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Velocity- and power-load relationships in the half, parallel and full back squat

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ABSTRACT
This study aimed to compare the load-velocity and load-power relationships of three common variations of the squat exercise. 52 strength-trained males performed a progressive loading test up to the one-repetition maximum (1RM) in the full (F-SQ), parallel (P-SQ) and half (H-SQ) squat, conducted in random order on separate days. Bar velocity and vertical force were measured by means of a linear velocity transducer time-synchronized with a force platform. The relative load that maximized power output (Pmax) was analyzed using three outcome measures: mean concentric (MP), mean propulsive (MPP) and peak power (PP), while also including or excluding body mass in force calculations. 1RM was significantly different between exercises. Load-velocity and load-power relationships were significantly different between the F-SQ, P-SQ and H-SQ variations. Close relationships ($R^2 = 0.92–0.96$) between load (%1RM) and bar velocity were found and they were specific for each squat variation, with faster velocities the greater the squat depth. Unlike the F-SQ and P-SQ, no sticking region was observed for the H-SQ when lifting high loads. The Pmax corresponded to a broad load range and was greatly influenced by how force output is calculated (including or excluding body mass) as well as the exact outcome variable used (MP, MPP, PP).

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KEYWORDS
Resistance training; muscle strength; force platform; propulsive phase; squat depth; lumbar spine

Introduction

The squat 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). The dynamic squat is a closed kinetic chain exercise (Escamilla et al., 1998) that involves the largest and strongest muscles of the body (quadriceps, hamstrings, gluteus maximus, triceps surae, erector spinae, etc.) and demands a coordinated multi-joint (spine, hip, knee and ankle) movement (Gullett, Tillman, Gutierrez, & Chow, 2009; Robertson, Wilson, & Pierre, 2008; Schoenfeld, 2010). When performed with correct technique, proper loads and following an adequate learning progression, the squat has proved to be a safe exercise on the musculoskeletal system (Chandler, Wilson, & Stone, 1989; Hartmann et al., 2013; Panariello, Backus, & Parker, 1994; Robertson et al., 2008).

In the last three decades, numerous publications have found that increases in lower-body strength following squat training transfer positively to athletic performance in short-duration actions that demand maximal neuromuscular activation such as sprinting and vertical jumping (Hartmann et al., 2012; Ronnestad, Kojedal, Losnegard, Kvamme, & Raastad, 2012; Seitz, Reyes, Tran, de Villarreal, & Haff, 2014; Wirth et al., 2016). Recent studies have also observed greater functional and specific performance improvements in medium to long distance athletes (e.g. rowing, cross-country skiing, cycling, running or canoeing) who performed RT concurrently with endurance training, with the squat being the main exercise in these training routines (Ronnestad, Hansen, Hollan, & Ellefsen, 2015; Ronnestad & Mujika, 2014).

The variation in range of motion (ROM) during the squat influences several biomechanical factors which are related to specificity of the movement pattern and can affect the development of force, rate of force development, activation and synchronization of motor units, as well as dynamic joint stability (Rhea, Kenn, Peterson, 2016). The choice of the optimal ROM for resistance exercises has been a matter of debate and controversy since the 1980s, especially with regards to the squat exercise (Bloomquist et al., 2013; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; Hartmann et al., 2013; Rhea et al., 2016). Some authors argue that, in order to maximize the athlete's functional adaptations, the squat exercise should be performed within a limited ROM, since it is at these reduced angles that the higher momentary peak force of the whole knee excursion occurs (Sullivan, Knowlton, DeVita, & Brown, 1996), or simply because it seems the most specific knee, ankle and hip angle in the athlete's own technical movement (usually running or jumping) (Rhea et al., 2016; Zatsiorsky & Kraemer, 2006). Other authors also recommend using short ROM squats due to the belief that continued training at deep squats may increase the odds of developing muscular and tendinous injuries, especially in the knee (Escamilla, MacLeod, Wilk, Paulos, & Andrews, 2012). On the other hand, several recent studies suggest that prolonged training interventions that involve the SQ exercise performed to larger depths maximize the neuromuscular and functional

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performance of well-trained athletes (Bloomquist et al., 2013; Drinkwater, Galna, McKenna, Hunt, & Pyne, 2007; Hartmann et al., 2012; Weiss, Frx, Wood, Relyea, & Melton, 2000), and can even minimize the risk of injury (Hartmann et al., 2013) when compared to RT programs in which the SQ is performed to shorter ROM.

In other regards, research attention has recently been placed on monitoring movement velocity during RT (Gonzalez-Badillo & Sanchez-Medina, 2010; Moran-Navarro et al., 2017; Sánchez-Medina, Pallarés, Pérez, Morán-Navarro, & González-Badillo, 2017). A very close relationship between relative load (percentage of one-repetition maximum, %1RM) and mean vertical bar velocity was found for both upper – (Gonzalez-Badillo & Sanchez-Medina, 2010; Sanchez-Medina, Gonzalez-Badillo, Perez, & Pallares, 2014; Sánchez-Moreno, Rodríguez-Rosell, Pareja-Blanco, Mora-Custodio, & González-Badillo, 2017) and lower-body (Sánchez-Medina et al., 2017) exercises, a novel finding which has important practical applications for the prescription and monitoring of training loads in RT (Sanchez-Medina & Gonzalez-Badillo, 2011).

It therefore seemed pertinent to provide a detailed comparison of the load-velocity and load-power relationships of these three commonly used variations of the squat exercise (F-SQ, P-SQ and H-SQ) in a large sample of experienced strength-trained athletes. Additionally, we also aimed to i) assess the possibility of using bar velocity to estimate loading magnitude (%1RM), ii) analyze the relative contribution of the propulsive and braking phases (Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010), and iii) determine the relative load that maximizes power output in the three exercise variations analyzed.

Materials and methods

Subjects

Fifty-two men (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%) volunteered to take part in this study. In the 12 months preceding the study, subjects had been performing 2–4 resistance training sessions per week and all incorporated the squat as part of their physical conditioning. The study, which was conducted according to the Declaration of Helsinki, was approved by the Bioethics Commission of the University of Murcia, and after being informed of the purpose and experimental procedures, participants signed a written informed consent form.

Testing procedures

Each subject performed a total of 13 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 analyzed (described later in detail, Figure 1). Then, in random order, each subject performed 3 familiarization sessions for each squat variation (i.e. 9 sessions in total). After a resting day, three testing sessions (one for each squat variation: full squat (F-SQ), parallel squat (P-SQ) and half squat (H-SQ)) were conducted in random order.

