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ORIGINAL ARTICLE

Full squat produces greater neuromuscular and functional adaptations and lower pain than partial squats after prolonged resistance training

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Abstract
The choice of the optimal squatting depth for resistance training (RT) has been a matter of debate for decades and is still controversial. In this study, fifty-three resistance-trained men were randomly assigned to one of four training groups: full squat (F-SQ), parallel squat (P-SQ), half squat (H-SQ), and Control (training cessation). Experimental groups completed a 10-week velocity-based RT programme using the same relative load (linear periodization from 60% to 80% 1RM), only differing in the depth of the squat trained. The individual range of motion and spinal curvatures for each squat variation were determined in the familiarization and subsequently replicated in every lift during the training and testing sessions. Neuromuscular adaptations were evaluated by one-repetition maximum strength (1RM) and mean propulsive velocity (MPV) at each squatting depth. Functional performance was assessed by countermovement jump, 20-m sprint and Wingate tests. Physical functional disability included pain and stiffness records. F-SQ was the only group that increased 1RM and MPV in the three squat variations (ES = 0.77–2.36), and achieved the highest functional performance (ES = 0.35–0.85). P-SQ group obtained the second best results (ES = 0.15–0.56). H-SQ produced no increments in neuromuscular and functional performance (ES = −0.11–0.28) and was the only group reporting significant increases in pain, stiffness and physical functional disability (ES = 1.21–0.87). Controls declined on all tests (ES = 0.02–1.32). We recommend using F-SQ or P-SQ exercises to improve strength and functional performance in well-trained athletes. In turn, the use of H-SQ is inadvisable due to the limited performance improvements and the increments in pain and discomfort after continued training.

Keywords: Muscle strength, velocity-based resistance training, propulsive phase, lumbar spine

Highlights

- Training at F-SQ produced the greatest improvements in all neuromuscular performance parameters for the three squatting depths. In contrast, intervention with H-SQ produced the worst results.
- Whereas individuals improved more at the specific depth at which they trained, results from the F-SQ group were still the best.
- The three groups reported a moderate rise in pain perception scores following the 10-week RT program, but the H-SQ experienced an acute increase in pain, stiffness and physical functional disability indexes.
- According to these findings, we conclude that F-SQ and P-SQ are the safest and most effective squat exercises to improve strength and functional performance, while H-SQ is unadvisable given the limited benefits and high discomfort.

Introduction

The back squat (SQ) is one of the most widely used and effective resistance training (RT) exercises for strengthening the lower-limb, protecting against injuries and improving athletic performance (Hartmann, Wirth, & Klusemann, 2013). In the last three decades, numerous publications have found that increases in lower-body strength following SQ training transfer positively to functional athletic performance in short-duration actions that demand maximal voluntary contractions, such as sprinting and vertical jumping (Hartmann et al., 2012; Seitz, Reyes, Tran, de Villarreal, & Haff, 2014; Suchomel, Nimphius, & Stone, 2016; Wirth et al., 2016).

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Recent studies have also observed greater functional and specific performance improvements in medium to long distance athletes (e.g. rowing, cross-country skiing, cycling) after RT including the SQ exercise (Izquierdo-Gabarren et al., 2010; García-Pallarés, Sánchez-Medina, Carrasco, Díaz, & Izquierdo, 2009; Rønnestad, Hansen, Hollan, & Ellefsen, 2015; Ronnestad & Mujika, 2014).

There are four main SQ technique variations according to the squatting depth (i.e. the angles reached in the hip, knee and ankle joints at the bottom position): the deep or full squat (F-SQ), parallel squat (P-SQ), half squat (H-SQ) and quarter squat. In the F-SQ, the subject descends until the top of the thighs fall below the horizontal plane, with knees flexed to a tibiofemoral angle of 35–45° in the sagittal plane (Hartmann et al., 2013; Martínez-Cava, Morán-Navarro, Sánchez-Medina, González-Badillo, & Pallarés, 2019). In the P-SQ, the eccentric phase ends when the inguinal fold is in a straight horizontal line with the top of the knee, while in the H-SQ the eccentric phase is carried out until reaching 90° of knee flexion (Hartmann et al., 2013; Wretenberg, Feng, & Arborelius, 1996). Lastly, the quarter squat is executed to 110–140° of knee extension (Hartmann et al., 2013; Rhea, Kenn, Peterson, & Massey, 2016). The use of a certain SQ depth influences several biomechanical factors which are related to the specificity of the movement pattern and can affect the development of force, rate of force development, activation and synchronization of motor units, and dynamic joint stability (Martínez-Cava et al., 2019; Rhea et al., 2016).

The choice of the optimal SQ depth has been a matter of debate for decades and is still controversial. Training at partial SQ < 90° of knee flexion (H-SQ and quarter squat) has been traditionally recommended on the basis of the training principle of specificity to sports including running or jumping (Rhea et al., 2016; Wilson, 1998; Young, Benton, Duthie, & Pryor, 2001; Zatsiorsky & Kraemer, 2006). In addition, training at larger depths (P-SQ and F-SQ) has been suggested to increase muscular and tendinous injuries, especially in the knee (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). However, contrary to these common beliefs, recent studies propose that prolonged RT interventions involving P-SQ or F-SQ maximize the neuromuscular and functional performance in novice (Bloomquist et al., 2013) and well-trained athletes (Hartmann et al., 2012), and even minimize the risk of injury to passive tissues compared to shorter ROM (Hartmann et al., 2013).

