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Original Article

The force-curve in squatting according to performance level

VIKTOR OLIVA[1],GABRIEL BUZGO[2], ADRIAN NOVOSAD[3], MATEJ VAJDA[4]
[1,2,]Department of Biological and Medical Sciences, Faculty of Physical Education and Sport, Comenius University in Bratislava, Bratislava, SLOVAKIA
[3] Department of Track and Field, Faculty of Physical Education and Sport, Comenius University in Bratislava, Bratislava, SLOVAKIA
[4] Diagnostic Centre of Prof. Hamar, Faculty of Physical Education and Sport, Comenius University in Bratislava, Bratislava, SLOVAKIA

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Abstract:
The purpose of this study was to compare the stability of the range of squat motion and the efficiency of the bottom position of squatting among athletes of different squat performancelevels. Two groups of trained male subjects, non-squatters (NS_G; n=24; age=22.6±2.8 y; body height (BH)=180.5 ± 6.5 cm; body weight (BW)=75.4 ± 11.3 kg) and squatters (S_G; n=19; age=24.3±1.2 y; BH=183.2 ± 4.4 cm; BW=85.5 ± 10.9 kg), performed a progressive loading diagnostic test duringa high-bar back squat with a calf raise via a linear position transducer and dynamometricforce plate. The load was derived from the BW of a subject (0–100% of BW). The stability of the range of squat motion and the efficiency of the bottom position of the squat was measured by parameters such as the eccentric range of squat motion related to BH, the variation coefficient of eccentric range of motion (ROM), and power output during the concentricand the acceleration phases. Significant differences between groups were found in the eccentric range of squat motion and in the eccentric range of squat motion related to BH with a greater range of motion for S_G. The NS_Ggroup showed a significantly greater variation in the coefficient of eccentric range of squat motion and the percentage shift of the peak force during the concentric phase. The mean power outputs during the concentric and acceleration phases and peak force production during the concentric phase were significantly greater for S_G. There was a significantly greater force by the athletes and barbell (F_W) and peak force ratio forthe bottom position of the squat ($Fmax_{BPS}$) for the S_G in favour of $Fmax_{BPS}$ for each load. For the F_W and peak force during the concentric phase ($Fmax_{CONC}$) ratio, significant differences between groups were also observed for each load with a larger ratio for S_G in favour of $Fmax_{CONC}$. Our results suggest that a person who effectively masters the squat can subsequently generate greater force and higher power output during the concentric and the acceleration phases of a squat. We also predict more stable ROM when performing a squat, especially when increasing external resistance, which can contribute to reducing the risk of injury during the training process.
Key Words:**Squat, range of motion, efficiency, force production, power output**

Introduction

Resistance training programs involve methods used to increase force and power output (Haff et al., 2001; Kraemer et al., 2002; Zink et al., 2006; Reid et al., 2012; Straight et al., 2016). The squat is one of the most frequently used exercises for the development of strength and power of the lower limb muscles (McLaughlin et al., 1977; Rahmani et al., 2001; Kellis et al., 2005; Schoenfeld, 2010; Buzgó et al., 2014; Vecchio, 2018). The biomechanics of squatting has a lot in common with components of everyday movements, such ascending and descending stairs, sitting down, and standing up, and it has its place in the field of rehabilitation (Lynn et al., 2012; List et al., 2013; Buzgó et al., 2014; Lorenzetti et al., 2018; Vecchio, 2018).

Strength training has many health benefits, and compared to other sports, it has a general low injury risk. Additionally, there has been an increase in the implementation of strength training programs in sports in recent decades. However, the execution of a squat, which is among the most frequently used exercises in the field of strength training, has been identified with an increased risk of injury for the lower limbs and the trunk compared to other resistance exercises. There are many squatting variations, and each has a unique biomechanical profile (Lorenzetti et al., 2018). When two techniques of squatting were compared, the first one where the knee was not allowed to pass anterior to the toe and the second one where the knee was free to pass beyond the toe, there were significant differences in the range of motion of the knee, the lumbar, and the thoracic spine. Furthermore, when adding a greater external load, the data showed a significant decrease in the range of motion of the lumbar curvature, and there was also evidence of a decrease of thoracic curvature range of motion with load on the barbell from 25 to 50% of the subject's body weight (BW) (Fry et al., 2003; Lorenzetti at al.,