Velocity and power-load relationships and 1RM strength determination

Following the familiarization sessions, the individual load-velocity and load-power output relationships were determined by means of a progressive loading test up to the 1RM for the three squat variations, performed in a Smith machine. A detailed description of this testing protocol has been provided elsewhere (Pallares, Sanchez-Medina, Perez, De La Cruz-Sanchez, & Mora-Rodriguez, 2014; Sánchez-Medina et al., 2017). Following the warm-up protocol, 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 $m \cdot s^{-1}$. Thereafter, load was individually adjusted with smaller increments (5 down to 2.5 kg) so that the 1RM could be precisely determined. The heaviest load that each subject could properly lift while completing full ROM for each squat variation, without any external help, was considered to be his 1RM. An average of 8.1 ± 1.4 (F-SQ), 8.8 ± 1.7 (P-SQ) and 11.3 ± 2.2 (H-SQ) increasing loads were used in the progression to 1RM.

Squat execution technique

The individual ROM during the three squat variations was carefully determined during the first familiarization session,

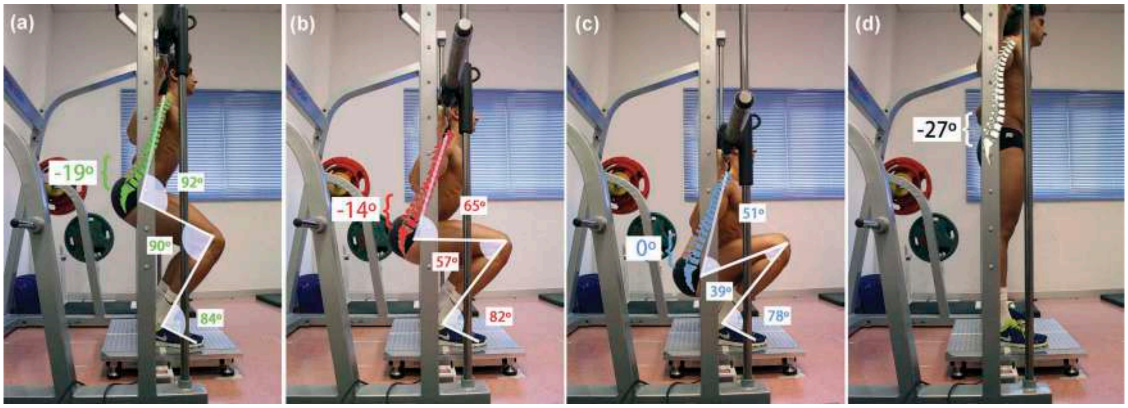

Figure 1. A representative example of the starting and finishing (d) positions of the concentric phase for the half (a), parallel (b) and full or deep (c) squat variations. Angles at the ankle, knee and hip joints as well as lumbar spine angle are shown.

and subsequently replicated in each trial with the help of two telescopic (± 1 cm precision) bar holders placed at the left and right sides of the Smith machine (Pallares et al., 2014).

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 bar rested across the back at the level of the acromion. Stance width and feet position were individually adjusted and carefully replicated on every lift. Participants were not allowed to jump off the ground, but they were permitted to raise their heels at the end of the concentric phase. Bar was required to remain in contact with the back and shoulders at all times. From this position, they were required to descend in a continuous motion until reaching their previously determined concentric initial position for each squat variation:

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 0º (described later in detail) (Figure 1(c)).

Parallel squat (P-SQ): descent until the inguinal crease was in projection with the top of the knee (Hartmann et al., 2013; Wretenberg, Feng, & Arborelius, 1996) (Figure 1(b)).

Half squat (H-SQ): descent until reaching a 90º knee angle (Hartmann et al., 2013) (Figure 1(a)).

For all trials, participants were required to always perform the concentric phase in an explosive manner, at maximal intended velocity. The eccentric phase was, however, performed at a controlled mean velocity (0.45–0.65 $m\cdot s^{-1}$) (Pallares et al., 2014; Sánchez-Medina et al., 2017).

A Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) was used for all sessions. The weight of the bar, including the guidance system, was 20 kg. Extra load was added by sliding calibrated weight discs (Eleiko, Sport AB, Halmstad, Sweden) onto both ends of the bar. A linear velocity transducer was attached to one end of the bar and its associated software (T-Force System version 3.65, Ergotech, Murcia, Spain) automatically calculated the kinematics of every repetition. Applied vertical (ground reaction) force was measured using a 80 × 80 cm force platform (FP-500, Ergotech, Murcia, Spain) placed on the floor (Figure 1). The force signal was time-synchronized with the bar velocity signal coming from the linear velocity transducer, and both were sampled at 1,000 Hz. Both velocity and force signals were smoothed with a 4th order low-pass Butterworth filter with no phase shift and 10 Hz and 200 Hz cut-off frequencies, respectively. From the directly measured force-velocity signal, force was calculated in two conditions: i) excluding the contribution of each subject's body mass to force output; and ii) including body mass to force output. Power output for these two conditions was then calculated as the instantaneous product of force output and bar velocity. Then, in order to calculate the load that maximized mechanical power output (Pmax load) for each condition, a second-order polynomial was fitted to individual load-power data points. The propulsive phase was defined as that portion of the concentric action during which the measured acceleration (a) is greater than acceleration due to gravity, ($a \geq -9.81\ m\cdot s^{-2}$) (Sanchez-Medina et al., 2010).

Determination of joint angles in the sagittal plane

The spinal curvature in the sagittal plane at the starting position for each of the three concentric squat variations analyzed was determined using the Spinal Mouse system (Idiag, Volketswil, Switzerland), a handheld computer-aided electromechanical device. The device was guided along the midline of the spine, starting at the spinous process of C7 and finishing at the top of the anal crease, approximately at S3. These landmarks were previously determined by palpation and marked on the skin surface of each participant. Data were sampled every 1.3 mm as the mouse was rolled along the spine, providing a sampling frequency of ~150 Hz. All determinations were performed by the same experienced researcher in accordance with the manufacturer's guidelines. In a previous pilot study with part of these subjects (n = 22), the intra-class correlation coefficient (ICC) values for the thoracic, lumbar and sacroiliac/hip angles were 0.893, 0.912 and 0.883, respectively. It has been shown that the Spinal Mouse system has acceptable validity (assessed by radiography) in adults (Guermazi et al., 2006). In addition, photogrammetric analysis was used for determination of the hip, knee and ankle angles in the sagittal plane at the starting position of each concentric squat variation (Figure 1). Skin markers were placed at five body locations: shoulder (humeral head), hip (superior part of greater trochanter), knee (lateral epicondyle), ankle (lateral malleolus), and foot (head of fifth metatarsal) (Kellis, Arambatzi, & Papadopoulos, 2005). The coordinates for these markers were extracted using photogrammetric analysis. A digital camera (Casio EX-FH20, Tokyo, Japan) with the optical axis perpendicular to the sagittal plane of movement was placed to the right of all subjects at a distance of 3 m. Images were analyzed using Kinovea software (version 0.8.15, www.kinovea.org). Intra-rater reliability of Kinovea for determining similar lower-body joint angles has been shown to be high (ICC = 0.96–0.99) (Bowerman, WHatMan, Harris, & Bradshaw, 2013).

