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Knee Kinetics during Squats of Varying Loads and Depths in Recreationally Trained Females

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Abstract:

The back squat exercise is typically practiced with varying squat depths and barbell loads. However, depth has been inconsistently defined, resulting in unclear safety precautions when squatting with loads. Additionally, females exhibit anatomical and kinematic **differences to** males which may predispose them to knee joint injuries. The purpose of this study was to characterize peak knee extensor moments (pKEMs) at three commonly practiced squat depths of above parallel, parallel, and full depth, and with three loads of 0% (unloaded), 50%, and 85% depth-specific one repetition maximum (1RM) in recreationally active females. Nineteen females (age, 25.1 ± 5.8 years; body mass, 62.5 ± 10.2 kg; height, 1.6 ± 0.10 m; mean ± *SD*) performed squats of randomized depth and load. Inverse dynamics were used to obtain pKEMs from three-dimensional knee kinematics. Depth and load had significant interaction effects on pKEMs (p = 0.014). Significantly greater pKEMs were observed at full depth compared to parallel depth with 50% 1RM load (p = 0.001, **d = 0.615**), and 85% 1RM load (p = 0.010, **d = 0.714**). Greater pKEMs were also observed at full depth compared to above parallel depth with 50% 1RM load (p = 0.003, **d = 0.504**). **Results indicate effect of load on female pKEMs do not follow a progressively increasing pattern with either increasing depth or load. Therefore, when high knee loading is a concern, individuals are must carefully consider both the depth of squat being performed and the relative load they are using.**

Key Words: back squat, biomechanics, knee joint moments, full depth squat

INTRODUCTION

The back squat is a popular resistance training exercise used for **developing** the **lower body** muscles. **The back squat** increases lower body strength, improves lower body rate of force development, and is a necessary component in many athletic and clinically based populations (11,24). **In therapeutic environments, squat depths are typically performed using between 0 and 60° of knee flexion (half and quarter squats) as these ranges of motion result in the least amount of patellofemoral compressive forces observed (16).** However, deeper squat depths have been encouraged to engage the entire **lower body** musculature (9,24). For example, powerlifters typically train to parallel depths, defined as when the inguinal crease falls below the proximal patella at approximately 110° of knee flexion, and Olympic weightlifters often train to full depth, defined as when the back of the hamstrings come into complete contact with the calves at approximately 135° of knee flexion (16,23,30,42). Depth is normally paired with specific barbell loads depending on desired training outcomes. Loads of 75-85% one repetition maximum (1RM) are generally recommended for strength adaptations, 50-65% 1RM for power training (36), and unloaded (bodyweight) squats are commonly used in rehabilitation and novice training **(18,23,32)**.

While there are numerous benefits of incorporating loaded back squats in performance training and rehabilitation (11,17,18,36), there are also potential risks as the peak patellofemoral joint (PFJ) reaction forces and stresses that result from loaded back squats have been related to patellofemoral pain syndrome (PFPS), articular cartilage degeneration, and chronic knee pain (5,28,31,33).

Patellofemoral pain syndrome is of high economic relevance because it accounts for 25% of knee injuries in sports medical clinics, specifically affecting 15-33% of active adults, and 21-45% of adolescents (40). Between both populations, females are twice as susceptible as males in PFPS incidence rate (4). This may be due to females generally having greater femur internal rotation and valgus alignment, tibiofemoral joint laxity, and larger Q-angles than males (3,13).

Patellofemoral joint stress has been previously estimated using biomechanical models that rely on cadaveric loading rigs and magnetic resonance imaging (MRI; 8,27). However, in vitro stress testing is problematic because extrapolating results to in vivo situations are limited, and cadaver knees are usually obtained from older populations (35). Magnetic resonance imaging assessments are also problematic because they are expensive and may be inaccessible. An alternative for estimating PFJ stresses without cadaver and MRI reliance is computing the peak knee extensor moment (pKEM). Peak knee extensor moments represent the peak internal torque generated by the quadricep muscles and ligaments, and are commonly used in biomechanical models to obtain PFJ stresses (10,31). **Compared to mean knee extensor moments, pKEMs estimate peak PFJ reaction forces and stresses which have been related to PFPS and cartilage degeneration (5,28,31,33). Because previous research has shown a direct and linear relationship between both pKEMs and peak PFJ reaction forces and stresses (33,37), pKEMs can be used as a proxy for PFJ stress.**