Corresponding Author: VIKTOR OLIVA, E-mail: viktor.oliva@uniba.sk

2012;List et al., 2013; Lorenzetti et al., 2018).The strength of a muscle's contraction is influenced by a variety of factors.One of the factors is the length-tension relationship of muscles. Along with the body's lever systems, the length-tension relationship creates biomechanically disadvantageous positions,known as sticking points (Anderson et al., 2008; Nijem et al., 2016). The sticking points createinadequate conditionsfor producing maximal force and acceleration. For example, the sticking point for the squat motion will be the bottom position of a squat, whereas positions during the concentric phase of motion that are close tothe concentric end range of motion allow for greater force production (Nijem et al., 2016). In the terms of muscle activity, Caterisano et al. (2002) found that the activity of a primary hip extensor muscle,gluteus maximus significantly increased when squats were performed below parallel with a load equal to 100–125% of the body weight.

Power production is the crucial determinant of athletic success for many sports, work-related tasks, and daily activities (Stone, 1993; Haff et al., 2001; Baker, 2001; Bevan et al., 2010; Nimphius et al., 2010; Suchomel et al., 2016). This is reflected in the considerable attention focused on the development of power in athletes (Chu, 1996; Baker et al., 2001; Komi, 2003) and the increase in research that examines specific techniques used to maximize power development in recent decades (Hydock, 2001; Armstrong, 2008). When using constant resistance, athletes may not be able to elicit maximal activation of the primary muscles throughout the entire range of motionbecause of mechanical advantages or disadvantages at specific joint angles (Foran, 1985). This can result in significant reductions in movement velocity and power output during the early and/or later stages of the concentric phase ofmotion (Cronin et al., 2000; Frost et al., 2010). When using a barbell as a constant weight resistance, the largest accelerations tend to occur at the transition between eccentric and concentric phases of the lift due to large changes in velocity in a very short period of time (Frost et al., 2010). Conversely, if the lift focuses on maximum force production to elicit an increased motor unit recruitment, the maximal velocity is compromised (Hutschison et al., 2019). Peak force (acceleration) has been shown to occur at the onset of the concentric action (McLaughlin et al., 1977; Elliott et al., 1989), which thus leads to more variation in the force curve, greater changes in momentum (Cronin et al., 2001) and, thus, may be one of the reasons for an extended deceleration phase. The point of the concentric phase at which peak velocity occurs is reduced with a decrease in load. Thus, the contributions from force and velocity change despite similar power outputs (Frost et al., 2010).

In one study, Rahmani et al. (2001) found that the force–velocity relationship during squat movements could be modelled using linear polynomial models with high coefficients (0.83–0.99). However, these results were based on the average force–velocity values across three efforts by an individual. Because the squat is a multi-articular movement, the force at any instant is the result of specific muscle actions produced at varying angular positions of each joint involved in the movement. Although the average force exerted over the entire period of movement may provide an indication of the force–velocity curves of the squat, examination of the same relationship using the maximum point on the force–time curve may provide additional information on the nature of this relationship. Such information may be more important for strength coaches because performance in most explosive movements often depends on the production of maximal force (Kellis et al., 2005).

Many published studies haveinvolved research on advanced squatters, such as Olympic or National weightlifters (Wretenberg et al., 1996; Escamilla et al., 2001; Baker et al., 2001) and powerlifters (Swinton et al., 2012; Lorenzetti et al., 2018), thus, we decided that the main focus of the present study would be on understanding the major influences of squat technique from the perspective of both more and less experienced participants similar to the work of, e.g., Lorenzetti et al. (2018).

Thus, the purpose of our study was to compare the stability of the range of squat motion, the mean power output during the concentric and acceleration phases of movement, peak force production during the concentric phase of squat execution, and the efficiency of the bottom position of squatting among athletes of varying squat performance levels.

Material & methods

Participants

Forty-three healthy college-age trained male students were recruited as volunteers and divided into two groups based on their squat performance levels. The squat performance level was assessed by a training program that consisted of 36 weeks with two training sessions per week as part of a subject at University that was aimed at mastering a proper squatting technique. The non-squatters (NS_G; n=24; age=22.6 ± 2.8 y; body height=180.5 ± 6.5 cm; body weight=75.4 ± 11.3 kg) included individuals who reported no or minimal performing experience with proper squatting technique.

