

BIOMECHANICAL, ANTHROPOMETRIC, AND PSYCHOLOGICAL DETERMINANTS OF BARBELL BACK SQUAT STRENGTH

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ABSTRACT

Vigotsky, AD, Bryanton, MA, Nuckols, G, Beardsley, C, Contreras, B, Evans, J, and Schoenfeld, BJ. Biomechanical, anthropometric, and psychological determinants of barbell back squat strength. *J Strength Cond Res* 33(7S): S26–S35, 2019—Previous investigations of strength have only focused on biomechanical or psychological determinants, while ignoring the potential interplay and relative contributions of these variables. The purpose of this study was to investigate the relative contributions of biomechanical, anthropometric, and psychological variables to the prediction of maximum parallel barbell back squat strength. Twenty-one college-aged participants (male = 14; female = 7; age = 23 ± 3 years) reported to the laboratory for 2 visits. The first visit consisted of anthropometric, psychometric, and parallel barbell back squat 1 repetition maximum (1RM) testing. On the second visit, participants performed isometric dynamometry testing for the knee, hip, and spinal extensors in a sticking point position-specific manner. Multiple linear regression and correlations were used to investigate the combined and individual relationships between biomechanical, anthropometric, and psychological variables and squat 1RM. Multiple regression revealed only 1 statistically predictive determinant: fat-free mass normalized to height (standardized estimate ± SE = 0.6 ± 0.3; $t(16) = 2.28$; $p = 0.037$). Correlation coefficients for individual variables and squat 1RM ranged from $r = -0.79$ to 0.83, with biomechanical, anthropometric, experiential, and sex predictors showing the strongest relationships, and psychological variables displaying the weakest relationships. These data suggest that back squat strength in

a heterogeneous population is multifactorial and more related to physical rather than psychological variables.

KEY WORDS lean body mass, self-efficacy, performance, regression, powerlifting

INTRODUCTION

In 1956, Lietzke (44) reported a strong relationship between body mass and strength. Since then, a number of authors have used allometric scaling to predict strength in a variety of exercises across different strength sports (13,65,71). More simplistic statistical modeling studies have investigated the relationship between strength and fat-free mass, muscle size, and muscle mass; in all 3 cases, there seem to be strong relationships with squat performance (5,75,79). However, there are limitations to these studies. Previous work has primarily used homogeneous samples (5,44,46,49,75,79); relationships in heterogeneous populations remain to be determined. How other factors, such as heterogeneity in limb length and height—which would presumably impact resistance moment arms—affect scaling is ambiguous (46,49,75). Training type and interindividual differences in muscle moment arms and architectural characteristics (43) may mediate, and thus confound, the relationship between muscle size and strength (35,52). Finally, the assumption that skeletal mass increases proportionally with other tissue mass implicit in allometric scaling is questionable (25).

A less-often discussed determinant of strength is the psychological phenomenon known as self-efficacy, or the “conviction that one can successfully execute the behavior required to produce (an outcome)” (4). The role of self-efficacy on strength and physical performance has long been established. Nelson and Furst (55) investigated the effects of actual vs. expected strength on arm wrestling performance on college students and found that expected strength, rather than actual strength, was a better determinant of performance;

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studies conducted thereafter further support the role of self-efficacy as a determinant of strength (23,73). Recently, Slimani and Chéour (64) found that changes in strength and “muscular power,” including half-squat strength, were strongly correlated with changes in self-efficacy ($r=0.75-0.84$). Therefore, there is a strong rationale for the role of self-efficacy as a determinant of maximum squat strength, but role of self-efficacy relative to biomechanical variables is unclear.

The back squat is one of the most popular, highly regarded, and well-researched exercises in strength and conditioning. It not only has important applications for sport performance (60), but is also often used in the rehabilitation setting (14). Consequently, its biomechanics—ranging from joint-level kinetics and kinematics (3,21,67) to internal forces (17,20) and muscle contributions (72)—have been well studied; however, the determinants of squat strength are less understood. To perform the back squat, the hip, knee, and spinal extensors must overcome large external flexion moments (21,67). Recently, it was suggested that the inability to overcome these moments is what lead to “failure,” but the joint responsible may be individual dependent during movement performance (24). Although mechanically this is irrefutable, it raises questions as to whether the same joint is the bottleneck in each attempt for each individual. If weak links (i.e., joints) are similar between individuals, certain single-joint exercises may have better transfer than others (e.g., knee vs. hip extension-focused exercises). Therefore, the purpose of this study was to improve our understanding of the relative roles that biomechanical, anthropometric, and psychological factors play in predicting maximum back squat strength through the use of regression analysis. It was hypothesized that all 3 factors would have similar predictive contributions to back squat strength.