Statistical analyses

Standard statistical methods were used for the calculation of means, standard deviations (SD), confidence intervals (CI) and *Pearson* product-moment correlation coefficients (r). Relationships between load (% 1RM) and velocity and power output were studied by fitting second-order polynomials to data. 1RM strength, concentric displacement and joint angles in the sagittal plane for the three squat variations were analyzed using one-way ANOVA. A two-way (exercise x load) ANOVA was used to detect differences between power output at different loads. The *Greenhouse-Geisser* adjustment for sphericity was calculated. After a significant F-test, differences among means were identified using pairwise comparisons with *Scheffé* method. Significance was accepted at the $p \leq 0.05$ level. Analyses were performed using SPSS software version 20.0 (IBM Corp., Armonk, NY).

Results

1RM strength, ROM and joint angles in the sagittal plane for each squat variation

1RM strength, both in absolute and relative values (1RM/body mass), was significantly different ($p < 0.001$) between exercises: F-SQ< P-SQ< H-SQ. In addition, concentric displacement, hip and knee angles, as well as lumbar curvature were significantly different ($p < 0.001$) between exercises: F-SQ> P-SQ> H-SQ (Table 1).

Relationships between relative load and bar velocity

After plotting mean propulsive velocity (MPV) against % 1RM and fitting a second-order polynomial to all data points, a very close fit between these two variables was found for the F-SQ ($R^2 = 0.96$), P-SQ ($R^2 = 0.94$) and H-SQ ($R^2 = 0.92$) exercise variations (Figure 2). Individual curve fits for each test gave an R^2 of 0.990 ± 0.011 (range: 0.924–1.000; CV = 1.20 %) for F-SQ, R^2 of 0.986 ± 0.011 (range: 0.937–0.999; CV = 1.10 %) for P-SQ and R^2 of 0.984 ± 0.015 (range: 0.913–0.998; CV = 1.54 %) for H-SQ.

Significant differences were detected in the MPV against each %1RM between the F-SQ and P-SQ variations for loads of 40–75% 1RM, whereas significant differences between these two variations and the H-SQ were observed for loads of 40–90% 1RM. However, no significant differences were found in the actual mean velocity attained against the 1RM load (V_{1RM}) between the three squat variations (0.28 ± 0.04 $m\cdot s^{-1}$ for F-SQ, 0.29 ± 0.03 $m\cdot s^{-1}$ for P-SQ and 0.29 ± 0.04 $m\cdot s^{-1}$ for H-SQ; $p > 0.05$) (Table 2).

An example of the actual velocity-time curves for a representative subject when lifting his 1RM in the 3 squat variations analyzed is provided in Figure 3. A sticking region was observed in the P-SQ and F-SQ variations, but not in the H-SQ. The maximum load that could be lifted (1RM) was significantly higher in the H-SQ compared to the P-SQ and F-SQ exercise variations (Table 1, Figure 3).

Predicting load (% 1RM) from velocity data

A prediction equation to estimate relative load from velocity (MPV, in $m\cdot s^{-1}$) could be obtained for the three squat variations:

F-SQ Load = $4.468\ MPV^2 – 96.223\ MPV + 127.51$ ($R^2 = 0.96$)

P-SQ Load = $24.413\ MPV^2 – 133.800\ MPV + 139.53$ ($R^2 = 0.94$)

H-SQ Load = $54.421\ MPV^2 – 181.420\ MPV + 147.79$ ($R^2 = 0.92$)

In the case that mean concentric velocity (MV) is used, the resulting equations were:

F-SQ Load = $- 12.266\ MV^2 – 82.567\ MV + 124.75$ ($R^2 = 0.95$)

P-SQ Load = $9.548\ MV^2 - 123.460\ MV + 137.74$ ($R^2 = 0.94$)

H-SQ Load = $44.314\ MV^2 – 180.000\ MV + 148.53$ ($R^2 = 0.92$)

Contribution of the propulsive and braking phases to different loading conditions

Table 2 shows the contribution of the propulsive and braking phases to the total concentric time from 40 to 100% 1RM, according to calculations made using the high correlation that exists between load (% 1RM) and relative contribution of the propulsive phase to the total concentric duration of the lift in the three exercise variations (F-SQ: $r = 0.924$, $p < 0.001$; P-SQ $r = 0.922$, $p < 0.001$; H-SQ $r = 0.933$, $p < 0.001$) from individual data pairs obtained in the 50 F-SQ, P-SQ and H-SQ progressive loading tests.

In the three squat variations, the propulsive phase accounted for □84% of concentric duration at 40% 1RM, progressively increasing until reaching 100% at the 90% 1RM load in the H-SQ exercise, and at the 100% load (1RM) in the F-SQ and P-SQ (Table 2).

The load that maximized the mechanical power output (pmax load)

The load that maximized the mechanical power was found to be dependent on the outcome variable used (MP, MPP or PP) and the inclusion or exclusion of body mass in the calculations of force output (external load only vs. external load + body mass). The Pmax load was significantly different ($p < 0.05$) between the exercise variations (F-SQ, P-SQ or H-SQ) in most of the studied conditions (Figure 4).

Discussion

The main finding of the present study was that the load-velocity and load-power relationships were significantly different between the F-SQ, P-SQ and H-SQ exercise variations. Although the mean bar velocities associated to the highest loads of the spectrum (>90% 1RM) were similar between the squat variations analyzed, velocities attained against lower loads (40–90% 1RM) were considerably higher the greater the squat depth (F-SQ>P-SQ>H-SQ). Nevertheless, the close

Table 1. Comparison of 1RM strength, concentric displacement and joint angles in the sagittal plane at the starting position of the three squat variations analyzed: full squat (F-SQ), parallel squat (P-SQ) and half squat (H-SQ) (n = 50).

