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ORIGINAL RESEARCH

STATIC LOADS ON THE KNEE AND ANKLE FOR TWO MODALITIES OF THE ISOMETRIC SMITH SQUAT

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ABSTRACT

Introduction: The back squat is a popular strength training exercise that recruits approximately 75% of the muscular system. However, knowledge of muscular and joint loads incurred when performing two variations of the back squat, namely the high bar and the low bar isometric parallel-depth Smith squat, is limited. Therefore, this study aims to determine the lower limb muscle forces and the compressive and shear joint forces at the knee and ankle incurred in these two subtle variations of the one repetition maximum (1RM) isometric Smith squat.

Method: Eight healthy male 400-m sprinters participated in the study. The participants performed the two modalities of the squat using a 7° backward-inclined Smith machine. The bottom of the squat corresponded to a position in which the thighs are parallel to the ground. The mean ± SD 1RM external load for the eight participants was 100.3 ± 7.2 kg. During the squat, the participants paused for 2-3 s at the bottom of the squat. This was, therefore, considered a static position for the calculation of isometric muscle forces and joint loads using static mechanical analysis. Moment arms, and joint and segmental angles were calculated from video images of the squat obtained at 25 Hz. Internal forces were computed using a geometrical model of the lower limb.

Results: Quadriceps muscle and knee joint forces were higher in the high bar squat; where, the mean patello-femoral joint reaction force was 3.7 body weights (BW). The ankle extensor muscle and ankle joint forces were larger in the low bar squat; whereby, the mean compressive force at the ankle joint was 3.0 BW.

Discussion: The high bar squatting modality may be avoided in the rehabilitation of ACL injury. Conversely, the low bar technique may be discouraged in conditions of ankle joint instability, strained Achilles tendon, and damaged gastrocnemius and soleus muscles. The findings of the static biomechanical evaluation provide an in-depth understanding of the musculoskeletal loads associated with the two squat modalities in isometric conditions and offer a foundation for the dynamic modelling of the high bar and low bar Smith squat. Further, the knowledge gained can be used for the prevention of injury in strength training and in the design of rehabilitation programs that control muscle recruitment and joint loads.

Keywords: Ankle, compressive force, isometric squat, knee, rehabilitation, shear force, Smith machine, Statics.

INTRODUCTION

The squat is an integral part of strength training and injury prevention programs, and it is frequently prescribed in rehabilitative interventions [1,2]. Different squat techniques and equipment provide varied modalities of administration of the resistance load. Therefore, the squat exercise can be adjusted according to the training stimuli demands and injury status of individual athletes [3]. Here we review the following: 1. Musculoskeletal loads incurred when using different modalities of the squat exercise; 2. Attributes of the free squat and the Smith squat modalities; 3. Benefits of using the static isometric squat in training, rehabilitation and research programs; and 4. State of the literature on two subtle variations of the back squat, namely the high bar and low bar squat techniques.

Musculoskeletal loads in different modalities of the squat exercise

Previous research recommends that in the common squat the knee should not be displaced forward across the virtual vertical line of the toes (*knee-shifted* squat) to minimise knee joint loading [3,4]. Using inverse dynamics, Strutzenberger *et al.* [3] obtained significantly higher knee varus moments and ankle dorsiflexion moments for the knee-shifted squat and concluded that the knee-shifted modality should be avoided in squat training. Similarly, Escamilla *et al.* [4] calculated the cruciate ligament forces and patellofemoral joint force for the long wall squat (feet farther from the wall and knee behind the vertical line of the toes) and the short wall squat (feet closer to the wall and knee shifted over the vertical line of the toes). Higher posterior cruciate ligament forces occurred in the long wall squat, however the patellofemoral joint forces were lower compared to the short wall squat. Previous work has shown that the relative contribution of the knee and ankle to the free squat movement, and therefore the relative injury risk, is external-resistance dependent [5]. The knee contribution declines with increasing resistance, whereas the ankle contribution increases when using larger resistances [5]. In the rehabilitation of patella tendinopathy, higher loading on the patella tendon aids in the rehabilitation process [6,7]. Squatting on a declined surface, typically implemented by raising the heel by 3-4 cm, is therefore advisable as this increases the strain load on the patella tendon [6,7,8]. However, Biscarini *et al.* [9] have suggested that a raised heel during the squat increases the medial displacement of the knee in the downward phase; thus, augmenting the risk of meniscal, anterior (ACL) and posterior (PCL) cruciate ligament, and medial collateral ligament (MCL) damage. Compensation for poor joint mechanics can be achieved by performing the squat in a Smith machine with a forward or backward incline [10]. The inclined path of the barbell alters muscle recruitment and joint stress, and can help in recruiting weak muscles in the rehabilitation of specific injuries [11]. Hence, previous research highlights the implications of varied forms of the squat exercise for the prevention and rehabilitation of injury.