METHODS

Experimental Approach to the Problem

Participants reported to the laboratory for 2 visits. During the first visit, anthropometric measures were taken, self-efficacy was assessed, and back squat 1 repetition maximum (1RM) was tested. While performing the back squat, 2D sagittal plane motion capture was used to assess kinematics, which was used to inform the joint angles used for dynamometry. During the second visit, at least 48 hours after the first visit, participants' isometric joint strength was tested using dynamometry, using each participant's joint angles during the sticking point. Finally, data were analyzed using regression analysis.

Subjects

To identify the determinants of 1RM back squat strength, a sample of both males and females (aged 19-32 years) was recruited from a university fitness center (Table 1). Both sexes were included to help diminish the sex sampling disparity in exercise science and sports medicine research (16). Power analysis revealed that at least 18 participants would be necessary to

TABLE 1. Participant demographics.*

Sex	<i>n</i>	Age (y)	Body mass (kg)	Height (m)
Female	7	23 ± 3	57.29 ± 8.01	1.57 ± 0.08
Male	14	24 ± 4	82.00 ± 10.29	1.76 ± 0.07
Combined	21	23 ± 3	73.76 ± 15.18	1.69 ± 0.11

*Data are mean ± SD.

achieve 80% power for a “very large” effect size (partial $R^2 = 0.49$; $\alpha = 0.05$; $1-\beta = 0.80$; predictors = 4) (22). A “very large” effect size, equivalent to a Pearson's r of 0.7 (34), was chosen because previous investigations have described correlation coefficients greater than 0.8 for one of the primary outcomes (relative fat-free mass) (79). All participants were required to have at least 1 year of resistance training experience and to have performed the back squat at least once per week for the previous year. In addition, participants must have been free from musculoskeletal and neuromuscular injuries that may have interfered with, or be worsened by, performance of the back squat. Owing to contraindications of the bioelectrical impedance testing, participants were excluded if they had an electronic implant (heart pacemaker and brain stimulator), limb amputation, or were pregnant. Participants were asked to refrain from lower-body resistance training for 48 hours before each visit. Before beginning, all participants provided informed consent. Because proper performance of the back squat was integral to the carrying out of this study, if any participant was unable to perform a back squat to parallel, as defined by the hip and knee joint centers having a vertical differential of zero, they were excluded from the study. This study was approved by the Lehman College Institutional Review Board.

Procedures

Anthropometry and Body Composition. Participants' masses, heights, and segment lengths were measured using a scale, stadiometer, and tape measure, respectively. The following segment lengths were recorded using a tape measure: trunk (acromion process to greater trochanter), thigh (greater trochanter to lateral femoral epicondyle), shank (lateral femoral epicondyle to lateral malleolus), and shoe in which they squatted (longest distance from the tip of the toes to the heel) (54). The shoe was measured rather than the foot in the case that foot measurement would underestimate their base of support during the squat. Each measurement was taken 3 times, and the average of all 3 measurements was used for analysis. All measurements were taken on the left side of participants' bodies, as this was also the side that was recorded using 2D sagittal plane motion capture during the performance of the squat.

Assessment of fat mass, fat-free mass, segmental body mass, and body water content was performed using an InBody 770 multifrequency bioelectrical impedance device

TABLE 2. Results of multiple linear regression on determinants of barbell back squat strength.*†

	Estimate	SE	t value	p value	Standardized estimate	Standardized SE	t value	p
Intercept	135.165	8.911	15.168	<0.0001				
Moment sum ^c	-0.004	0.022	-0.187	0.8540	-0.040	0.212	-0.187	0.8540
Physical self-efficacy ^c	-0.064	0.439	-0.146	0.8857	-0.021	0.147	-0.146	0.8857
Sex (female)	-26.100	22.387	-1.166	0.2608	-0.339	0.291	-1.166	0.2608
Relative FFM ^c	3.713	1.632	2.276	0.0369	0.575	0.253	2.276	0.0369

*FFM = fat-free mass.

c = centered.