	F-SQ	P-SQ	H-SQ
1RM strength (kg)	87.3 ± 15.0	94.3 ± 15.0*	131.4 ± 22.2*#
1RM to body mass ratio	1.17 ± 0.24	1.27 ± 0.25*	1.75 ± 0.38*#
Concentric displacement (cm)	63.9 ± 5.3	54.0 ± 5.4*	36.4 ± 4.8*#
Thoracic curvature (º)	21.8 ± 12.2	20.1 ± 9.5	19.7 ± 8.7
Lumbar curvature (º)	−1.2 ± 1.1	−14.4 ± 4.8*	−18.5 ± 6.2*#
Sacroiliac/hip curvature (º)	27.5 ± 5.4	41.0 ± 5.7*	40.8 ± 7.9*
Hip angle (º)	54.6 ± 4.7	62.0 ± 4.1*	90.4 ± 4.9*#
Knee angle (º)	43.7 ± 4.1	62.7 ± 3.6*	90.6 ± 0.7*#
Ankle angle (º)	76.5 ± 6.4	80.5 ± 3.6*	82.9 ± 4.3*

*Significantly different than F-SQ; #significantly different than P-SQ ($p < 0.05$).

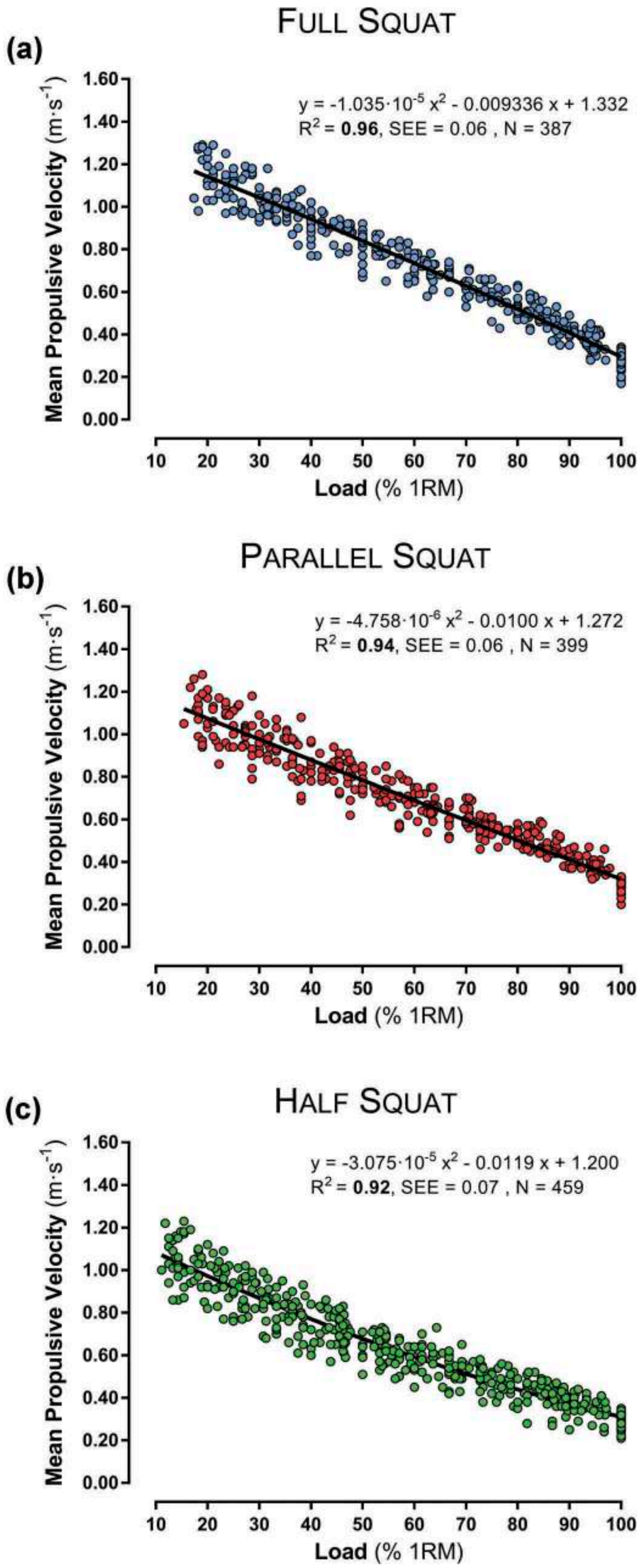

Figure 2. Relationships between relative load (% 1RM) and MPV for the three squat variations analyzed: (a) F-SQ; (b) P-SQ; (c) H-SQ. Raw load-velocity data pairs were obtained from the 50 progressive loading tests performed.

relationships (r > 0.96) observed between relative load and mean bar velocity in each of the three exercise variations, enable us to determine the load (%1RM) being used by an athlete “on the go”, as soon as the first repetition with any given absolute load is performed with maximal voluntary effort, although it will be necessary to use the specific equation provided for each squat variation (H-SQ, P-SQ or F-SQ). In addition, since for a shorter squat ROM the athlete is required to lift more weight to reach the same relative loading magnitude (% 1RM), the absolute power output that can be developed is notably higher in the H-SQ compared to the P-SQ or the F-SQ. This study also shows that the load-power relationship, and specifically the Pmax load, are dependent on the outcome variable used (MP, MPP or PP), but above all, depend on including or excluding the contribution of the athlete’s body mass in the calculation of force output.

Interestingly, while mean concentric displacement showed a proportional decrease between the three squat variations (F-SQ vs. P-SQ: −9.9 cm, 15.5%; F-SQ vs. H-SQ: −7.6 cm, 32.6%), the 1RM strength and 1RM/body mass values showed a disproportional increase between the P-SQ and H-SQ variations (F-SQ vs. P-SQ: −7.0 kg, 8.0%; P-SQ vs. H-SQ = −37.1 kg, 39.3%) (Table 1). This large increase in 1RM strength associated to the H-SQ exercise must be related to the fact that the muscle moment arms and the specific joint angles in the starting position of this exercise variation preclude subjects from actually reaching a sticking region during the concentric phase of the movement when lifting maximal or near-maximal loads, a phenomenon that does occur in the P-SQ and F-SQ exercise variations (Figures 1 and 3). This sticking region is thought to coincide with a poor mechanical force position, where the lengths and moment arms of the muscles involved are such that their capacity to exert force is reduced. This region can be detected in the velocity-time curve of the F-SQ and P-SQ between the first bar peak velocity and its first local minimum thereafter (Escamilla et al., 2001; Kompf & Arandjelovic, 2016; van Den Tillaar, Andersen, & Saeterbakken, 2014) (Figure 3). In agreement with the present results, Escamilla et al. (Escamilla et al., 2001), using a narrow stance technique measured by 2D, also located this sticking region around 67 ± 9º of knee flexion in the squat exercise, an intermediate angle between our P-SQ (62.7 ± 3.6º) and H-SQ (90.6 ± 0.7º) exercise variations (Table 1, Figure 1). This fact seems to be responsible for the aforementioned important differences in 1RM strength (both in absolute and relative terms) between the F-SQ and P-SQ exercises when compared to the H-SQ. These differences between exercise variations are thought to have implications for training prescription, since the absolute weights that an athlete must use in order to train with the same load (% 1RM) will be considerably heavier the shorter the squat ROM; this, in turn, could affect the amount of stress supported by muscle-tendon units and ligaments (Hartmann et al., 2016).