Only two studies have examined the effects of training at different SQ depths on strength and functional performance on well-trained and experienced athletes (Hartmann et al., 2012; Rhea et al., 2016). In both studies, maximum strength, jump height and sprint performance were evaluated after a periodized RT programme (using loads from 10RM to 2RM during 10–16 wk) in groups training at different squatting depths. Results confirmed greater gains in maximum strength on the specific squat variation used in training, compared to the other ones (Hartmann et al., 2012; Rhea et al., 2016). However, the effects on functional performance reported in these studies are clearly contradictory. While Rhea et al. (2016) described greater athletic adaptations (i.e. squat jump and 40-yard sprint) in the quarter squat group, Hartmann et al. (2012) only found positive adaptations in the squat jump and countermovement jump following F-SQ training. This controversy is further complicated by the existing methodological differences between both studies. Only Hartmann et al. (2012) included a control group that did not perform any type of strength training (i.e. RCT design). Moreover, Rhea et al. (2016) required participants to complete the RT routine with additional resistance exercises different to the squat (power cleans, lunges, reverse hamstring curls, and step ups), without any control of the ROM, which likely can influence the changes observed in the dependent variables under study. In both investigations, participants lifted loads up to 95% of their one-repetition maximum (1RM), reached muscle failure in each training set (Rhea et al., 2016) and even performed forced repetitions (Hartmann et al., 2012). These procedures somewhat contradict recent findings which showed that training against very high loads (>85% 1RM) and reaching muscle failure had a negative impact on athletes' functional performance (Izquierdo-Gabarren et al., 2010; Morán-Navarro et al., 2017; Pareja-Blanco et al., 2017). In addition, neither the study of Rhea et al. (2016) nor the one of Hartmann et al. (2012) could verify the effects of training at different squatting depths on different zones of the athletes' load-velocity relationship (e.g. light vs. heavy loads) or on their cardiorespiratory performance. It thus seems that these contradictory results and the lack of solid evidence require further investigation in a carefully designed randomized controlled trial.

Therefore, the aims of this study were (i) to clear up the effect of a prolonged RT programme at different SQ depths on neuromuscular and functional adaptations in well-trained athletes using the novel velocity-based resistance methods, and (ii) to provide evidence about the incidence of injuries and discomfort caused after prolonged SQ training at different depths.

Methods

Participants

The required sample size was determined for the primary outcome variable, the F-SQ one-repetition maximum strength (1RM). According to similar interventions on subjects with comparable characteristics (Hartmann et al., 2012), a clinically relevant change is about 25.3 ± 20.5% 1RM increments after a 10-week training programme. A sample size of nine participants were estimated to detect these differences with a power of 90% and a significance α of 0.05 using the MedCalc Statistical Software version 18.2.1. Assuming a maximum loss of follow-up of 20%, we recruited at least 11 healthy athletes per experimental group meeting the following inclusion criteria: (i) having a 1RM strength/ body mass ratio (relative strength ratio, RSR) higher than 0.80 in the F-SQ and (ii) no physical limitations, health problems, or musculoskeletal injuries that could affect training. Fifty-three resistance-trained men volunteered to participate in this study (age 23.0 ± 4.4 years, body mass 76.0 ± 12.8 kg, height 174.0 ± 7.4 cm, body fat 12.1 ± 4.9%). Their initial 1RM strength for the F-SQ exercise was 87.3 ± 15.0 kg and RSR of 1.17 ± 0.24. In the 6 months preceding this study, participants completed 2–4 resistance training sessions per week including the three squat variations under study as part of their conditioning. In this period, participants were instructed in proper technical execution for the three squat variations, while optimal spinal curvature was controlled to avoid excessive pelvic tilt (i.e. lumbar rectification), as explained further below. Participants were randomly assigned in a counterbalanced way according to their initial F-SQ strength to one of four groups (three experimental and one control). The experimental groups were classified according to the specific SQ performed during the RT intervention: F-SQ (n = 13), P-SQ (n = 13), and H-SQ (n = 13). Members of the fourth group (n = 14) were assigned as Controls and fully discontinued any kind of physical training programme. In the 12 months preceding the study, participants performed 2–4 RT sessions per week, and were accustomed to performing the squat exercises under study with the correct technique. The study complied with the Declaration of Helsinki and was approved by the Bioethics Commission of the Local University. Written informed consent was obtained from all participants.