(Biospace Co., Ltd., Seoul, Korea) according to the manufacturer's instructions. Participants were requested to avoid eating for 12 hours before testing, eliminate alcohol consumption for 24 hours, abstain from strenuous exercise for 24 hours, refrain from consuming fluids the morning of testing, and void immediately before the test. Analysis of body composition was determined by the unit with participants remaining as motionless as possible. The between-day test-retest intraclass correlation coefficients (ICCs) from our laboratory for each of lean body mass, skeletal muscle mass, fat mass, arm mass, trunk mass, and leg mass are 0.999, 0.999, 0.997, 0.998, 0.999, and 0.999, respectively.

Physical Self-Efficacy Survey. Physical self-efficacy (PSE) was calculated using the PSE survey, which has been shown to have a test-retest ICC of 0.80 when administered 6 weeks apart (58). The PSE survey consists of 22 questions, each on

a 6-point Likert scale, and is composed of 2 subscales: perceived physical ability (score range = 10–60) and physical self-presentation confidence (score range = 12–72). Higher scores in the perceived physical ability scale are indicative of greater perceived physical ability, whereas greater scores on the physical self-presentation confidence are indicative of one's confidence in presenting their physical skills (58).

Back Squat Protocol. A 5-minute warm-up was performed on a treadmill at what each individual deemed to be a moderate intensity. Further warm-up was optional and self-selected. After the warm-up, participants were asked to estimate their 1RM. The squat was performed with the bar in the high bar position—across the shoulders on the trapezius, slightly above the posterior aspect of the deltoids (15,30)—feet shoulders' width apart, and with shoes on. No weightlifting belts or knee wraps were allowed during testing, but