One of the major drawbacks that have traditionally been pointed out when incorporating the F-SQ or P-SQ exercise variations in RT routines is the hypothetical drastic increase in the probability of injury, not only at the knee joint (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2012) but also on the back, specifically at the lumbar level (Bazrgari, Shirazi-Adl, & Arjmand, 2007). While recent studies seem to rule out the incidence of joint injuries in the knee produced by continued RT using the F-SQ and P-SQ exercises (Hartmann et al., 2016),

Table 2. Mean propulsive velocity ($m \cdot s^{-1}$) attained against each load (% 1RM) and relative contribution of the propulsive phase to the total concentric duration in the three squat variations: full squat (F-SQ), parallel squat (P-SQ) and half squat (H-SQ) (n = 50).

Load (% 1RM)	F-SQ			P-SQ			H-SQ		
	MPV ($m \cdot s^{-1}$)	95% CI ($m \cdot s^{-1}$)	Propulsive Phase (%)	MPV ($m \cdot s^{-1}$)	95% CI ($m \cdot s^{-1}$)	Propulsive Phase (%)	MPV ($m \cdot s^{-1}$)	95% CI ($m \cdot s^{-1}$)	Propulsive Phase (%)
40	**0.94 ± 0.06**	0.92–0.95	84	**0.88 ± 0.07**$^{\#}$	0.86–0.90	83	**0.77 ± 0.07***	0.79–0.75	84
45	**0.89 ± 0.06**	0.87–0.91	86	**0.83 ± 0.06**$^{\#}$	0.81–0.85	84	**0.72 ± 0.06***	0.70–0.74	86
50	**0.84 ± 0.05**	0.82–0.86	87	**0.78 ± 0.06**$^{\#}$	0.76–0.80	86	**0.68 ± 0.06***	0.66–0.70	89
55	**0.79 ± 0.05**	0.77–0.81	89	**0.73 ± 0.06**$^{\#}$	0.71–0.75	88	**0.63 ± 0.06***	0.61–0.65	91
60	**0.74 ± 0.05**	0.72–0.75	90	**0.69 ± 0.05**$^{\#}$	0.67–0.70	89	**0.59 ± 0.06***	0.57–0.60	93
65	**0.69 ± 0.05**	0.67–0.70	91	**0.64 ± 0.05**$^{\#}$	0.63–0.66	91	**0.55 ± 0.05***	0.54–0.57	94
70	**0.63 ± 0.05**	0.62–0.65	93	**0.59 ± 0.05**$^{\#}$	0.58–0.61	92	**0.51 ± 0.05***	0.49–0.52	96
75	**0.58 ± 0.05**	0.57–0.59	94	**0.54 ± 0.04**$^{\#}$	0.53–0.55	94	**0.47 ± 0.05***	0.45–0.49	97
80	**0.52 ± 0.04**	0.51–0.53	95	**0.50 ± 0.04**	0.51–0.53	95	**0.43 ± 0.04***	0.42–0.44	98
85	**0.47 ± 0.04**	0.46–0.48	96	**0.45 ± 0.04**	0.44–0.47	96	**0.40 ± 0.04***	0.39–0.41	99
90	**0.41 ± 0.04**	0.40–0.42	98	**0.40 ± 0.04**	0.39–0.41	98	**0.36 ± 0.04***	0.35–0.37	100
95	**0.36 ± 0.04**	0.35–0.38	99	**0.36 ± 0.04**	0.35–0.38	99	**0.33 ± 0.04**	0.34–0.35	100
100	**0.30 ± 0.04**	0.28–0.31	100	**0.30 ± 0.04**	0.28–0.31	100	**0.30 ± 0.04**	0.29–0.31	100

MPV: Mean propulsive velocity; CI: confidence interval; *significantly different to the F-SQ and P-SQ; $^{\#}$ significantly different to the F-SQ ($p < 0.001$)

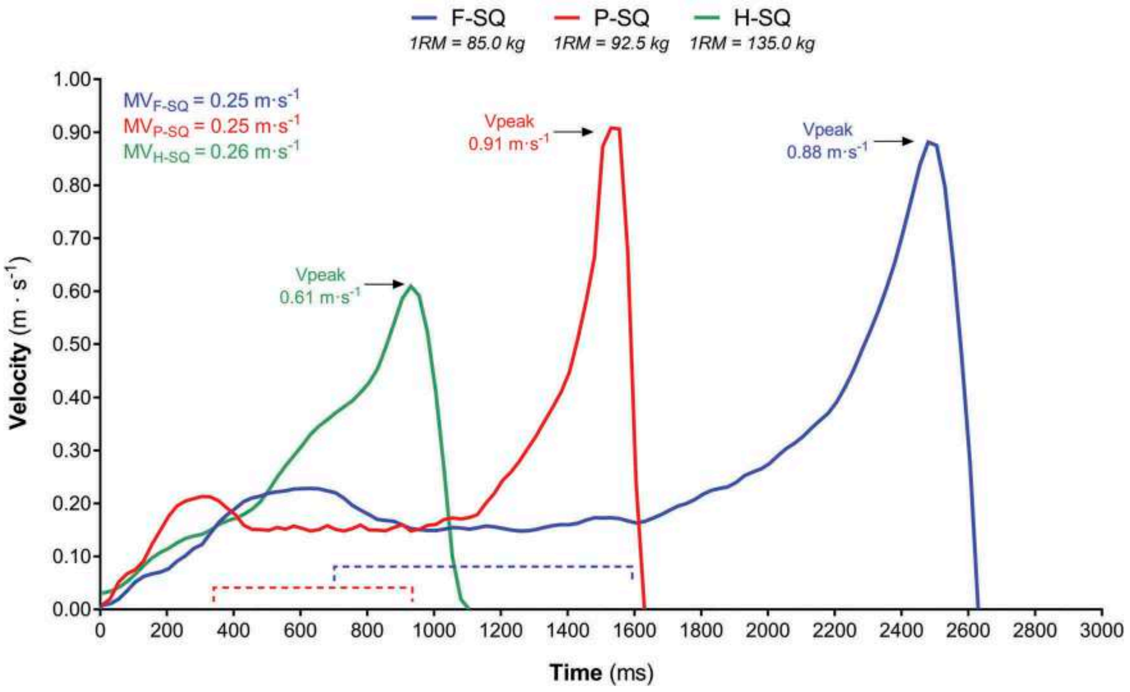

Figure 3. Example of the actual velocity-time curves for the concentric phase of each exercise variation when lifting the maximal 1RM load for a representative subject. Square brackets indicate the duration of the sticking region for each exercise. Vpeak: peak velocity; MV: mean velocity; 1RM: one-repetition maximum; H-SQ: half squat; P-SQ: parallel squat; F-SQ: full squat.

