muscle activity in the front squat than the back squat was the ES, but all other muscle activity was higher in back squat than front squat although not significantly. Hence the authors concluded that the front squat may be superior for muscle recruitment as for less compressive forces and extensor moments, muscle activation was similar. This may be useful when programming to reduce training load by reducing total amount of weight lifted without reducing volume or for tapering before competitions. Gullet et al (2009) also suggested that in those with knee injuries, which could be aggravated with squatting, the front squat could be an important exercise in rehabilitation or returning to back squatting.

Korak (2018) also studied the differences in front and back squat but exclusively in 13 females. Using slightly but not significantly different loads, 75% compared to 70%, to the study by Gullet et al (2009) above, the same results were produced which were that there were no differences in muscle activation between squat type. This was concluded to result from similar degrees of hip flexion.

Yavuz et al. (2015) explored differences in front and back squats in 12 males. There was a greater forward lean in the back squat than the front squat likely due to the positioning of the barbell whereas front squats require an upright position in order to maintain the position of the barbell across the front of the shoulders, this evidences how bar positioning alters the mechanical positions of the squat and subsequently how it could affect muscle activation. However, this forward lean did not have an effect on the knee kinematics. The primary movers in both front and back squat are the quadricep muscles, there were limited differences in EMG activation despite significantly heavier loads employed in the back squat, except VM activity was greater in the front squat. This lends support to the hypothesis that front squats are better than back squats for quadricep development. Minimum hip angle was significantly higher during front squat as product of more upright torso (Figure 2.), it may be that a greater forward lean increases hamstring activity in which case back squats should elicit greater hamstring activation than front squats. However, this forward lean may also increase the risk of disc herniation by transferring load from muscles to passive tissues (Myer et al., 2014). Thus, when seeking to optimise muscle activation under a decreased load, front squats may be optimal (Gullet et al., 2009).

Differences in mechanical positions and muscle activation between front and back squats or between individuals could be a product of differing movement patterns as a result of muscle dominance. Muscle dominance means the tendency of an individual to rely on one joint more than the other. Individuals may be knee-dominant or hip-dominant. For individuals who are knee dominant flexion at the knee will precede flexion at the hip when squatting and individuals are more likely to rely on the quadriceps. For hip dominant individuals hip flexion will precede knee flexion and it is more likely for them to recruit hamstrings and glutes. Hip dominant athletes present a greater forward lean in squats whilst knee dominant athletes have a more vertical torso (Fry et al., 2003). This may have led to the misconception that front squats have greater quadricep activation because the bar positioning encourages a more upright torso and hence a more knee dominant movement pattern but this difference in quadricep activation is not universally present in literature.

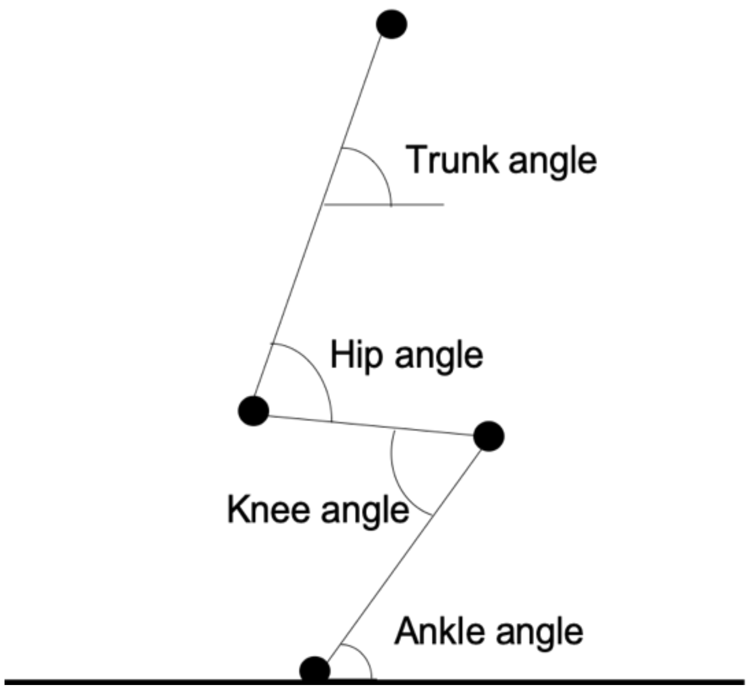

Figure 2: *A schematic demonstration of the joint angles described.*

There are certain factors that can affect EMG signal that cannot be controlled, such as firing characteristics of motor units including firing rate, the number of detected motor units, and the amplitude, duration, and shape of motor unit action potentials. As a result of these factors there is likely to be variation in EMG between subjects, conditions or even contractions despite normalisation (De Luca, 2004). Additionally, crosstalk between nearby muscles can impact EMG signal, previous research has demonstrated that 17% of electrical activity of nearby muscles can be detected alongside the muscle being studied which could lead to misconceptions regarding the activation of the muscle being studied (De Luca, 2004; DeLuca & Merletti, 1988). These factors could introduce inconsistencies between studies above making them difficult to compare.

1.2. Depth

When full range of motion is used it maximises the value of the exercise (Haff & Triplett, 2016). Full range of motion is arguably different for everyone depending on mobility limitations. A deep squat, where hips are below the height of knees, could be considered to be optimal based on the idea that this is the full range of motion for the squat movement and imposes the greatest mechanical demand (Esformes & Bampouras, 2013). However common mobility limitations of the hips, ankles and thoracic spine prevent many individuals from performing deep squats without a high injury risk. In this case parallel squats, where the top of the thighs are parallel, are a potentially safer option as for some this is their safe full range of motion. A deep squat is essential in Olympic Weightlifting due to the transfer to the bottom positions of the Clean and the Snatch (Lucero et al., 2019). Whereas the parallel squat is most commonly used in Powerlifting where the rules state that the hip joint must be parallel or below the knee joint or the top of the thigh parallel to the floor (Glassbrook et al., 2019). The quarter squat, defined as a knee angle of approximately 55-65 degrees of knee flexion (Rhea et al., 2016), is used in many sporting contexts to overload the musculature whilst decreasing mechanical demands and fatigue (Haff & Triplett, 2016). Long term use of the quarter squat may reduce mobility hence should not be used exclusively or in large volumes such as in this study (Haff & Triplett, 2016). When studying squat performance, the effects of depth must be considered both between participants, and between squat types as there are arguable effects on EMG, hence in this study participants only performed full or parallel squats and partial squats were not included.

1.2.1. Parallel and full

In competitive strength sports, parallel and full squats are the most commonly employed (Austin & Mann, 2021; Lucero et al., 2019). These two different depths have been argued to produce differing muscle activation.

In a study performed by Contreras et al. (2015), with an all-female sample, front, full and parallel back squats produced similar mean muscle activation in the GM, BF and VL however there were marginal differences in peak EMG for the VL where parallel elicited slightly greater VL activation than full squats or front squats. Contreras et al. (2015) also noted that the BF was not activated much in any variation, indicating that there is minimal recruitment of the hamstrings in squats. Further exercises should be performed for optimal hamstring development. This study concluded that, in terms of muscle activation, there is no need to go to the full range of motion for full squats and additionally front squats do not necessarily produce any different results from the easier less technical back squat. However, Contreras et al. (2015) stresses that where appropriate the full squat should be employed unless the individual has mobility issues or injury that may be aggravated by full range of motion.

A later study by Hammond et al (2016) compared muscle activation differences between full, parallel and quarter squats. Hammond et al (2016) recruited 8 males with approximately five years of experience using the barbell back squat to full depth. All trials were performed on the same day, whilst this ensures that the EMG signal is reliably comparable between squat types there may be some element of fatigue between squat types. Although they allowed 10 minutes of rest time to dissipate fatigue, it could be argued that performing warm ups and 5RMs for three squat types within the same session would produce more fatigue than could be dissipated by this rest period. In a review by Clark et al (2012), it was summarised that muscle activation and power is reduced for up to 30 minutes following a high load power test hence fatigue may have altered performance of squat types dependent on order performed.

Muscle activation was greater in the concentric phase than the eccentric phase. Activation was not significantly different between full and parallel squat, in accordance with Contreras et al (2015). However, Hammond et al (2016) also noted a higher GM activation in the parallel squat, it was suggested to be the result of a number of reasons including potentially reduction of the demand on the GM by increased activity of the quadriceps, evidenced by higher VM activity. However, Caterisano et al. (2002) suggest that as squat depth increases, only gluteus maximus activity increases, with no differences in BF, VL or VM.

In accordance with Contreras et al. (2015), parallel and full squats produced similarly low levels of activity in the BF. Hammond et al (2016) concludes that for GM building, a parallel squat is optimal whilst for quadricep development parallel or lower is suitable. There is no evidence of benefit, or detriment, of squatting to below parallel.

Oshikawa et al (2018) also studied the difference between parallel and full squats however studying trunk and lower-limb muscle activation with differing hip joint rotational positions using different loads in 10 males. The two hip joint rotational positions were neutral and external. The neutral position was defined as the patella and toe facing forward and the external position as the patella and toes rotated 45° outward. The study used 80% of 1RM for parallel and 60% of 1RM for full squat making them difficult to compare. Despite the lighter load the full back squat elicited similar if not higher levels of muscle activation than the parallel. Hence it can be concluded that unless seeking to improve range of motion or compete in Olympic weightlifting, a parallel squat is sufficient.

1.2.2. Partial

In some cases, a partial squat may be employed. Such as when seeking to overload the musculature without increasing mechanical demands and fatigue (Haff & Triplett, 2016). This squat may produce differing muscle activation when compared to parallel and full squats as it is a smaller movement often with a greater load.

Hammond et al. (2016) also studied partial squats in addition to parallel and full, finding that the VM and VL were evidenced to be more active during the parallel and full back squat than the partial in the concentric phase. Additionally, partial squats produced even less activation of the BF than parallel and full squats. Therefore, when seeking to increase muscle activation of the quadriceps and hamstrings, the partial squat may not be as effective as the parallel and full squat.

In contrast, research by Da Silva et al (2017) concluded that the partial back squat could maximise muscle activation of the GM and BF when compared to the full squat. This study differed to the work by Hammond et al. (2016) in that a larger sample of 15 experienced males performed a 10RM for partial and full squats and there was a 30-minute rest break between squat types. The higher muscle activation in the GM and BF may have been the result of the heavier load that can be employed as a partial squat is a smaller movement or because stability in the bottom of a full squat does not require increased activation of the GM. It was also reported that there were no differences in quadricep activation between partial and full squat. Both studies have a small sample so both studies could be underpowered.

Although there is debate surrounding muscle activation differences in partial squats compared to full and parallel, partial squats have been proven to be beneficial in sporting contexts. For example, partial squats have been demonstrated to be beneficial in improving sprint time and vertical jump height as a result of the similar hip and knee joint ranges involved (Del Vecchio et al., 2018).

This research evidences that more research needs to be undertaken with larger samples to confirm the role of the quadriceps and hamstrings in the back squat at different depths as there are contrasting findings using multiple loads. There may also be differences in depth between front and back squat in the same individual due to the different mechanical positions employed as a result of different bar positioning.

1.3. Stability

Stability is most often defined as the ability of a body to return to equilibrium after being displaced. The barbell squat requires stability in the sagittal, frontal, and transverse planes (Saeterbakken et al., 2019). As load increases, more stability is required to avoid excess displacement or buckling, if unstable this could result in loss of balance, failure of the lift and possible injury (McGill & Cholewicki, 2001). The positioning of the barbell in the back squat allows more stability than the front squat (Braidot et al., 2007). Braidot et al (2007) notes that instability in squats alters spine and abdominal muscle activation hence it may be the case that erector spinae activity is greater in the front squat as it is more unstable. However, this greater instability may be unhelpful for beginners and those recovering from injury as it may result in loss of balance and injury.

Front squats are more unstable than back squats and this is the result of bar positioning being across the front of the shoulders rather than behind. The front rack position is created by keeping the elbows high, ideally parallel to the floor, and creating a ‘rack’ across the front of the shoulders, whilst preventing the bar from pushing on the throat which requires sufficient mobility. Additionally the core and spine must maintain an upright position despite the forward pull of the bar. There is evidence to suggest that increasing instability in squats can alter muscle activation, this has been shown in the use of flexible bars and in overhead squats.

Fletcher and Bagley (2013) compared muscle activation between a stable Smith Machine squat, a barbell back squat and a Tendo-destabilizing bar squat, the most unstable. It was evidenced that EMG was greater in the most unstable condition as decreased stability poses a greater challenge to the core (Aspe & Swinton, 2014). The instability increases demand on co-ordination and muscle synergy and hence may be more transferable to sport situations. Hence flexible or unstable bars can alter muscle activation by increasing instability.

Work by Caterisano and Hutchinson (2017) support this hypothesis, noting that there was greater muscle activation in the VL and RF when using a flexible bar compared to standard Olympic bar however no differences in BF and ES. It was also reported that the flexible bar increases ground reaction forces. The study was performed using NCAA Division I footballers, so whilst the individuals are likely to be healthy and trained, it is unclear how much weight training experience they have and this is not specified in the study. The participants performed 12 repetitions at a speed of 52 repetitions per minute at 30% of 1RM which allows insight into how the flexible bar is different to steel bar in speed training, for example in the difference in force-velocity relationship and neuromuscular function.

There may be reason to repeat the study with experienced weight trained athletes at a higher percentage of 1RM with a lower repetition range to study differences in muscle activation and force production at maximal weight. Brown (2018), inventor of the flexible Tsunami bar, suggests that the bar allows dispersal of weight to the outer sections of the body from the spinal column therefore reducing spinal injury risk. Further research might investigate this claim further as an advantage of using a flexible bar compared to steel bar.

The overhead squat uses significantly lower weights than the back squat but it was suggested that due to the extra stability requirements needed to keep the bar secure overhead, overhead squats may elicit greater electromyographic activity of the trunk musculature (Aspe and Swinton, 2014). Results showed that although as weights increased ES muscle activity increased in both types, it was not significantly higher in the overhead condition compared to back squat. However, the overhead squat elicited greater muscle activation in the rectus abdominus and external oblique when using relative loads. It was concluded that, although not definitively, overhead squats can alter muscle activation of the core by increasing instability. Nevertheless, the back squat remains superior in muscle activation of the lower body muscles due to the ability to use heavier loads as well as the stability of bar positioning. If it is the case that stability enables greater power production it will be greater in the back squat.

1.4. Equipment

As percentages increase closer to maximal, individuals may utilize equipment to support them in squats such as weightlifting belts, knee wraps, and most commonly weightlifting shoes. Weightlifting shoes have a heel height that ranges from 1.5cm to 2.5cm with the average being 1.9cm. This enables a deeper squat with greater knee flexion because less ankle dorsiflexion is required and mobility becomes less of a limitation (Figure 1b.)

In a study comparing barefoot, running shoe, and weightlifting shoes, Sinclair et al (2015) concluded that out of 14 male participants there was a significant preference for squatting barefoot, seven preferred to squat barefoot and the other seven chose either weightlifting shoe, bare-foot inspired shoe and the running shoe. Depth was greater with the running shoe than barefoot and there were no differences between weightlifting shoes and other shoe types which contradicts the expectation that weightlifting shoes enable a deeper squat (Lee et al., 2019). Peak knee flexion and ankle dorsiflexion were slightly higher in weightlifting shoes than other shoe types with peak hip flexion being slightly lower but only ankle dorsiflexion was considered significant. Running shoes also have a higher heel but not as high or sturdy as the weightlifting shoe as they are usually made of rubber whilst weightlifting shoes are wood or hard plastic. This may have enabled the greater squat depth seen in running shoes compared to barefoot, in which case the hypothesis that a heel allows a deep squat is still correct. It was also evidenced that muscle activation of the RF was higher in the running shoes compared to barefoot as a product of the increased depth.

Ankle mobility has been demonstrated to be negatively correlated with trunk angle meaning that deficits in ankle mobility result in a less upright trunk (Fuglsang et al., 2017). These deficits in some cases could be helped by employing a weightlifting shoe. Lee et al (2019) reported that there were no significant differences in spinal and quadricep muscle activation or trunk and knee kinematics using a weightlifting shoe. It is stressed that the use of weightlifting shoes will not prevent back injury, and as such should be not be employed on the basis of preventing injury but enabling a deeper squat by reducing emphasis on ankle mobility. Authors noticed a greater peak knee flexion of 2-2.5 degrees in lifting shoes compared to barefoot. The shoes also offer an increased stability to lifters and this may contribute to the preference for wearing them. There is limited evidence for a large performance enhancing effect of weightlifting shoes on the back squat and wearing them should be decided based on the preference of the athlete.

Additionally, knee wraps or sleeves can be used to decrease the difficulty by supporting the athlete. Gomes (2015) explored the effect that knee sleeves have at low and maximal loads in 14 males. At 60% of 1RM the use of knee wraps increased the GM and VL activation and at both intensities decreased knee flexion. This implies that knee sleeves limit depth and should be employed only by athletes that evidence adequate mobility.

1.5. Sex

It is important to consider the role of sex in muscle activation during squats. The studies above all recruit samples of exclusively one sex, or in the case of Gullett et al. (2009) disregard the role of sex. Mehls et al. (2020) note a significantly higher muscle activation in the BF of males in the eccentric phase of the back squat. Mehls reported that there were no other muscle activity differences in the sample of 24 participants but further study into muscle activation differences between sexes may dispel confusion surrounding the role of the BF and GM in squats. As Mehls et al., (2020) concludes, males may be more able to recruit and activate the BF than females.