Although previous studies have investigated the relationship between depth and load on pKEMs, results are incongruent and incomplete due to varying methodologies. For example, studies assessing pKEMs have used various loads including 1RM, three repetition maximum, or percent of body weight (20,27,33). Some studies also inconsistently defined depths with a broad range of knee flexion such as shallow (0-90° of knee flexion), parallel (100-125° of knee flexion), and deep squat depths (110-140° of knee flexion; 8,12,20). Lastly, studies have either excluded female participants, or combined their results with male data (12,20).

To date, no study has quantified female pKEMs during above parallel, parallel, and full depth squats with loading patterns based on depth-specific 1RMs. Quantifying pKEMs can give an estimate to subsequent peak PFJ stresses that may help therapists, trainers, and athletes optimally advise usage of the back squat exercise. Therefore, the purpose of this study was to assess pKEMs at three commonly practiced squat depths and with three commonly prescribed loads in recreationally active females based on depth-specific 1RM. More specifically, this investigation compared pKEMs at approximately 90° (above parallel), 110° (parallel), and 135° (full depth) of knee flexion, and with 0, 50, and 85% of depth-specific 1RM. It was hypothesized that pKEMs would increase with increasing depth, and increasing barbell load would increase the magnitude of pKEMs at each depth.

METHODS

Experimental Approach to the Problem

To avoid inconsistences in squat depth, above parallel, parallel and full depths were defined, measured, and replicated for each participant. Correct depth was ensured using customized equipment that detected the barbell's height from the ground. Experimental loads were calculated based on depth-specific 1RM determined at each depth and were assigned as either 0% (unloaded), 50%, or 85% 1RM.

Participants performed a total of nine conditions of randomly assigned depth and load. Peak knee extensor moments were determined for each condition by using inverse dynamics analyses from three-dimensional kinematic data and ground reaction forces.

Subjects

A total of 19 healthy, recreationally active females (mean age: 25.1 ± 5.8 years, height: 1.6 ± 0.10 m, body mass: 62.5 ± 10.2 kg, years of squat experience: 3.8 ± 2.6 years) were recruited from the university campus and surrounding community. Participants had no history of surgery or ligamentous injury to either **lower limb**, no participation in elite lifting competitions, and were visually assessed by the investigator for proper technique squatting to full squat depth. Proper technique was defined as achieving a full depth squat with heels on the ground, neutral lumbar lordosis, and no pain. Study procedures were explained to the participants who then provided written informed consent as approved by the Institutional Review Board. Participants were advised against vigorous physical activity 24 hours prior to testing and were not compensated for their time.

Procedures

One Repetition Maximum Testing

A non-standardized 10-minute warm up preceded 1RM testing. Participants were instructed to follow their typical warm up routine. One repetition maximum was then tested with a standard barbell for the full depth, parallel, and above parallel depths (Figure 1). This specific order was used due to reported 1RM decreases with increasing squat depth (12). Full depth was defined according to weightlifting practices in which **hamstrings** must come into complete contact with the calves (30,42). Parallel was defined according to USA Powerlifting rules in which a qualified parallel squat resulted in the inguinal crease falling below the proximal patella (12,38). Above parallel was measured with a goniometer to 90° of knee flexion. Participants were instructed to descend and ascend as they normally would during squat training. National Strength and Conditioning Association procedures for 1RM testing were used in which increments of 10-20% bodyweight were added until the participant could not ascend from the bottom of the squat (1). Loud, verbal encouragement was provided and participants were allowed to rest **for at least one to two minutes between attempts** (29).