some publications have shown that the maintenance of lordosis during lifting enables the extensor musculature to reduce the load shear in addition to supporting the extensor torque, therefore reducing the possibility of injury at this level (Bazrgari et al., 2007; Potvin, McGill, & Norman, 1991). As seen in previous research (Schoenfeld, 2010), the results of the present study show that as hip flexion occurs, the lumbar curvature is rectified (Table 1 and Figure 1), although this occurs to a different extent depending on the anthropometric characteristics and particular joint angles of each subject. It is for these reasons that we performed an individualized preliminary analysis of the spine curvatures for each of the three starting concentric positions (H-SQ, P-SQ and F-SQ) used in this study. While no subject reached lumbar rectification (i.e. 0º lumbar lordosis) in the H-SQ and P-SQ, 37 subjects (71.2%) reached lumbar inversion (lumbar curvature higher than 0º) before the posterior thighs and calves made contact in the F-SQ. Therefore, as described in the methods section, the starting squat position for these 37 subjects was individualized so that, with the aid of the telescopic bar holders, a squat depth that resulted in a 0º lumbar rectification was used for all subsequent testing sessions. Thus, no subject started the concentric phase of any squat variation in a position of lumbar rectification. For these 37 subjects, the eccentric ROM and knee angle at the F-SQ starting position was clearly different than that at their P-SQ starting position (minimum differences of 14º in knee angle and 9 cm in ROM displacement). This methodological novelty can allow athletes to benefit from all the advantages that training with a deeper squat ROM (F-SQ and P-SQ) can offer in terms of

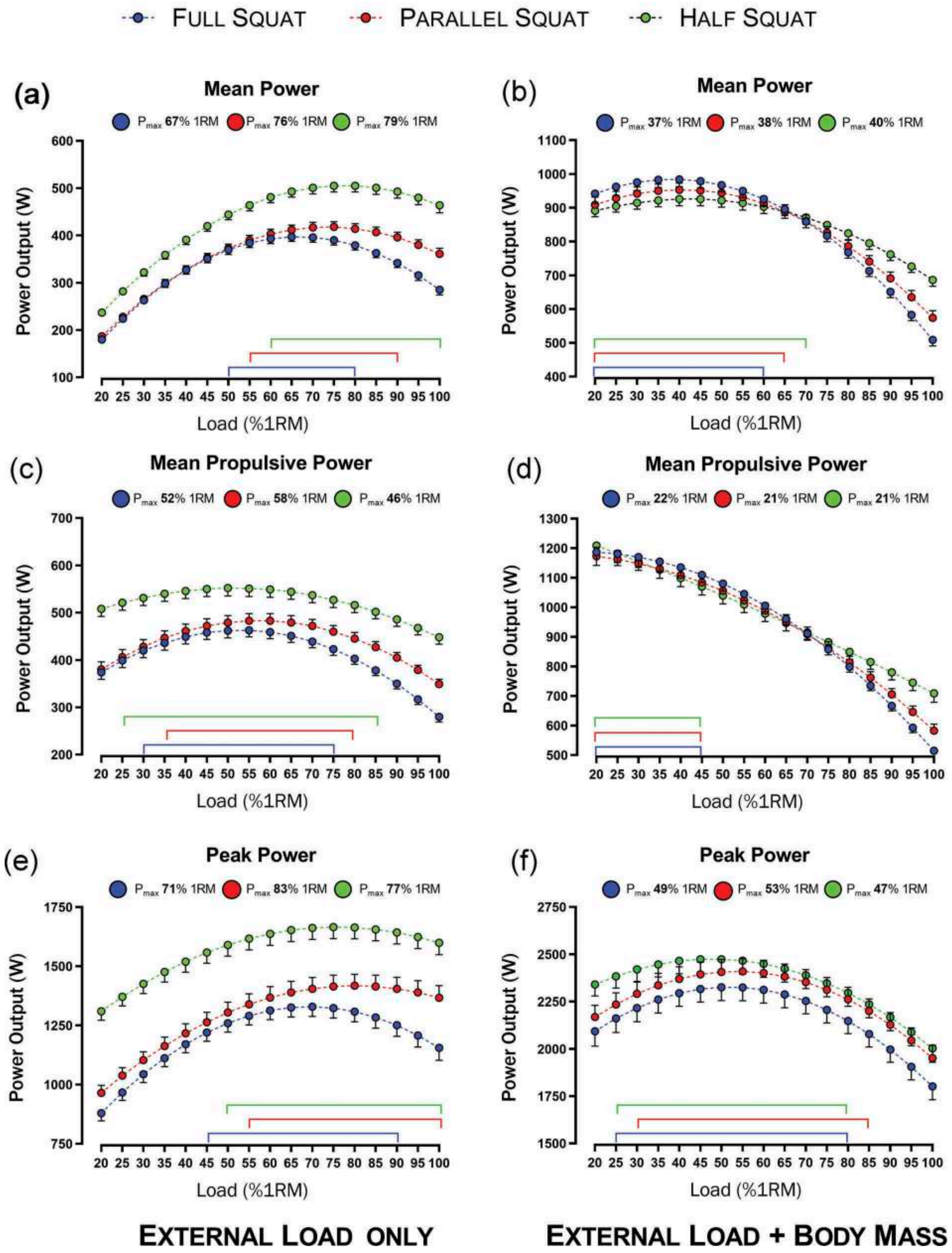

Figure 4. Load-power relationships for the F-SQ, P-SQ and H-SQ exercise variations according to three different outcome measures of power output: mean power (a, b), mean propulsive power (c, d) and peak power (e, f) as well as the inclusion or exclusion of body mass in force calculations. Square brackets indicate the range of loads at which power is not significantly different between the three squat variations. Pmax: load at which mechanical power output is maximized.

neuromuscular and functional performance, compared to squatting at lower depths, while minimizing the risk of injury by disc herniation or lumbar prolapse (Bazrgari et al., 2007; Potvin et al., 1991). However, the potential adaptive differences and incidence of injuries when using this monitoring method of the spine curvatures should be clarified in future investigations that analyze the effect of training interventions using different ROM squats.