In males, VM activity has been found to be greater in the front squat than in the back squat whilst ST activity is greater in back squat concentric action than front squat (Yavuz et al., 2015). In a study of both sexes, though with a small participant number of seven, no differences were shown between the squat types in RF, VL, VM, BF, ST, and ES only that muscle activity was higher in the concentric than eccentric phase (Gullet et al., 2009). Contreras et al. (2015) noted no differences in front and back squat in GM or BF activation in females whereas in males Boylett-Long (2019) reported significant differences in BF and GM activation between front and back with the back squat eliciting higher activation. This may be the reason why differences were not found in a study involving both sexes, such as that by Gullet et al. (2009), as the effect is cancelled out when sexes are combined. Boylett-Long (2019) also suggest that the front squat elicits higher ES activity than the back squat possibly because of the necessity to keep an upright posture. This may also be related to squat depth as Wretenberg et al (1996) suggest that as depth increases, trunk angle decreases in order to maintain balance, hence why using low-bar back squat limits depth as the trunk is already leant forward.

Table 1: Sample characteristics and outcomes of the main back squat EMG studies (From Section 1).

Author	Sample characteristics	Weight training experience (years)	Study Outcomes
Aspe & Swinton. (2014)	**n:** 14 (14 male) **age:** 26 ± 7 years, **height:** 182.5 ± 13.5 cm, **weight:** 90.5 ± 17.5 kg	9 ± 7	Muscle activation increased as load increased, heavier weights elicited a greater kinetic stimulus. The concentric phase of the heaviest weight elicited almost maximal activity.
Caterisano & Hutchison (2017)	**n:** 10 (10 male) **age:** 19.5 ± 1.4 years, **height:** 182 ± 7.4cm, **weight:** 89.4 ± 17.1kg	-	Greater muscle activity in the VL and RF with increased instability caused by flexible bar, no differences in BF or ES activity. Flexible bar increases ground reaction forces and possibly motor unit activation.
Contreras et al. (2015)	**n:** 13 (13 female), **age:** 28.9 ± 5.1, **height:** 164 ± 6.3 cm, **weight:** 58.2 ± 6.4 kg	3 +	Similar mean EMG activation of GM, BF and VL in front, full and parallel squats. However, peak VL EMG activity was higher during front squats than parallel squats, BF not highly activated in any squat variations.
Da Silva et al. (2017)	**n:** 15 (15 male) **age:** 26 ± 5 years, **height:** 173 ± 6 cm, **weight:** 80 ± 8 kg	5 ± 2	Muscle activity of GM, BF and Soleus were higher in partial back squat than parallel. The range of motion in the back squat alters muscle activation of the prime mover, GM, and the stabilizers, Soleus and BF.
Erdag & Yavuz. (2020)	**n:** 14 (14 male) **age:** 23.7 ± 2.7 years, **weight:** 86.8±10.2 kg	3 ± 1	Highest RF, VL and VM activities during front squat and significantly different to Zercher Squats. ES and semitendinosus activity was lowest during Hack squat. For quadricep focus, front squat should be selected whereas for knee and spinal stabilization hack squat is preferable.
Fletcher & Bagley (2013)	**n:** 14 (14 male) **age:** 21.7 ± 2.6 years, **height:** 179 ± 7 cm, **weight:** 83.2 ± 14.1kg	1 +	Muscle activation of the trunk can be increased by introducing instability, the back squat elicited greater muscle activation than the smith machine squat.
Gomes et al. (2015)	**n:** 14 (14 male) **age:** 24 ± 4 years, **height:** 176 ± 7 cm, **weight**: 81 ± 11kg	3 ± 1	Higher muscle activity in VL and GM at 90%1RM than 60%1RM and also significant differences in peak hip joint flexion.
Gullet et al. (2008)	**n:** 15 (9 male, 6 female), **age:** 22.1 ± 3.6 years, **height**: 171.2 ± 6.4 cm, **weight:** 69.7 ± 6.2 kg.	1 +	Higher compressive forces and knee extensor moments in the back squat compared to the front squat with no differences in shear forces. No differences in muscle activation between squat types but activation was greater in ascent than descent. Front squats can minimise compressive forces and are more optimal for muscle recruitment
Hammond et al. (2016)	**n:** 8 (8 male) **age:** 21 ± 1, **height:** 176 ± 5 cm, **weight:** 80 ± 9 kg	5 ± 1	GM activity was greater in parallel compared to full squats. The highest EMG values were seen in VM and the lowest in BF. Parallel or below squats induce greatest quadricep activation.
Korak et al. (2018)	**n**: 13 (13 female), **age:** 22.8 ± 3.1, **height:** 166.4 ± 4.2cm, **weight**: 73.4 ± 14 kg	1 +	No significant differences among deadlift, front squat and back squat in muscle activation of the VM, VL, BF, and RF. Greater GM muscle activity during the front squat than deadlift and (insignificantly) back squat.
Lee et al. (2019)	**n:** 14 (7 male, 7 female), **age:** 26±2.5 years, **height**: 168 ± 11cm, **weight**: 72.7 ± 12.9kg	4 ± 2	Raising the heels does not affect muscle activity or trunk and knee kinematics in the back squat so are unlikely to provide protection against back injuries.
Mehls et al. (2020)	**n:** 28 (14 male, 14 female) **males age:** 23.71 ± 3.02 years, **height:** 179.94 ± 6.61 cm; **weight:** 86.03 ± 9.10 **females age:** 20.64 ± 1.45 years, **height:** 169.0 ± 8.74 cm; **weight:** 77.85 ± 17.51	1 +	Higher muscle activation in males BF during descent of back squat but no other sex differences in muscle activation. Males may activate the BF muscle more, or more efficiently recruit it, than females.
Oshikawa et al. (2018)	**n**: 10 (10 male) **age:** 20 ± 2 years, **height:** 175.6 ± 7.2 cm, **weight:** 88.9 ± 15.0 kg	-	Greater lumbar lordosis when hips were externally rotated compared to neutral during parallel back squats but no differences in muscle activation of trunk and hips. During full back squats, ES and Multifidus activities were lower in hip external rotation, but GM activity was significantly higher in hip external rotation.
Sinclair et al. (2015)	**n:** 14 (14 male) **age:** 19.14 ± 0.71 years; **height:** 1.74 ± 6.38 cm; **weight:** 69.75 ± 6.38 kg.	5 +	Greater squat depth, knee flexion and mean and peak RF activation in running shoes compared to barefoot but barefoot was preferred by individuals. Peak range of motion was greater in weightlifting and running shoes. No differences between shoe types in torso or hip kinematics but footwear may alter kinematics and EMG of squat.
Yavuz and Erdag (2017)	**n:** 14 (14 male) **age:** 21.6 ± 2.3 years, **height:** 178.4 ± 5.1 cm, **weight:** 80.1 ± 7.2 kg	3 ± 1	Increase in muscle activities with increasing loads, there was an increase in forward lean accompanied by a change in movement pattern of at the hip joint but no change in Semitendinosus muscle activation. BF elicited more muscle activity than the Semitendinosus. GM activity increased in descent at 90% loading and further increased in both descent and ascent at 100%. At 100% the forward lean increased in descent then subsequently decreased in ascent.
Yavuz et al. (2015)	**n:** 12 (12 male) **age:** 21.2 ± 1.9 years	-	EMG was greater in the back squat during the ascending phase. Compared to the front squat version, back squat exhibited significantly greater trunk lean, with no differences occurring in the knee joint kinematics throughout the movement.

All of the above factors discussed have an effect both on back squat performance and may play a role in differences between front and back squat.

2. Ground reaction forces and kinematics in squats

As previously stated, there is a need to explore force production and kinematic differences in front and back squats as well as differences in performance by males and females. In rehabilitation from lower limb injury, bodyweight squats are often used and in the later stages where they can begin to be loaded it is important to consider ways to reduce unnecessary stress on the joints, such as by optimising choice of squat type, for example, high bar back squats, low bar back squats, or front squats. For upper limb kinematics, front squatting places more pressure on the wrists in those with limited mobility or in beginners who are unsure of how to position the bar. Hence in sports where power production needs to be trained directly, back squats may be more appropriate due to greater stability of bar positioning and more confidence in technique. Differences in the mechanical positions produced by front and back squat may alter cadence and knee flexion and subsequently force production,

2.1. Squat differences

To the authors knowledge, GRF differences between front and back squats has not been studied directly however there is study on GRF in the back squat (Glassbrook, 2017; Zink et al., 2006; Bentley et al., 2010; Dali et al., 2013). Increasing the external load will result in increased ground reaction forces (Zink et al., 2006) hence it can be expected that back squats will produce higher GRF due to the employment of a larger load.

The cadence of the squat can also alter GRF. It has been suggested that a faster cadence results in higher GRF (Bentley et al., 2010) hence hesitation due to instability or a heavier weight causing slower movement may reduce GRF. Subsequently, the greater instability of the front squat as a result of bar position may result in lower GRF or alternatively a slower movement as a result of fatigue could also result in lower GRF. Instability has also been suggested to have effects on GRF, with greater instability resulting in lower GRF (Lawrence & Carlson, 2015). Braidot et al. (2007) report that the greater stability of the back squat resulted in faster cadence hence it could be expected than the front squat would have significantly lower GRF.

Angle of knee flexion has been suggested to influence vertical GRF in back squats, less knee flexion can result in lower ground reaction forces (Dali et al., 2013). If knee flexion is influential, vertical GRF can be expected to be different for front and back squats where front squats demonstrate a higher degree of knee flexion. In a study of full and parallel squats (Swinton et al.,2012), vertical GRF was found to be similar in the two squat types across different loads indicating that depth does not alter GRF. The findings do contest the above suggestion that knee flexion alters GRF as full and parallel squats did not differ in GRF despite significantly different degrees of knee flexion.

A key difference in the kinematics of front and back squats is that front squats are more knee-dominant while back squats are more hip-dominant as earlier discussed, and this may impact muscle activation and force production studied. Energy generation in the knee is greater in the front squat, supporting the notion of a difference in knee and hip dominance in the front and back squat (Braidot et al., 2007) (Figure 2.). In back squats there is a smaller degree of ankle dorsiflexion and knee flexion encouraging greater range of motion at the hip (Krzyszkowski & Kipp, 2020), which may prove optimal for those with limited mobility or previous injury.

When comparing high bar and low bar back squats, Glassbrook et al (2017) noted that an increased forward lean increases the force placed on the hip compared to the knee and reduces stress on the Anterior Cruciate Ligament (ACL) by increasing hamstring activation (Escamilla, 2001). Therefore, it could be said that knee and hip dominance differs in front and back squats due to the differences in trunk inclination, the angle of the hip is greater in a back squat so the trunk is likely to be inclined further forward. Additionally, the position of the barbell on the shoulders also pushes the trunk forward which is why back squats are often failed forward despite the barbell being on the back, this can place pressure on the lower back if not performed correctly (Braidot et al., 2007). Decker et al. (2003) also observed that the greater energy absorption at the knee in women was likely due to a more erect landing posture so the more upright position demanded from the front squat correlates with greater knee flexion. Trunk inclination increases as load increases (Kellis et al. 2005) but this is less prominent in the front squat than the back squat (Russell and Phillips, 1989; Diggin et al. 2011).

The role of the lower back in front and back squats is also a topic of debate. While Goršič et al. (2020) found no differences in trunk flexion angles in front and back squat, they did acknowledge an increased number of lower back moments in the front squat due to anterior tilting of the pelvis to compensate for the limited trunk flexion. The front squat produced fewer hip and ankle moments compared to the back squat but knee moments were increased (Goršič et al., 2020). As trunk flexion decreases, the compressive forces are increased and the shear forces decreased, this is regardless of squat type and load. Earlier research presented that higher peak compressive forces and peak shear forces act on the lumbar spine in the back squat than the front squat (Clancy, 2010) but these forces are dependent on posture rather than the load. This implies that it is not the squat type that elicits the most impact but the degree of trunk inclination and this differing degree of trunk angle may alter muscle activation of the core and back.

2.2. Sex differences

Not only is it important to compare squat types but also to consider sex differences in performance which may predispose to injury or require alterations in exercise prescription and loading.

There is limited evidence for sex differences in GRF in squatting but unless normalised to bodyweight it can be expected that the higher mass of males would result in higher GRF. In overhead squatting males had greater normalized peak vertical ground reaction forces (vGRF) than females (Mauntel et al., 2015). Some GRF differences between sexes were suggested to result from males exhibiting greater knee flexion and ankle plantarflexion (Harry et al., 2019). Flanagan & Salem (2007) noted no differences in GRF between sexes under any load but also that every subject was individual in bilateral differences shown and the side of bilateral advantage was maintained throughout.

There are multiple studies investigating GRF in double leg landings, meaning a drop landing onto both legs, however maximum knee flexion and hip flexion angles are higher in squat than double leg landing, and maximum external knee abduction moments are higher in double leg landing (Donohue et al., 2015). For this reason, it is difficult to compare the results of previous studies using countermovement jumps or bilateral landings with those of squat studies like this one as the eccentric and concentric movements of jumps and squats are not necessarily comparable (Donohue et al., 2015; Wallace & Kernozek, 2008).

Although not studied in this work, it is important to consider how differences in kinematics may have influenced muscle activation and ground reaction forces, particularly how sex differences may have arisen as a result of these kinematic differences as there are a number of differences between males and females.

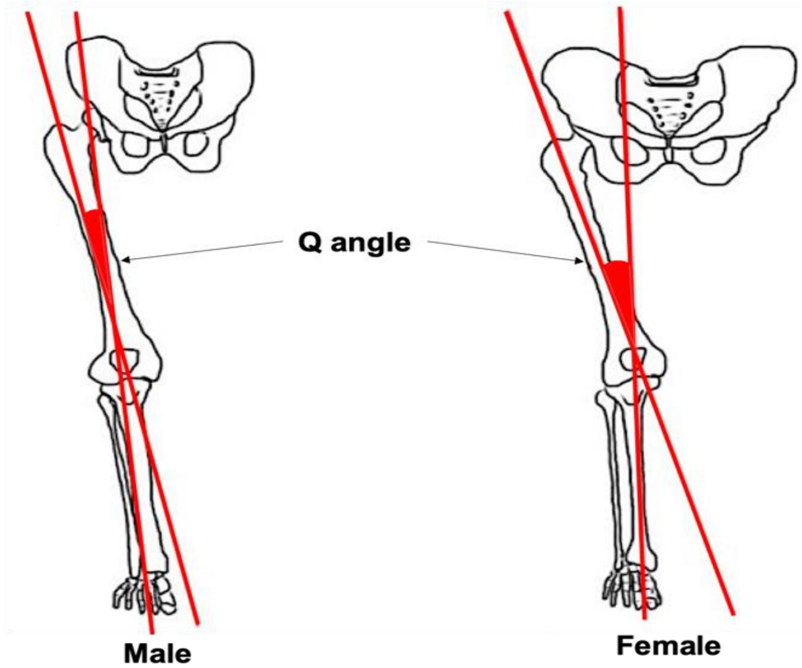

Figure 3: *Diagram demonstrating differences between males and females in the Q angle between the quadriceps and patella tendon. (Adapted from Canbolat et al. 2018)*

It has been confirmed that there are sex differences in the movement pattern in performance of the back squat. Females have a greater degree of ankle dorsiflexion and ankle pronation than males which predisposes to lower limb injury (Zeller et al.,2003), although this report was on single legged squats. Females have an increased tendency towards bone stress injuries, stress fractures (Wentz et al., 2011; Kunte et al., 2017) particularly at the knee (Lin et al., 2018). This increased tendency toward injury may be due to the increased mobility seen in females (Chimera et al., 2015; Blackburn et al., 2004; Marshall & Siegler, 2014; Grimston et al., 1993), as well as having more anatomical risk factors and an increased susceptibility due to the hormone Relaxin which affects the musculoskeletal system by relaxing cartilage and ligaments and increasing lower extremity injury risk particularly at the ACL (Dehghan et al., 2014). The squat is frequently used in rehabilitation for ACL injury. ACL injuries, as mentioned, are more commonly associated with females (Mendigucha et al., 2014). Females have a greater Q angle, the angle between quadriceps and patella tendon (Piantanida & Yedlinksy, 2008), than males (Figure 3.). When this angle is significantly great it can predispose to excessive lateral tracking of patella, meaning it is no longer aligned with other joints, and results in subsequent knee injuries (Khasawneh et al., 2019). A greater Q angle also predisposes to knee valgus, increased hip adduction and internal rotation due to decreased hip abduction strength in females (Petersen et al., 2014). Comparing 18 male and female college athletes performing a one-legged squat, Zeller et al (2003) noted that females show more ankle dorsiflexion, ankle pronation, hip adduction, hip flexion and hip external rotation than males, demonstrating a tendency for women to adopt positions that place strain on lower extremities. Increased dorsiflexion is said to be of benefit in squatting because a limitation in ankle flexibility results in rising of the heels off the ground and increased ACL forces so this may be a factor in minimising ACL injury in females (Schoenfeld, 2010).

The increased tendency for hip adduction shown by females also leads to greater knee valgus angle, which increases ACL stress (Schoenfeld, 2010), and this leads to increased recruitment of the quadriceps to support the knee during the concentric phase of the squat (Robertson et al., 2008). Youdas et al. (2007) noted that males are more able to effectively activate hamstrings in a single leg squat than females, moderate hamstring activity has been shown to help unload the ACL of the knee (Escamilla et al., 2012; Schoenfeld, 2010). If this is the case, higher quadricep activation would be seen in females to support the knee during back squats due to the lower activation of the hamstrings but this increases the risk of lower extremity injury. When studying muscle recruitment in females with and without patellofemoral pain, Powers (2000) concluded that the EMG ratio of VL to VM was predictive of lateral tracking of patella, specifically greater activation of VM. Youdas et al. (2007) also noted that females are quadricep dominant in the single leg squat, although quadricep dominance has been shown in unweighted squats for both sexes it has not been confirmed that this dominance exists in females in the back squat (Hale et al., 2014). Mehls et al., (2020) reported no muscle activation differences in VL, VM, RF, GM or ST, only higher BF activity in males during the eccentric phase when performing 3 sets of 4 back squats at 85% of 1 rep max. Females also show increased knee abduction and this is in part due to uncontrolled lateral trunk motion and increased likelihood of hip adduction (Mendiguchia et al., 2014). Increased knee abduction and hip adduction has been evidenced to increase likelihood of ACL injury (Hewitt et al., 2005).