Proper depth on each squat was ensured using a customized photocell consisting of a field laser (Banner Engineering Corp., Minneapolis, MN) and piezo light switch (Banner Engineering Corp., Minneapolis, MN) set in front of the participant (Figure 2). The piezo light switch audibly and visually cued participants to hold the bottom of the squat for one full second before ascending. A one second pause between the descent and ascent phases was used to avoid rebounding at the bottom most part of the squat. The field laser position was changed for each depth and carefully replicated for subsequent testing. Participants' stance widths and foot positions were recorded with tape to control for variation, and replicated in later trials. The tape outlined the posterior edge of the shoe near the heel, and the lateral most part of the shoe near the fifth metatarsal.

[Insert Figure 1 about here]

[Insert Figure 2 about here]

Data Collection Procedures

Motion capture data collection occurred between 24 hours and one week following 1RM testing. Participants performed two repetitions of each squat condition, with the order of squat conditions being randomized. Conditions were defined as follows: above parallel with 0% load (AP0), parallel with 0% load (P0), full depth with 0% (FD0), above parallel with 50% load (AP50), parallel with 50% load (P50), full depth with 50% (FD50), above parallel with 85% load (AP85), parallel with 85% load (P85), and full depth with 85% load (FD85). During all repetitions three-dimensional kinematic data was recorded using a 12 camera motion capture system (Qualisys Inc., Gothenburg, Sweden) sampling at 250 Hz. Squats were performed with each foot on a separate force plate (Model 600900-10, Bertec Corp., Columbus, OH; Figure 3), with ground reaction forces sampled at 1000 Hz.

Nineteen reflective markers were placed bilaterally to create eight segments: two feet, two legs, two thighs, a pelvis, and a torso (25). Anatomical markers included the acromioclavicular joints, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), lateral and medial epicondyles, lateral and medial malleoli, second metatarsal heads, and the calcanei (Figure 4). Additional tracking markers were placed on the iliac crests, midway between iliac crests and PSIS, on the base of the 5th metatarsal, on a headband over the forehead midway between the ears, and on the manubrium. Rigid plastic contoured shells containing four non-collinear tracking markers each were attached to the lateral aspects of the thighs and legs. Four additional tracking markers were placed on the dowel and barbell. Raw marker trajectories and ground reaction forces were exported to Visual 3D (C-Motion, Inc., Rockville, MD) where they were filtered using fourth-order, zero-lag Butterworth filters with cutoff frequencies of 6 Hz and 15 Hz, respectively.

Cutoff frequencies for the markers were determined based on residual analysis (39). Since pKEMs were the main variable of interest, a cutoff frequency close to that of the markers was used to avoid overestimating the peak value (26).

[Insert Figure 3 about here]

[Insert Figure 4 about here]

Hip joint centers were determined using the CODA pelvis segment regression equations (2) while knee and ankle joint centers were estimated as the midpoint between the medial and lateral femoral epicondyles and malleoli, respectively. Joint angles were calculated as the rotation of the distal segment with respect to the proximal segment using an XYZ Cardan rotation sequence corresponding to flexion/extension, ab/adduction, and axial rotation (22). Joint moments were calculated as internal joint moments using Newton-Euler equations of motion. For both repetitions in each of the nine conditions, knee extensor moments across the entire squat movement were calculated, normalized by body mass, and reported in units of Nm/kg. The highest knee extensor moment at each condition was determined as the pKEM from either the left or right knee. The pKEM slope (rate of pKEM increase) was then calculated for each depth from 0-50%, 50-85%, and 0-85% 1RM.

Statistical Analyses

A one-way repeated measures analysis of variance (ANOVA) was used to evaluate differences in 1RM between the three different depths. A three by three (depth x load) repeated measures ANOVA was used to evaluate how pKEM and pKEM rate of increase changed with increasing depths and loads. All statistical analyses were conducted with SPSS

(IBM, Chicago IL, version 22), with significance levels set to $p < 0 .05$. In the event of a significant omnibus test, a stepwise Sidak correction was used for subsequent post hoc pairwise **comparisons, and Cohen's d was reported for effect size between the two means**.