Study design

A randomized controlled experimental design was used. The three experimental groups (F-SQ, P-SQ and H-SQ) trained twice a week (48–72 h apart) for 10 weeks for a total of 20 sessions, following a progressive RT programme (described later in detail; Table I). The Control group was required to fully discontinue any kind of programmed resistance or endurance stimuli other than the normal physical activity of the active life of these young adults during the intervention. Participants completed a set of neuromuscular and functional evaluations pre- (the week before; T0) and post-training (the week after; T1) in three sessions (Monday, Wednesday and Friday) under a paced schedule (Supplementary Material 1). In addition to a selection of the functional assessments (Monday – 20 m sprint and CMJ tests, Wednesday – Wingate test; Friday – WOMAC Questionnaire), each testing day participants performed in a randomized and counterbalanced way one of the three squat progressive loading tests (F-SQ, P-SQ or H-SQ). Once a progressive loading test schedule was assigned to each subject in T0, the same order was replicated in T1. Prior to evaluations, participants performed nine familiarization sessions separated by 48–72 h. The first session was used for body composition assessment, personal data and health history questionnaire administration, medical examination and identification of the starting position for each of the three squat variations (described later in detail). Then, in random order, each subject performed three

Table I. Descriptive characteristics of the resistance training programme performed by the Full Squat (F-SQ), Parallel Squat (P-SQ) and Half Squat (H-SQ) groups.

Scheduled	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10
%1RM	~60%	~60%	~65%	~65%	~70%	~70%	~75%	~75%	~80%	~80%
Sets x Reps	4 × 8	5 × 8	4 × 8	5 × 8	4 × 6	5 × 6	4 × 5	5 × 5	4 × 4	5 × 4
Target MPV ($m \cdot s^{-1}$)										
Group F-SQ	0.74	0.74	0.68	0.68	0.63	0.63	0.58	0.58	0.52	0.52
Group *P*-SQ	0.68	0.68	0.63	0.63	0.58	0.58	0.53	0.53	0.48	0.48
Group H-SQ	0.59	0.59	0.55	0.55	0.51	0.51	0.47	0.47	0.43	0.43

Note: 1RM: one-repetition maximum; Wk.: week; Reference rep: maximal intended velocity repetition performed at the end of each session's warm-up to ensure that the load (kg) to be used matched the velocity associated with the intended %1RM.

familiarization sessions for each squat exercise and were instructed on how to properly perform the lifts. Some practice sets with light and medium loads were then carried out. Participants were required not to engage in any other type of strenuous physical activity, exercise training, or sports competition for the duration of the present investigation.

Velocity-load relationship and 1RM strength determination

Following the familiarization sessions, the individual load-velocity relationships were determined by means of a progressive loading test up to the 1RM for the three SQ variations, performed in a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain). Following the warm-up, initial load was set at 20 kg and was gradually increased in 10 kg increments until the attained mean propulsive velocity (MPV) was ≤ 0.60 m s^{-1} (Sánchez-Medina, Perez, & González-Badillo, 2010). Thereafter, load was individually adjusted with smaller increments (5 down to 2.5 kg) so that the 1RM could be precisely determined. Three repetitions were executed for light (<50% 1RM), two for medium (50–80% 1RM), and only one for the heaviest loads (>50% 1RM). Inter-set recoveries ranged from 3 min (light loads) to 5 min (heavy loads). The 1RM was considered as the heaviest load that each subject could properly lift while completing full ROM for each SQ, without external help. A very high test-retest reliability of this testing protocol (ICC = 0.99, 95% CI = 0.99–1.00, CV = 2.5%) has been recently described (Courel-Ibáñez et al., 2019).

For the three squat variations, participants started from an upright position, with the knees and hips fully extended, stance approximately shoulder-width apart with both feet positioned flat on the floor in parallel or externally rotated to a maximum of 15°. The barbell rested across the back at the level of the acromion. Stance width and feet position were individually adjusted and carefully replicated on every lift. From this position, they were required to descend in a continuous motion until reaching their previously determined concentric initial position for each squat variation:

- Half squat (H-SQ): descent until reaching a 90° knee angle (Hartmann et al., 2013).
- Parallel squat (P-SQ): descent until the inguinal crease was in projection with the top of the knee (Hartmann et al., 2013; Wretenberg et al., 1996).
- Full squat (F-SQ): descent until the first of these two criteria was met: (i) when posterior thighs and calves made contact with each other, or (ii) when the lumbar spine angle was equal to 0° (Martínez-Cava et al., 2019).

The spinal curvature in the sagittal plane for the F-SQ starting position was determined using the Spinal Mouse system (Idiag, Volketswil, Switzerland) (Guermazi et al., 2006). Measurements from the angle between the spinous process of C7 and the top of the anal crease (approximately at S3) were evaluated to control that each lift was made to avoid lumbar spine angle >0° (Martínez-Cava et al., 2019).

Individual's ROM for the three squat variations was carefully determined during the first familiarization session, and subsequently replicated in each training and testing session with the help of two bar spotters placed at the left and right sides of the Smith machine with a precision scale (±1 cm) (Martínez-Cava et al., 2019). This was designed to: (i) precisely control and replicate the individual eccentric ROM between trials, and (ii) allow participants to momentarily release the weight of the bar in the spotters for 2 s, and therefore minimize the contribution of the stretch-shortening cycle (i.e. rebound effect), thus increasing the reliability of the measurement (Pallarés, Sánchez-Medina, Pérez, De La Cruz-Sánchez, & Mora-Rodriguez, 2014).