Attributes of the free squat and the Smith squat

In the free barbell squat, the line of gravity of the athlete plus barbell system must fall between the heel and the forefoot to allow the athlete to preserve balance [1-3]. Therefore, the hip, knee, and ankle joints are constrained to contribute with a certain angular range and share of the musculoskeletal load [2]. Each phase of the free squat exercise is characterised by a well-defined joint torque distribution among the joints involved [5]. In contrast, in the Smith squat, the reaction forces created by the barbell tracks counteract any forward-backward imbalances of the combined athlete-barbell centre of mass and permit selective forward-backward positioning of the feet relative to the barbell, and varied amounts of trunk tilt [9,10,12]. Thus, the optional foot positioning characteristic of the Smith squat allows selective muscle and joint loading, and therefore optimised strength training and injury rehabilitation strategies [9,10,12].

Schwanbeck *et al.* [12] reported higher electromyographical activity of the lower limb prime movers when performing free squats compared to Smith squats. Hence, the free squat is considered more beneficial than the Smith squat for individuals that aim to strengthen plantar flexors, knee flexors, and knee extensors. However, it has been suggested that the inherently safe lifting environment provided by the Smith machine permits the athlete to attain a deeper squat, which may not otherwise be attained in a free squat [12]. Research by Hartmann *et al.* [13] advocates the use of deep squats which present an effective training exercise and protection against injuries. With increasing knee flexion, the '*wrapping effect*' enhances load distribution around the soft tissues of the lower limb [13]. With greater knee flexion a cranial displacement of facet contact areas with enlargement of the retropatellar articulating surface takes place, leading to lower retropatellar compressive stress. Also, a deeper squat incurs gains in flexibility of the lower limb musculature [1,5]. The literature, therefore, presents good arguments as to why the Smith squat may supplement the traditional free squat in strength and conditioning programs.

Further, the Smith machine allows the athlete to take advantage of the different types of loading mechanisms found in modern Smith machines and, hence, optimise different exercise protocols [14]. Such loading mechanisms of Smith machines include the basic constrained weighted barbell, counterweight system, and viscous resistance mechanism. Arandjelović [14] has recommended that at low intensities (55-75% of one repetition maximum (1RM)) typically used in strength-endurance training, the viscous resistance mechanism provided by Smith machines is preferable. At medium intensities (75-85% of 1RM) used in hypertrophy-specific training, a counterweighted Smith machine offers advantages to attain both high-force development and greater total external work. At high training intensity (90-100% of 1RM), the optimal prescription should address the specific muscular weaknesses and injury history of the athlete [14].

Recently, Biscarini *et al.* [9] developed a biomechanical model for the Smith squat exercise and calculated the static lumbosacral, hip and knee joint torques, the shear and compressive components of the tibiofemoral joint loads, and the patellofemoral compressive force for varied external loads, foot positioning, and trunk tilt. Compared to the free barbell squat, Biscarini *et al.* [9] confirmed that the Smith squat can be easily adapted to modulate the distribution of muscle activity and minimise the mechanical load on joint structures. Backward-inclined Smith machines allow further capability for the modulation of muscle activity and joint load distribution [12,15]. However, little research attention has been devoted to the analysis of the biomechanical properties of the isometric Smith squat and the postural and technical variations that can be accommodated using a Smith machine. Therefore, the intricacies of using the Smith machine for strength training, and injury prevention and rehabilitation need further research.