RESULTS

There was a significant difference in squat 1RM between depths $F_{(1.14, 20.47)} = 10.26$, $p = 0.003$ (Figure 5). The above parallel squat resulted in the highest 1RM (72.37 ± 4.44 kg), followed by the parallel squat (63.13 ± 4.00 kg), and the full depth squat (58.85 ± 4.25 kg). On average, participants squatted to a maximum knee flexion angle of 95.62 ± 7.61° for the above parallel trials, 111.42 ± 7.10° for parallel, and 135.43 ± 8.82° for full depth during kinematic data collection. Depth and load had a significant effect on knee flexion angle ($F_{(2, 36)} = 220.891$, $p < 0.0001$, d = 0.925; $F_{(2, 36)} = 7.452$, $p = 0.002$, d = 0.293 respectively).

There was a significant depth by load interaction for pKEMs $F_{(2.08, 37.45)} = 4.67$, $p = 0.014$ (Figure 6). Post-hoc comparisons revealed that in the unloaded condition, pKEM did not change with increasing depth (above vs parallel $p = 0.662$, above vs full $p = 0.547$, and parallel vs full $p = 0.912$). In the 50% 1RM condition, pKEMs were higher during full depth than either parallel $p = 0.001$, d = 0.676) or above parallel depths ($p = 0.003$, d = 0.590). Finally, at 85% 1RM, pKEMs were higher in full than parallel depth ($p = 0.010$, d = 0.678), but not different between full and above parallel depths ($p = 0.064$).

The effects of depth and load on rate of pKEM increase are shown in Figures 6 and 7. There was a main effect of depth on pKEM rate of increase ($F_{(1.455, 36)} = 4.57$, $p = 0.030$, d = 0.202). Post-hoc comparisons revealed that rate of pKEM increase was higher in both the above parallel and full depths, compared to the parallel depth in Figure 7 ($p = 0.010$, d

= 0.550; *p* = 0.026, d = 0.410 respectively). There was not a significant effect of load ($F_{(2, 36)}$ = 0.657, *p* = 0.525) or a depth by load interaction ($F_{(4, 72)}$ = 1.067, *p* = 0.379).

[Insert Figure 5 about here]

[Insert Figure 6 about here]

[Insert Figure 7 about here]

DISCUSSION

The primary purpose of this study was to investigate the influence of squat depth and barbell load on female pKEMs at three commonly practiced depths and prescribed loads. Results revealed that the effect of load on female pKEMs is dependent on squat depth and does not increase with either increasing depth or load.

To assess the effects of depth and load on pKEMs, it was necessary to first independently test 1RM for each squat depth. The finding that average load lifted significantly decreased with increasing depth is consistent with previous 1RM analysis in males (12), and patterns observed from electromyographical (EMG) analyses in competitive lifting (42). Powerlifters recruit more hip and low back extensor muscles to overcome heavier loads at parallel depth compared to knee extensor recruitment at full depth in weightlifters (41). Hip recruitment in the back squat has been documented as the dominant contributor throughout the movement compared to the knee and ankle as load increases, and as the limiting joint in a failed 90° back squat (7,8,19). Thus, more load can be managed during above parallel and parallel depths compared to full depth. Hip extensor muscular effort has also been observed to increase from 30-119° of knee flexion, while knee extensor muscular effort peaks at 105-119° of knee flexion (8), suggesting the majority of the lift will be managed by the knee extensors at maximum knee flexion.

The reliance on only the knee extensors may explain why the participants of this study lifted reduced loads at greater depths.

The surprising lack of difference between all depths in the unloaded condition demonstrated pKEMs change little at 90, 110, and 135° of knee flexion when not overcoming resistance above body weight (Figure 6). This finding is contrary to research that reported increases in knee moments with increasing knee flexion angle (12,15,37,42), and suggests there is no increased risk of knee joint forces and stresses at these specific knee flexion angles. Salem and Powers (2001) similarly found no significant differences in pKEMs at shallow, medium, and deep squats (approximately 72, 92, and 110° of knee flexion, respectively) with an 85% 1RM load in collegiate females. Bryanton et al. (2012) also found no differences in knee extensor relative muscular effort (RME) in the 90-104° range of knee flexion with 50-90% 1RM loads. The finding of a consistent pKEM range at these unloaded depths indicate squatting to full depth does not increase knee extensor activation, nor has deleterious effects on the knee joints. However, direct comparison is limited because Salem and Powers (2001) and Bryanton et al. (2012) did not measure pKEMs at 0% 1RM. Salem and Powers also did not determine depth-specific 1RM, potentially **misinterpreting** pKEMs observed at greater depths, and Bryanton et al. (2012) did not report pKEM values used to obtain knee extensor RME.