McKean et al., (2010a) suggests that females are able to perform a more synchronised squat than males, as they have a greater tendency for reaching maximum knee and hip angles at the same time. These angles are shown in Figure 2. This synchronicity may increase knee stability as co-contractions of the quadriceps, hamstrings and gastrocnemius could support the knee (Escamilla, 200l). However, females maintain these angles regardless of load and this may be a detriment, males increase knee and hip angles to enable a deeper squat at heavier loads (McKean et al, 2010a). Females have been suggested to execute double leg landings with a more erect posture and less trunk flexion, this more erect posture may predispose the knee joint to injury as, compared to males, females exhibit greater energy absorption from the knee extensors and ankle plantar-flexors (Decker et al., 2003; Graci et al., 2012; Pincivero et al., 2003). This observation was later supported by research evidencing that females use lower limb and core muscles differently to men based on different muscle activation patterns (Wallace & Kernozek, 2008) and males and females demonstrate differences in neuromuscular activation patterns of the RF (Clark, 2005).

The front squat arguably requires more core stability than the back squat to maintain upright position, there has been evidence that males exhibit higher abdominal endurance than females in dynamic trunk flexion (Brotons-Gil, 2013) but not in isometric (Evans et al., 2007). This research suggests that males would be able to perform more front squats with lesser detriment in form than females due to higher abdominal endurance in dynamic exercise performance. However, females demonstrate a more upright posture in squats than males so potentially may demonstrate a more stable front squat. Hence in this study it is unclear whether males or females will fatigue differently in front squats due to differences in abdominal endurance.

As lumbar flexion increases outside of safe ranges, so do shear forces (Schoenfeld, 2010) but compressive forces decrease (Russell & Phillips, 1989). Females show a smaller degree of lumbar flexion and greater activity of the lumbar extensors in stabilisation than males so it could be implied that females will have lesser shear forces in squatting (Bolgla et al., 2014; McKean et al., 2010b), but to compensate pelvic tilt and range of movement of the sacrum is greater (Mohan & Huynh, 2019;McKean et al., 2010b) and this trunk and pelvic movement pattern increases injury risk particularly at the knee (Graci et al., 2012; Mendiguchia et al., 2014). It has been suggested that individuals engaging in regular weight training experience spinal adaptation and increased compressive tolerance to mechanical stress because they are capable of squatting at above the threshold of spinal failure without injury (Schoenfeld, 2010; Hartmann et al., 2013). Females have smaller vertebral bodies and so even with adaptation to mechanical stress will still experience higher compressive forces than males (Gilsanz et al., 1994). In experienced lifters, such as those recruited in this study, muscle activation of the ES in front and back squats may not differ as a result of spinal adaptation from using front and back squats in a regular weight training programme however males and females may differ as a result of females experiencing greater mechanical stress despite adaptation and females may exhibit greater ES activation.

3. Mechanisms underpinning sex differences in exercise performance.

Table 2: Sex differences in various physiological parameters.

	Males	**Females**
Anthropometric	Larger body mass [1]	Lower muscle volume [3]
	Higher muscle mass [1]	Lower muscle quality [3]
	Lower body fat percentage [2]	Increased fat storage around glutes, hips, and femoral region [4]
	Greater proportion of Type II fibres [5]	Greater proportion of Type I fibres [5]
Hormonal	Higher testosterone [6]	Higher oestrogen[7]
Circulatory	Higher blood pressure [10]	Less occlusion of blood flow [8]
	More susceptible to post-exercise syncope [11]	Lower red blood cell count and haemoglobin levels [9]
Metabolic	Higher rate of carbohydrate oxidation [12]	Accumulate less intramuscular lactate [6]
	Higher energy expenditure [12]	Higher oxygen utilisation per unit of fat free mass [13]
Cardiovascular	Higher levels of plasma norepinephrine [10]	Lesser reliance on sympathetic activity post-exercise [14]
	Less risk of Torsade de Pointes and cardiac arrest [10]	Longer QT interval [10]

[1]*Janssen et al., 2000*
[2]*Bredella, 2017*
[3]*Merrigan et al. 2017*
[4]*Blaak, 2001*
[5]*Glenmark et al., 2004*
[6]*Abe et al., 2003*
[7]*Janse de Jonge et al. 2001*
[8]*Clark et al., 2003*
[9]*Rushton et al., 2001*
[10]*Huxley 2007*
[11]*Halliwill et al. 2014*
[12]*Gaffney et al., 2021*
[13]*Pauley et al., 2016*
[14]*Barnett et al., 1999*

There are several factors underpinning sex differences in exercise performance including differences in skeletal muscle, cardiovascular function, blood flow and hormonal differences (Table 2.). These all contribute to differences in performance capacity but also in fatigue. More research into female response to physiological and environmental stressors is required as the majority of research is currently on males which disregards potential sex differences.

Anthropometric differences underlie many differences in male and female performance and therefore must be discussed when considering why results may differ between sexes. The factors discussed below outline why it may be hypothesised that males and females will differ in resistance exercise performance.

3.1. Skeletal muscle

Naturally men have a larger body mass and hence more skeletal muscle mass but differences in skeletal muscle mass remain even when controlled for weight and height. Skeletal mass relative to bodyweight was reported to be 7% lower in females (Janssen et al., 2000). It cannot be assumed that differences in strength are accounted for by total mass alone. Males have a higher fat free mass, generally presenting a lower body fat percentage than females despite similar body mass indexes (BMI) (Bredella, 2017). It has been suggested that strength disparity between sexes is accounted for by muscle mass quantity and quality differences rather than total mass differences (Bishop et al., 1986). Muscle quality refers to ratio of muscle strength per unit of muscle quantity, it is affected by a number of factors including muscle composition and metabolism. Hence the strength of a muscle is dependent on the muscle size, the quality and the architecture (Barbat-Artigas, 2013). In a study of the elbow extensors of trained men and women, Merrigan et al. (2017) found that men had almost double the muscle volume of women but that they produced similar relative force per cm^3, hence men were able to produce more force. This provides evidence that men and women can produce similar force but lower muscle mass and quality in females limits the amount of possible force generation (Mala et al., 2015). Merrigan et al. (2017) also reported that the relationship between muscle quality and body fat was different between sexes, with a higher body fat being more closely related to decreased muscle quality in females than in males. Barbat-Artigas (2013) argues that muscle mass is a weak indicator of functional capacity in comparison to muscle quality.

Greater sex differences in skeletal muscle are shown in upper body than lower body due to differences in distribution of lean mass (Miller et al., 1993; Janssen et al., 2000; Gallagher & Heymsfield, 1998), there is a smaller difference in muscle cross-sectional area of the thigh than upper body between male and female non-athletes (Kanehisa et al., 1994; Bishop & Cureton, 1989). To better compare natural muscular strength between sexes it may be better to compare untrained individuals as this strength disparity is more apparent and it also minimises any possible training differences such as males being more likely to train upper body. However even with training there are still clear differences in the strength performance of recreational and elite athletes. In a study of trained individuals performing the bench press Amasay et al. (2016) reported women's strength to be just 32% that of men compared to the previously reported 52% (Miller et al., 1993), however neither study controlled for the frequency of bench press in participant training programmes only experience performing it. Chen et al. (2012) produced a broad percentage of results for female upper body, between 41-58% of male's strength, but also studied lower limb strength differences and found women had 57-68% of the leg strength of males, providing further evidence that there is a smaller strength disparity in the lower than upper body.

There are broadly four muscle fibre types: type I, type IIa, type IIb and type IIx which correspond to the particular isoform of myosin (Anderson et al., 2000; Schiaffino & Reggiani, 1994). Type II fibres are all fast twitch and contain high levels of glycolytic enzymes but are separated based on their fatigability, type IIa have a higher proportion of oxidative enzymes which enables them to be more fatigue resistant than type IIb for this reason they are called fast oxidative glycolytic compared to fast glycolytic. Type IIx have been identified as the intermediate between type IIa and IIb. Type I fibres are simply slow twitch oxidative. Classification as fast or slow twitch is dependent on rate of cross-bridge cycling and therefore speed of muscle shortening (Schiaffino & Reggiani, 2011).

These muscle fibre types compose a motor unit containing all the same fibre type, however, the muscle is formed from many motor units which can have differing muscle fibre types. Therefore, a muscle is comprised of multiple fibre types to enable it to be adaptable to different tasks, proportions can be variable and are dependent on the demand on the muscle (Scott et al., 2001). The expression of the isoforms may change in response to demand or inactivity, for example, under endurance training, fast twitch fibres can adapt to become slow twitch, and results in increases of IIA with decreases of IIB. There is limited evidence for possible conversion of type I to type IIa fibres which is why changes are minimal in predominantly slow twitch fibre muscles (Pette & Staron, 1997).

Males and females exhibit differences in predominance of muscle fibres and hence contractile speed (Glenmark et al., 2004). Females have a greater proportion of type I fibres than males, regardless of training status (Lundsgaard & Kiens., 2014). Miller et al (1993) noted no sex differences in number of fibres per motor unit however it is consistently report that females have smaller muscle fibre cross-sectional areas for all muscle fibre than males (Simoneau & Bouchard (1989); Staron et al., 2000). Due to a higher proportion of type II fibres, males are more likely to rely on anaerobic metabolism to enable faster muscle contractions as contraction and half-relaxation (reduction to 50% of peak force) times were shorter (Glenmark et al., 2004).

The different fibre types and proportions result in a suitability towards an exercise type. Type I fibres for endurance e.g. long distance running or swimming, Type IIa for exercise requiring endurance but also power generation e.g. weightlifters, and type IIb for relatively rapid movements against resistance e.g. sprinting (Qaisar et al., 2016). This indicates that females may be better at endurance sports than males, and although there is evidence of a greater resistance to fatigue in females (Hunter, 2009; Hunter & Enoka, 2001, Hunter et al. 2004), discussed later, males are still repeatedly evidenced to be stronger, faster, and more powerful following puberty (Handelsman, 2017).

3.2. Body fat percentage

Energy expenditure is greatly influenced by BMI, those with a higher BMI such as athletes or obese individuals have a higher energy expenditure. Naturally, men are likely to have a higher BMI, lean mass and fat free mass (Westerterp, 2017) which equates to higher energy expenditure. Females have a higher body fat percentage, when studying male and female national athletes Nudri et al. (1996) identified the males to have 13.8 ± 4.5% compared to females 24.7 ± 5.3%. More recent research suggests that while the disparity in body fat percentage still exists it is slightly smaller in the modern elite athlete. In elite handball players, Cichy et al. (2020) found males to have a body fat percentage 8.3% lower pre-training and 7.6% lower post training than females. Additionally, in a study of elite soccer players there was an average difference of 6.3% (Mascherini et al., 2017). This may be the result of improvement in measurement tools, increased knowledge or a greater focus on female athletes and how to produce optimal training. With a disparity identified in athletes it is unsurprising that this extends to the average individual, males generally exhibit a body fat percentage between 15-20% whilst for females it is 24-30% (Jeukendrup & Gleeson, 2018). This results in a larger amount of inactive adipose tissue deposited around glutes, hips, and femoral region in females (Blaak, 2001) and higher oxygen utilisation per unit of fat free mass making women less energy economical than men (Mondal and Mishra, 2017; Pauley et al., 2016). For this reason, body fat percentage is not necessarily as indicative of fitness in women as it is in men (Paul et al., 2004).

3.3. Testosterone

These anthropometric measurement differences are partially the result of differences in testosterone levels. Males are more able to increase muscle mass and to attain greater strength increases than females due to differences in testosterone levels (Abe et al., 2003). Testosterone levels are related to fat free mass, muscle size and strength levels. An average female's testosterone levels are about 2.3 nmol/L and average male's is 17nmol (King et al., 2005) so creating significant differences in propensity for muscle protein synthesis, strength gains and activation of satellite cells (Figure 4.). Satellite cells aid hypertrophy by proliferating and differentiating into myotubes which can fuse with muscle fibres to lead to muscle fibre growth (Kadi, 2008). Testosterone increases, alongside effective strength training, can result in changes in body composition and muscle pennation angle, hence males have a favourable advantage in strength sports based on baseline levels of testosterone.

There is a suggestion that increased testosterone levels, such as by steroid use, increases muscle fibre size for all muscle fibres but predominantly in type I muscle fibres (Kadi, 1999; Eriksson, 2005). Increases in lean body mass, muscle fibre area and muscle strength are dose-dependent (Yu et al., 2014) and differences between fibre response to testosterone are suggested to be because Type I fibres respond to lower doses of testosterone than Type II fibres (Sinha-Hikim et al.,2006).

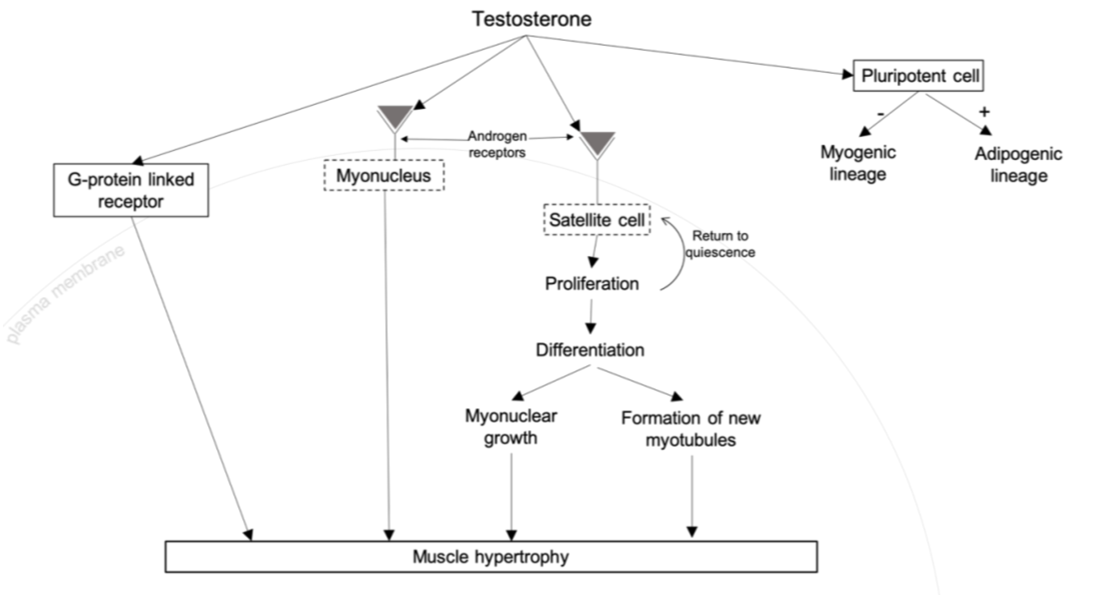

Figure 4: Diagram demonstrating the effects of testosterone on muscle hypertrophy *(based on and adapted from Kadi et al, 2008)*

3.4. Cardiovascular and circulatory differences

Cardiovascular adaptations, like neural and muscular, are a product of the exercise type and demands placed upon the systems. Although there is not as intense a demand on the cardiovascular system in strength training as there is in endurance sports, there is still a requirement for good cardiovascular fitness although this may be different to the well-known expressions and measures e.g. maximal oxygen uptake (Goldberg et al., 1994). Despite the lack of strain on the cardiovascular system, weight training has been evidenced to decrease blood pressure and the cardiovascular demands imposed by exercise (Kraemer et al., 2002). Some exercise forms like CrossFit overlap the demands of weight training and aerobic conditioning and are becoming increasingly popular (Kliszczewicz et al. 2014).

Males have higher blood pressure and this has been related to a higher blood viscosity, the higher viscosity increases resistance to blood flow hence the heart must work harder. Not only does the higher viscosity relate to higher blood pressure but there is also an increased likelihood of clots (de Simone et al.,1991; Huxley (2007). Consequently, there is a greater chance of hypertension and heart failure. However, following a myocardial infarction this difference in risk is dissipated and there is no sex difference in likelihood of heart failure. As expected males have a greater heart size and mass of about 15-30% compared to females (Leinwand, 2003), and this has been noted to create the difference in heart rate seen in males and females. In stress or exercise, males respond to metabolic vasodilation by increases in vascular resistance whereas females increase heart rate, this is likely due to stroke volume being a limiting factor in women as their smaller stroke volume limits cardiac output and heart rate is increased to compensate (Huxley, 2007). Further compensatory mechanisms include reduced energy expenditure or adjustments in mechanical efficiency (Wheatley et al., 2014). It has also been reported that there are sex differences in the use of the baroreflex system to control blood pressure, females exhibit a lesser reliance on sympathetic activity post-exercise and at rest, they have a higher activation of the parasympathetic branch (Barnett et al., 1999). As a result of a more frequent stimulation of the sympathetic branch, males have higher levels of plasma norepinephrine (Huxley, 2007). In a study comparing 18 male and female responses to sympathetic activity, Coovadia et al. (2020) highlight that following sympathetic stimulation females show greater and prolonged increases in blood pressure compared to men indicating that they require less sympathetic stimulation to achieve the same outcome as males.

Females have 12% lower haemoglobin levels than males and generally a lower red blood cell count (Rushton et al., 2001; Murphy, 2014), this has been linked to sex hormones due to the fact that the differences are not exhibited in children and postmenopausal women (Humpeler et al., 1977). Rushton et al. (2001) argue that this cannot be the explanation as the difference is not shown in other primates, and notes iron deficiency resulting from inadequate diet to be responsible. Humpeler & Amor (1973) reported a lower oxygen affinity in females and this may be a consequence of the lower haemoglobin content of the blood.