Current results, together with previous data for the bench press (Gonzalez-Badillo & Sanchez-Medina, 2010), prone bench pull (Sanchez-Medina et al., 2014), push-up (Sánchez-Moreno et al., 2017) and full squat (Pallares et al., 2014; Sánchez-Medina et al., 2017) exercises emphasize the practical importance of considering movement velocity for monitoring training load in resistance exercise. The close relationships observed between relative load and MPV for the F-SQ (R^2 = 0.96), P-SQ (R^2 = 0.94) and H-SQ (R^2 = 0.92) in the present study (Figure 2) makes it possible to determine with great precision, using the equation provided for each squat variation, the relative load (% 1RM) being used assuming that the first repetition of a set is performed with maximal voluntary velocity. It also allows us to determine the real effort being incurred by an athlete when using any load from 30% to 95% 1RM (Table 2).

Lastly, some potential limitations of this study should be acknowledged. Firstly, it must be taken into account that three typical variations of the squat were analyzed but jumping at the end of the concentric phase was not allowed in any of them, i.e. non-ballistic exercises were used. The final deceleration phase that occurs at the end of the concentric phase influences the measured mechanical variables; thus, applied force and velocity values reached (and hence power output developed) would be somewhat lower when the exercise is performed in a non-ballistic mode (Bartolomei et al., 2018; Sánchez-Medina et al., 2010). In this regard, several studies have analyzed the effect of squat jump depth on mechanical performance variables (Kirby, McBride, Haines, & Dayne, 2011; McBride et al.. 2010). Secondly, we must note that the squats were performed in a Smith machine. Even though such a machine restricts movement to only the vertical plane, its use provides more consistent and safe measurements and it allowed us to standardize with great care and precision the eccentric ROM for each subject in the three squat variations analyzed, which was a requisite for the present study. It has been shown that the electromyographic activity of the major muscle groups of the legs is higher when squats are performed using free weights vs. a Smith machine (Schwanbeck, Chilibeck, & Binsted, 2009). When using free weight squats the results could be somewhat different to those obtained in the present study. Finally, we must point out that the Spinal Mouse system used in this study for assessing the spinal curvatures in the sagittal plane, although very practical, safe and cost-effective in the clinical setting, is not as accurate as imaging techniques such as x-rays or magnetic resonance.

In conclusion, this study shows that the depth of the squat considerably modifies the load-velocity and load-power relationships of the three squat variations analyzed. Therefore, when estimating load from velocity measures (or vice versa) it will be necessary to use the specific equation provided for each exercise variation (H-SQ, P-SQ or F-SQ). Moreover, the fact that the Pmax load (which corresponds to a broad load range) and the shape of the load-power output relationship are greatly influenced by how force output is calculated (including or excluding body mass) as well as the exact outcome variable used (MP, MPP, PP) (Figure 4) seems to discourage the use of power as a monitoring variable in RT. On the contrary, monitoring repetition velocity seems to be a much simpler, practical and useful method.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Bartolomei, S., Nigro, F., Ruggeri, S., Malagoli Lanzoni, I., Ciacci, S., Merni, F., … Semprini, G. (2018). Comparison between bench press throw and ballistic push-up tests to assess upper-body power in trained individuals. *The Journal of Strength and Conditioning Research*, *32*(6), 1503–1510.

Bazrgari, B., Shirazi-Adl, A., & Arjmand, N. (2007). Analysis of squat and stoop dynamic liftings: Muscle forces and internal spinal loads. *European Spine Journal*, *16*(5), 687–699.

Bloomquist, K., Langberg, H., Karlsen, S., Madsgaard, S., Boesen, M., & Raastad, T. (2013). Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *European Journal of Applied Physiology*, *113*(8), 2133–2142.

Bowerman, E., WHatMan, C., Harris, N., & Bradshaw, E. (2013). Reliability of 2D lower extremity alignment measures in elite adolescent ballet dancers. *New Zealand Journal of Sports Medicine*, *40*(2), 70–73.

Chandler, T. J., Wilson, G. D., & Stone, M. H. (1989). The effect of the squat exercise on knee stability. *Medicine and Science in Sports and Exercise*, *21*(3), 299–303.

Donnelly, D. V., Berg, W. P., & Fiske, D. M. (2006). The effect of the direction of gaze on the kinematics of the squat exercise. *Journal of Strength and Conditioning Research*, *20*(1), 145–150.

Drinkwater, E. J., Galna, B., McKenna, M. J., Hunt, P. H., & Pyne, D. B. (2007). Validation of an optical encoder during free weight resistance movements and analysis of bench press sticking point power during fatigue. *Journal of Strength and Conditioning Research*, *21*(2), 510–517.

Escamilla, R. F., Fleisig, G. S., Lowry, T. M., Barrentine, S. W., & Andrews, J. R. (2001). A three-dimensional biomechanical analysis of the squat during varying stance widths. *Medicine and Science in Sports and Exercise*, *33*(6), 984–998.

Escamilla, R. F., Fleisig, G. S., Zheng, N. G., Barrentine, S. W., Wilk, K. E., & Andrews, J. R. (1998). Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Medicine and Science in Sports and Exercise*, *30*(4), 556–569.

Escamilla, R. F., MacLeod, T. D., Wilk, K. E., Paulos, L., & Andrews, J. R. (2012). Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: A guide to exercise selection. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(3), 208–220.

Gonzalez-Badillo, J. J., & Sanchez-Medina, L. (2010). Movement velocity as a measure of loading intensity in resistance training. *International Journal of Sports Medicine*, *31*(5), 347–352.

Guermazi, M., Ghroubi, S., Kassis, M., Jaziri, O., Keskes, H., Kessomtini, W., … Elleuch, M.-H. (2006). Validité et reproductibilité du Spinal Mouse® pour l'étude de la mobilité en flexion du rachis lombaire. In *In Annales de réadaptation et de médecine physique, 49*, 172–177.

Gullett, J. C., Tillman, M. D., Gutierrez, G. M., & Chow, J. W. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *Journal of Strength and Conditioning Research*, *23*(1), 284–292.

Hartmann, H., Wirth, K., & Klusemann, M. (2013). Analysis of the load on the knee joint and vertebral column with changes in squatting depth and weight load. *Sports Medicine*, *43*(10), 993–1008.

Hartmann, H., Wirth, K., Klusemann, M., Dalic, J., Matuschek, C., & Schmidtbleicher, D. (2012). Influence of squatting depth on jumping performance. *Journal of Strength and Conditioning Research*, *26*(12), 3243–3261.