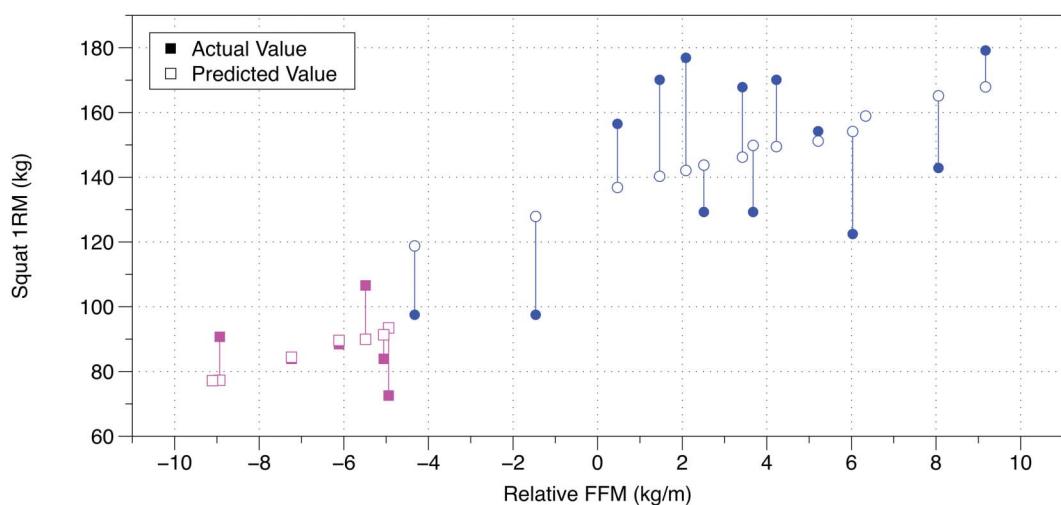
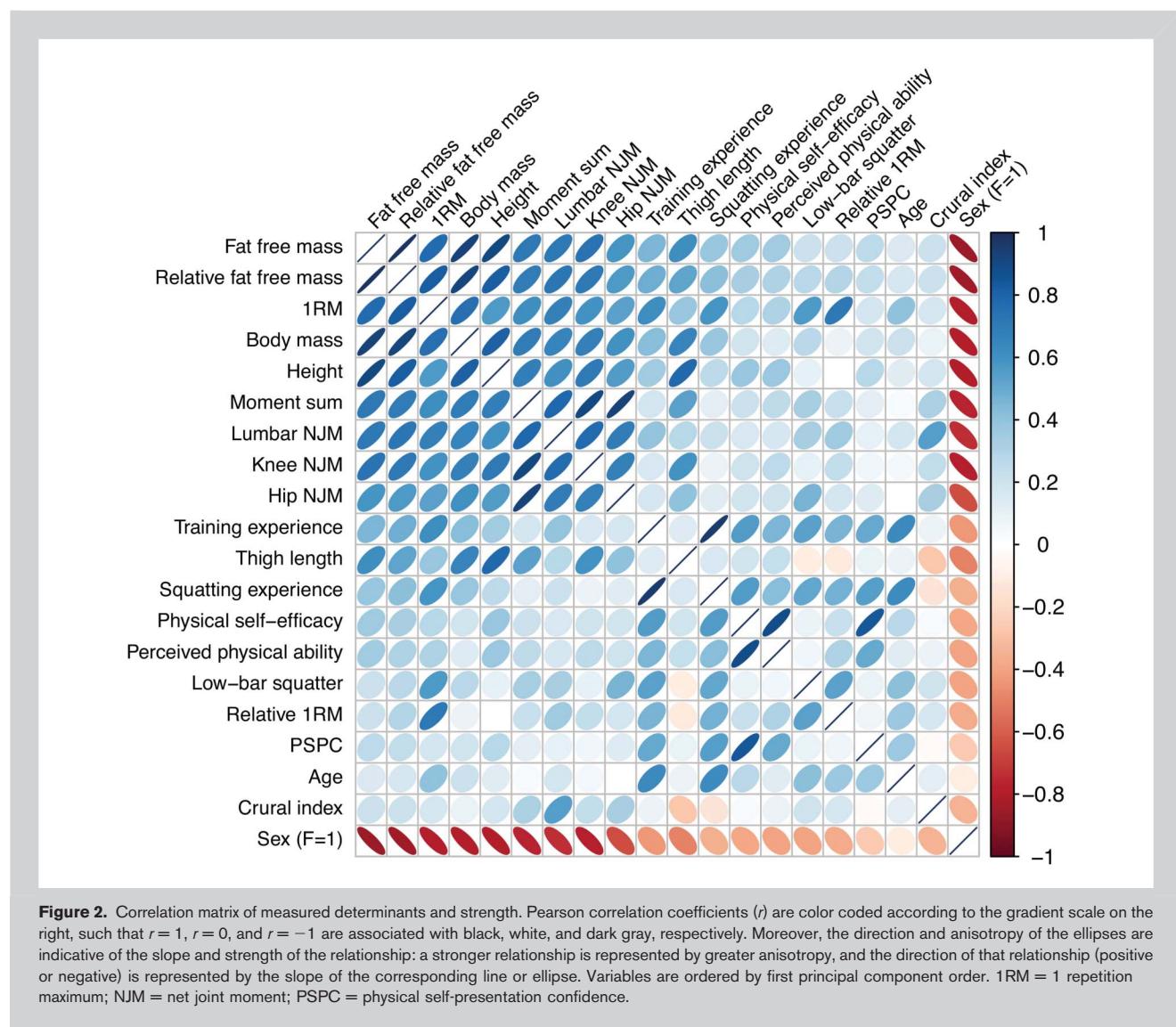


Figure 1. Centered multiple linear regression. Actual (● or ■) barbell back squat strength and values predicted by the multiple linear regression (○ or □) as a function of relative fat-free mass (FFM). Gray squares = female and black circles = male. *Nota bene* all independent variables, except sex, are centered. 1RM = 1 repetition maximum.

weightlifting shoes were permitted. Depth was ensured by the same investigator in all trials, who instructed participants using verbal cues, "Down, down, down... up!" This cueing technique was used in all warm-up and 1RM trials. Using 50 and 80% of their estimated 1RM, participants performed 5–10 and 3–5 repetitions, respectively, as a warm-up, with 2 minutes of rest between each set (40). Participants performed 1RM trials with at least 5 minutes of rest between each attempt. Actual time rested was ~5 minutes for most attempts and was based on the lifter's perceived readiness to engage in another attempt. Strong verbal encouragement was provided to obtain the best performance. After each successful attempt, the weight was increased (or decreased in the case of a failed attempt) by what the investigators and subject deemed to be feasible, based on the bar speed and effort (rating of perceive exertion) required to complete the last repetition (32). Failed trials were discarded.