Participants were required to perform the concentric phase in an explosive manner (at maximal intended velocity) and the eccentric phase at a controlled mean velocity of 0.45–0.65 m s^{-1} (Pareja-Blanco, Rodríguez-Rosell, Sánchez-Medina, Gorostiaga, & González-Badillo, 2014). This protocol was practiced during the familiarization sessions accomplished with the aid of the visual and auditory feedback in real-time provided by the linear velocity transducer software, so that participants could adjust the eccentric velocity to the required range. Repetitions that failed to meet any of these requirements were automatically discarded and repeated after a 3 min rest.

All testing and training lifts were made using a Smith machine with no counterweight mechanism. A dynamic measurement system (T-Force System, Ergotech, Murcia, Spain; 1000 Hz) automatically calculated the relevant kinematic parameters of every repetition, provided auditory and visual velocity feedback in real-time and stored data on disk for analysis. Measures from the following neuromuscular parameters were considered for the analysis: 1RM strength in kg, 1RM to body mass ratio (1RM/BM), average MPV attained against all absolute loads common to T0 and T1 (MPV_{ALL}), average MPV attained against absolute loads lower than 50% 1RM common to T0 and T1 ($MPV_{<50\%\ 1RM}$, "low" loads), and average MPV attained against absolute loads higher than 50% 1RM common to T0 and T1 ($MPV_{>50\%\ 1RM}$, "high" loads).

Sprint and vertical jump tests. Two maximal 20-m sprints, separated by a 3-min rest, were performed on a running track. Sprint times were measured using photocells timing gates (Polifemo Radio Light, Microgate, Bolzano, Italy), placed at 0 and 20 m, so that the times to cover 0–20 m (T20) could be determined. Following 5 min of recovery, participants performed 5 maximal countermovement vertical jumps (CMJs), separated by 1 min rests. Jump height was determined using an infrared timing system (Optojump, Microgate, Bolzano, Italy). Test–retest reliability measured by the coefficient of variation (CV) were 0.9% and 1.5% for 20-m sprint and CMJ, respectively. The intraclass correlation coefficients (ICCs) were 0.957 (95% confidence interval, CI: 0.903–0.981) for 20-m sprint, and 0.995 (95% CI: 0.990–0.998) for CMJ (Pareja-Blanco et al., 2017).

Wingate test. All Wingate tests (WGT) were performed in a mechanically braked cycle ergometer (Monark© 874E, Varberg, Sweden) adapted with a crank-based power metre (scientific model; SRM, Julich, Germany, 1 Hz, ±1% accuracy). The manufacturer calibrated the powermeter prior to the beginning of the study, and zero offset procedure was performed prior to each test. The saddle and handlebar positions of the cycle ergometer were individually adjusted and reproduced on every test to fit with participants' body dimensions. After a 3-min warm-up (100 W at 90 rpm interspersed with two short bouts of maximal acceleration of 2–3 s), from a complete stop with the pedal of the dominant leg placed at 45° from the vertical, participants performed a 30 s all-out effort at a resistance of 0.075 kg^{-1} body mass. Peak Power (WGT_{PEAK}) was defined as the greatest power value recorded by the SRM power metre. The average power (WGT_{MEAN}) of the 30 s was established. Test-retest reliability for WGT_{PEAK} has been found to be high (ICC = 0.87, ICC 95% CI = 0.78–0.96, CV = 3.5%) (Pallarés et al., 2013).

WOMAC questionnaire. The WOMAC (Western Ontario and McMaster Universities) is a multidimensional measure of pain, stiffness, and physical functional disability symptoms (Bellamy, Buchanan, Goldsmith, Campbell, & Stitt, 1988). The WOMAC questionnaire is rated on an ordinal scale of 0–4, with lower scores indicating lower levels of symptoms or physical disability. Each subscale is summated to a maximum score of 20, 8, and 68, respectively. The global index score was calculated by summating the scores for the three subscales. Participants completed the Spanish version of the WOMAC questionnaire (Escobar, Quintana, Bilbao, Azkárate, & Güenaga, 2002).

Resistance training programme

The intervention consisted of a 10-week RT programme (2 days a week). The three experimental groups (F-SQ, P-SQ and H-SQ) trained using the same relative loading magnitude (progressively increasing from 60% to 80% 1RM over the time course of the study), inter-set recoveries (4 min) and volume (4–5 sets and 8–4 repetitions) but differed in the depth of the SQ trained (Table I). Relative loads were determined from the load-velocity relationship as it has recently been shown that there exists a very close relationship between % 1RM and MPV in the three SQ variations under study (Martínez-Cava et al., 2019). Thus, a target MPV to be attained in the first (usually the fastest) repetition of the 1st exercise set in each session was used as an estimation of % 1RM; i.e. a velocity-based training was actually performed, instead of a traditional loading-based RT programme (Morán-Navarro et al., 2017). Following the standardized warm-up and previous to the first RT set, the absolute load (kg) was individually adjusted to match the velocity associated (±0.03 m/s) with the %1RM that was intended for that session. During training, subjects received immediate velocity feedback while being encouraged to perform each repetition at maximal intended velocity. This procedure ensures that each athlete performs every squat repetition at the programmed load intensity during the training sessions, thus avoiding the mismatches that typically occur when programming is solely based on the % 1RM value measured in T0. As recently pointed out, the 1RM value measured at the beginning of a RT programme (T0) will be considerably altered over the training weeks due to the neuromuscular improvements and/or fatigue processes that occur in the athletes ́ functional performance (Pareja-Blanco et al., 2017).