Benefits of the static isometric squat

There are advantages in athletic training for using static isometric squats to complement dynamic squat training. In a static squat, the athlete can hold the isometric contraction through different angles of the range of motion to target specific length-tension properties of the muscle [3,4]. The isometric mode permits the muscle to develop higher tension according to the force–velocity relationship [3,16]. Further, the static squat eliminates inertial effects, therefore providing a form of high-torque isokinetic training in which the velocity is zero [3,16]. Also, if the athlete had a history of patella tendinopathy the static squat helps increase tensile strength of the patellar tendon [6,7]. From a methodological viewpoint, static analysis of the isometric squat provides insight into the musculoskeletal loads associated with variations in squatting technique prior to conducting a more complex dynamic analysis of the squat that may involve inverse dynamic analysis, intricate numerical modelling, and computer aided engineering simulation [9,10]. Hence, it is important to gain further insight into the biomechanics of the isometric squat.

The high bar and low bar squat techniques

A form of altering the squatting technique and joint mechanics is by selecting either a high bar or a low bar back squat [2]. In the high bar squat modality, the barbell is positioned at the base of the neck and above the posterior deltoid muscles [16]. When using the low bar technique, the athlete holds the bar across the posterior deltoids and through the middle of the trapezius muscles [16]. However, our understanding of the muscular and joint loads incurred by these two subtle variations of the back squat, namely the high bar and low bar techniques, performed isometrically on a Smith machine is limited. Therefore, this study aims to determine the quadriceps muscle force and knee joint forces incurred in the high bar and the low bar isometric parallel-depth Smith squats during 1RM lifting performance. In the parallel-depth squat, the bottom of the squat corresponds to a position in which the thighs are parallel with the ground. Biomechanical knowledge of the high bar and the low bar squat exercise can be used in the design of effective conditioning programs and rehabilitation protocols that activate selected muscle groups and unload specific joint structures. Also, the findings of the static biomechanical evaluation provide an in-depth understanding of these two subtle modalities of the back squat under isometric conditions and establish a foundation for the dynamic analysis of the high bar and low bar Smith squats.

METHOD

Study Design

This study consisted of an experimental repeated measures design in which the same participants performed both the high bar and low bar parallel-depth 1RM Smith squats. Data collection was carried out under controlled laboratory conditions which permitted standardising squat instructions and test protocols.

Participants

Eight healthy male athletes of mean ± SD age of 22.3 ± 1.4 years, height of 178.9 ± 10.2 cm and mass of 80.0 ± 12.6 kg participated in the study. The athletes were 400-m sprinters of club level, with a mean ± SD 400-m performance of 51 ± 1.5 s. The participants performed sprint training 5 times per week, were experienced in using the back squat, and performed one session of squats as part of their weekly strength training program. All the participants were healthy, active individuals with no history of ankle, knee or lower back pathology. The participants did not take part in any strength or sprint training for 48 hours prior to data collection to ensure that their leg muscles were fully recuperated from previous training sessions and to prevent any delay onset of muscle soreness (DOMS); previous research has found that factors such as muscular fatigue and DOMS affect lifting technique [3,9]. This study was approved by the Institution's Research Ethics Committee.

Execution of the Squats

The participants performed the high bar and low bar isometric Smith squats based on the technique model illustrated by Baechle and Earle [16]: squat depth characterised by thighs parallel to the ground, shoulder width stance, feet parallel to one another, unrestricted knee forward displacement relative to the toes, and push through the heels. The participants were instructed to place their feet directly below the bar at set-up, so that the barbell line of gravity falls between the heel and toes. This foot positioning at set-up permits standardisation of the initial squatting position and also feels natural to the athletes [1,2]. All squatting movements were performed using a LifeFitness Hammer Strength 7° backward-inclined Smith Machine. The participants used their individual 1RM load for both squatting techniques. The 1RM was established two days prior to data collection using the high bar free squat technique, which was identified by the participants as their preferred technique for the determination of 1RM. The 1RM was established using the *direct method*, in which the maximum is achieved through a series of trials, as detailed by the American College of Sports Medicine [17]. The mean ± SD 1RM of the participants was 100.3 ± 7.2 kg (1.25 ± 0.09 BW). Tagesson and Kvist [18] state that the 1RM exercise is commonly used in strength training studies and the test-retest reliability of 1RM measurements is high among experienced athletes. On the day of data collection, 2 sets of 10 repetitions were performed to warm up using an individually chosen submaximal weight [19]. Both the high bar and low bar squat techniques were performed on the same day and in randomised order [5,12,13]. A 5-min rest interval between squat types was implemented, based on previous research that indicates that 3-4 mins is an optimum rest interval [19]. The rest interval prevented fatigue affecting the validity of the biomechanical analysis. The bottom of the squat was monitored by an experienced Strength & Conditioning coach using direct visual observation (Fig. 1) [16]. The participants received concurrent verbal feedback during the execution of the squat movement by the coach to guide the participants to the *'parallel with the ground'* thigh position. During the squat, the participants paused for 2-3 s at the bottom of the squat. This was, therefore, considered a static position for the subsequent calculation of isometric muscle forces and joint loads using static mechanical analysis [9,10]. Holding the squat for 2-3 s under isometric conditions did not prevent the participants from completing the subsequent raise up phase of the squat, possibly due to the higher capability for force production characteristic of isometric contractions, according to the principle of force-velocity relationship [16].