The squatters (S_G; n=19; age=24.3 ± 1.2 y; body height=183.2 ± 4.4 cm; body weight=85.5 ± 10.9 kg) included individuals who completed a 36-week training program aimed at mastering proper squatting technique. All participants were students of the Faculty of Physical Education and Sport, University of Comenius in Bratislava. Subject characteristics are shown in Table 1. All the participants signed an informed consent before enrolling in the study. The study was approved by the Ethical Committee of the Faculty of Physical Education and Sport, Comenius University in Bratislava (number 5/2019).

Table 1 Sample size and characteristics

GROUP	SG - SQUATTERS (n = 19)	NSG - NON-SQUATTERS (n = 24)
AGE [years]	24.3 ± 1.2	22.6 ± 2.8
HEIGHT [cm]	183.2 ± 4.4	180.5 ± 6.5
WEIGHT [kg]	85.5 ± 10.9	75.4 ± 11.3

(Data show means ± SD)

Study design

The main goal of the study was to assess parameters of ROM, and we included a range of eccentric motion (ROM_{ECC})–squat depth and percentage differences in squat depth in relation to body height (BH/ROM_{ECC}). The stability of ROM was evaluated by the variation in the coefficient of range of eccentric motion–squat depth ($CVROM_{ECC}$)and shift of the peak force during the concentric phase from the bottom position of the squatduring the entire diagnostic test. We also measured the mean power output during concentric ($Pmean_{CONC}$) and acceleration ($Pmean_{ACC}$) phases and peak force during the concentric phase (Peak $Force_{CONC}$). Effectiveness of the bottom position of the squat was evaluated by the force of the athlete and barbell (F_W) and peak force ratio in the bottom position of the squat ($Fmax_{BPS}$) and the ratio of force of the athlete and barbell (F_W) and peak force during the concentric phase ($Fmax_{CONC}$).

Measurements and procedures

Modified form of progressive loading diagnostic test - High bar back squat with calf raise

The study procedures for assessing the modified form of progressive loading diagnostic test were described by Tuffano et al. (2018). All subjects were tested once, and subjects were instructed to perform a modified form of progressive loading diagnostic test in the high-bar back squat with a calf raise. The load was derived from the body weight (BW) of each subject ranging from 0 to 100% of BW (0, 25, 50, 75, and 100% of BW). On every external load, the subjects performed two repetitions. Two minutes of rest between attempts was provided for each subject. The subjects were instructed to control the eccentric phase of the squatand then to perform the concentric phase as explosively as possible by even forcefully plantar flexing the ankles so that acceleration during the concentric phase was maximized. The testing procedures were ensured for all lifts by the principal examiner and additional spotters. All were experienced at performing and evaluating the back squat lift technique according to the guidelines set by Buzgó et al. (2014).

Warm-up

Familiarization with the warm-up followed for both groups at the beginning of the testing procedure. Subjects performed a warm-up consisting of a general part that lasted 6-8 min and was aimed at mobilising key joints and activating key muscle groups involved during squatting. This was followed by a specific warm-up that was comprised of movements that have a similar movement structure to the testing exercise with 1 set of 10 repetitions of lunges (5 repetitions on each side) and 1 set of 10 repetitions of BW squats with a calf raise. Following a 5-min rest, the modified form of progressive loading diagnostic test in the high-bar back squat with a calf raise was performed.

Data acquisition

For research purposes, a linear position transducer (FiTROdyne Premium, FiTRONiCs.r.o., Slovakia) and dynamometric force plate (FiTRO Force Plate, FiTRONiCs.r.o., Slovakia) were used to register the values of force and to monitor the speed, power, and range of motion during exercise execution (Jennings et al., 2005;Cormie et al., 2007; Garnacho-Castaño et al., 2015; Lorenzetti et al., 2017).