Statistical analyses

Means, standard deviation and standard error of the means were calculated. Assumption of normality was verified using the Shapiro–Wilk test and the homogeneity of variance across groups (F-SQ, P-SQ, H-SQ and CON) using the Levene's test. A 4 × 2 factorial ANOVA with post-hoc was performed to evaluate absolute changes in the neuromuscular and functional parameters between groups (F-SQ, P-SQ, H-SQ and CON) and time points (T0 and T1). One-way

ANOVA was run to compare the percentage of change scores (%) between T0 vs. T1 in the selected variables between experimental groups. Statistical significance was established at the $p < 0.05$ level. Effect Sizes (ES) were classified as "small" if lower than 0.2, "medium" if between 0.2 and 0.5, and "large" if higher than 0.8 (Lakens, 2013). Statistical analyses were performed using SPSS software version 24.0 (IBM Corp., Armonk, NY).

Results

There were three dropouts during this study, including one in the F-SQ group due to personal issues and the inability to complete the training programme, and two in the H-SQ group due to important cervical pain and complaints. Training compliance was 100% of all sessions for the participants who completed the study. No significant differences between the groups were found at T0 for any of the variables analyzed.

The F-SQ group increased in all neuromuscular parameters (Table II and Supplementary Material 2) for all the three SQ variations. The P-SQ group presented significant enhancements in all neuromuscular parameters ($p < 0.05$; 7.2–14.8%; ES = 0.72–1.45), except the 1RM and 1RM/BM for the F-SQ and H-SQ exercises ($p > 0.05$; 8.8–10.1%; ES = 0.37–0.61). The H-SQ group achieved no significant improvements in neuromuscular performance ($p > 0.05$), although medium effect sizes were found for the H-SQ exercise (ES = 0.33–0.48). The Controls declined on all the neuromuscular parameters, mainly on the 1RM and 1RM/BM performance ($p < 0.05$; −8.1–−13.8%; ES = 0.95–1.32).

Comparisons between the three groups of training in absolute (Table II) and relative terms (Supplementary Material 2) revealed that the greater the squat depth, the higher the increments in strength (F-SQ > P-SQ > H-SQ). However, individuals in all three training groups improved significantly more at the specific depth at which they trained (i.e. F-SQ for F-SQ group, P-SQ for P-SQ group, and H-SQ for H-SQ group, $p < 0.05$; Table II and Supplementary Material 2). Increments in functional performance (Table III) in WGT_{PEAK}, WGT_{MEAN} and CMJ were superior in F-SQ (4.3–12.8%; ES = 0.35–0.85) and P-SQ (3.8–9.0%; ES = 0.15–0.56) compared to H-SQ (−1.2–5.3%; ES = 0.11–0.28). Records for Time 0–20 m test were improved for F-SQ (−2.4%; ES = 0.48) and P-SQ (−1.0%; ES = 0.30), while H-SQ remained unchanged (<0.1%; ES < 0.01).

The three experimental groups perceived significant increases ($p < 0.05$) in the pain index after the intervention (Table IV). Increments in pain were

Table II. Changes in selected neuromuscular performance variables from pre- to post-training for each squat group.