The differences in blood pressure and circulation make women more prone to orthostatic hypotension and fainting. In resistance exercise, arterial blood pressure is increased significantly, particularly in maximal attempts, and following attempts can drop quickly and this can result in fainting, especially if individuals employ the Valsalva manoeuvre in lifts which slows the heart and can cause a decrease in blood pressure and subsequent fainting (Halliwill et al., 2013). If females are more prone to fainting generally, it would be expected that they would be more likely to faint following maximal lifts. Halliwill et al. (2014) noted that males appear to be more susceptible to post-exercise syncope than females despite females being more susceptible generally. Although a case report, Arad et al (1993) noted that an individual with post-exercise syncope had higher levels of plasma epinephrine than 6 matched controls. Given this, and the knowledge that males have higher levels of epinephrine, it could be suggested that this may be a significant factor in the sex differences of post-exercise syncope. Athletes and sedentary individuals show no differences in syncope in exercise, however we could expect to see more syncope in athletes who are more likely to exert themselves to a maximal level (Brignole & Puggioni, 2002).

Females exhibit a longer QT interval meaning ventricular depolarisation and repolarisation take longer, this puts females more at risk of torsade de pointes which can result in sudden cardiac arrest. A longer QT segment can result in rapid and erratic arrhythmias most commonly under stress or in exercise (Huxley, 2007; Monitillo et al., 2016). This difference appears following puberty, as the QT interval in males shortens but does not in females, endogenous administration of oestrogen has been demonstrated to lengthen QT whilst testosterone decreases it (Sedlak et al., 2012; Surawicz & Parikh, 2003). Genovesi et al. (2007) suggest that trained females show a shorter QT segment than sedentary females, suggesting that the increased risk of cardiac arrest can be dissipated with healthy active lifestyle. This change is unrelated to oestrogen levels which implies that there are more factors at play in the sex differences in electrocardiogram (ECG).

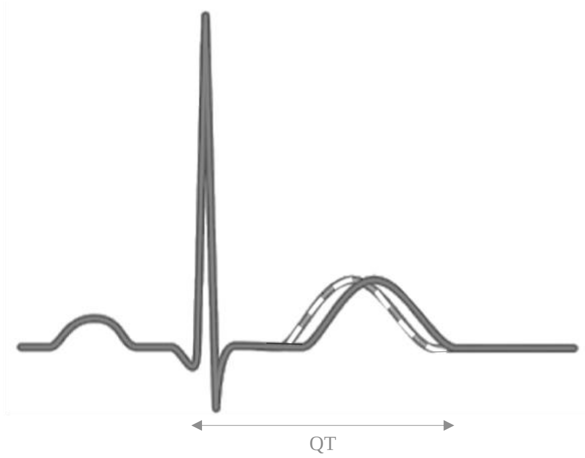

Figure 5: Demonstration of male (dashed) and female (block) ECG QT intervals. *Adapted from Jonsson et al (2010).*

4. Fatigue

Fatigue is defined most often as a decline in maximal force, velocity, or power production, a loss of exercise capacity, or an increased sense of effort. It is reversible and can occur before task failure occurs (Miller et al., 1995; Bigland-Ritchie et al., 1986). Fatigue has been demonstrated to be dependent on the status of the individual, the location of the fatigue and the task itself (Williams & Ratel, 2009). What cannot be ignored is the task-dependency of fatigue; the intensity, the muscles involved, the rest periods, the environment and the activity itself (Williams & Ratel, 2009; Enoka & Stuart 1992). Fatigue is also greatly individual which is why the individual athlete needs to be monitored during fatiguing tasks, a protocol may induce fatigue extremely quickly in one but may need to be performed twice by another before a decline in performance or form occurs that may invite injury (Jones et al., 2017).

Fatigue can be divided into two components; central and peripheral (Wan et al., 2017). Peripheral fatigue can occur anywhere in the neuromuscular system and is identified at the neuromuscular junction, the cell membrane, and impairment to excitation-contraction coupling (Gore, 2007). While central fatigue occurs in the brain and spinal cord (Allen et al., 2008), it is identified in impairment of central drive and neuromuscular propagation (Albert et al., 2006). It is significantly harder to identify central fatigue than peripheral fatigue in a dynamic task, central fatigue encompasses reductions in neural drive and psychological changes that are less easily tracked than changes in the motor unit (Taylor et al., 2016; Norris, 2011). Peripheral fatigue has been measured using EMG, rate of perceived exertion, changes in substrate utilisation and reduction in evoked force production using electrical stimulations of the muscle at rest although none of these are definitive measures, when taken together they can be used to provide a more reliable measurement of fatigue. Central fatigue is often measured using similar measures but also as reduction in voluntary activation with a superimposed twitch during a task using transcranial magnetic stimulation for example (Froyd et al., 2018). It has been stated that central fatigue can occur in maximal tasks and can limit muscle activation (Allen et al., 2008) and hence central fatigue can be recognised by a decrease in muscle activation frequency and force output (Pincivero et al., 2000) or an increase in EMG amplitude (Kallenberg et al., 2007) resulting from changes in neuromuscular activity (Taylor et al., 2016).

4.1. Mechanisms of fatigue in squats

Improvement in the squat or any strength exercise relies on the principle of progressive overload meaning the workload is greater than what the individual is accustomed to (Zając et al., 2015). Progressive overload induces change by forcing neuromuscular adaptation (Kavanaugh, 2007) and consequently neuromuscular fatigue.

There is debate over the involvement of central fatigue mechanisms in resistance training exercises as most research has focused on peripheral fatigue as being the main factor behind performance detriments in resistance exercise (Davis et al., 1997). Peripheral fatigue has been stated to result from a depletion of energy stores, accumulation of metabolic by-products such as hydrogen and inorganic phosphate, or alteration of muscle contractile mechanisms (Zając et al., 2015). Central fatigue has subsequently been defined as the failure to maintain force or power output not explained by peripheral fatigue, including physiological and metabolic responses. Subsequently some performance detriments must result from central fatigue, however research is limited in exploring this (Davis et al., 1997; Noakes et al., 2012; Zając et al., 2015).

During exercise, motor units are recruited as required by nerve stimulation (Baird et al., 2012). These motor units consist of nerve fibres and muscle fibres. Group III/IV muscle afferents are a determinant for motor unit control and facilitate central fatigue by inhibiting central motor drive (Amann, 2013) and these are activated by ATP, inorganic phosphate and hydrogen ions. In resistance exercise, such as squats, muscle damage occurs which results in a release of ATP subsequently activating Group III/IV muscle afferents and resulting in a reduction in central motor drive (Zając et al., 2015). This muscle damage also results in an increase in serum creatine kinase levels which can be used as a marker of a breakdown in muscle cell structure however quantitative analysis should be interpreted with caution due to the high levels of individuality associated with CK responses (Koch et al, 2014).

There is debate over whether EMG activation can be used to distinguish peripheral from central fatigue in squats as it evidences a lack of sensitivity in differentiation. Whilst EMG can be used as an indicator of central activation is should be used with caution (Place et al., 2007). Clark (2005) reports higher relative EMG following fatiguing task and that this is related to central activation changes. A greater increase in EMG amplitude is suggested to result from faster recruitment of motor unit pool (Enoka & Duchateau, 2007), as under fatigue more motor units are recruited as the same amount of force is being produced (Merletti & Farina, 2006). Faster recruitment is associated with higher impulse discharge rates of motor neurons and greater explosive force in males (Del Vecchio et al., 2019). This faster recruitment alongside more central fatigue shown at lower intensities may be a consequence of a control strategy implemented by the central nervous system (CNS) rather than simply in response to a decrease in force production by active fibres (Barry & Enoka, 2007). As

Behm (2004) states, sustaining force is a compromise between fatigue induced impairments and neuromuscular strategies.

There is evidence from evoked force by transcranial magnetic stimulation study that weight training leads to adaption of the CNS and control strategies, and subsequently an increase in ability to voluntarily activate muscle. Transcranial magnetic stimulation is used as a technique to measure voluntary activation based on the principle that if extra force is evoked by supramaximal electrical pulse during an MVC, not all motor units were recruited or they were discharging at sub-tetanic rate (del Olmo et al., 2006; Todd et al., 2003). Those that had two years of weight training experience had a smaller evoked force by transcranial magnetic stimulation than the untrained (del Olmo et al., 2006) suggesting they were already close to optimally activating muscle voluntarily. This has been evidenced in earlier work suggesting untrained individuals are less able to produce maximal activation of motor units (Hortobágyi et al., 1996). However transcranial magnetic stimulation has been suggested to not be optimal in the study of central activation, especially at contraction strengths below 50% (Gandevia et al.,1996). Additionally, these findings cannot be confirmed to be directly transferable to dynamic lifts as they were explored using MVCs.

It is important to acknowledge that there are some studies that have produced evidence of EMG amplitude reducing in response to fatigue (Linnamo et al., 1998) which may indicate loss of recruitment or synergistic activation of multiple muscles (Davis & Walsh, 2010). Therefore, when interpreting EMG amplitude changes across conditions it is important to consider the possible influence of both peripheral and central fatigue.

4.2. Central and peripheral fatigue in squats

Research surrounding neuromuscular fatigue in squats is limited, partially as a result of a lack of objective measures for dynamic exercise, as explored by Zając et al. (2015). Reductions in force, voluntary activation and changes to EMG as a result of fatigue have been evidenced in maximal voluntary contractions (MVC) but this is not necessarily transferable to dynamic movements like the squat as earlier discussed (Bigland-Ritchie et al., 1978; Taylor and Gandevia 2008; Del Olmo et al., 2006). It has been suggested that high intensity strength training sessions, such as the protocol used in this study, can result in a temporary decrease in neural activation, force production and jump performance as a result of both central and peripheral fatigue (Raeder et al., 2016; Pincivero et al., 2000). Raeder et al. (2016) demonstrated that neuromuscular fatigue, measured using jump performanc, remained in the 48 hours following a squat protocol consisting of 4 sets of 6 repetitions at 85% of 1RM. It was concluded that the squat protocol induced damage to Type II muscle fibres due to the detriments produced in jump performance. Research by Thomas et al. (2018) found that neuromuscular fatigue in response to 10 sets of 5 back squats at 80% of 1RM took up to 72 hours to resolve. The 10 male participants also exhibited reductions in voluntary activation for the 48 hours following which suggests central fatigue was present as a result of the protocol.

However, Raeder et al. (2016) stresses that strength training effects are dependent on the type of training method used such as using squat jumps, increasing loading on the eccentric, or performing repetitions at a decreasing weight until muscle failure. There is evidence of differences between the strength exercise employed, not just the loading and method, with suggestions that compared to the deadlift, higher levels of peripheral fatigue were evidenced in the squat and this greater peripheral fatigue was concluded to result from greater quadricep recruitment (Barnes, 2017).

Earlier work by Linnamo et al. (1998) had previously concluded that high load resistance training using bilateral leg extensions resulted in notable central and peripheral fatigue however it was noted that peripheral fatigue was greater when using maximal loading compared to power focused loading 40% of maximal load but central fatigue was more likely to result from power focused loading. Both types of loading resulted in decreases in maximal integrated EMG and strength as well as increases in lactate, although more markedly in maximal loading condition.
Based on the presented studies, it could be concluded that maximal loading in the barbell squat, such as is evidenced in this study and measured by jump performance, results in peripheral fatigue that dissipates in 72 hours. This is based on the assumption that vertical jump performance is peripheral in origin which may not necessarily be the case (Taylor et al., 2015) as there is increasing evidence for a role of central fatigue in this fatigue measure. The findings that there were reductions in voluntary activation following a maximal loading protocol (Thomas et al., 2018), as well as decreased force production (Linnamo et al., 1998) following a dynamic high load resistance training protocol suggest that central fatigue does exist alongside peripheral fatigue to contribute to neuromuscular fatigue however it is difficult to measure.

5. Sex differences in fatigue

Sex differences in fatigue have been studied for a long time, evidence suggests that women are less fatigable than men. Women are able to sustain contraction for longer with less of a reduction of maximal force before failure (Hunter, 2009). From studies of isometric contractions, sex differences have been suggested to be muscle specific, for example, Avin et al. (2011) found females to be more fatigue resistant than males at the elbow but not ankle. This resistance to fatigability in the elbow is supported by Hunter & Enoka (2001) and Hunter et al. (2004). Females are also more resistant to fatigue than males in the lumbar extensors (Clark et al., 2003), adductor pollicis in the hand (Fulco et al., 1999), RF, VL and VM of the quadriceps (Clark et al. 2005; Wust et al., 2008), and dorsiflexors (Russ & Kent-Braun, 2003). Sex differences are also task-specific, this is proposed to be due to the differing fatigue mechanisms and the task stressing different parts of the neuromuscular system (Hunter, 2009; Hunter, 2016), so although resistance to fatigue has been found in isometric contraction tasks, this may not transfer into dynamic tasks. In the bench press at 75% of 1RM, women fatigue more slowly during multiple sets but recover at a similar rate to males (Nuckols, 2019), and also have been shown to perform more reps on eccentric only and concentric only sets but not in combined, this was concluded to be due to greater stretch shortening cycle response (Flanagan et al, 2014).

Evidence for fatigue resistance in females may be exhibited in technique. Fatigue-related problems do occur when performing squats, especially in high volume, and this has been noted to be more prominent in females (Smilios et al., 2010; Hooper et al., 2014). Hooper et al. (2014) described this mechanism as self-preservation where early reps were cut short or not performed to depth. This alteration is likely made to compensate for a decrease in muscular force (Howe, 2020). Performing sets to failure can alter movement patterns but arguably not in the same way as high volume, Brice et al. (2019) noted no differences in technique between beginning and end only an alteration in joint loading that had no impact on squat depth or range of motion. However, Hodges et al. (2011) observed no differences in joint loading with increases in fatigue. Functional asymmetries were recognised in healthy individuals and these asymmetries did not worsen or exaggerate with fatigue. In a study of sex differences in jump landings, Bell et al. (2016) reported females to be more resistant to fatigue as males showed a greater tendency to adjust landing mechanics in a way that might cause injury such as lateral trunk flexion and lack of flexion of the hip and also increased landing force.

5.1. Central and peripheral fatigue.

Males and females exhibit differences in firing of III/IV afferents, which facilitate central fatigue, and from this it could be expected that they would also show differences in central and peripheral fatigue (McCord & Kaufman 2010). Sex differences are reported to be present in peripheral fatigue, not central (Albert et al., 2006; Wüst et al., 2008) as there has been no noted reduction in voluntary activation (Hunter, 2016). Studying male and female cyclists and triathletes, Glace et al (2013) reported extreme differences in peripheral fatigue but no differences in central fatigue, stating that females exhibited no decrease in stimulated force following a 2-hour cycling protocol compared to the significant decrease seen in males. There were no differences in central activation ratio (CAR), a measure of central activation using electrical stimulation in a Superimposed-Burst Technique. It was concluded that men experienced more peripheral fatigue as a result of the aforementioned factors such as blood vessel occlusion, where it was highlighted that although females showed a lesser decline in CAR than males in under normal conditions, under ischemic conditions the decline was similar to males (Russ & Kent-Braun (2003). The authors identified this to be due to females relying more on aerobic metabolism, or reduced motor unit activation.

Martin & Rattey (2007) observed a greater central fatigue in males than females in leg extensors when performing maximal sustained isometric contractions as they had a greater reduction in voluntary force and deficits in voluntary activation. However, in contrast to previous evidence, they noted limited sex differences in peripheral fatigue measured by speed of contraction and relaxation. Possibly explained by the maximal nature of the task rather than the previously studied submaximal. Low-force and high-force (maximal) isometric fatiguing contractions produce different fatigue outcomes, low-force contractions produce more central fatigue in both sexes than high-force (Yoon et al., 2007; Eichelberger & Bilodeau, 2007), however, studies were performed on the finger and elbow flexors so may not be applicable to larger muscle groups such as the quadriceps. In a protocol using bilateral leg extensions at two different loading types of maximal and power, Linnamo et al. (1998) reported that females were less fatigable than males particularly in the power loading condition, stating that men were more likely to exhibit central fatigue than females supporting the notion that greater central fatigue is evident in males even when recruiting larger muscle groups.

5.2. Mechanisms underpinning sex differences in fatigue

Differences in fatigue in maximal isometric and dynamic contractions have been suggested to be a product of fibre type and distribution (Haizlip et al., 2015), blood flow (Russ & Kent-Braun, 2003), differences in muscle metabolism (Russ et al., 2005), hormonal differences and disparities in muscle mass and absolute forces (Hicks et al, 2001) (Figure 6.).

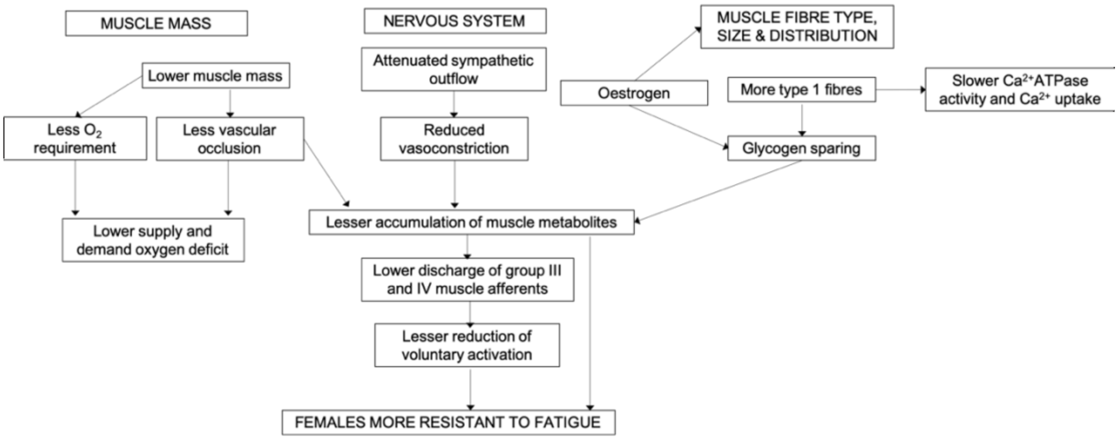

Figure 6: Diagram presenting possible mechanisms for female resistance to fatigue. *Adapted from Hicks (2001), Hunter (2009;2014) & Haizlip (2015).*

5.2.1. Muscle mass and absolute forces

Lower muscle mass and absolute forces results in lower oxygen demands and consequently a lower deficit in supply and demand compared to males (Clark et al., 2003). It has been shown that in response to a similar physiological demand, running in a weighted vest, males exhibit a higher rate of carbohydrate oxidation and higher lactate production than females (Gaffney et al., 2021). Further support for the role of blood flow in sex differences was put forward by Russ & Kent-Braun (2003) who identified that under ischaemic conditions, where blood flow was limited, there were no sex differences in fatigue in the ankle dorsiflexors. Clark et al. (2005) produced the same conclusion when studying the quadriceps, the longer time to task failure for females was dissipated when blood flow was occluded. Both studies used equal numbers of males and females. Clark et al (2005) reported that females exhibited higher muscle activation than males however this was not identified in Russ & Kent-

Braun's (2003) study, this may be related to the muscle composition differences in quadriceps and ankle dorsiflexors, as the ankle dorsiflexors have a higher percentage of type I muscle fibres (Edgerton et al.,1975; Holmbäck et al., 2003). Muscle activity may increase throughout sets to overcome fatigue up to a maximal point so if females evidence a significantly higher muscle activation when blood flow is occluded this suggests that a key factor in female fatigability lies in a lower oxygen demands (Smilios et al. 2010). Hunter et al. (2004) reports that when matched for absolute strength, men and women show no differences in fatigability, despite females showing a lesser rate of increase in muscle activation. When taken together, it appears that when differences in absolute strength and oxygen demand are removed, males and females show similar fatigability. Females may have higher muscle activation but experience less of an increase under fatigue compared to males.