Figure 1: Photograph of the 'bottom of the squat' with the thighs approximately parallel to the ground

Videoing and Digitisation

To facilitate the digitisation of video images, circular anatomical markers were placed on the surface of the skin overlying the 5th metatarsal joint, lateral malleolus, lateral femoral epicondyle, and greater trochanter on the right side of the body [20]. An additional marker was placed on the end of the barbell bar; Fig. 1. The participants performed the squat barefoot to increase accuracy in the placement of the markers on the skin overlying the 5th metatarsal joint and lateral malleolus, and also to remove any sources of variability introduced by the participants wearing shoes of different heel heights, sole stiffness, and other mechanical properties [3]. Two-dimensional video recording was conducted using one Canon MV550i digital video camera operating at 25 Hz that captured the weightlifting movement in the sagittal plane [20]. The camera was placed 12 m away from the athlete to minimise parallax error [21]. An exposure time of 1/250 s was used to prevent blurring of the video images when played back on freeze frame [21]. Manual digitisation was carried out using Quintic Biomechanics® 9.3 software and video playback at 50 Hz. The five anatomical markers were used to guide video digitisation for the construction of a stick figure consisting of trunk, thigh, shank, and foot segments for the calculation of moment arms, and joint and segmental angles [20,21].

Static Analysis

Internal forces were calculated using a geometrical model of the lower limb [10]. The static calculations were performed using the body mass, 1RM barbell mass, and lower limb kinematic values for each participant.

KNEE JOINT

Calculation of weight over one knee

The weight over one knee (W) was obtained using *eq*. 1.

$$\boldsymbol{W} = \left[\frac{\left[\left(m_a + m_b\right) g\right]}{2}\right] - \left[\left(m_{l+f} \times m_a\right) g\right] \qquad (1)$$

where, m_a = mass of the athlete, m_b = mass of the barbell, g = gravitational acceleration, and m_{l+f} = ratio of lower leg plus foot mass to total body mass [22].

Determination of quadriceps femoris muscle force

The quadriceps femoris muscle force (M) was obtained using the 2nd condition of equilibrium (ΣMoments = 0); *eq*. 2.

$$\left(\boldsymbol{W} \times \boldsymbol{d}_{wk}\right) + \left(\boldsymbol{M} \times \boldsymbol{d}_{mk}\right) = 0 \qquad (2)$$

where, d_{wk} = moment arm of W about the knee joint axis of rotation and d_{mk} = moment arm of M (Fig. 2, in which α = knee angle and θ_k = patellar tendon angle based on 5° relative to the lower leg segment) [22]. In Fig. 2, clockwise moments are positive and anti-clockwise moments are negative.

The horizontal (F_h) and vertical (F_v) force components, resultant joint reaction force (R), and angle of the resultant joint reaction force (θ_1) were determined using *eqs*. 3-6, respectively.

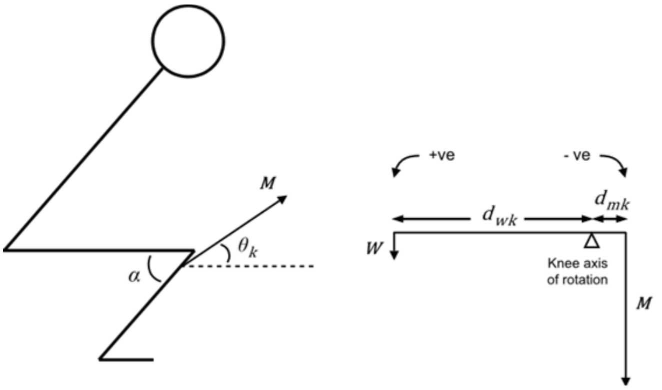

Figure 2: The M and angle θ_k (left) and moments about the knee joint (right) [16,21,22]

M = quadriceps femoris muscle force; θ_k = patellar tendon angle based on 5° relative to the lower leg segment; α = knee angle; W = weight over one knee; d_{wk} = moment arm of W about the knee joint axis of rotation; d_{mk} = moment arm of M .