		Exercise / Pre-post								
		F-SQ			P-SQ			H-SQ		
Group	Variable	T0	T1	ES	T0	T1	ES	T0	T1	ES
F-SQ	1RM (kg)	82.7 ± 11.2	96.3 ± 11.1*	1.22	90.6 ± 10.1	102.5 ± 11.0*	1.13	124.6 ± 20.1	139.4 ± 18.5*	0.77
(*n* = 12)	1RM/BM	1.14 ± 0.10	1.34 ± 0.12*	1.81	1.26 ± 0.14	1.43 ± 0.16*	1.13	1.72 ± 0.18	1.93 ± 0.19*	1.13
	MPV_{ALL} ($m \cdot s^{-1}$)	0.74 ± 0.05	0.86 ± 0.05*	2.40	0.73 ± 0.08	0.82 ± 0.06*	1.27	0.68 ± 0.07	0.75 ± 0.06*	1.07
	$MPV_{<50\%1RM}$ ($m \cdot s^{-1}$)	1.03 ± 0.08	1.14 ± 0.08*	1.38	0.97 ± 0.08	1.07 ± 0.08*	1.25	0.92 ± 0.08	1.01 ± 0.07*	1.20
	$MPV_{>50\%1RM}$ ($m \cdot s^{-1}$)	0.50 ± 0.04	0.62 ± 0.06*	2.35	0.53 ± 0.05	0.62 ± 0.04*	1.99	0.49 ± 0.06	0.55 ± 0.06*	1.00
P-SQ	1RM (kg)	81.3 ± 12.0	89.7 ± 11.2*	0.72	88.8 ± 13.1	100.8 ± 14.2*	0.88	121.5 ± 22.2	133.8 ± 20.2	0.58
(*n* = 13)	1RM/BM	1.12 ± 0.16	1.22 ± 0.17	0.61	1.22 ± 0.20	1.37 ± 0.20*	0.75	1.69 ± 0.39	1.83 ± 0.37	0.37
	MPV_{ALL} ($m \cdot s^{-1}$)	0.74 ± 0.06	0.81 ± 0.05*	1.27	0.74 ± 0.06	0.82 ± 0.05*	1.45	0.67 ± 0.06	0.72 ± 0.06*	0.83
	$MPV_{<50\%1RM}$ ($m \cdot s^{-1}$)	0.99 ± 0.08	1.06 ± 0.06*	0.99	0.96 ± 0.08	1.03 ± 0.06*	0.99	0.86 ± 0.08	0.92 ± 0.08*	0.75
	$MPV_{>50\%1RM}$ ($m \cdot s^{-1}$)	0.50 ± 0.06	0.57 ± 0.07*	1.07	0.52 ± 0.04	0.60 ± 0.05*	1.77	0.52 ± 0.04	0.57 ± 0.07*	0.88
H-SQ	1RM (kg)	82.3 ± 11.0	84.5 ± 9.9	0.21	89.3 ± 12.7	92.5 ± 10.3	0.28	119.3 ± 18.5	127.7 ± 16.8	0.48
(*n* = 11)	1RM/BM	1.15 ± 0.20	1.19 ± 0.19	0.21	1.25 ± 0.23	1.30 ± 0.23	0.22	1.68 ± 0.35	1.80 ± 0.38	0.33
	MPV_{ALL} ($m \cdot s^{-1}$)	0.85 ± 0.24	0.85 ± 0.18	<0.01	0.77 ± 0.10	0.78 ± 0.08	0.11	0.68 ± 0.11	0.71 ± 0.13	0.25
	$MPV_{<50\%1RM}$ ($m \cdot s^{-1}$)	0.99 ± 0.10	0.99 ± 0.12	<0.01	0.96 ± 0.10	0.98 ± 0.09	0.21	0.93 ± 0.10	0.97 ± 0.10	0.40
	$MPV_{>50\%1RM}$ ($m \cdot s^{-1}$)	0.51 ± 0.06	0.53 ± 0.07	0.31	0.53 ± 0.07	0.55 ± 0.07	0.29	0.50 ± 0.07	0.54 ± 0.06*	0.61
Control	1RM (kg)	84.1 ± 5.7	77.3 ± 7.6*	1.01	91.8 ± 6.3	83.9 ± 7.1*	1.18	125.5 ± 14.6	108.6 ± 13.4*	1.21
(*n* = 14)	1RM/BM	1.24 ± 0.11	1.14 ± 0.10*	0.95	1.36 ± 0.13	1.24 ± 0.10*	1.03	1.86 ± 0.22	1.60 ± 0.17*	1.32
	MPV_{ALL} ($m \cdot s^{-1}$)	0.75 ± 0.09	0.71 ± 0.06	0.52	0.73 ± 0.07	0.69 ± 0.07	0.57	0.72 ± 0.06	0.67 ± 0.06*	0.83
	$MPV_{<50\%1RM}$ ($m \cdot s^{-1}$)	1.06 ± 0.09	1.02 ± 0.08	0.47	1.00 ± 0.06	0.96 ± 0.07	0.61	0.96 ± 0.09	0.90 ± 0.07	0.74
	$MPV_{>50\%1RM}$ ($m \cdot s^{-1}$)	0.57 ± 0.07	0.52 ± 0.05*	0.82	0.57 ± 0.06	0.53 ± 0.06	0.67	0.52 ± 0.08	0.47 ± 0.09	0.59

Note: Data are mean ± SD. ES: effect size; F-SQ: Full Squat; P-SQ: Parallel Squat; H-SQ: Half Squat; 1RM: one-repetition maximum; BM: body mass; MPV: mean propulsive velocity. *Significant differences compared to T0.

Table III. Changes in selected functional performance variables from pre- to post-training for each squat group.

Group	Variable	Pre-post		
		T0	T1	ES
F-SQ (*n* = 12)	WGT_{PEAK} (W)	1035 ± 185	1103 ± 200	0.35
	WGT_{MEAN} (W)	677 ± 84	707 ± 72	0.38
	CMJ (cm)	35.8 ± 5.3	40.4 ± 5.5*	0.85
	Time 0-20m (s)	2.95 ± 0.14	2.88 ± 0.15	0.48
P-SQ (*n* = 13)	WGT_{PEAK} (W)	855 ± 323	906 ± 338	0.15
	WGT_{MEAN} (W)	643 ± 79	667 ± 75	0.31
	CMJ (cm)	34.0 ± 5.6	37.1 ± 5.5	0.56
	Time 0-20m (s)	2.96 ± 0.11	2.93 ± 0.09	0.30
H-SQ (*n* = 11)	WGT_{PEAK} (W)	996 ± 121	984 ± 103	−0.11
	WGT_{MEAN} (W)	650 ± 211	656 ± 59	0.04
	CMJ (cm)	33.9 ± 6.6	35.7 ± 6.3	0.28
	Time 0-20m (s)	2.94 ± 0.09	2.94 ± 0.09	<0.01
Control (*n* = 14)	WGT_{PEAK} (W)	1023 ± 121	1020 ± 134	0.02
	WGT_{MEAN} (W)	648 ± 57	642 ± 65	0.10
	CMJ (cm)	37.5 ± 5.1	36.2 ± 5.1	0.25
	Time 0-20m (s)	2.92 ± 0.14	2.97 ± 0.12	0.38