Hartmann, H., Wirth, K., Mickel, C., Keiner, M., Sander, A., & Yaghobi, D. (2016). Stress for vertebral bodies and intervertebral discs with respect to squatting depth. *Journal of Functional Morphology and Kinesiology*, *1* (2), 254–268.

Kellis, E., Arambatzi, F., & Papadopoulos, C. (2005). Effects of load on ground reaction force and lower limb kinematics during concentric squats. *Journal of Sports Sciences*, *23*(10), 1045–1055.

Kirby, T. J., McBride, J. M., Haines, T. L., & Dayne, A. M. (2011). Relative net vertical impulse determines jumping performance. *Journal of Applied Biomechanics*, *27*(3), 207–214.

Kompf, J., & Arandjelovic, O. (2016). Understanding and overcoming the sticking point in resistance exercise. *Sports Medicine*, *46*(6), 751–762.

McBride, J. M., Kirby, T. J., Haines, T. L., & Skinner, J. (2010). Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. *International Journal of Sports Physiology and Performance*, *5*(4), 484–496.

Moran-Navarro, R., Perez, C. E., Mora-Rodriguez, R., de la Cruz-Sanchez, E., Gonzalez-Badillo, J. J., Sanchez-Medina, L., & Pallares, J. G. (2017). Time course of recovery following resistance training leading or not to failure. *European Journal of Applied Physiology*, *117*(12), 2387–2399.

Pallares, J. G., Sanchez-Medina, L., Perez, C. E., De La Cruz-Sanchez, E., & Mora-Rodriguez, R. (2014). Imposing a pause between the eccentric and concentric phases increases the reliability of isoinertial strength assessments. *Journal of Sports Sciences*, *32*(12), 1165–1175.

Panariello, R. A., Backus, S. I., & Parker, J. W. (1994). The effect of the squat exercise on anterior-posterior knee translation in professional football players. *American Journal of Sports Medicine*, *22*(6), 768–773.

Potvin, J. R., McGill, S. M., & Norman, R. W. (1991). Trunk muscle and lumbar ligament contributions to dynamic lifts with varying degrees of trunk flexion. *Spine*, *16*(9), 1099–1107.

Rhea, M. R., Kenn, J. G., & Peterson, M. D. (2016). Joint-angle specific strength adaptations influence improvements in power in highly trained athletes. *Human Movement*, *17*, 43–49.

Robertson, D. G. E., Wilson, J. M. J., & Pierre, T. A. S. (2008). Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics*, *24* (4), 333–339.

Ronnestad, B. R., Hansen, J., Hollan, I., & Ellefsen, S. (2015). Strength training improves performance and pedaling characteristics in elite cyclists. *Scandinavian Journal of Medicine & Science in Sports*, *25*(1), E89–E98.

Ronnestad, B. R., Kojedal, O., Losnegard, T., Kvamme, B., & Raastad, T. (2012). Effect of heavy strength training on muscle thickness, strength, jump performance, and endurance performance in well-trained nordic combined athletes. *European Journal of Applied Physiology*, *112*(6), 2341–2352.

Ronnestad, B. R., & Mujika, I. (2014). Optimizing strength training for running and cycling endurance performance: A review. *Scandinavian Journal of Medicine & Science in Sports*, *24*(4), 603–612.

Sanchez-Medina, L., & Gonzalez-Badillo, J. J. (2011). Velocity loss as an indicator of neuromuscular fatigue during resistance training. *Medicine and Science in Sports and Exercise*, *43*(9), 1725–1734.

Sanchez-Medina, L., Gonzalez-Badillo, J. J., Perez, C. E., & Pallares, J. G. (2014). Velocity- and power-load relationships of the bench pull vs. bench press exercises. *International Journal of Sports Medicine*, *35*(3), 209–216.

Sánchez-Medina, L., Pallarés, J. G., Pérez, C. E., Morán-Navarro, R., & González-Badillo, J. J. (2017). Estimation of relative load from bar velocity in the full back squat exercise. *Sports Medicine International Open*, *1* (02), E80–E88.

Sanchez-Medina, L., Perez, C. E., & Gonzalez-Badillo, J. J. (2010). Importance of the propulsive phase in strength assessment. *International Journal of Sports Medicine*, *31*(2), 123–129.

Sánchez-Moreno, M., Rodríguez-Rosell, D., Pareja-Blanco, F., Mora-Custodio, R., & González-Badillo, J. J. (2017). Movement velocity as indicator of relative intensity and level of effort attained during the set in pull-up exercise. *International Journal of Sports Physiology and Performance*, *12*(10), 1378–1384.

Schoenfeld, B. J. (2010). Squatting kinematics and kinetics and their application to exercise performance. *J Strength Cond Res*, *24*(12), 3497–3506.

Schwanbeck, S., Chilibeck, P. D., & Binsted, G. (2009). A comparison of free weight squat to Smith machine squat using electromyography. *The Journal of Strength & Conditioning Research*, *23*(9), 2588–2591.

Seitz, L. B., Reyes, A., Tran, T. T., de Villarreal, E. S., & Haff, G. G. (2014). Increases in lower-body strength transfer positively to sprint performance: A systematic review with meta-analysis. *Sports Medicine*, *44*(12), 1693–1702.

Sullivan, J. J., Knowlton, R. G., DeVita, P., & Brown, D. D. (1996). Cardiovascular response to restricted range of motion resistance exercise. *The Journal of Strength & Conditioning Research*, *10*(1), 3–7.

van Den Tillaar, R., Andersen, V., & Saeterbakken, A. H. (2014). The existence of a sticking region in free weight squats. *Journal of Human Kinetics*, *42*(1), 63–71.

Weiss, L. W., Frx, A. C., Wood, L. E., Relyea, G. E., & Melton, C. (2000). Comparative effects of deep versus shallow squat and leg-press training on vertical jumping ability and related factors. *The Journal of Strength & Conditioning Research*, *14*(3), 241–247.

Wirth, K., Hartmann, H., Sander, A., Mickel, C., Szilvas, E., & Keiner, M. (2016). The impact of back squat and leg-press exercises on maximal strength and speed-strength parameters. *Journal of Strength and Conditioning Research*, *30*(5), 1205–1212.

Wretenberg, P., Feng, Y., & Arborelius, U. P. (1996). High- and low-bar squatting techniques during weight-training. *Medicine and Science in Sports and Exercise*, *28*(2), 218–224.

Zatsiorsky, V. M., & Kraemer, W. J. (2006). *Science and practice of strength training*. Champaign, IL: Human Kinetics.