Kinematic Analysis. Sagittal plane kinematics were captured at 30 Hz using a Logitech C920 webcam (Logitech International S.A., Lausanne, Switzerland) with a resolution of $1,920 \times 1,080$ pixels. Narrow stance squats were used so as to limit motion in the transverse and frontal planes, which would preclude one from obtaining valid sagittal plane measures. Previous work has shown differences of less than 5° for the hip and knee joints at the sticking point between 2D and 3D motion capture in narrow stance squats (21). Trials were imported to Dartfish 6 Connect (Dartfish, Fribourg, Switzerland), wherein participants' left greater trochanter, lateral femoral epicondyle, lateral malleolus, and the end of the bar were used to calculate ankle, knee, and hip angles.

Temporospatial characteristics of the knee during 1RM trials with the highest load were used to determine the point of minimum bar velocity during the concentric phase—this point was deemed to be the "sticking point." The "sticking



point" is the part of a lift, that is, most difficult for an individual to overcome (38,39), and consequently, this point in the lift is considered to be the bottleneck. Mechanically, the impulse-momentum relationship suggests that this is the point at which an individual would first reverse direction (i.e., fail) if they could not produce enough force to overcome external resistance, as is the case in the bench press (70). From the sticking point, hip, knee, and ankle angles were obtained, which were then used for isometric dynamometry testing.

Dynamometry. On the second day, at least 48 hours after initial 1RM testing, participants performed isometric dynamometry testing (Biodex Isokinetic Dynamometer System 4 Pro, Shirley, NY). Hip and knee angles observed during each participant's sticking point were used as angles used for dynamometry. During knee extension trials, participants were allowed to hold onto handles attached to the dynamometer and were strapped across the ipsilateral thigh, hips, and torso. During hip extension trials, participants were strapped across the torso and hips. In addition to hip and knee extension strength, isometric spinal extension at the L5/S1 level was also tested at 20° lumbar flexion (approximate lumbar flexion during the squat) (50), during which participants were strapped across the hips. Right then left trials were performed for knee then hip extension strength, followed by lumbar extension. Each trial lasted for 5 seconds, followed by 30 seconds of rest, for a total of 3–4 trials in each

position. If a participant's net joint moment continued to increase in the third trial, then a fourth trial was performed. Participants were verbally encouraged and were also allowed to view the screen for biofeedback and increased performance (10). The highest peak net extension moments from each of the 3 trials for each position were used for analysis.

Statistical Analyses

All analyses were performed in R (version 3.4.0). A multiple linear regression was used to examine the contribution of "primary" anthropometric, psychometric, and isometric strength variables to predict 1RM loads. "Primary" variables were selected based on previous studies (5,79) by combining variables contained within categories of interest (anthropometry, biomechanical, and psychological), and by qualitatively inspecting residual and correlation plots. By combining variables within the same category: (a) highly correlated variables, such as isometric knee and hip net joint moments, were reduced to a single variable, so as not to wash out effects in the multiple regression and (b) an entire category of variables was reduced to 1 variable, which allows for the quantification of the relative contribution of that entire category. Relative fat-free mass (fat-free mass divided by height) was used to represent anthropometry; PSE was used to represent the psychological category; and the sum of the hip and knee moments were used to represent the biomechanical category. For the purposes of analysis, PSE data were assumed to be continuous because the data were

normally distributed (Shapiro-Wilk) (66). Because of substantial differences in these variables between sexes, sex was added to the regression, which was dummy coded such that females received a value of 1. Two multiple regression analyses were performed: unstandardized and standardized. The standardized regression allows one to compare the relative contributions of different variables, whereas unstandardized is based on raw values. All independent variables, except for sex, were centered before performing the regression. Finally, a correlation matrix was generated to describe bivariate relationships. For discussion purposes, correlations coefficients were compared directly using their 95% confidence intervals. Correlation coefficients were interpreted using criteria recommended