Compared to the unloaded conditions, increasing load at a given depth did not result in the hypothesized gradual increase in pKEM magnitudes as there was a significant depth by load interaction. Significantly higher pKEMs were only observed in full depth compared to above parallel and parallel depths with 50% 1RM load, and parallel with 85% 1RM load (Figure 6).

This variation in pKEMs is contrary to the hypothesis that pKEMs would increase as both depth and load increased, and aforementioned studies that reported increases in knee moments with increasing depth and load (8,12,42). Rather, this suggests the effect load has on female pKEMs depends on squat depth. Furthermore, post hoc comparisons revealed **that there were no significant differences between** in pKEMs between above parallel and full depth with 85% 1RM load. This would appear to indicate that heavy loaded back squats at either 90 or 135° of knee flexion can result in the same amount of increased PFJ or tibiofemoral joint forces and stresses. Both depths promote the possibility of injury risk in novice female lifters working at 85% 1RM loads or higher. There has been speculation that deep squats near 140-145° of knee flexion result in less forces and injury of passive tissues because lower loads are lifted and soft-tissue contact between the thigh and calf occurs to some degree (23). However, this idea is questionable by the results from Cotter et al. (2013) who observed a progressing linear relationship between depth and load on peak knee flexor moments (pKFMs). Cotter et al. (2013) found that although lower loads were lifted in deep squats near 140° of knee flexion, the decrease in load was not enough to offset the increasing pKFMs from depth alone.

The role of depth as the main factor on pKEMs was also seen in the pKEM rate of increase when increasing load from 0-50%, 50-85%, and 0-85% 1RM (Figure 6). The pKEM rate of increase was included in this study to further understand the potential for knee joint injury when increasing load at a certain depth. Comparing the effects of depth, load progression, and both on pKEM rate, only a main effect of depth was observed. More specifically, above parallel and full depths resulted in steeper and faster pKEM rates of increase, regardless of load progression (Figure 7).

This finding is contrary to those found in males, in which the pKEM rate of increase for 0-50% and 50-85% 1RM intensified as depth and load progression increased (12). This may possibly be due to the differences in squatting kinematics discernible between genders. However, it is important to note that although the results suggest there was no effect of depth with load progression on pKEM rate of increase, **the depth chosen for load progression may influence pKEM magnitude**.

This study has several limitations that should be considered when interpreting the results. Participants were encouraged to perform the squat how they typically would during training, leading to variance in shoe types worn, barbell positions used, and self-selected pace. Of the 19 participants, one wore weightlifting shoes and three utilized a low bar position while the rest squatted with a high bar position. The raised heel design has been shown to significantly affect foot dorsiflexion angle, consequently affecting knee and hip kinetics (34). Utilizing a low bar position results in increased hip flexor moments (41), and an accelerated or decelerated self-selected pace affects force production (14). **If an individual performed the concentric portion faster in a given depth and load combination than others, that could influence the rate of pKEM change. However, to date there is no literature on how speed of the concentric portion of a squat influences pKEMs, thus this is a suggested topic for future study.** This study utilized a one second pause that may not be typically practiced in recreational strength training. **Some athletic trainers, therapists, and coaches may prescribe it as a pause squat for several reasons depending on their client's goals and needs.** A one second pause was necessary to prevent rebounding at the bottom of the squat, which is typically seen in full depth squat training.

Rebounding at the bottom of the squat also increases tibiofemoral joint shear forces by 33%, and may cause an acute injury (15). It is also important to consider the limitations in using inverse dynamics to measure pKEMs. Inverse dynamics estimates the total joint torque produced by the agonist and antagonist muscles, and the ligaments at that joint (25). It is impossible to distinguish which muscle or ligament is most responsible for the resulting net forces and moments. Lastly, thigh-calf and heel-buttock contact pressures were not measured to assess their effects on knee moments in the full depth squat. Contact pressure significantly affects joint forces and moments and absorbs as much as 39% of bodyweight in an unloaded full depth squat (43).