Statistical analysis

The data on the range of eccentric motion, stability of the range of squat motion, mean power output during concentric and acceleration phases, peak force production during the concentric phase, and the efficiency of the bottom position of the squat are presented via the means ± standard deviation (SD). One-way ANOVA was used to determine whether significant differences ($p \leq 0.05$) in the monitored parameters were present between groups. Additionally, the effect size (ES) by Cohen expresses the magnitudes of mean differences between the groups and can be interpreted as 0–0.2 as trivial, 0.2–0.6 as small, 0.6–1.2 as moderate, 1.2–2.0 as large, 2.0–4.0 as very large, and >4.0 as extremely large effect (Hopkins, 2020). The level of significance was set at $p \leq 0.05$. SPSS software 23.0 version was used for statistical analysis (IBM, Inc., USA). GraphPad software, Inc., Prism 8.0.1 was used for creating graphs to present the results.

Results

Parameters of range of motion during the entire diagnostic test

There was a significant difference found in the mean squat depth between the groups (p=0.012; ES=0.80) with a 9.36% greater range of eccentric motion reached by S_G (Figure 1). Differences were also observed in the significant percentage differences in the squat depth in relation to body height (p=0.016; ES=0.77) with an 8.57% lower squat depth in relation to BH reached by NS_G (Figure 1).

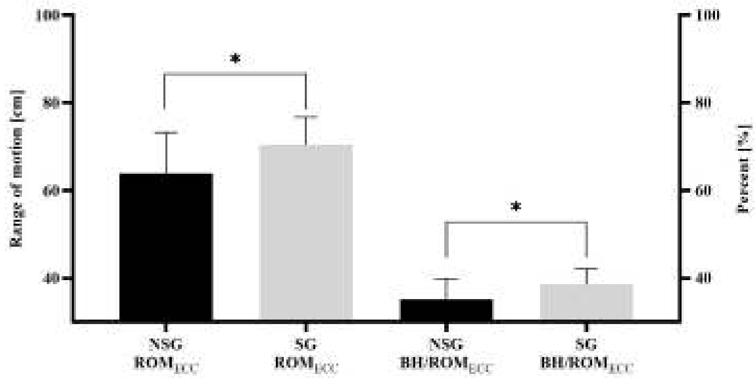

Figure 1Difference between mean squat depth (ROM_{ECC}; p=0.012; ES=0.80) and percentage differences in squat depth in relation to body height (BH/ROM_{ECC}) for squatters (S_G) and non-squatters (NS_G) (p=0.016; ES=0.77).*–p≤0.05

Variation incoefficient of eccentric range of motion during squat and shift of the peak force during the concentric phase during the entire diagnostic test

Figure 2 provides the variation in the coefficient of the eccentric range of motion during squat execution. Compared with the variation coefficient for the eccentric range of motion, we found significantly greater percentage in the variation coefficient reached by NS_G (p=0.001; ES=1.05). Comparing the shift of the peak force during the concentric phase, we found a significantly greater percentage shift was reached by NS_G (p=0.001; ES=1.10) (Figure 3).

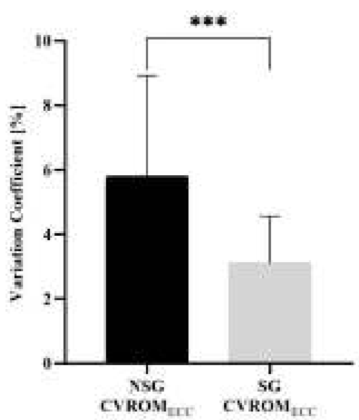

Figure2. Difference between the variation in the coefficient of eccentric range of motion during squat execution ($CVROM_{ECC}$) for the squatters (S_G) vs. non-squatters (NS_G) (p=0.001; ES=1.05). ***–p ≤ 0.001

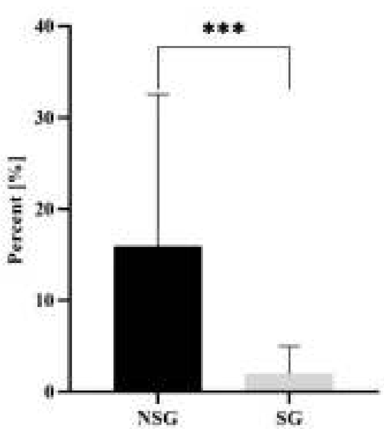

Figure3. Differences between the shift of the peak force during the concentric phase duringthe entire diagnostic test for squatters (S_G) vs. non-squatters (NS_G) (p=0.001; ES=1.10). *** – p ≤ 0.001

Mean power output during the concentric and acceleration phasesduringthe entire diagnostic test

The mean power output during the concentric phase was significantly greater ($p < 0.001$; ES=2.47) for S_G by 26.46% (Figure 4). A similar result was observed when compared to the mean power output during the acceleration phase. The registered difference was also significantly greater ($p < 0.001$; ES=2.61) for S_G by 30.03% (Figure 4).