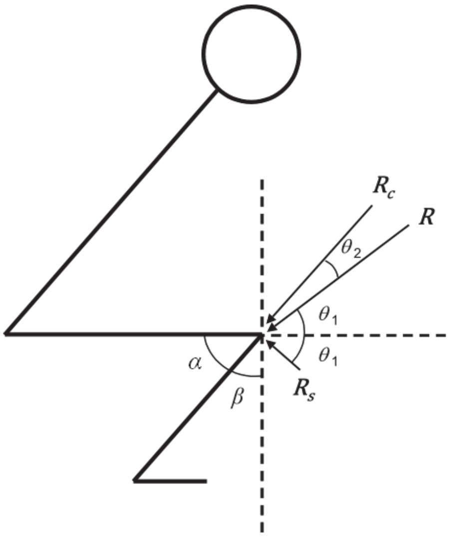

Figure 3: Computation of R_c and R_s at the knee joint [16,21,22]

R = resultant joint reaction force; R_c = compressive force at the knee; R_s = shear force at the knee; α = knee angle; β = complementary angle; θ_1 = angle of the resultant joint reaction force; θ_2 = angle of the compressive force.

$$\boldsymbol{F}_h = \boldsymbol{M}\cos\theta \qquad (3)$$

$$\boldsymbol{F}_v = \boldsymbol{M}\sin\theta \qquad (4)$$

$$\boldsymbol{R} = \sqrt{\boldsymbol{F}_h^{\,2} + \boldsymbol{F}_v^{\,2}} \qquad (5)$$

$$\tan\theta_1 = \boldsymbol{F}_v / \boldsymbol{F}_h \qquad (6)$$

Calculation of compressive and shear force

Compressive (R_c) and shear (R_s) forces at the knee were resolved from R (*eqs*. 7 & 8). The angle of the compressive force is θ_2 and β is the complementary angle (Fig. 3) [9,10].

$$\boldsymbol{R}_c = \boldsymbol{R}\cos\theta_2 \qquad (7)$$

$$\boldsymbol{R}_s = \boldsymbol{R}\sin\theta_2 \qquad (8)$$

Computation of patello-femoral joint reaction force

The patello-femoral joint reaction force (R_{pf}) was obtained from *eq*. 9; Fig. 4 [22].

$$\boldsymbol{R}_{pf} = \sqrt{\boldsymbol{F}_h^{\,2} + \boldsymbol{F}_v^{\,2}} \qquad (9)$$

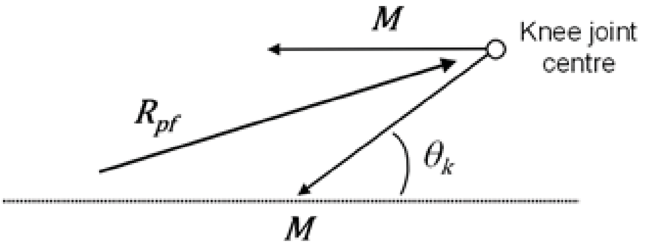

Figure 4: Computation of R_{pf} at the knee joint [16,21,22]

M = quadriceps femoris muscle force; R_{pf} = patello-femoral joint reaction force; θ_k = patellar tendon angle based on 5° relative to the lower leg segment.

ANKLE JOINT

Calculation of weight over one ankle

The weight over one ankle (W) was obtained using *eq*. 10.

$$\boldsymbol{W} = \left[\frac{\left[\left(m_a + m_b\right) g\right]}{2}\right] - \left[\left(m_f \times m_a\right) g\right] \qquad (10)$$

where, m_f = ratio of foot mass to total body mass [22].