PRACTICAL APPLICATIONS

Increased knowledge of knee joint moments at typical training depths and loads is valuable for health professionals utilizing the squat for female individuals with and without knee pathologies. Based on the results of this study, health professionals designing strength training programs must obtain depth-specific 1RM testing because decreased loads are expected as depth is increased. One repetition maximum measured at one depth should not be used for other depths. **Professionals should also consider the effect squat depth has on knee joint loading** as this will help guide them when prescribing a depth with a certain load. If a female client would like to squat without load, prescribing above parallel, parallel, and full depth squats would be permitted as these did not significantly increase pKEMs. If a female client would like to squat with load, parallel is advised as this resulted in the lowest knee joint loading.

However, if the goal is to increase knee extensor activation, then heavy loads at full depth are suggested as this had the highest pKEMs. Lastly, when designing programs to facilitate load progression, caution and supervision is strongly encouraged as females will experience a significant increase in knee joint loads at above parallel and full depths.

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FIGURES LEGEND

Figure 1. Full depth, parallel, and above parallel squat depths.

Figure 2. Field laser and piezo light switch.

Figure 3. Motion capture data collection trial.

Figure 4. Anterior and posterior view of marker set-up.

Figure 5. Bar graph of 1RM testing. Data are presented as mean ± standard error of mean.

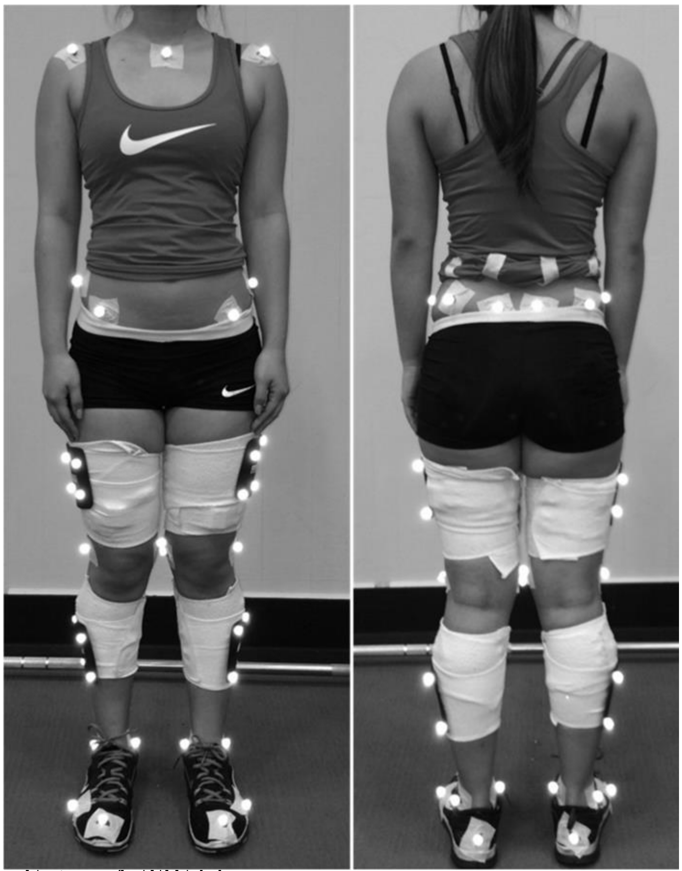
Figure 6. Line graph of normalized pKEM and load post hoc comparisons. Data are presented as mean ± standard error of mean.

Figure 7. Bar graph of pKEM slope and load. Data are presented as mean ± standard error of mean.