5.2.2. Glycogen sparing and muscle metabolism

The contraction and relaxation of skeletal muscle is regulated by free Calcium (Ca^{2+}) concentration, the dissociation of Ca^{2+} from the Troponin C complex results in relaxation (Hasselbach, 1964). In type II fibres, Ca^{2+} is taken into the sarcoplasmic reticulum, whilst in type I fibres the activity of the Ca^{2+} ATPase is lower. (Gillis, 1997). Females have a higher proportion of type I than type II fibres so have slower Ca^{2+} ATPase activity and type II fibres have been noted to have three times the Ca^{2+}ATPase activity of Type I fibres, hence males have higher peak rates of relaxation (Hunter, 2014). Changes to contractile mechanisms are responsible for fatigue in dynamic contractions (Yoon et al. 2015), females had lower peak rates of relaxation during excitation-contraction coupling and recovered peak rates faster following exercise.

Males generally rely on glycogen sources earlier on in exercise than females, and females show a lower muscle glucose uptake and glycogen utilisation meaning a lesser reliance on carbohydrate metabolism (Venables et al., 2005; Carter et al., 2001), and this is termed glycogen sparing. This results from a higher proportion of type I fibres and hence a higher oxidative capacity (Wust et al., 2008). Glycogen sparing and a greater reliance on fatty acid oxidation has been related to prolonged endurance (Hawley & Leckey, 2015; Hicks,2001).

Lactate is a known biomarker for muscle fatigue (Wan et al.,2017), so although its accumulation may not be the cause of fatigue, it is a helpful indicator. Lactate is produced during anaerobic glycolysis, the breakdown of glucose into a pyruvate, hydrogen and a small amount of Adenosine Triphosphate (ATP), hence an earlier reliance on glucose as seen in males, will likely result in a faster accumulation of lactate and hydrogen, this can lead to lactic acidosis and decreases in muscle pH that may interfere with cross-bridge cycling and impair muscle force production based on animal studies (Fabiato & Fabiato, 1978; Wan et al. 2017). Females have been shown to be capable of achieving higher intensities without an increase in blood lactate (Baumgart et al., 2014) because they accumulate less intramuscular lactate, this is suggested to be due to lower total muscle mass, lower muscle glucose uptake and higher fat oxidation than males (Abe et al., 2003; Carter et al., 2001). What must also be considered is that because females experience less blood vessel occlusion they are able to maintain blood flow to avoid lactate accumulation, this will be explored later.

The earlier mentioned blood vessel occlusion allows rapid accumulation of metabolites (See Figure 6.). These metabolites act as a stimulus to group III/IV muscle afferent neurons (McCord & Kaufman 2010). These neurons are involved in cardiovascular and ventilatory responses to exercise carrying signals to the brain and spinal cord (Amann, 2013). They are greatly involved in central fatigue as they act as inhibitory signals to central motor drive to create deficits in motor and autonomic activity (Laurin et al., 2015). The lesser occlusion of blood flow in females and subsequent lesser accumulation of metabolites results in less activation of III–IV afferents (Ansdell et al., 2020).

5.2.3. Hormonal differences

Oestrogen's role within energy metabolism is greatly debated. In the menstrual cycle, there are fluctuations in Luteinizing Hormone, Follicle Stimulating Hormone, Estradiol and Progesterone. Janse de Jonge et al. (2001) noted no differences in muscle strength or fatigability in quadriceps, knee flexors, knee extensors or hand grip throughout the menstrual cycle, concluding that hormone fluctuations in the menstrual cycle have limited or no effect on muscle contractile properties, fatigability and strength in contrast to much of the prior work. When studying the early follicular phase, ovulation phase, and the midluteal phase, Friden et al. (2003) found no differences in muscle strength and endurance despite hormone fluctuations.

The difference between the studies that identify a difference and those that do not appears to be whether or not hormones were actually measured to identify phases or whether they interpreted results based on the estimated average cycle. Sarwar et al. (1996) published findings claiming an increase in muscular strength of the quadriceps in ovulation phase, alongside this the muscle contractile properties were altered to result in slower relaxation and muscle fatigability increased. However, participants cycles varied between 26 and 32 days and ovulation was predicted based on first day of bleeding and participants were not excluded for an irregular cycle. Participants were sedentary so irregularity in cycle is less expected but should still be controlled for.

What must also be acknowledged is the difference between sedentary and active women. There may be some differences in menstrual cycle, for example athletes are more likely to experience menstrual irregularity or a menstrual disorder than those that are sedentary (Stefani et al., 2016). Therefore, when reporting on athletes, such as the work by Friden et al (2003), closer testing of cycle, for example hormone testing, must occur to exclude irregularities or those that might produce anomalies in data.

Oestrogen has been stated to act primarily in the liver, where it has an inhibitory effect on fatty acid oxidation (Wu and O'Sullivan, 2011) to increase fat storage, and during moderate intensity exercise decreases glucose release (Devries, 2016). Oestrogen was noted to decrease rate of glucose appearance and disappearance (Devries et al., 2005) when supplemented in males but has only been confirmed to encourage glycogen sparing and fat oxidation when supplemented in rats (Rooney et al., 1993). Oestrogen also provides some protection against diabetes as oestrogen preserves insulin sensitivity in females, and hence this protects against hyperglycaemia despite the higher fat mass exhibited in females (Tramunt et al. 2020). Oestrogen undoubtedly does have an impact on energy balance and metabolic homeostasis but the differences in muscle metabolism of males and females cannot be confirmed by sex hormones alone.

6. Purpose of study

Sex differences in response to fatigue have been widely studied but mostly in aerobic capacities and less so in strength research. If males and females respond differently to fatigue i.e. females are more resistant this may affect the way volume is prescribed in training as well as the way athletes warm up in competitions. Additionally, if muscle activation is significantly different this may affect the way strength training programmes are designed, the focus for weightlifting accessories, and the volume of accessories to supplement squats. Often men and women are prescribed similar training programmes on the basis that there is no difference in the way that they should train for improvements. In general, this is true, but if such differences exist and such imbalances in use of muscles exist then it may be that training programmes need to address these differences in males and females, for example if females are more likely to be quadricep dominant, they may need more hamstring accessory work.

Therefore the aims of this study were to compare muscle activation of six muscle sites and ground reaction forces between males and females and between front and back squats before and after fatigue. It was hypothesised that muscle activation would decrease with fatigue and hence EMG signals would be greater in the pre-fatigue condition compared to the post-fatigue condition. It was also hypothesised that there would be muscle activation differences in the quadriceps and erector spinae between front and back squats based on previous literature and the differences in kinematics.

Methodology

1. Initial assessment

Initial testing involved signing a consent form, a screening questionnaire (based on American College of Sports Medicine, 2016), anthropometrics by stadiometer (217, Seca, Hamburg, Germany), body mass scales (799, Seca, Hamburg, Germany) and bioelectrical impedance scale (DC-430P, Tanita, Tokyo, Japan), followed by a blood pressure measurement.

1.1. Ethics

Written informed consent was taken before experimentation. Ethical approval and study standards conformed to the seventh revision of the declaration of Helsinki and was approved by Lancaster University Medical School. All participants were allocated a number to retain anonymity and all data collection was taken under this number, and participants had the right to withdraw at any time.

1.2. Participants

35 participants (30 male and 5 female) were recruited to take part in the study from university sports teams including rugby union, powerlifting, weightlifting, CrossFit and swimming (Table. 3). An additional 8 participants completed screening but either did not meet the criteria as they did not squat to parallel or they could not squat bodyweight (n = 5) or dropped out due to time commitments (n = 3).

Table 3: Mean ± SD of anthropometric measurements of participants separated by sex*. n= 35 (5 female, 30 male)*

Measurement	Males (mean ± SD)	Females (mean ± SD)
Age (yrs)	21.1 ± 2.2	22.6 ± 3.8
Height(cm)	178.4 ± 5.0	167.0 ± 5.5
Body mass (kg)	83.1 ± 8.7	62.8 ± 8.8
Experience(yrs)	3.5 ± 2.1	4.5 ± 3.7
Body Mass Index	26.1 ± 2.7	22.5 ± 2.3
Body Fat (%)	16.0 ± 4.3	20.0 ± 2.9
Front Squat (kg)	115.8 ± 23.1	70.2 ± 9.4
Back Squat (kg)	143.6 ± 25.1	84 ± 11.9

1.2.1. Inclusion and exclusion criteria

Table 4: Table describing the inclusion and exclusion criteria to participate in the study.

Inclusion Criteria	Exclusion Criteria
• 18-30 years old	• Sedentary or untrained
• Over 1-year experience using front and back squats in a regular strength training programme	• Quarter squat or low bar back squat
• Parallel or deep squat	• Injury or mobility limitations
• Front squat of at least 100% of own body mass.	• Evidence of instability

Participants were all aged 18-30 years old with over a year's experience using front and back squats in a regular strength training programme. All female participants confirmed they were not menstruating at time of experimentation nor had any chance of pregnancy however exact phase of menstrual cycle or pill use was not controlled. They also completed a questionnaire detailing their use of contraceptives and their normal cycle. Three were naturally menstruating, one was an oral contraceptive user and one was using contraceptive injection. All participants had a 1RM performance in parallel or below parallel front squat of at least 100% of the participant's body mass. 100% body mass was selected as the required weight as it is used in a number of studies as the working weight for trained individuals (Joseph et al., 2020; Caterisano et al., 2002). Hence in this study 100% of body mass was selected as the minimal weight required in order to evidence proficiency in the movement. Whether squats were performed to parallel or to full depth was recorded and any participant that did not perform squats to depth was excluded. 22 participants squatted to parallel (19 male, 3 female), and 13 squatted below parallel (11 male, 2 female). Performance was overseen and depth judged by an experienced weightlifter and personal trainer, depth was not measured or standardised but judged visually to meet the criteria (Table 3). If individuals showed evidence of instability such as the heels losing contact with the ground, outward or inward rotation of the feet during the squat, feet moving during the squat, or slipping of the bar they were excluded (Brown, 2012). Walsh et al (2007) detail that when heels begin to rise off the floor as depth increases, hyperextension is employed to force weight back into heels. This increases risk of spinal injury hence any participants who were unable to maintain full foot contact were excluded.

All participants presented as normotensive (blood pressure of 120/80 mmHg) and were not taking any medication that would interfere with safety of testing or would interfere with study measurements. Participants were excluded if they reported any injury or mobility issue that could be aggravated by participation or limit performance. All were free from any cardiovascular or orthopaedic disease, as judged by a medical history questionnaire (based on American College of Sports Medicine, 2016). A power calculation based on previous literature determined that 24 participants (12 male and 12 female) would be sufficient. In order to detect an effect size of Cohen's f = 0.25 with 80% power (alpha = .05, two-tailed), G*Power suggests we would need 24 participants in a repeated measures study with 4 conditions. However, due to time constraints and participant availability, 35 participants (30 male and 5 female) were recruited to take part in the study. This was as a result of a limited available sample of women engaging in regular strength training and a lack of familiarity with front squats, not only does the sample confirm that males are more likely to engage in strength training but also that female strength levels are lower than males and so it is much more difficult to attain a bodyweight front squat for females than for males (Szabo et al. 2013)

It is also important to note that some participants used weightlifting belts as per their preference (n = 16) it has been reported that weightlifting belts produce no differences in EMG activity in any of the studied muscles and only allow the individual to perform the squat eccentric and concentric phases faster (Zink et al., 2001). Participants were also allowed to wear weightlifting shoes which have a raised heel to allow increased mobility and stability (Glassbrook et al.,2017). This heel has been shown to reduce trunk inclination with less dorsiflexion at the ankle (Glassbrook et al.,2017). 5 participants squatted barefoot, 16 wore trainers and 14 wore lifting shoes as participants were allowed to select their preference. Which shoe was employed may have an effect on depth (Sinclair et al., 2015) and stability (Lee et al., 2019) however these factors were not measured.

2. Procedures

2.1. 1RM testing

Participants were asked to participate in 1RM testing at screening using a protocol adapted from Seo et al (2012). Participants were advised not to exercise 24 hours prior to the screening, they were also advised to eat well in advance of the tests and to stay hydrated. They were not given a control meal prior to this testing as no experimental data was recorded. Participants were asked to warm up for 5 minutes on a stationary bike (Technogym Skillbike, Via Calcinaro, Cesena), 3 minutes dynamic stretching using stretches of their choice. For back squat, participants racked the barbell behind the neck across their shoulders and were instructed to descend until the thigh was at least parallel to the floor and then to power up and extend the knees and hips against the weight. All participants were reminded of the instructions throughout. For the front squat, participants were instructed to place hands just outside shoulders, rack the bar across the front of their shoulders, drive the elbows up under the bar, keep their chest up and performed the squat as instructed for the back squat (Figure 6.). Where mobility was a limitation for the front squat, individuals were allowed to cross their arms over the top of the bar rather than holding it in front rack. They were asked to perform 8-10 repetitions at a weight they knew they could complete, after a minute rest they were asked to perform 4-6 repetitions at their full range of motion at a weight they knew they could complete. Following this, participants performed one repetition at increasing weights as they felt comfortable until a failed attempt, participants were allowed 3 minutes rest between attempts or as long as they felt they needed within reason. Participants were required to give a rating of perceived exertion (RPE) following each repetition. The maximum weight they achieved was recorded. Participants performed one squat type then had a maximum of thirty-minutes rest break before performing the other as in the protocol by Da Silva et al. (2017). Front squat was performed first due to the likelihood that maximum weights would be lighter however this may have introduced order bias. Randomisation and completion of maximum lifts would have been completed on separate days if not for the time constraints of the study and of participants.

All squat tests were performed with a 20kg Olympic barbell (Eleiko IWF Weightlifting Training Bar, Halmstad, Sweden) and plates (Eleiko Sport Training Discs, Halmstad, Sweden).

Figure 6: A demonstration of how participants were instructed to perform the squats. *Top Left: full back squat. Top Right: full front squat. Bottom Left: parallel back squat. Bottom Right: Parallel front squat. Full squat was ideal but parallel was accepted.*

2.2. Experimental Procedure

Experimental procedures were at least one week apart to account for fatigue and recovery times. Tests were held at the same time of day to account for diurnal variations (Sedliak et al., 2007). Participants were provided with a control meal to consume 1-2 hours before arriving at the laboratory for testing, dependent on preference (Table 5.). Which squat type was performed first was randomised using an online number generator (Research Randomiser, https://www.randomizer.org/) to account for possible learning effects (Altman et al., 1999). Participants were asked to perform the same warm-up as in the 1RM testing session followed by a maximal voluntary contraction. This was done by maximally loading the bar so it could not be unracked and participants setting themselves as if to unrack. They were then asked to push up against the bar with as much force as possible for 3 seconds (Burden, 2010). They then were asked to perform a countermovement jump (CMJ), with their hands on their waist and with legs extended after push-off, as high as possible (Howe et al., 2021). They then

Table 5: Nutritional value of the standardised meal *consumed by all participants 1-2 hours before procedure. (ASDA Tomato & Basil Micro Pasta, Asda,*

Typical Values	Per serving
Energy kJ	1422kJ/338kcal
Fat	6.4g
of which saturates	1.2g
Carbohydrate	53g
of which sugars	8.0g
Fibre	9.6g
Protein	12g
Salt	0.66g

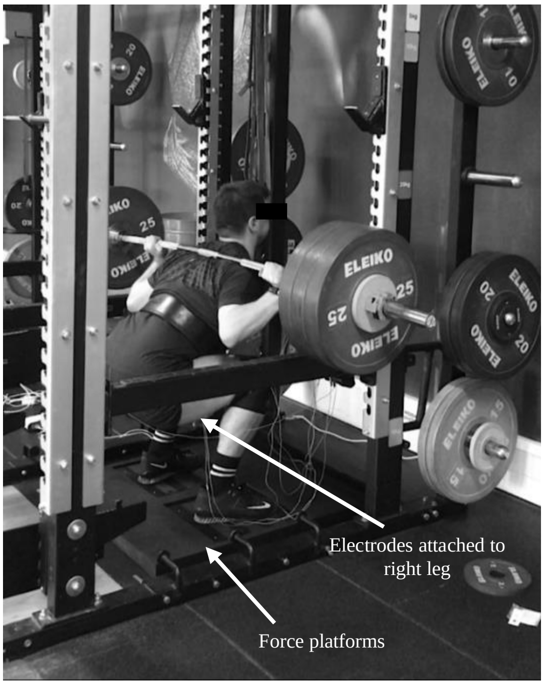

***Figure 7: A photo showing the set-up of the measures and a participant completing the protocol*.**

began the protocol (Figure 7.), they performed their 3RM at calculated weight (93% of 1RM; Lander, 1984) followed by the fatigue protocol (adapted from Raeder et al., 2016) which included sets of 6 repetitions at 75 % of subject's 1RM performed with a 2 second eccentric followed by explosive concentric phase with limited rest between sets of approximately 1 minute. Following each set of the fatigue protocol, participants were asked to perform another CMJ. If the CMJ height decreased by 20% of the original jump height, the participant was considered fatigued (Figure 8.). Alternatively, if participants failed a repetition they were considered fatigued (Weinhandl et al., 2011), this occurred for 6 participants in the front squat condition and 4 participants in the back-squat condition with no evidence of a decrease in jump height. Where fatigue was not present, participants were asked to perform another set or sets, the maximum number of sets allowed was 20, due to time constraints. 2 participants reached 20 sets for both squat types without a decrease in jump height or a failed repetition. Following fatigue protocol and final jump demonstrating fatigue effects, participants had 3 minutes rest and then performed their 3RM again (Figure 8.). Participants were advised to cooldown for 5 minutes on a bike self-paced and perform static stretches following the procedure.