Determination of gastrocnemius and soleus muscles force

The gastrocnemius and soleus muscles force (M) was obtained using the 2nd condition of equilibrium; *eq*. 11.

$$\left(\boldsymbol{W} \times d_{wa}\right) + \left(\boldsymbol{M} \times d_{ma}\right) = 0 \qquad (11)$$

where, d_{wa} = moment arm of the W about the ankle joint and d_{ma} = moment arm of M (Fig. 5, in which θ_a = Achilles tendon angle) [22].

The F_h and F_v force components, R and θ_1 for the ankle were calculated using *eqs*. 3-6 above.

Calculation of compressive and shear force

The R_c and R_s forces for the ankle were resolved from R using *eqs*. 7 & 8 above; Fig. 6 [9,10].

The data were diagnosed for normality of distribution using Kolmogorov-Smirnov and Shapiro-Wilk normality tests. The data met the assumptions of normality ($p \leq 0.200$). Paired *t*-tests were used to evaluate the differences in musculoskeletal forces between the high and low bar techniques. The significance levels were set at Bonferroni-corrected $p < 0.01$ for the knee joint and $p < 0.0125$ for the ankle joint. Effect size (η^2) and statistical power were obtained.

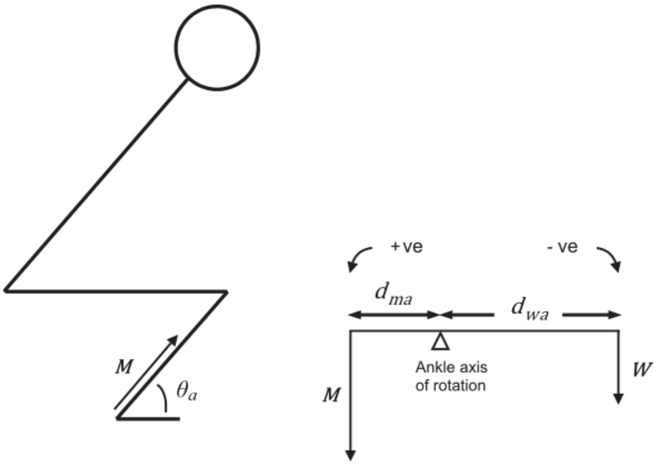

Figure 5: The M and Angle θ_a (left) and moments about the ankle joint (right) [16,21,22]

M = gastrocnemius and soleus muscles force; θ_a = Achilles tendon angle; W = weight over one ankle; d_{ma} = moment arm of M about the ankle joint; d_{wa} = moment arm of the W.

RESULTS

The high bar technique involved a more vertical position of the trunk and consequently a larger moment arm about the knee than the low bar

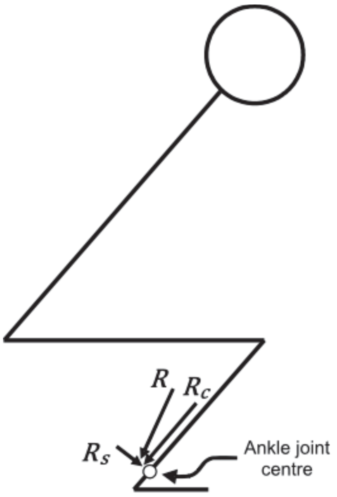

Figure 6: Computation of R_c and R_s at the ankle joint [16,21,22]

R = resultant joint reaction force; R_c = compressive force at the ankle; R_s = shear force at the ankle.

technique. The mean ± SD angles of trunk inclination to the right horizontal for the 8 participants were 68.3° ± 4.6° (high bar technique) and 63.1° ± 7.1° (low bar). The knee angles were 90.5° ± 5.9° (high bar) and 91.2° ± 7.1° (low bar). The patellar tendon angles were 61.3° ± 3.4° (high bar) and 62.5° ± 4.7° (low bar). The horizontal distances between the bar and the hip joint centre were 0.25 ± 0.04 m (high bar) and 0.27 ± 0.04 m (low bar), whereby the hip was posterior to the bar. The horizontal distances between the bar and the knee joint centre were 0.10 ± 0.03 m (high bar) and 0.08 ± 0.04 m (low bar). Mean quadriceps muscle and knee joint forces were higher when performing the high bar technique (Fig. 7); where, R_{pf} reached forces of 3.7 ± 0.4 BW. The SDs were slightly higher for the high bar technique. The differences between the high bar and low bar techniques were statistically significant for all knee variables (Table 1). The η^2 ranged from 0.51 to 1.00 and statistical power ranged from 0.64 to 1.00.