TABLE 3. Experimental data.*†

Sex	Women	Men	Average
1RM (kg)	86.18 ± 10.96	146.61 ± 27.53	126.47 ± 37.16
Relative 1RM (AU)	1.54 ± 0.33	1.79 ± 0.32	1.71 ± 0.34
Fat-free mass (kg)	45.20 ± 4.44	68.18 ± 7.93	60.52 ± 13.04
Relative fat-free mass (kg·m ⁻¹)	28.83 ± 1.76	38.87 ± 3.64	35.52 ± 5.75
Leg FFM:FFM (%)	28.48 ± 1.67	28.30 ± 1.22	28.36 ± 1.35
Leg FFM:BM (%)	22.61 ± 1.94	23.62 ± 2.29	23.28 ± 2.19
FFM:BM (%)	79.50 ± 6.99	83.37 ± 5.99	82.08 ± 6.44
PPA	43 ± 9	49 ± 6	47 ± 8
PSPC	48 ± 5	51 ± 7	50 ± 7
PSE	91 ± 12	101 ± 12	97 ± 12
Training experience (y)	2 ± 2	5 ± 3	4 ± 3
Squatting experience (y)	2 ± 2	5 ± 3	4 ± 3
Preferred bar position (high/low)	7/0	9/5	16/5
Max summed knee NJM (N·m)	440 ± 84	730 ± 132	633 ± 181
Max summed hip NJM (N·m)	538 ± 60	820 ± 199	726 ± 213
Max lumbar NJM (N·m)	333 ± 76	561 ± 116	485 ± 150
Crural index (AU)	1.02 ± 0.05	1.09 ± 0.10	1.07 ± 0.09

*1RM = 1 repetition maximum; AU = arbitrary units; FFM = fat-free mass; BM = body mass; PPA = perceived physical ability; PSPC = physical self-presentation confidence; PSE = physical self-efficacy; NJM = net joint moment.

†Data are mean ± SD.

by Hopkins (34): trivial ($0 \leq r < 0.1$); small ($0.2 \leq r < 0.3$); moderate ($0.3 \leq r < 0.5$); large/strong ($0.5 \leq r < 0.7$); very large/very strong ($0.7 \leq r < 0.9$); nearly perfect ($0.9 \leq r < 1.0$); and perfect ($r = 1.0$).

RESULTS

Multiple linear regression analysis was highly predictive of barbell back squat strength ($F(4,16) = 9.856$; $p = 0.0003$; $R^2 = 0.7113$; adjusted $R^2 = 0.6392$; $1-\beta > 0.999$) (Figure 1).

It was revealed that the only variable statistically predictive of barbell back squat strength is relative fat-free mass (fat-free mass divided by height) (Table 2). Moreover, standardized estimates showed that relative fat-free mass was also weighted highest in the multiple linear regression (Table 2); thus, relative fat-free mass was chosen to be the primary independent variable in Figure 1.

Bivariate Pearson correlations can be found in Figure 2. In line with the multiple regression, anthropometric measures showed greater correlation coefficients ($r = 0.384$ – 0.827) with barbell back squat 1RM than biomechanical ($r = 0.533$ – 0.672) and psychological variables ($r = 0.189$ – 0.301) (Figure 2).

Pooled experimental data can be found in Table 3.

DISCUSSION

To the authors' knowledge, this is the first study to investigate the interplay between biomechanical, anthropometric, and psychological variables and their ability to predict back squat 1RM strength. Contrary to our hypothesis, multiple regression revealed that anthropometric factors were best able to predict squat performance (Table 2).

In line with previous work (5,46,79), both multiple regression (Table 2) and bivariate correlations (Figure 2) suggest that anthropometric variables, especially fat-free mass and relative fat-free mass, are highly predictive of squat performance. Although fat-free mass is not homologous to skeletal muscle mass, the 2 measures have been shown to be proportional to one another (1); therefore, fat-free mass may be able to be used as a proxy measure for muscle size. The observed relationship between squat 1RM and relative fat-free mass is quite logical, as the size of an actuator (muscle) is related to its ability to produce force (47), and normalizing to height corrects for muscle mass because of sarcomeres in series (length) rather than in parallel (cross-sectional area). In more controlled experiments, the relationship between fat-free mass and isometric strength (net joint moment) has also been shown to be quite strong ($R^2 \approx 0.54$) (25), so it is unlikely that this relationship is spurious.