Figure 1, TIF file

Figure 2; TIF file

Figure 3; TIF file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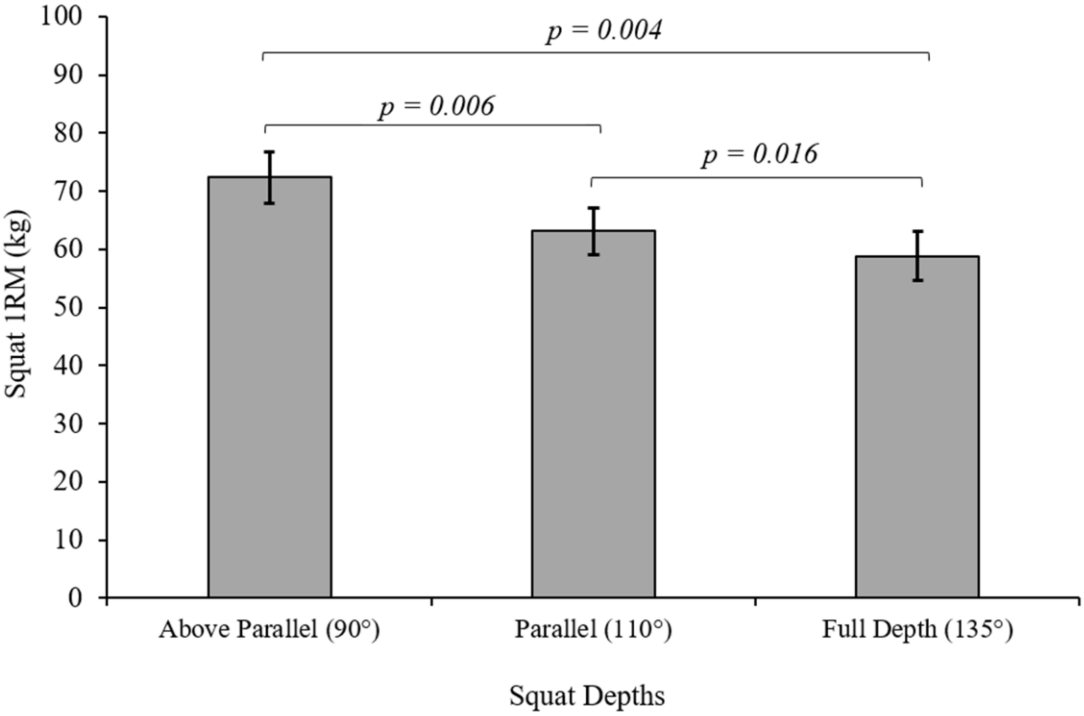

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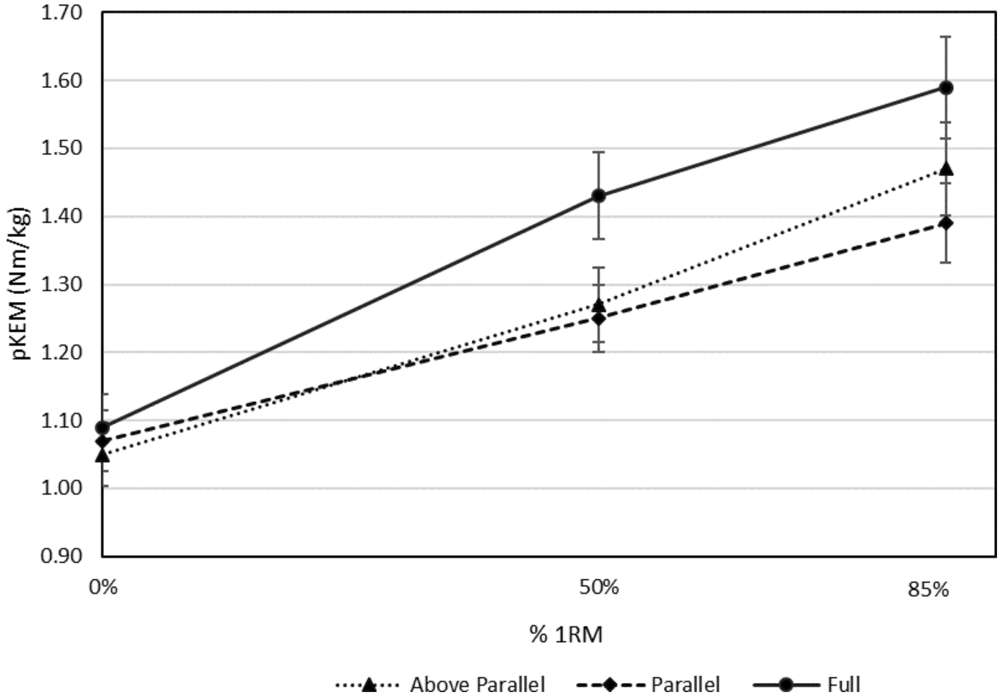