The mean ± SD Achilles tendon angle was 70.1° ± 2.3° (high bar) and 68.2° ± 1.1° (low bar). The horizontal distances between the bar and the ankle joint centre were 0.05 ± 0.01 m (high bar) and 0.07 ± 0.01 m (low bar); whereby, the bar was anterior to the ankle joint centre. Larger forces at the ankle joint occurred when using the low bar technique; whereby, R and R_c both reached a mean of 3.0 BW (Fig. 8). Table 2 shows that the differences between the high bar and low bar techniques were statistically significant for all ankle variables. The η^2 ranged from 0.66 to 0.99 and statistical power ranged from 0.88 to 1.00.

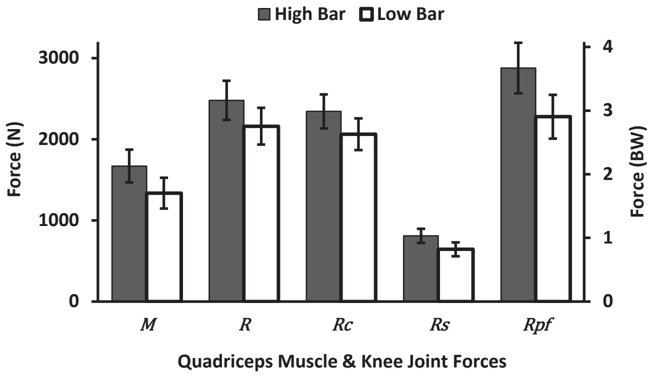

Figure 7: Muscular and joint forces at the knee presented as mean ± SD

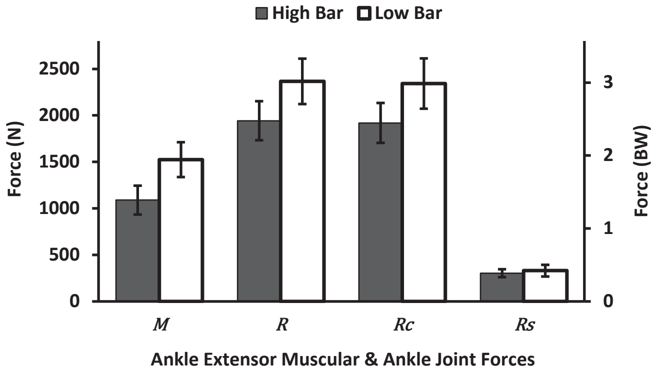

Figure 8: Muscular and joint forces at the ankle presented as mean ± SD

Table 1: Knee joint results of the paired t-tests.

Variable	t value	df	sig.	η^2	power
M	30.5	7	0.001	0.99	1.00
R	2.71	7	0.030	0.51	0.64
R_c	11.36	7	0.001	0.95	1.00
R_s	122.26	7	0.001	1.00	1.00
R_{pf}	36.89	7	0.001	0.99	1.00

M = quadriceps femoris muscle force; R = resultant joint reaction force at the knee; R_c = compressive force at the knee; R_s = shear force at the knee; R_{pf} = patello-femoral joint reaction force.

Table 2: Ankle joint results of the paired t-tests.

Variable	t value	df	sig.	η^2	power
M	-14.87	7	0.001	0.97	1.00
R	-26.17	7	0.001	0.99	1.00
R_c	-18.52	7	0.001	0.98	1.00
R_s	-3.69	7	0.008	0.66	0.88

M = gastrocnemius and soleus muscles force; R = resultant joint reaction force at the ankle; R_c = compressive force at the ankle; R_s = shear force at the ankle.