Height has been proposed to play an important role in determining squat strength, as those who are taller, or have longer femurs, may have longer resistance moment arms (37). However, it has been argued that both internal and external moment arms scale isotropically with segment lengths (57); as such, those with longer femurs may not be as disadvantaged in the squat as previously thought. This is further evidenced by height having no (49,75), or even

a positive (26,63), correlation with strength performance in previous studies. Although height was found to have a positive correlation with performance in this study ($r = 0.563$), this finding is confounded by fat-free mass. After controlling for fat-free mass, this relationship reverses ($r = -0.500$), as is also the case for thigh length, whose correlation drops from $r = 0.384$ to -0.191 after controlling for fat-free mass. These data suggest that height may indeed be detrimental to squat proficiency.

With regards to isometric strength, the finding that the sum of the hip and knee moments was not found to have a statistical contribution to the multiple regression must be interpreted with caution. It might seem to be in contrast to previous work (77); however, these findings simply suggest that the strength variables may be redundantly correlated or do not account for enough of the variance to be contributory to the regression model. In isolation, however, it seems that single-joint strength variables are strongly correlated with squat performance ($r = 0.533$ – 0.672), and these correlation coefficients were not statistically different from one another. From these data, it is unclear if strengthening a single muscle group (e.g., knee extensors) would increase squat strength, as the strength of 1 muscle group does not seem to relate more strongly to squat strength than another. Furthermore, there are nuances to the squat that may complicate this relationship, which are discussed herein.

The complexity of the squat as a multi-joint exercise likely plays a role in the findings of this study. Hip, knee, and spinal extensors must be able to overcome the flexion moment imposed on each respective joint. However, the isometric strength of the hips and knees working in isolation may not be an extraordinarily accurate predictor as to what the bottleneck is in each individual's squat. During simultaneous hip and knee extension, the biarticular hamstrings are used to produce a hip extension moment (7,19,72), but concomitant with this utilization of the hamstrings is a larger knee extension moment because of the hamstrings' knee flexion moment (7,72). Thus, net joint moments observed during the squat do not approach 100% of what each joint can produce in isolation (9). Whether or not a single muscle group is the bottleneck in a 1RM squat for an individual is predicated on not only individual kinematics, but also the other muscles involved. The relationship between individual joint strength and multi-joint strength may be highly nonlinear and paradoxical, owing to the increased degrees of freedom of multi-joint movements. For example, in theory, if an individual has an unusually strong bi-to-monoarticular hip extensor ratio, but squats with what is traditionally considered "hip dominant" kinematics (2,11,27,45,77), then despite having a small knee extensor net joint moment for a given amount of knee flexion, the internal resistance moment that the knee extensors must overcome may be quite large because of the reliance on the hamstrings to overcome the hip extension net joint moment (77).

The maximum isometric knee and hip extension net joint moments measured in this study are greater than the knee (633 vs. 449.5 N·m) and hip (726 vs. 604.0 N·m) extension net joint moments linearly extrapolated from Swinton et al. (67) ($r = 0.97$), whose participants were heavier (100.2 vs. 73.76 kg) and used greater loads (220.2 vs. 126.47 kg). One should be cautious when interpreting these data, though, as these are net moments and thus describe the minimum muscular effort, or the sum of all muscles acting on the joint in a movement where cocontraction is not negligible (8). However, isometric net joint moments are collected in isolation and with minimal cocontraction. When performing simultaneous hip and knee extension, neither the rectus femoris, hamstrings, nor gluteus maximus reach maximal electromyography (EMG) amplitude (19,29,78), potentially at least partially because of reciprocal inhibition (18). Another possible consideration as to why these muscles do not reach maximum EMG amplitude is that these muscles could not produce the necessary endpoint wrench (i.e., forces and moments that interact with the environment) if they were to do so (69), as each lower extremity muscle provides a unique contribution in wrench space (36,41). Although one would expect EMG amplitudes to increase proportionally with one another until one reaches a ceiling, such an outcome may not be possible while achieving the necessary endpoint wrench (68). However, EMG observations may be confounded by electrode placement, in that the biarticular muscles that cross the thigh have multiple innervation zones (33,59,76) with corresponding functional implications (48,59). Notwithstanding these limitations, it seems that one may not be able to maximally activate the biarticular muscles of the thigh during simultaneous hip and knee extension, which suggests that humans may be less than the sum of their parts when it comes to multi-joint force production.