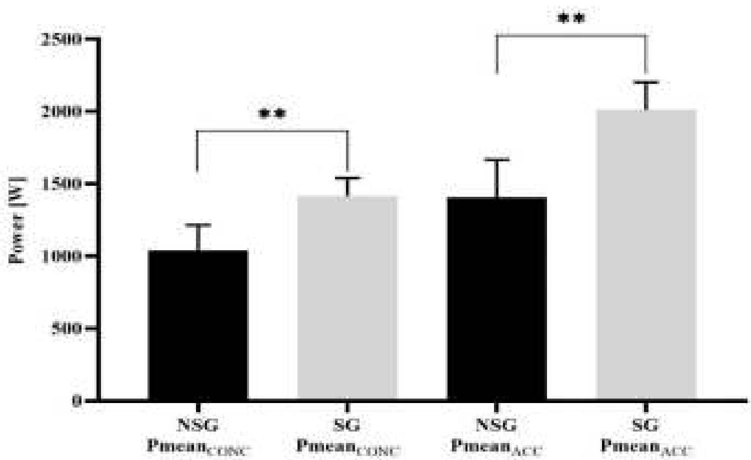

Fig. 4Mean power output during the concentric phase ($Pmean_{CONC}$; $p < 0.001$; ES=2.47) and acceleration phase ($Pmean_{ACC}$)duringthe entire diagnostic test for squatters (S_G) vs. non-squatters (NS_G) ($p < 0.001$; ES=2.61). ** – $p \leq 0.01$

Force production during the concentric phase during the entire diagnostic test

There was a significant difference in the force production during the concentric phase between the groups ($p < 0.001$; ES=2.69) with 22.83% greater force production by S_G (Figure 5).

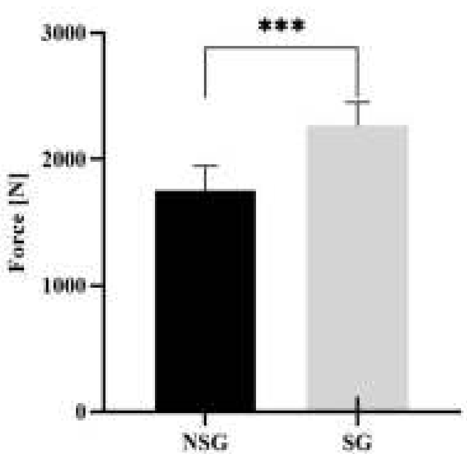

Fig. 5Peak force production during the concentric phase (Peak $Force_{CONC}$) during the diagnostic test for squatters (S_G) vs, non-squatters (NS_G) ($p < 0.001$; ES=2.70). *** – $p \leq 0.001$

Efficiency of the bottom position of squatting

When comparing the efficiency of the bottom position of squatting, there were significant differences between groups in terms of force of the athlete and the barbell and peak force ratio in the bottom position of the squat for each load: +0% of BW (p=0.012; ES=0.82); +25% of BW ($p < 0.001$; ES=1.19); +50% of BW (p=0.001; ES=1.06); +75% of BW (p=0.001; ES=1.13); +100% of BW ($p < 0.001$; ES=1.42) with a greater ratio for the S_G in favour of $Fmax_{BPS}$ (Figure 6). For the force of the athlete and the barbell and peak force ratio during the concentric phase, significant differences between groups were also observed for each load: +0% of BW (p=0.028; ES=0.69), +25% of BW (p=0.001; ES=1.15), +50% of BW (p=0.002; ES=1.03), +75% of BW (p=0.004; ES=0.96), +100% of BW ($p < 0.001$; ES=1.38) with a greater ratio for the S_G in favour of $Fmax_{CONC}$ (Figure 7).