2.3. Data Recording

EMG electrodes (SX230, Wired EMG Sensor, DataLOG, Biometrics, Virginia, U.S.A) were placed on the vastus lateralis, vastus medialis, rectus femoris, biceps femoris and semitendinosus of the right leg and the erector spinae (longissimus) in line with SENIAM guidelines (Hermens & Freriks, 2000). The area was cleansed with an alcohol wipe then shaved before the electrode was applied with a double-sided adhesive. Once applied, values were zeroed with the muscle at rest. Additionally, goniometry (Wired Twin-Axis Goniometer, DataLOG, Biometrics, Virginia, U.S.A) was employed to identify eccentric and concentric squat phases. Raw EMG signals were collected at 2000Hz (Biometrics Analysis Software, Biometrics, Virginia, U.S.A). EMG was smoothed by converting to root mean square (RMS) with a 100ms window and normalised to the peak of the participants MVIC trial for each muscle, in accordance with work by Yavuz et al. (2015) and Contreras et al. (2015). Peak RMS was calculated using the peak of each squat, mean RMS calculated for each squat and then averaged to produce mean RMS.

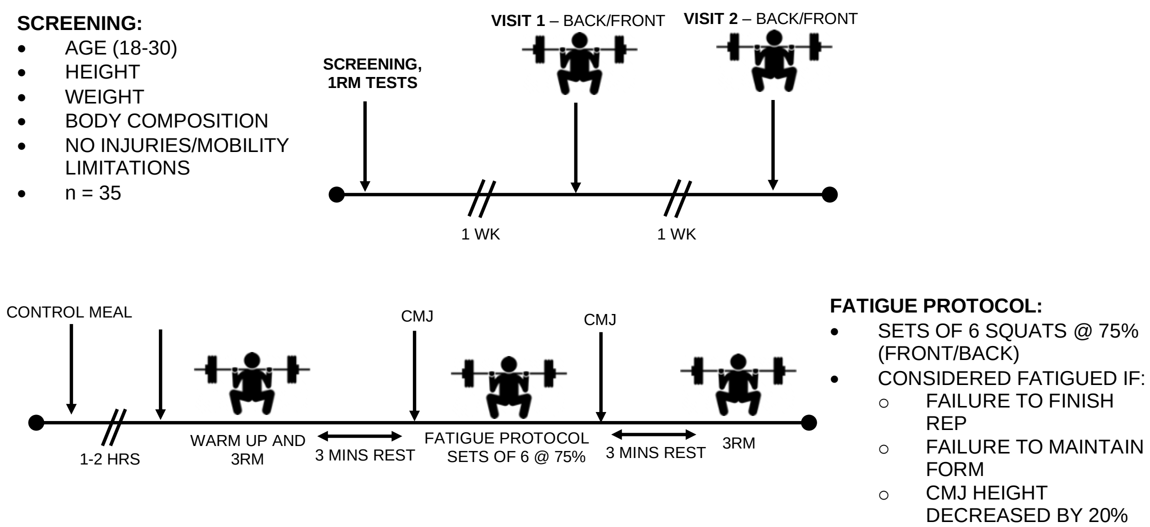

Figure 8: A schematic representation of the screening visits and experimental procedure.

Two force plates (PS2141, single axis force plates, Pasco, California, U.S.A) were used to measure peak vertical ground reaction force, video capture data was taken via Capstone software (PASCO Capstone version: 2.3.1, PASCO scientific, California, United States). Force plates were calibrated prior to each participant. Force data were recorded at a sampling rate of 200Hz as per studies of squats and squat jumps (Samozino et al., 2008; Earp et al., 2016).

2.4. Coefficient of variation and reproducibility

The coefficient of variation was calculated for force platforms and evidenced the reliability and reproducibility of the force platforms as a valid measure. This was done by stepping onto the platforms and taking a mean measurement. Three muscles were used to calculate co-efficient of variation for EMG. This was done by applying the electrodes to the muscle position in accordance with SENIAM guidelines (Hermens & Freriks, 2000), and taking the peak of the reading during a squat, this was repeated three times. There was greater variation in these results as the measure was taken of a squat which can naturally vary due to changes in stance width and depth, as well as the limits of EMG such as difficulty in placing the electrode at the exact same site. All the coefficient of variation values were low to moderate (Wilding, 1985) (Table 6.).

Table 6: Coefficient of variation for force and EMG measures.

Measure	CV (%)
VL EMG	13.8
RF EMG	27.6
VM EMG	10.6
Force Platforms	0.2

Participants were offered an information sheet or verbal explanation before and throughout, all chose to be verbally instructed, whilst this enabled participants to feel like they were in less of a clinical environment it may have reduced reproducibility as they may not have been precisely uniform throughout despite the researcher's familiarity with procedure.

2.5. Statistical Analysis

30 males were used to analyse differences between pre to post squats and front to back squats, data were analysed by two-way repeated measures analysis of variance (ANOVA) 2 (squat: front, back) x 2 (pre, post) for each muscle. For force data, a two-way repeated measures ANOVA comparing the peaks was employed. Tukey HSD post hoc tests were used to identify pairwise differences. All data was checked for normality of distribution using the Shapiro-Wilk test. All force data were normally distributed, however, EMG data that were not normally distributed were analysed using the appropriate non-parametric alternative (Friedman's two-way ANOVA). Some data points were missing (10% of EMG data, 7.86% of force mean peak, and 19.76% of force peaks) so the Markov Chain Monte-Carlo method (with 20 imputations) was used to replace the missing values to avoid a reduction in statistical power and avoid excluding pairwise comparisons. The peak and mean of each squat were taken for EMG data, the mean and peak of each squat was recorded and averaged. The peak of each squat was taken for the force plate data and averaged to produce mean peak ground reaction force. Where participants performed two or three squats the data was averaged, however, if only one squat was performed due to failure this was taken as the value. T-tests were performed for anthropometric comparisons and differences between number of sets performed. Effect sizes were calculated with

Cohen’s f, where 0.1 constitutes as small, 0.25 as medium and 0.4 as large (Cohen, 1988; Coe, 2012).

All results are presented at mean ± standard deviations unless otherwise stated. Statistical significance was marked as $p < 0.05$. Statistical analyses were performed using Graph Pad Prism (Version 9.1; GraphPad Software; California, USA).
Due to less female participant recruitment than required, the five females were matched with five males for both sport and training age and preliminary comparisons were made. Although these will not be definitive, the findings may evidence areas for further research.

Results

Maximum weight lifted in back squats was significantly greater than in front squats as expected ($p < 0.001$). There were limited differences in EMG between front and back squats as well as between pre and post (Figure 9), however there were differences in GRF (Table 6). There was also evidence of sex differences in EMG and GRF (Figure 10; Figure 11), however these findings are not generalisable to the general population due to the small sample size.

There was an average jump height of 36.3cm which fell by an average of 7.1cm, the expected 20% decrease. 5 This difference was not significant ($p = 0.15$). There were differences in number of jumps performed before fatigue between males and females.

Sex differences were present in GRFs where males showed a consistently higher ground reaction force than females ($p = 0.008$) (Table 10). Sex differences were also present in RF muscle activation (Figure 10).

1. Squat differences

The below data pertains to the 30 males that were used to analyse differences between pre to post squats and front to back squats.

1.1. Electromyography

Activity of the semitendinosus was greater in the back squat than the front squat, with front pre and back pre-conditions being significantly different for both mean and peak activation ($p < 0.05$). These findings are presented in Figure 9.

There were no other significant differences between electromyography for the other muscles studied for front and back squat and no differences between pre and post fatigue conditions in the same squat type for both mean (Figure 9A) and peak electromyography (Figure 9B).

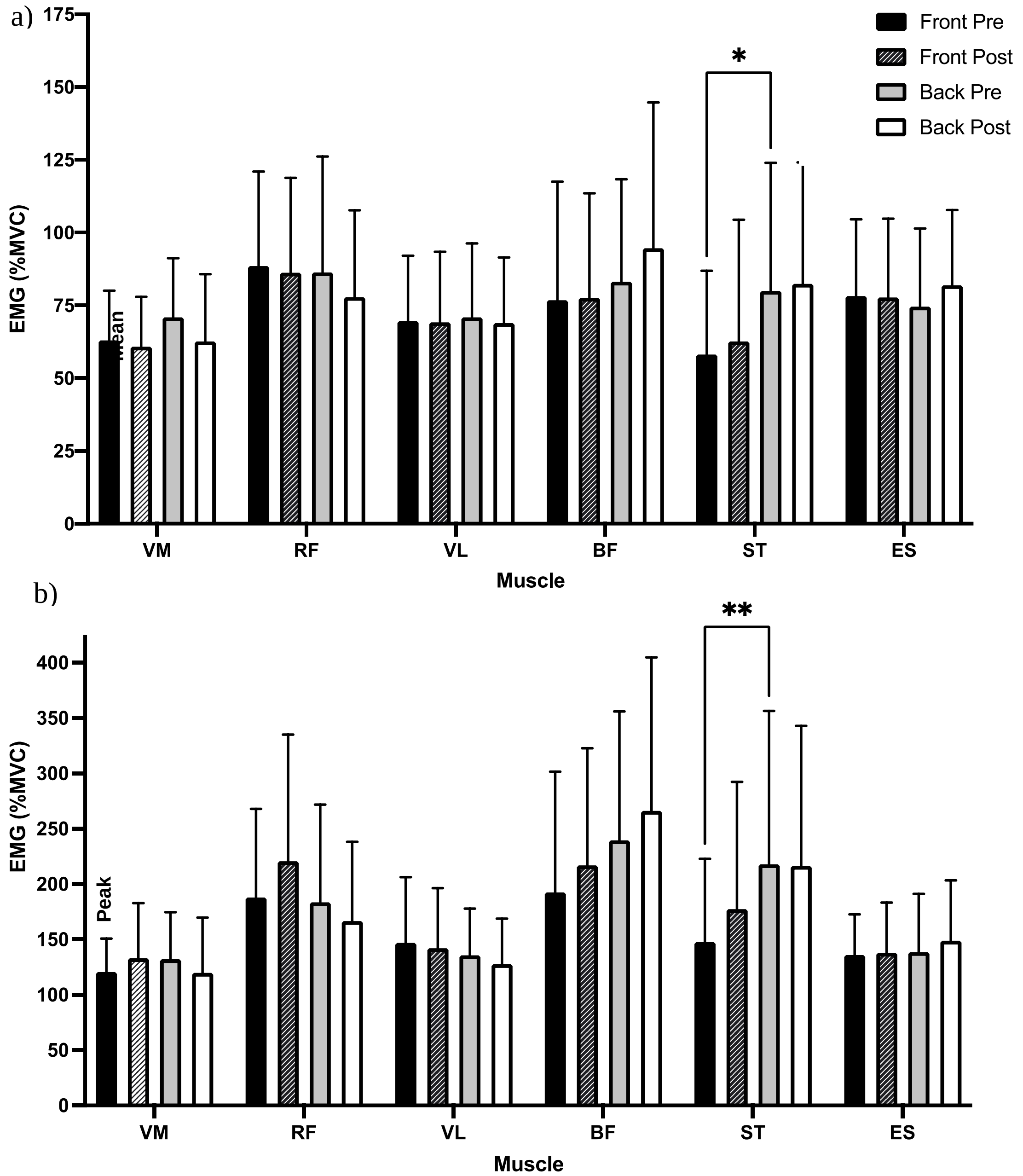

Figure 9: a) Mean and b) Peak* ± SD *muscle activation for the six muscles studied presented as %MVC for each condition. *Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01).*

1.2. Ground reaction forces

There was significantly lower GRF in the front squat than the back squat for both pre and post fatigue conditions (*p* <0.001) (Table 7.). When peaks were averaged to produce a peak pre and peak post (Table 7.), there was evidence that ground reaction forces were lower in the post fatigue condition for back squat than pre-fatigue condition (*p* = 0.002) despite there being no differences in individual squat peaks (Table 8.). Between individual peaks, there were no differences between pre or post fatigue for either squat type, however there was a significant difference in GRF between front and back squat for squat 2.

Table 7: Peak ground reaction forces (N) ± SD. *Significance between front and back squats is highlighted with *, differences between pre and post are highlighted by the p value. Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01, ***, p < 0.001), ns indicates p > 0.05.*

	Pre (N)	**Post (N)**	***p* Value**
Front	2185 ± 317****	2119 ±441****	ns
Back	2437 ± 318****	2361 ± 373****	0.002**

Table 8: Peak GRF (N) ± SD of each squat in the 3RM for front and back squat, pre and post fatigue.
*Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01)*

	Squat 1 (N)	**Squat 2 (N)**	**Squat 3 (N)**
Front Pre	2187 ± 333	2194 ± 315	2175 ± 312
Front Post	2168 ± 359	2036 ± 575**	2151 ± 355
Back Pre	2424 ± 305	2475 ± 313	2414± 341
Back Post	2266 ± 399	2434 ± 383**	2383 ± 326

As evidenced earlier, front and back squat GRFs were significantly different (*p* <0.001) which can be seen in Table 9. The effect sizes, 0.26 to 0.35, indicate a moderate strength experimental effect (Cohen, 1988). Only one effect size was found to be small.

Table 9: Mean difference and effect sizes between front and back squat for pre and post individual squats. *Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01, ***, p < 0.001), ns indicates a p value that was nonsignificant at p < 0.05. For effect sizes (ES), 0.1 constitutes as small, 0.25 as medium and 0.4 as large effect size.*

	Pre		**Post**	
	Mean difference(N)	**ES**	**Mean difference (N)**	**ES**
Squat 1	237****	0.37	98	0.15
Squat 2	280****	0.45	398****	0.41
Squat 3	239****	0.37	232****	0.34

The average GRF produced for the back squat is 2399N, the post fatigue back squat 1 is 133N lower than this average. This resulted in the value being closer to that of the front squat average of 2151N (Table 7.) resulting in a difference of 98 (Table 8.).

2. Sex differences

The below data is an analysis of 5 males and 5 females matched for sport and experience levels.

2.1. Electromyography

There was only one significant difference in muscle activation between pre and post conditions for either sex, which was that female peak RF activation was significantly higher pre-fatigue than post-fatigue in the front squat condition ($p < 0.001$). The differences across all muscles and all conditions are shown in Figure 10.

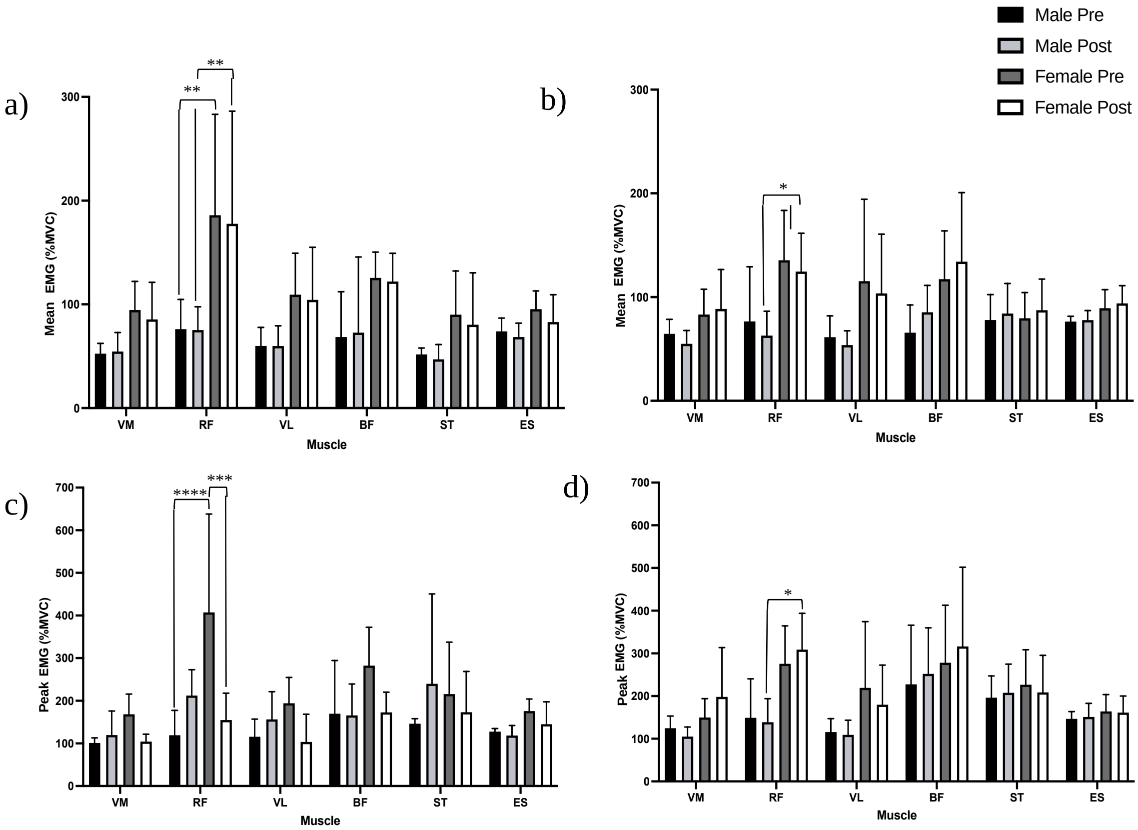

Figure 10: Sex differences in EMG activation for each muscle presented as mean or peak ± SD (%MVIC). *a) mean front squat, b) mean back squat, c) peak front squat, d) peak back squat. Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01, ***, p < 0.001, **** p <0.0001). n = 10.*

There were significant sex differences in RF activation, whereby females had higher mean RF activation in pre and post front squat and post back squat, as well as higher peak RF activation in front pre and back post (Figure 10.).