DISCUSSION

The calculated knee R_s provide an indication of the anteriorly-directed shear force that loads the ACL (Fig. 7). The knee R_s values suggest that the low bar squat ($R_s = 0.8 \pm 0.1$ BW) places less stress on the ACL than the high bar squat ($R_s = 1.0 \pm 0.1$ BW), therefore the low bar modality may be recommended for athletes suffering from ACL injuries to minimise ligament strain. [4,10] Peri-patellar pain and chronic patellar tendinopathy are a nemesis in athletes that engage in recurrent squatting using heavy loads [6-8]. The quadriceps force was 0.4 BW higher and the R_{pf} was nearly 1 BW higher when using the high bar technique suggesting that athletes with a history of patello-femoral and tendinous maladies may use the low bar squat to reduce patello-femoral compressive forces and patellar tendon strain [6-8,22]. In cases of chronic patellar tendinopathy, the isometric low bar Smith squat, in preference to the high bar Smith squat, may be introduced at the late stage of rehabilitation to minimise joint loads [7,15,22]. In the rehabilitation of knee injuries, the parallel squat depth used in the present study, with knee angles of 90.5° ± 5.9° (high bar) and 91.2° ± 7.1° (low bar), can be considered appropriate to prevent large forces on the patellofemoral joint, patellar tendon, and menisci. In contrast, musculoskeletal loads have been reported to increase considerably in deeper squats beyond 60-70° of knee flexion [7,10]. Contrary to the pattern of forces obtained for the knee, it is the low bar technique that applies larger forces on the ankle musculoskeletal structures (Fig. 8), suggesting that the high bar squat may be preferable in cases of ankle joint instability, strained Achilles tendon, or damaged gastrocnemius and soleus muscles [2,5,14,20,22]. The present study suggests, therefore, that optional use of the high bar and low bar techniques allows redistribution of the muscle and joint loads around both the knee and the ankle. There is preferential use of the low bar and the high bar techniques according to whether the knee joint or the ankle joint, respectively, is injured. However, with this redistribution there is potential to develop muscular imbalances. Therefore, in the context of injury prevention and rehabilitation, the Sports Therapist needs to be aware of the muscle loads incurred when using these two subtle modalities of the isometric Smith squat [4,7]. It is also suggested that, for the purposes of rehabilitation, the free squat modality is utilised as a progression of the isometric squat performed on the Smith machine, and once strength, power, flexibility and lifting form have been improved with the aid of the Smith machine [1,9,12].

The present study is restricted to the evaluation of the isolated effect of the quadriceps muscle force on knee joint forces, and does not include the action of the hamstrings muscle group in stabilising the knee joint. Exclusion of the hamstrings is acceptable in the assessment of healthy individuals as Biscarini *et al.* [10] reported that in the squat, the ACL is lightly loaded at knee angles larger than 50° and the PCL remains unloaded. The knee stabilising effect of the hamstrings may be considered in the evaluation of ACL deficient athletes. In the present study, the mathematical modelling of knee and ankle muscular and joint forces is limited to the bottom of the squat position. Further work may include the determination of musculoskeletal forces at various squat depths [8,13]. Another limitation of the present study is that the squat techniques analysed correspond to well-trained athletes that use a proficient technique and form when squatting. However, the squatting techniques of less-skilled athletes may differ from those used by proficient athletes [13,17,19]. Future work may assess whether the high and low bar techniques cause medial displacement of the knee, therefore augmenting the risk of meniscal, ACL, PCL and MCL damage [9,10,15]. The static biomechanical evaluation provides a foundational understanding of the two back squat modalities in isometric conditions and forms the basis for the construction of future dynamic models of the squat that incorporate accelerations of the lifted resistance, as well as accelerations and inertial effects of the lower body segments [6,8,14,20,21].

CONCLUSION

The findings of the present study suggests that optional use of the high bar or low bar isometric parallel-depth Smith squat techniques allows redistribution of the muscle and joint loads around the knee and the ankle joints. Athletes with a history of peri-patellar pain and patellar tendinopathy may use the low bar technique to reduce patella-femoral compressive forces and patellar tendon strain. The lower knee R_s of 0.8 BW suggests that the low bar isometric parallel-depth Smith squat may be preferred to the high bar squat (R_s = 1.0 BW) in the presence of ACL injuries. The knee R_{pf} is also lower (about 1BW less) when using the low bar technique. Nonetheless, the low bar technique yields larger forces at the ankle joint, suggesting that the high bar technique may be advisable in cases of ankle joint instability, strained Achilles tendon, or damaged gastrocnemius and soleus muscles. The R and R_c forces at the ankle joint when using the high bar technique were 0.5 BW less than for the low bar technique. The study points to the preferential use of the low bar and the high bar techniques according to whether athlete has sustained an injury in the knee joint or the ankle joint, respectively. Mathematical modelling of knee and ankle muscular and joint forces for the high bar and low bar Smith squat in dynamic conditions may be carried out in future work to determine musculoskeletal loading for the safe implementation of strength training protocols and rehabilitation exercise.

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