Note: Data are mean ± SD. ES: effect size; F-SQ: Full Squat; P-SQ: Parallel Squat; H-SQ: Half Squat; WGT_{PEAK}: Wingate peak power output; WGT_{MEAN}: Wingate mean power output; CMJ: counter movement jump height. *Significant differences compared to T0.

moderately similar for F-SQ and P-SQ groups (ES = 0.79–0.84) but more acute for H-SQ (ES = 1.62). The H-SQ group was the only one that reported significant increases ($p < 0.05$) in the stiffness and physical functional disability indexes (ES = 1.21–0.87) and the WOMAC questionnaire total score (ES = 1.03) at the end of the intervention. The Controls went down in all the scores (ES = 0.45).

Discussion

The main findings of the current study were: (i) The F-SQ exercise was the only one that produced significant improvements in all neuromuscular performance parameters for the three squat variations (F-SQ, P-SQ and H-SQ) after 10 weeks of RT, while P-SQ group obtained the second best results, (ii)

Table IV. Changes in selected measures of pain, stiffness, and physical functional disability thought the WOMAC questionnaire from pre- to post-training for each squat group

Group	Variable	Pre-post		
		T0	T1	ES
F-SQ (*n* = 12)	Pain Stiff	0.02 ± 0.13	0.36 ± 0.68*	0.84
	Functional disability	0.17 ± 0.38	0.33 ± 0.59	0.34
	Total score	0.01 ± 0.12	0.10 ± 0.40	0.32
	Pain Stiff	0.03 ± 0.16	0.18 ± 0.49	0.46
P-SQ (*n* = 13)	Pain Stiff	0.05 ± 0.22	0.40 ± 0.67*	0.79
	Functional disability	0.25 ± 0.44	0.33 ± 0.48	0.18
	Total score	0.02 ± 0.14	0.09 ± 0.31	0.33
	Pain Stiff	0.05 ± 0.21	0.18 ± 0.44	0.41
H-SQ (*n* = 11)	Pain Stiff	0.05 ± 0.38	1.40 ± 1.29*	1.62
	Functional disability	0.14 ± 0.36	1.32 ± 1.58*	1.21
	Total score	0.14 ± 0.40	0.86 ± 1.27*	0.87
	Pain Stiff	0.14 ± 0.39	1.01 ± 1.32*	1.03
Control (*n* = 14)	Pain Stiff	0.62 ± 0.90	0.18 ± 0.39*	−0.67
	Functional disability	0.65 ± 0.63	0.23 ± 0.43*	−0.80
	Total score	0.13 ± 0.37	0.03 ± 0.18	−0.35
	Pain Stiff	0.27 ± 0.59	0.08 ± 0.27	−0.45

Note: Data are mean ± SD. ES: effect size; F-SQ: Full Squat; P-SQ: Parallel Squat; H-SQ: Half Squat. *Significant differences compared to T0.

moderate to high increments in functional performance were observed only after F-SQ and P-SQ training, (iii) intervention with H-SQ produced the worst results in both neuromuscular and functional performance, (iv) individuals in all three training groups improved significantly more at the specific SQ at which they trained, (v) the three groups reported a moderate rise in pain perception scores following the 10-week RT programme, but the H-SQ experienced an acute increase in pain, stiffness and physical functional disability indexes, and (vi) ten weeks of RT cessation in this kind of highly-trained athletes (control group) significantly reduced all the neuromuscular and functional strength performance, mainly against high loads. These findings confirm that F-SQ and P-SQ, with correct technique and proper loads, are the safest and most effective exercises to improve strength and functional performance in well-trained athletes.

Evidence supports the recommendation that training at deeper ROM (F-SQ and P-SQ) elicits the greatest neuromuscular strength adaptations following prolonged (10–12 weeks) RT programmes (Bloomquist et al., 2013; Hartmann et al., 2012). Other authors, in contrast, suggest higher improvements after 16-week of periodized RT at shorter ROM such as the quarter squat (Rhea et al., 2016). Our findings corroborate the first assumption and demonstrate that F-SQ and P-SQ are the best and second-best exercises for increasing neuromuscular strength, both at maximal (1RM) and submaximal low (<50% 1RM) and high (>50% 1RM) loads. More importantly, working at these angles produced moderate to high increases in 1RM, 1RM/BM and MPV on the three SQ depths. In turn, training at shorter ROM such as the H-SQ (90° knee angle) resulted in lower performance increments and the worst transfer to other depths.

An innovative aspect of the present study is the use of velocity-based resistance training methods to check that every squat repetition was executed at the programmed load intensity (González-Badillo & Sánchez-Medina, 2010). Although previous interventions used a similar system to monitor the alterations in velocity of SQ movement (Rhea, Kenn, & Dermody, 2009), this is the first study testing changes in neuromuscular strength at different SQ depths, including an individual workload adjustment prior to each lift. This was possible by using the recently published relationships between relative load (% 1RM) and MPV for the three SQ variations (Martínez-Cava et al., 2019). The use of velocity-based devices and force-velocity calculations to accurately determine the individual load intensity at each lift is a main contribution of the present paper, and encourages future studies to replicate and extend these findings.