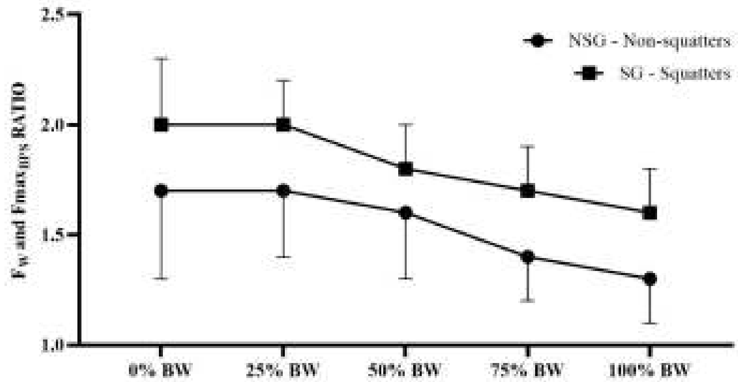

Fig. 6Differences between force of the athlete and the barbell (F_W) and peak force ratio in the bottom position of the squat ($Fmax_{BPS}$) for squatters (S_G) vs. non-squatters (NS_G)

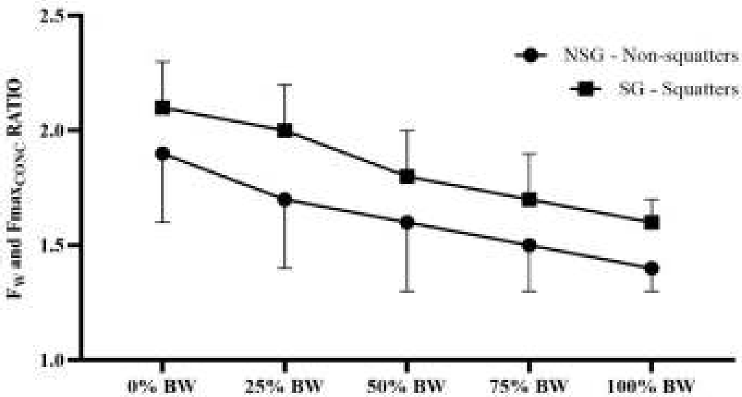

Fig. 7Differences between force of the athlete and the barbell (F_W) and peak force ratio during the concentric phase ($Fmax_{CONC}$) for squatters (S_G) vs. non-squatters (NS_G)

Dicussion

The squat has been an important part of strength training programs for many athletes and non-athletes for decades, and it is essential to understand the effects of different squatting techniques. This study shows the differences between a group of squatters vs. non-squatters and the effect of squat performance level on the stability of ROM, peak force production, mean power output, and effectiveness of the bottom position of the squat.

The main findings of this study were that S_G achieved larger ROM_{ECC} and higher percentage differences in TV/ROM_{ECC} compared to the N_{SG} group.Bloomquist et al. (2013) investigated the effect of squat training with short range versus longrange of motion. Twenty-four males were recruited for the study. All the subjects were sports science students. They performed strength training three times per week for twelve weeks. The authors assessed one repetition in maximum strength (1 RM) for the deep squat and the shallow squat, the isometric strength of the knee extensors on the right leg at knee angles of 40°, 75°, and 105°, the cross sectional area (CSA) of the front thigh muscles, back thigh muscles, and the patellar tendon, lean body mass (LBM) of the legs, muscle architecture of the right m. vastus lateralis, collagen synthesis in the patellar tendon, and squat jump (SJ) and counter movement jump (CMJ) performances. They found that 12 weeks of progressive heavy load squat training, regardless of the range of motion, resulted in increases in 1 RM strength and pennation angleas well as increases in CMJ height. However, only the deep squat group increased in SJ height, LBM of the legs, isometric strength at 75° and 105°, and front thigh muscle CSA at all measured points, which indicated that a larger ROM can have beneficial influence on power output, force production, and muscle mass development.