There were no significant differences in muscle activation between front and back squats in females or in males.

2.2. Ground reaction forces

Males showed a consistently higher ground reaction force than females ($p < 0.05$) and this was significant across all conditions (Table 11.) This is as a result of a higher combined mass of both lifter and barbell, as males have a higher body mass and heavier weight lifted (Table 10.). Males had an average combined mass of 98.4kg more than females.

Table 10: Differences in mean ± SD for body mass, front and back 1RM between sexes. *p value indicates between sex differences. Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01, ***, p < 0.001, **** p <0.0001). (females n =5, males n=5)*

	Males	**Females**	***p* Value**
Body mass (kg)	84.8 ± 8.0	62.8 ± 8.8	0.04*
Front 1RM (kg)	144.0 ± 29.5	70.2 ± 9.4	0.008**
Back 1RM (kg)	163.0 ± 29.5	84.0 ± 11.9	0.01*

Table 11: Ground reaction forces(N) of males and females (mean ± SD) for front and back pre and post fatigue. *p value indicates between sex differences, * denotes differences between conditions within sex. Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01, ***, p < 0.001, **** p <0.0001). n = 10.*

	Male (N)	**Female (N)**	***p* Value**
Front Pre	2491 ± 145	1494 ± 312	<0.0001****
Front Post	2266 ± 674	1526 ± 398*	<0.0001****
Back Pre	2794 ± 246	1760 ± 362	<0.0001****
Back Post	2728 ± 426	1816 ± 434*	<0.0001****

Figure 11 demonstrates the average GRF of each squat of the 3RM for front and back squat both pre and post fatigue. Between individual squat GRF, there were significant sex differences in front squat pre 1, back squat pre 2 and 3, and back squat post 2, males evidenced a significantly higher ground reaction force than females in these individual squats (Figure 11). There were no differences in individual squat GRF within the same set of 3 squats for males or females.

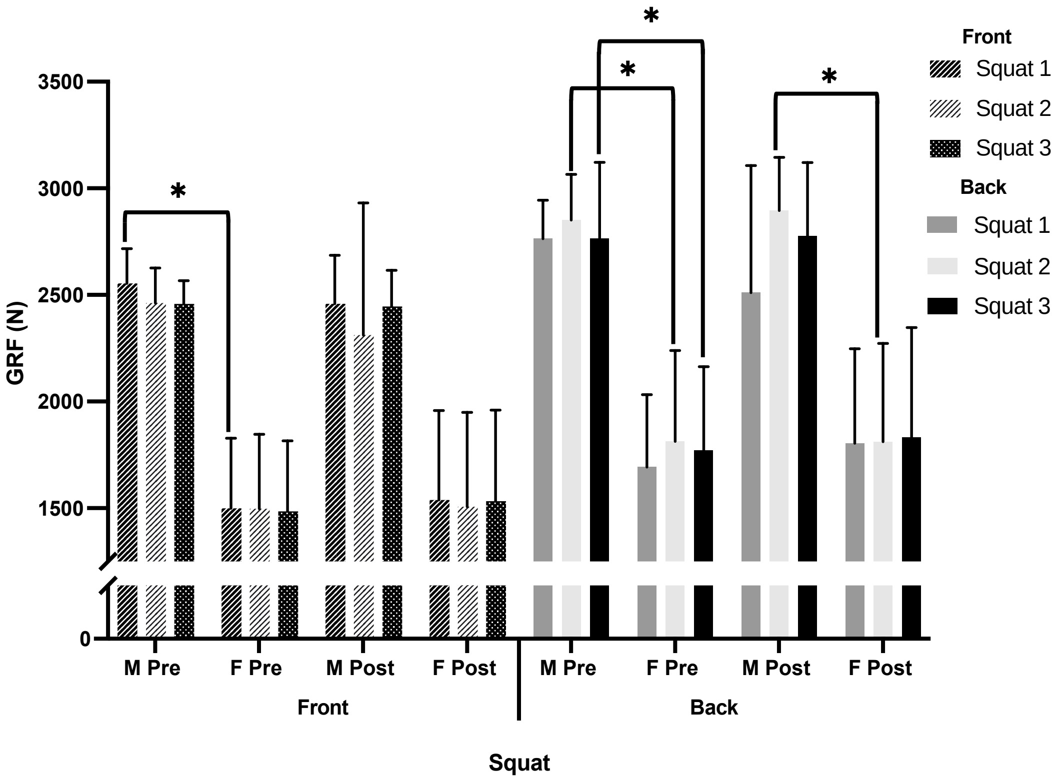

Figure 11: GRF differences between sexes for all trials performed for both squat types. Data is presented as mean ± SD *(n = 10). Significance level (p < 0.05) is indicated by *. Square brackets indicate where the significance lies. F indicates females, M indicates males. Pre indicates measurement before fatiguing intervention and Post indicates measurement after fatiguing intervention. Key to the right indicates each squat type and number of squats performed.*

2.3. Fatigue

In the front squat condition, males performed an average of 6 fewer jumps in the front squat (p = ns) and 5 fewer jumps in the back squat condition ($p < 0.05$). Males had significantly higher jump height, this was not necessarily related to physical height as physical height was not significantly different between males and females studied (Table 12.).

Table 12: Sex differences in jump performance. *Significant values are marked with * to indicate significance levels (* p < 0.05, ** p < 0.01). n = 10*

	Squat	Male	Female	*p* Value
Height (cm)		176.8 ± 4.9	167.0 ± 5.5	ns
Number of jumps	**Front**	3 ± 2	9 ± 6	ns
	Back	6 ± 5	10 ± 6	0.03*

Discussion

To the best of the author's knowledge, this is the first study with aims of exploring sex differences in different squat types and sex differences in fatigability of both squat types. This study confirms that the back squat does have increased hamstring activation compared to the front squat and does not corroborate the theory that front squats have considerably greater quadricep activation. The findings corroborate those of Gullet et al. (2009) and Contreras et al. (2015) whilst also supporting the work of Yavuz et al., (2015) by confirming the greater activation of the ST evidenced in the front squat compared to the back squat. In sex differences, this study supports the findings of Clark et al. (2005) who concluded that males and females demonstrate different neuromuscular activation patterns of the RF as in this study females evidenced significantly greater activation of the RF than males.

1. Squat Differences

1.1. Electromyography

Quadricep activation was not different between front and back squats or between pre and post conditions of the same squat, evidencing that the front squat does not have a greater quadricep focus than the back squat, in accordance with work done by Contreras et al. (2015) and Gullet et al (2009). It evidences that at lighter absolute load, the front squat can elicit activation equal to the back squat at a heavier absolute load even at maximal percentages, although this may relate to changes in joint loading and compensatory mechanisms. However, taken together with the findings of Gullett et al. (2009) this suggests that the greater compressive forces and increased knee extensor moments in the back squat can be avoided whilst still eliciting the same muscle activation. This suggests that when seeking to lower overall absolute training load the front squat can be an alternative to the back squat without the increased stress on joints.

Although there was no evidence of greater quadricep recruitment in front squats compared to back squats, there was indication that recruitment of the hamstrings differed between front and back squats. Mean and peak ST activation was significantly different between pre fatigue conditions, with lower activation in the front squat than the back. The hamstrings play a role in initiating flexion of the knee, in assisting in control of flexion at the hips, and near the end of the concentric phase the hamstrings act to reduce rate of knee extension to prevent hyperextension (Robertson et al., 2008). Hence, the back squat may require more hamstring activation in order to flex at the knee and stabilise the hips compared to the front squat. The increased hamstring activation could also be a product of the increased forward lean in the back squat compared to the front squat as a result of bar positioning, this increased forward lean increases the forces placed on the hip instead of the knee to reduce stress on the ACL and subsequently increases hamstring activation (Escamilla, 2001).

Despite this increased forward lean characteristic of the back squat, there were no differences in ES activation. This evidences that support of the weight in a front rack position rather than across the back of the shoulders does not alter back muscle activation and may mean that there is no difference in injury risk of the back and spine using either squat type (Glassbrook et al., 2017). It was hypothesised that front squat would show reduced lower back stress evidenced by lower EMG activation as Waller (2007) previously detailed how the front squat may reduce lower back pain as the back squat is more lower back focused and results in higher peak compressive forces and peak shear forces acting on the lumbar spine (Clancy, 2010). As this was not evidenced to be the case in this study as there were no differences in ES activation, it may be suggested that for posterior chain strength and hypertrophy development, the back squat maybe a better option due to increased load without evidence of increased lower back stress. The effect this has on the core were not explored in this study and hence require further study.

It is important to acknowledge that although EMG is a useful tool, it does have limitations. Placement of the electrodes is extremely important in avoiding interference or incorrect muscle measurements, this could cause changes in EMG signal between participants but also within the participants own data between squat types where placement has been different between trials (Merletti & Parker, 2004). In addition, such things as movement of the muscle under the electrodes, signal crosstalk, and changes in muscle length can have an effect on the magnitude of EMG amplitudes (Heckathorne and Childress, 1981; Earl et al., 2001). All participants had electrodes applied to their right leg and the dominant leg was not identified to enable simplicity in the set up as well as aiming to keep electrode placement more uniform. EMG was normalised to an MVC and presented as a percentage, due to time constraints the MVC was a whole-body isometric push meaning that possibly not all muscles will have been maximally activated. This was due to time constraints meaning it was not possible to test each muscle’s maximum contraction individually but also because it has been suggested that the optimal way to normalise EMG is to a movement similar to that being studied. The activation in this study was often 100% or more, particularly for peak muscle activation which suggests that the MVC either did not reveal maximum activation or that maximal activation can only be achieved in dynamic movements (Burden, 2010). Bolga and Uhl (2007) discussed the limitations of using MVC for normalising EMG, noting that it relies on the participant producing a real maximal effort which cannot always be guaranteed and so must be considered in this study.

1.2. Ground reaction forces

The heavier weights used in the back squat resulted in a higher mean ground reaction force compared to front squat as it is known that increasing the external load will result in increased ground reaction forces (Zink et al., 2006). The ability to lift heavier loads in the back squat is related to a number of factors including bar placement, stability, joint angles and differing demands on muscle group. As this work has evidenced the differing demands on muscle groups are disputed across studies and loads employed (Gullet et al., 2009; Contreras et al. 2015; Boylett-Long, 2019). In the back squat, these factors enable more room for error and compensatory movement than the front squat which has to be more balanced in order to avoid failure by inability to keep the bar in position either by tipping too far forward or back (Gullet et al., 2009). In this study, participants reported that front squats were more uncomfortable than back squats due to the high volume required in the study and failure was reported to often be a product of wrist discomfort or rubbing on collar bones in the front squat over an inability to lift the weight, however, this requires further research. This could be investigated through quantitative methods such as by questionnaire or through qualitative methods such as focused interviews, or mixed methods approaches. However, this anecdotal evidence corroborates the statement that the front squat places differing demands on the body compared to the back squat and how these differing demands result in a heavier weight being lifted in the back squat.

The lower GRF in front squats indicates a lesser force on joints and on muscles through tendons. This is supported by Gullet et al (2009) using inverse dynamics, participants squatted 70% of 1RM for both front and back squat with reflective markers on the greater trochanter, midthigh, lateral knee, midshank, second metatarsal head, lateral malleolus, and calcaneus of the participant’s right leg. Despite equal relative load the front squat had lower net compressive forces and fewer knee extensor moments (Gullet et al., 2009). Using the front squat may decrease injury risk and be a better exercise choice for those with previous joint injuries and in rehabilitation, particularly as this research has shown how front squats can activate the ST to support the knee and reduce stress on the ACL. It is important to note that the load is significantly higher in the present study than in the study by Gullet et al. (2009) and further research needs to study forces on joints at these higher percentages to confirm this hypothesis.

1.3. Fatigue

Fatigue was investigated in two different ways. It was investigated within the same set of three to see whether acute fatigue would result in differences in GRF between first and third squat, and also between sets of squats to investigate the effects before and after the fatigue protocol. Fatigue was evident based on the criteria set by the study meaning CMJ height reduced by 20% or more from first CMJ taken, a repetition was failed, or there was a significant decline in technique that was putting the participant at risk. Whilst these may be evidence of fatigue they are not definitive. For example, a repetition could be failed due to a technical fault, e.g. slipping of the bar in front squat, or being off balance. Jump height could decrease as a result of lack of motivation or in some cases jumps were not altered following fatigue sets, whilst this could indicate a fatigue resistance it could also indicate that jumps were not a valid measure of fatigue for some individuals.

Electromyography is often used as a measure for muscular level fatigue, however to measure immediate fatigue within the protocol another measure of fatigue was required. Due to COVID-19, blood lactate was considered not to be essential in the diagnosis of fatigue and so therefore was removed as a measure. For this reason, vertical jump height was used as the measure of fatigue. An alternative method for monitoring fatigue in real time would have been using velocity measurements using an accelerometer or a linear position transducer however, this equipment was not available. Velocity has been used in study of volitional fatigue and in 1RM testing (Lake et al.,2017). In this study, minimal velocity thresholds could have been used by measuring mean concentric velocity of the 1RM during screening, then in experimental protocol if concentric velocity fell below this level the participant could be considered fatigued (Izquierdo et al.,2006).

1.3.1. Within sets

This research shows no differences in GRFs between each squat in a set of three with no evidence of the force production of the final squat being affected by acute fatigue. Studying individual squats, in the first squat of the post condition there was an unexpected lack of difference in GRF and decreased effect size between front and back squat which can be clearly seen among the other comparisons. This is likely due to a decrease in GRF in the back squat, reducing the difference between the two squat types. This reduced GRF could be as a result of fatigue from the sets of six squats as fatigue could reduce squat cadence in the ascent and subsequently reduce GRFs (Bentley et al., 2010). However, this fatigue dissipates throughout the set to increase the difference between front and back squat and this decrease in force in the first squat of the set is not evidenced in the following two squats. This initial decrease and subsequent return to average could result from settling into the exercise and adjusting to the increase in weight from 75% 1RM to 93% 1RM which Hodges et al. (2011)

refers to as a 'practice effect'. Following this, there was a greater difference than the average between front and back squats for the second squat of the post condition this is shown both in the difference of 398 N in Table 9, as well as in the significant difference between values in Table 8. This was the result of GRF being lower than the average for the front squat as well as the back squat GRF returning to the average. The decrease in GRF in the front squat could again be the result of a sudden increase in fatigue in the second squat however it is difficult to make conclusions without studying whether there were changes in velocity, joint angles, shear and compressive forces or compensatory muscle activation as the squat is a multi-articular movement and force production is the product of each joint in changing angular positions (Kellis et al., 2007).

Whilst this data evidences some fluctuations in GRF, there were no significant differences between peaks of the squat. There were only greater or smaller differences evidenced between squat types so any effects of fatigue were not large enough to create significant differences in GRF compared to other squats within the set. Therefore, there was no evidence of a trend or effect of squat number within the set on GRF evidencing that the force produced by each squat in a set is completely random and individual and therefore difficult to compare particularly between squat types.

Hodges et al. (2011) reported no differences in joint loading as participants become more fatigued, this could be the case in this study within the set of three squats for each condition, however, this would need to be studied further. It is also important to consider that the way an athlete fatigues within a set and, as explored later, after multiple sets is very individual and specific to the athlete so it may be inconclusive to average lots of athletes from different sporting backgrounds (Jones et al., 2017).

1.3.2. Between sets

There was no significant difference between number of countermovement jumps and number of sets performed between front and back squats suggesting that the squat types fatigue similarly.

It was suggested that the effects of fatigue on GRF are minor (Nikooyan & Zadpoor, 2012), however, this was in a study of running and hence research exploring effects in strength sports was required. Contrasting the limited effects of fatigue within a set, there was a significant decrease in GRF between pre and post condition of the back squat. Bentley et al. (2010) reports that faster squat cadences result in a greater GRFs and that GRF is more dependent on descent than ascent speed so this decrease could be the result of the weight being moved more slowly, specifically a slower descent into the bottom position.

This fatigue did not translate into differences in EMG between the pre and post conditions of the same squat type. In previous research using 6RM bench press, van den Tillar & Saeterbakken (2014) noted an increase in EMG for the prime movers under fatigue and also found that there were no changes in EMG in antagonist muscles. It could have been expected that muscle activation of the quadriceps would increase following fatigue but that this increase would not be evidenced in the rest of the muscles studied (Kallenberg et al., 2007; Allen et al., 2008). This is supported by work by Smilios et al. (2010) which suggested that EMG of the prime movers increases as a result of fatigue in squats. Despite this, it is difficult to make conclusions as Looney et al (2016) has stated previously, it is difficult to confirm whether fatigue induced by exercise results in increased EMG in subsequent exercise, especially with low repetition and high load exercise and this could be why the same increases are not evidenced within this study.