Figure 6; TIF file

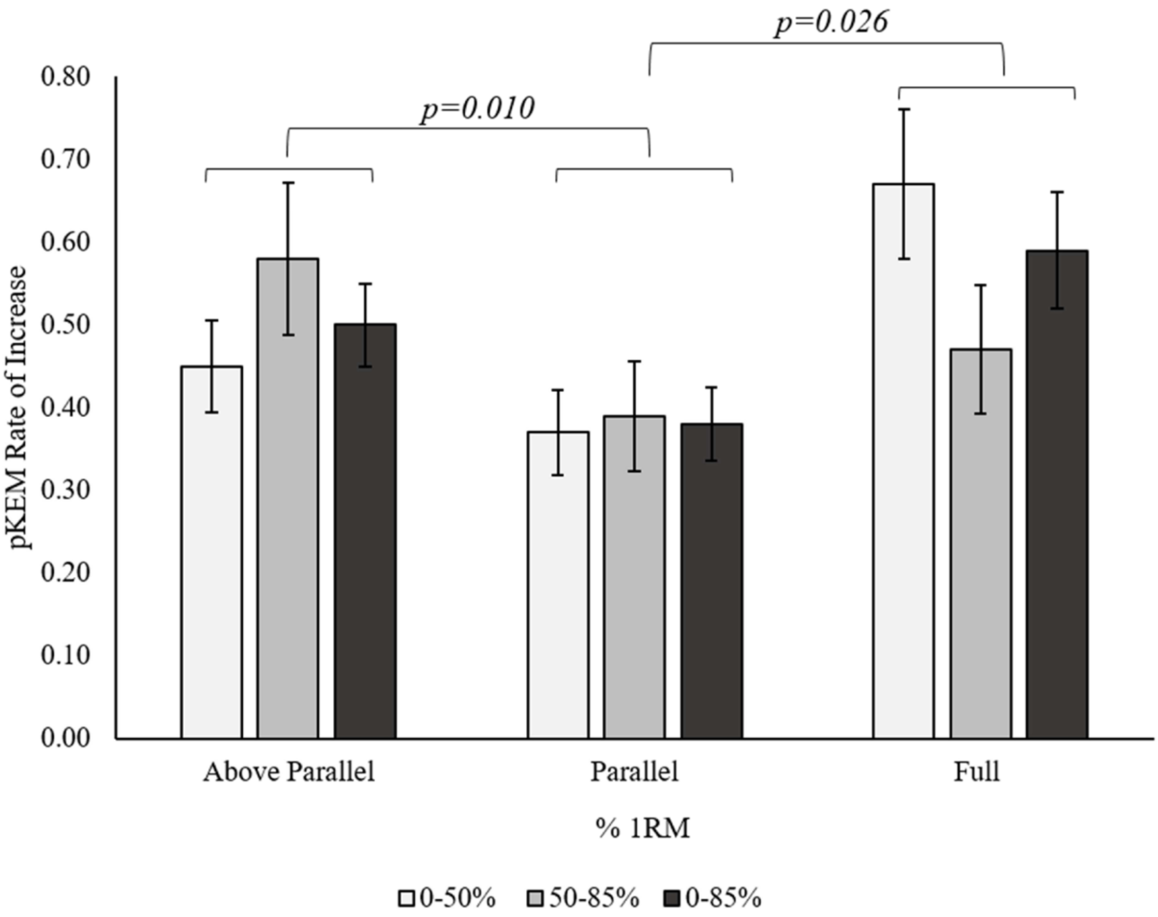

Figure 7; TIF file