Some authors pointed out that greater improvement and adaptations would occur at the specific angle and ROM of training (Rhea et al., 2016; Weiss, Fry, Wood, Relyea, & Melton, 2000; Zatsiorsky & Kraemer, 2006). Our findings partly support this argument by showing the highest increments in neuromuscular performance at each group SQ depth. However, according to our data, the deeper the SQ was, the greater the increments were at all the variations. This means that training at F-SQ produced greater (or at least equal) gains in strength in any of the three squat variations (F-SQ, P-SQ and H-SQ) compared to the other groups. Likewise, the P-SQ obtained better results than H-SQ at the three variations. More importantly, training at deeper SQ gave rise to moderate to high functional improvements in jump (CMJ) and running acceleration (Time 0–20 m). Although these changes were not significant (Table III), the percentages of change and effect sizes obtained after the intervention clearly denote a greater impact on functional capacity for the F-SQ and P-SQ groups. These results confirm those reported in previous studies (Bloomquist et al., 2013; Hartmann et al., 2012). In addition, the present paper contributes by identifying increments in anaerobic capacity and lower-body local muscle endurance (Wingate test) only after training at deeper squats (F-SQ and P-SQ). Altogether, these findings indicate that, among the studied variations, the F-SQ and P-SQ training produced the greatest transfer to other ROM and the greatest functional adaptations. Therefore, the recommendation that training at a specific ROM will result in better performance on similar movements needs to be revised.

The novel analysis of pain, stiffness and physical functional disability after SQ training are of importance in the interpretation of these findings. Contrary to popular belief, SQ depths <90° of knee flexion should be used rather than shorter ROM to reduce the amount of stress supported by muscle-tendon units and ligaments (Hartmann et al., 2012, 2016). This idea is consistent with previous studies reporting that shorter ROM >70° knee flexion preclude athletes reaching the poor mechanical force position (i.e. "sticking" region) during the concentric phase (Escamilla et al., 2001; Martínez-Cava et al., 2019). This false "advantage" of shorter ROM (e.g. H-SQ, quarter squat) results in huge increments in the weight loads that can be lifted at the same relative load (% 1RM) and the consequent stress produced on the body. For example, 80% 1RM loads for H-SQ (90° knee angle) could increase 1.5-fold (70 kg vs. 105 kg) compared to F-SQ in strength-trained athletes (Martínez-Cava et al., 2019). In the current study, while all groups trained at the same relative load (60–80% 1RM), the absolute weight lifted for the H-SQ group (~70–100 kg) were ~50% higher than F-SQ and P-SQ (~50–70 kg). Furthermore, our data from the WOMAC questionnaire demonstrated that this load increment in the H-SQ was accompanied by greater pain, stiffness and physical functional disability in H-SQ. It is worth mentioning that two dropouts occurred following the H-SQ intervention due to important cervical pain and complaints. This negative impact however was drastically reduced if training at deeper ROM (F-SQ and P-SQ groups). Altogether, these findings may explain the lower injury rate detected in long-term epidemiological studies for competitive weightlifters compared to other disciplines (Hamill, 1994), primarily in the lower back (Calhoon & Fry, 1999). To explain these results, it is important to consider that spinal curvature was controlled prior to each lift. This novel approach, combined with the pain reports, allows us to confirm that F-SQ and P-SQ, under proper technique in the execution, are safer and more efficient exercises than H-SQ.

One last finding worthy of discussion was that 10 weeks of RT cessation severely decrease neuromuscular and functional performance in strength-trained athletes. In particular, we found greater velocity reductions at high loads ($MPV_{>50\%1RM}$ = 7.0% to 9.8%) compared to low loads ($MPV_{<50\%1RM}$ = −3.5–−5.3%). Similarly, early reports showed that elite athletes suffered the worst declines in velocities at 45% 1RM in bench press (−12.6% 1RM) and prone bench pull (−10.0% 1RM) resistance exercises after a 5-week detraining period (García-Pallarés, Sánchez-Medina, Pérez, Izquierdo-Gabarren, & Izquierdo, 2010). The fact that athletes were training at higher loads (60%–80% 1RM) could explain this particular negative impact on lower loads, due to greater adaptations following regular exposure to heavy loads (Fry, 2004). In addition, we reported for the first time reductions in functional performance, finding ~1.3 cm less jumping height and ~0.5 s slower sprinting after 10-week detraining. These results highlight the importance of maintaining RT programmes during transition periods to minimize excessive declines in neuromuscular and functional performance (García-Pallarés et al., 2010).

In conclusion, F-SQ and P-SQ are the safest and most effective exercises to improve strength and functional performance in well-trained athletes. In turn, H-SQ produced limited improvements while increasing the pain and discomfort after continued training. These findings questioned the recommendation that greater improvement and adaptations occur at the specific angle and ROM of training. This is the first study combining velocity-based assessment and spinal curvature evaluation during a prolonged RT intervention. The thoroughness of this work encourages future studies to test SQ using these methods.

Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed here (http://dx.doi.org/[10.1080/17461391.2019.1612952]).

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