2. Sex Differences

Originally this study set out to explore sex differences in muscle activation and ground reaction forces between back and front squats prior to and post fatigue, however due to recruitment limitations the focus of this study shifted to exploring differences in squat type and effects of fatigue. Recruitment was limited by a number of factors. The first being the COVID-19 pandemic causing lockdowns and gym closures hence preventing regular exercise and strength training in gyms so many felt untrained and unable to perform the protocol. The maximal nature of the study put strain on those who had fallen out of a training routine and who had lost significant amounts of strength. Secondly, the pool of subjects available was small and made smaller due to the lack of popularity of strength sports amongst university students, this was particularly prominent in females. Female participation in sport in general is lower than males (Eime et al., 2016) and it is not surprising that this is exacerbated in strength sports, a male dominated sport (Sallis et al., 1996). There was a 6:1 ratio of males to females in this completed study. An additional 3 females attending screening but were not able to perform a bodyweight parallel front squat or did not meet the inclusion criteria (Table 4). Although there was a pool of strength trained females available, they did not have experience using front squats in a regular training programme. This could be a product of lack of training knowledge, not considering front squats as necessary in a programme, or finding them technically difficult, however more research would need to be performed to establish the reason for this gap. In order to study sex differences with adequate statistical power, a sample of 24 participants (12 male and 12 female) would be required. The findings presented are an analysis of 5 males and 5 females, matched for sport and experience levels.

2.1. Electromyography

There were no significant sex differences in electromyography except in the RF. Previous research has evidenced that females may have increased quadricep recruitment to support the knee and in an attempt to prevent knee valgus and excess hip adduction (Robertson et al., 2008; Schoenfeld, 2010), this increased quadricep activation could result from compensation for lower activation of the hamstrings and this could increase risk of lower extremity injury (Escamilla et al., 2012; Schoenfeld, 2010). This research provides support to this hypothesis as RF activation was significantly greater in females than males for the following conditions; peak pre front squat, peak post back squat, mean pre and post front squat, and mean post back squat. This greater RF activation in females is also supported by Clark (2005) who noted that males and females demonstrate different neuromuscular activation patterns of the RF and evidenced in work by Flaxman et al. (2013). In weight-bearing isometric exercises, greater RF activation was concluded to be required for knee stabilisation (Flaxman et al. 2013). This contrasts research by Mehls et al (2020) which reported no differences in RF however noted higher BF activation in males during eccentric phases, and research by Youdas et al. (2007) that evidenced males to be more able to effectively recruit the hamstrings in single leg squats however this research would support the hypothesis that RF activation is increased to compensate for lower hamstring recruitment as males have greater hamstring activation than females (Mehls et al. 2020; Youdas et al., 2007). This study did not split eccentric and concentric phases which may account for lack of significant findings surrounding BF activation. Additionally, this study used near maximal loads of 93%, whilst Mehls et al. (2020) used 85% of 1RM and hence this study may have seen greater levels of muscle activation.

Muscle activation in this study was evidenced not to be affected by fatigue for males however females evidenced a significant decrease in peak RF muscle activation following fatigue protocol in the front squat. This could result from an increased inability to recruit the quadriceps to support the knee as a result of fatigue.

These findings are not generalisable due to the small sample and more participants are required to confirm these findings as the sample to compare sexes was small.

2.2. Ground reaction forces

Males showed a consistently higher ground reaction force than females, a product of heavier mass and heavier weight lifted (Table 11). The 10 participants studied also exhibited the same trend of higher GRF in the back squat than the front squat. Between each individual squat peak, significant sex differences were shown between the pre front squat 1, pre back squat 2 and 3, and post back squat 2 (Figure 11). Highlighting the individuality of each squat, there was no trend or relationship between the force production of each squat across the sets in accordance with earlier presented findings in males that there were no trends across individual squats in a set.

Females have been evidenced to have lower maximal knee flexion than males in a number of activities including landing (Huston et al.,2011), cutting (Sheu et al., 2015), and using a dynamometer (Garceau et al., 2010). This lesser knee flexion can result in lower ground reaction forces (Dali et al, 2013). Additionally, Harbili (2012) earlier reported that females have slower knee flexion than males and this may result in a slower cadence and hence lower GRF. This may be particularly prominent in the front squat where the bar is less stable. Participants were allowed to squat to their desired depth as long as it was parallel or below, meaning the thigh was at least parallel to the floor, this meant that there could have been differences in depth between the back and front squat depth for the same participant however it was not measured. Further study is required to explore differences between parallel and full front and back squats to establish the role of knee flexion in GRF this could include using kinematic measures such as using cameras and marker tracking.

Askow et al. (2019) have also evidenced power production differences between males and females in the back squat and that this could alter GRF, however because of the higher absolute load of males and weight being lifted in this study it is difficult to conclude whether there were differences in GRF as a result of other factors. Hence, future research could normalise GRF to bodyweight and weight lifted to explore underlying factors.

2.3. Fatigue

2.3.1. Within sets.

In support of the earlier conclusion, there were no differences between individual squat peaks in the same set of three for either males or females which confirms that there are limited effects of fatigue within a set of three squats.

2.3.2. Between sets

There were no differences in GRF between pre and post conditions for either sex. However, males performed an average of 6 fewer jumps than females in the front squat condition, and 5 fewer jumps than females in the back squat condition. This lends early evidence to the hypothesis that females are less fatigable than males, and that this also applies in a strength endurance protocol as females were able to complete more sets of squats at the same relative load as males.

There were significant differences in jump height and these differences were likely not as a result of anthropometric differences in physical height or body mass (Markovic & Jaric, 2006), however could be related to body fat percentage (Abidin & Adam, 2013). These differences in jump height could be a factor in fatigue, for example if males became more exerted as they were jumping higher. Participants were not allowed to use arm swing as they had their hands placed on their hips hence upper body strength did not play a factor in males being able to jump higher

Higher CMJ in males has been related to greater power generation and greater velocity in concentric phase and take off (McMahon et al., 2017) so it could be expected this would also be evidenced in squats with males able to generate greater power out of the bottom position at relative weights. This is shown in the results of Askow et al. (2019) where males showed consistently higher peak and mean power and velocity during the back squat even when normalised to bodyweight, however, it was concluded that these differences were the result of strength differences rather than biological sex. Yet, as has been discussed in this thesis, strength differences are a result of biological sex so the conclusion that sex differences result in differences in power production can still be taken and this extra power production could be a detriment in strength endurance tasks by increasing fatigue. More research would need to compare rate of force development and power production differences between males and females during front and back squats and whether this power production difference has effects on fatigue.

3. Limitations

This study has a number of limitations to address, as earlier discussed there was limited female recruitment which resulted in a change in focus of the study. There were certain limitations in methodology and study technique such as in measures of fatigue and EMG. There was also scope for improvement such as involving measures of kinematics including velocity.

The importance of kinematic analysis has been highlighted throughout this study however this measurement was unavailable to the author at the time of study. The lack of kinematic analysis makes it difficult to form conclusions regarding the use of front squats in place of back squats in rehabilitation settings. Kinematic analysis would enable investigation of the possible reasons for differing muscle activation between front and back squats such as differences in knee flexion, hip and knee dominance, and joint loading as well as exploring differences in compressive and shear forces between squat types. This would also have allowed for standardisation of squat depth to parallel, however it is important to note that doing this may affect the established motor control patterns of lifters. Possible methods include using cameras and 3D analysis, marker tracking and measuring bar velocity using a linear position transducer or accelerometer with live feed which would allow a more accurate perception of fatigue. Unfortunately, this was unavailable. Additionally, the study could have included measures of other muscles such as the rectus abdominis and external oblique of the core. These were not included as there were no application guidelines by SENIAM (Hermens & Freriks, 2000) and the EMG equipment used only allowed for 6 muscles to be analysed. Analysis of muscle activation differences of the core between front and back squats may have been helpful in investigating the differences induced by the increased forward lean of the back squat compared to the upright position required in the front squat.

Ideally, front squat and back squat 1RM testing would have been performed in separate sessions, however time constraints of both the study and of participants prevented this. This may have resulted in back squat maximal lifts being slightly lower than actual maximum lifts, however self-reported maximums of participants were close to actual performed maxes. For the purpose of this study, participants performed a 3RM in the experimental procedure rather than a 1RM in order to allow some averaging of reps between the two maximal trials for increased reliability. This enables study of a high intensity close to 100% without increasing likelihood of failure in order to ensure an optimal amount of data is collected.

Ground reaction forces were not standardised to bodyweight of participants, this would have been too time consuming within the time restraints of the study however may have yielded different results for differences in ground reaction forces between front and back squat that were not just a result of the heavier weight lifted. Future work could also study eccentric and concentric phases separately as well as exploring the symmetry between GRF output to compare between front and back squats for stability.

Due to the variability in individuals, personal squat type i.e. stance width, toe direction, depth and joint ankles, squats can favour different muscles that may not relate to sex or squat type (Lorenzetti et al., 2018). For example, wide stance results in higher activity in the GM (Paoli et al., 2009; Caterisano et al., 2002). The squat depth and knee flexion in this study was not measured but participants performed self-selected squat depth to either parallel or below parallel as judged by a qualified instructor, parallel was judged as the top of the thigh being parallel to the floor and the hip joint aligned or below the knee joint. This depth was maintained throughout due to the use of experienced lifters in the study who would be likely to have set depth and motor control patterns as well as having an instructor to visually inspect and note any significant deviations. For this reason, it is unlikely that squat depth would have affected within condition differences i.e. pre and post conditions, however may have varied between front and back squat conditions.

Conclusions and further research

To conclude, in males there were significant differences in hamstring recruitment between front and back squat highlighted by greater peak ST muscle activation in back squats. This higher activation could be related to flexion of the knee in addition to hip extension and stabilisation. There were no differences in quadricep muscle activation. Significantly higher ground reaction forces in the back squat compared to the front squat were assumed to be the product of a heavier weight used, as well as contributions of stability, speed and joint angles. The same conclusions were also made for differences between males and females, with males exhibiting a heavier squat and higher ground reaction forces, and based on previous literature possibly greater knee flexion. Finally, females exhibited greater RF activation than males across multiple conditions and this may be to provide support for the knee and counteract knee valgus and excessive hip adduction hence females may require more hamstring isolation exercises compared to males in order to prevent muscle imbalances. These findings may change how squats are prescribed in injury rehabilitation and in long term training following an injury, with a greater shift towards the front squat, not just to increase muscle activation at a lower load but also to test and exercise flexibility at the hip, knee, shoulders and wrists. The front squat may allow those with injuries to reach higher intensities in squats, without compromising the joint. In elite performance, the front squat is useful when aiming to reduce total training load and joint stress without decreasing intensity, however the back squat may be more appropriate when seeking to increase hamstring recruitment and activation, for example in instances where the athlete is excessively quadricep dominant as large imbalances could lead to injury. To summarise, prescription of front and back squats in a programme is highly individual depending on training objectives, existing injuries, muscle imbalances and fatigability. This research highlights the importance of a personalised programme in both rehabilitation and elite sport.

Further research could confirm the sex differences in electromyography of front and back squats and in particular differences in rectus femoris activation, explore the effects of depth on ground reaction forces and how this differs between front and back squats, whether females and males exhibit differences in front and back squat stability and cadence, differences in compressive and shear forces on joints in the front and back squat and how this differs between sexes, and additionally a qualitative or quantitative analysis of how front and back squats differ from perspective of the athlete and whether this is a factor behind differences in performance including effects of bar placement on stability, depth and number of sets and repetitions performed before failure. Finally, the rate of force production and velocity in front and back squats needs further exploration to confirm whether greater stability of bar positioning in the back squat enables greater power generation.

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Appendices

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Screening Questionnaire

Name: ______________________________ **Study Code** [ ]

Risk Factors		**Risk Factor**	**No Risk Factor**
Q1. **Age** ______years	Male Female	≥45 ≥55	<45 <55
Q2. Are you a current **smoker**? *If yes, how many cigarettes do you smoker per day?* __________		Yes	No
If no, have you ever smoked? *If yes, how long has it been since you quit?* ______________		Yes	No
Q3. **Family history:** Have any parents or siblings had a heart attack, bypass surgery, angioplasty or sudden death* prior to 55 years (male relatives) or 65 years (female relatives)? *If yes, please circle what they had.*		Yes	No
Q4. What is your **ethnicity**? *Please provide here* ______________________________			
Q5. **Sport (if applicable):** ____________			
Q6. **Physical activity:** In the past year, have you engaged in a regular weight training programme including the front and back squat?		Yes	No
Q7. **Body Size:** Weight ________ kg Height ________ cm **Body Fat %**	Males Females	≥20 ≥30	
Q8. **Resting blood pressure:** Systolic BP __________ mmHg Diastolic BP __________ mmHg *Do you take blood pressure medication?*		≥140* ≥90* Yes	<140 <90 No

*Advise to visit GP   Question highlighted in **blue** will be completed after measurement taken

Personal History of Disease		
Q10. Heart disease	Yes	No

Q11. Peripheral vascular disease	Yes	No
Q12. Cerebrovascular disease (e.g. stroke)	Yes	No
Q13. Asthma	Yes	No
Q14. Chronic obstructive pulmonary disease	Yes	No
Q15. Diabetes mellitus Type 1 Type 2	Yes Yes	No No
Q16. Thyroid disorder	Yes	No
Q17. Renal (kidney) disease	Yes	No
Q18. Liver disease	Yes	No
Q19. Musculoskeletal conditions Osteoarthritis Rheumatoid arthritis Osteoporosis	Yes Yes Yes	No No No
Q20. Any other condition? Please provide details ___________________ ____	Yes	No
Q20. Do you have an injury that may be worsened with exercise? *If so, please provide details* ______________________________ ____	Yes	No
Q21. Are you taking any prescribed or non-prescribed medications/drugs? *If so, please provide details* ______________________________ ____	Yes	No

Additional Questions		
Q9. Have you had any **alcohol** to drink in the last 24 hours? *If yes,* how many units? ______________ units how long ago? ________________ hours	Yes	No
Q10. Are there any other factors that may affect your results today? E.g. viral infection, injury, smoking, exercise, recreational drugs. *If so please give details*		

Figure 1: The screening questionnaire used based on based on American College of Sports Medicine, 2016.

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Consent Form

Study Title: Sex differences in muscle activation in front and back squats when fatigued

We are asking if you would like to take part in the above research project.
Before you consent to participating in the study we ask that you read the participant information sheet and mark each box below with your initials if you agree. If you have any questions or queries before signing the consent form please speak to the researcher.

Please initial each statement

1. I confirm that I have read the information sheet and fully understand what is expected of me within this study ☐
2. I confirm that I have had the opportunity to ask any questions and to have them answered. ☐
3. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. ☐
4. I understand that once my data have been anonymised and incorporated it might not be possible for it to be withdrawn, though every attempt will be made to extract my data, up to the point of publication. ☐
5. I understand that the data will be anonymised and may be published; all reasonable steps will be taken to protect the anonymity of the participants involved in this project. ☐
6. I understand that the researcher will discuss data with their supervisor as needed. ☐
7. I consent to Lancaster University keeping the data collected for 10 years after the study has finished. ☐
8. I consent to take part in the above study. ☐

Name of Participant__________________ **Signature**____________________ **Date** ___________

Name of Researcher __________________**Signature** ____________________**Date** ___________

Figure 2: Informed consent form which all participants were required to fill in before participation

Study code:

Recently published research has evidenced differences in female performance in sport due to the different hormonal profiles experienced throughout the menstrual cycle. All of these questions are optional to answer and please do not feel pressured to do so, however the information may offer new insight into female participation in strength sports. All answers will remain anonymised to your study code.

Menstrual cycle			
Q1. Have you had a period in the last 3 months?	Yes	No	
Q2. Are you on any form of **hormonal** contraception? *If yes, which?* ___________________	Yes	No	
Q3. Have you been on any form of hormonal contraception in **the last 3 months?**	Yes	No	N/A
Q4. To your knowledge, is your cycle regular? Usually >21 and <35 days. *If no, is it longer or shorter?* ____________________	Yes	No	N/A
Q5. Is there any chance you could be pregnant?	Yes	No	
For your awareness, you must not participate in the experimental sessions of the experiment if you are menstruating. Organisation of research sessions will also be done around this.			

Figure 3: Menstrual cycle questionnaire for females to fill out to ensure they were not menstruating at the time of testing and if it were possible to analyse performance differences depending on cycle.

Table 1: A table presenting the EMG values (mean +- SD) for each muscle for each condition, presenting as %MVIC.

	Squat	VM	RF	VL	BF	ST	ES
Mean (%MVC)	**Front Pre**	67.54 ± 21.49%	102.46 ± 56.63%	75.31 ± 28.59%	83.8 ± 42.24%	62.69 ± 32.3%	80.71 ± 25.75%
	Front Post	64.37 ± 21.88%	99.35 ± 57.84%	74.25 ± 30.92%	83.98 ± 37.83%	65.21 ± 42.73%	78.49 ± 26.65%
	Back Pre	72.65 ± 21.01%	93.34 ± 43.95%	77.29 ± 39.12%	88.05 ± 38.19%	79.91 ± 41.51%	76.71 ± 26.07%
	Back Post	66.35 ± 26.65%	84.58 ± 34.5%	73.85 ± 31.16%	100.32 ± 53.44%	83.11 ± 39.92%	83.64± 24.95%
Peak (%MVC)	**Front Pre**	127.34 ± 36.51%	219.29 ± 133.34%	153.57 ± 61.89%	205.4 ± 110.03%	157.29 ± 84.67%*	141.63 ± 37.95%
	Front Post	128.84 ± 47.51%	211.28 ± 110.31%	137.7 ± 56.98%	210.57 ± 100.22%*	176.86 ± 110.95%	138.91 ± 45.53%
	Back Pre	134.69 ± 42.38%	196.66 ± 92.98%	146.86 ± 72.62%	245.05 ± 117.8%	219.03 ± 131.19%*	142.23 ± 51.23%
	Back Post	130.93 ± 66.85%	186.8 ± 88.2%	135.11 ± 53.22%	273.37 ± 143.95%*	215.36 ± 120.52%	150.63 ± 52.15%