A few years ago, it was claimed that deep squats could cause and increase injury risk of the knee joints and the lumbar spine. In a literature review, Hartmann et al. (2013) assessed whether half and quarter squats, characterized by less knee flexion, are safer on the musculoskeletal system than deep squats. They found that the highest compressive forces and stresses in a retropatellarregion of a knee jointare observed at 90° of knee flexion.The data were presented based on biomechanical calculations and measurements of knee joints in cadavers. With increasing knee flexion, lower retropatellar compressive forces were observed with enhanced load distribution and force transfer at the same time. Additionally, with greater knee flexion, enlargement of the retropatellar articulating surface occurs. This leads to lower retropatellar compressive stresses. All the structures around the knee joint are sensitive to anabolic processes and functional structural adaptations in response to mechanical loading. Thus, concerns about degenerative changes of the tendofemoral complex and the higher risk for chondromalacia, osteoarthritis, and osteochondritis during deep squatexecution are unfounded. Squats in a full range of motion do not contribute to an increased risk of injury to passive tissues. A study by Sayers et al. (2020) indicated that, from a perspective of spinal safety, it appears advantageous for novice weight trainers to perform back squats with their heels slightly elevated to reach the deep squat with proper technique, whereas regular weight trainers appear to receive only limited benefits from performing back squats with either an incline board or weightlifting shoes.

The shift in the peak force during the concentric phase from the bottom position of the squat was significantly greater in the case of NS_G. The peak force is usually observed at the bottom position of squatting during the transition between the eccentric and concentric phases. The value of the peak force depends on the speed of the eccentric phase of motion. For example, if the overall eccentric phase is faster, a greater deceleration would be required to slow the external load to a stop and reverse the movement into the concentric phase. To generate a deceleration of a greater magnitude, a greater force would be requiredbased on Newton's second law. Because a difference in the shift of the peak force during the concentric phase of motion from the bottom position of squatting was observed in the NS_G, we concluded that the NS_G group could not handle effectively the eccentric phase of motion. Thus, there may have been a lower power and force production during the concentric phase of motion for people with minimal performing experience with proper squatting technique. In support of this difference, a study by Stevenson et al. (2010) assessed the following variables during free-weight back squat exercises with and without the application of elastic bands in twenty-two healthy men (26.0 ± 4.4 y) who were experienced in weight training. Peak velocity in the eccentric and concentric phases, mean velocity in the eccentric and concentric phases, peak force, peak power in the concentric phase, and RFD values immediately before the zerovelocity point at the bottom of the movement, immediately after the zero-velocity point, and in the concentric phase were assessed.This study was designed to determine whether a greater eccentric force that is applied with elastic bands translates into a faster and more powerful concentric phase during the barbell back squat exercise when compared to the condition in which no bands are used. They found that peak force was not significantly different between the two conditions and was always attained at the bottom position of the squat during the transition between the eccentric and concentric phases.

Our current study focused on understanding the major influences of squat technique from the perspective of experienced and less experienced participants regarding squatting. Our purpose was to compare the stability of the range of squat motion and the efficiency of the bottom position of squatting among athletes with varying squat performance experience levels. The assumption of better control of the eccentric phase and the bottom position of squatting should also be reflected in the subsequent greater power output and force production during the concentric and acceleration phases of a squat, which our data, results, and between-group differences highlighted and confirm. Future studies should investigate different exercises that are frequently used in strength training programs.

Conclusions

Our squatters achieved a larger range of eccentric motion (squat depth), higher percentage differences in the squat depth in relation to body height, greater force production during the concentric phase of movement during the entire diagnostic test, greater mean power output during the concentric and the acceleration phasesduring the entire diagnostic test, and better squat stability during the diagnostic set (lower value of the variation coefficient for the range of eccentric motion) compared to the non-squatters. We found significant between-group differences in the efficiency of the bottom position of squatting for each external load. Our data, results, and between-group differences highlight the impact of squat performance experience level on the stability of the range of squat motion, greater peak force production, greater mean power output, and the effectiveness of the bottom position of squat. Our findings indicate that performancelevel is the key for effective handling of the eccentric phase of squat motion and better transfer into the concentric phase. Therefore, we confirm based on our results that a person who effectively masters the squat technique and the bottom position of squatting can subsequently generate greater force production and greater power output during the concentric and acceleration phases of squat motion. We also predict that a more stable range of motion when performing a squat, especially when increasing external resistance, can contribute to reducing the risk of injury during the training process.

Supporting Agencies
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Conflicts of interest
No conflict of interest, financial or otherwise are declared by the authors.
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