Although most previous research on the squat has focused on the hips and knees, few studies have investigated the role of the spinal extensors (12,67). By extrapolating previously reported traditional back squat data using a linear regression ($r = 0.99$), the projected L5/S1 net joint moment is 423.3 N·m at 100% 1RM (67). Because the participants in this study were much lighter than those in the study by Swinton et al. (67) (100.2 vs. 73.76 kg) and their 1RMs were much less (220.2 vs. 126.47 kg), it is likely that the L5/S1 net joint moments of the participants in this study were much lower. Nevertheless, the L5/S1 net joint moments reported by Swinton et al. (67) are lower than the maximum L5/S1 net joint moments observed in this present investigation (485 vs. 423.3 N·m). Therefore, although stronger squatters seem to have stronger spinal extensors, it does not seem that this strength would be a limiting factor in the back squat. Rather, this component may arise because of the relatively linear relationship between load and spinal extension demands (67). Indeed, the knees and hips are affected by the cocontraction of biarticular muscles and unpredictable,

nonlinear changes in joint moments. By contrast, the spinal erectors need only resist the net joint moment as well as a small abdominal cocontraction, which does not necessarily increase with load. It is possible that exerting a spinal extension moment on a dynamometer differs from doing so in the back squat, perhaps due to the coordination required in the squat, while a dynamometer provides a stable testing environment. Finally, it is unlikely that abdominal cocontraction would increase the spinal extension moment requisite in the squat to a significant degree because abdominal EMG amplitudes seem to be low (3,6,74).

Although Crural index has previously been shown to be predictive of success in elite powerlifters (46), this was not the case in this study (Figure 2). In theory, Crural index may be an indicator of the “strategy” used by the lifter. McLaughlin et al. (51) found that among national-level powerlifters, the more highly skilled squatters tended to favor a more “knee dominant strategy” with less trunk lean—a strategy that may be less viable for lifters with a small Crural index. These kinematic limitations, or lack thereof, have direct kinetic implications; a larger Crural index may allow for a greater number of movement options than those with a smaller Crural index, and thus, lifters with larger Crural indices may better be able to “choose” a kinematic “strategy” that results in kinetics that are more feasible to overcome. This theory has recently been brought into question, however, as Fuglsang et al. (28) did not find a correlation between Crural index and trunk angle during the parallel squat ($r \approx -0.350$). Thus, the findings of Lovera and Keogh (46) may be specific to elite lifters.

Although previous studies have elucidated the importance of PSE in strength and physical performance (23,55,56,64,73), the correlations observed in this study are unremarkable. In fact, the only remarkable correlations observed pertaining to PSE and its constituents involved experiential variables ($r = 0.469$ – 0.612) (Figure 2). Self-efficacy is predicated on previous experience (61,62,80); as one trains and gains experience with squatting, they should also become more confident in their ability to squat. The interplay between experience and PSE may explain why self-efficacy has been shown to be important in within-subject and homogeneous between-subject studies (23,55,56,64,73). This study, however, used a heterogeneous population. Self-efficacy in and of itself cannot increase the potential for an individual to generate a joint moment. However, as per previous studies, self-efficacy seems to increase the ability of an individual to make use of the muscles that one possesses.

There are several limitations to consider when interpreting the results of this study. First, testing conditions were not necessarily the same for every individual, as investigators were unable to control who was in the weight room at the time of testing or what songs were playing, which has been considered to be detrimental to internal validity (31); however, such an environment may be considered to be more

ecologically valid than a laboratory setting. Second, sticking points were determined in 2D, using Dartfish and a webcam rather than motion capture with retroreflective markers, but angles obtained are similar to those previously reported (21). Third, the net joint moments obtained using the dynamometer were collected isometrically rather than dynamically. This static assumption may be justified by the fact that accelerations in maximal squats are negligible (42) and the sticking point was defined to be where velocity was minimal. However, the reductionist nature of obtaining single-joint net joint moments in the dynamometer ignores the complexity of multi-joint efforts (19). Fourth, dynamometry fails to capture 3D joint angles and moments, which likely interact with those that were measured in 2D (e.g., simultaneous hip extension, abduction, and external rotation). With respect to psychological variables, it must be noted that self-efficacy is a complex phenomenon. Although our survey has been validated as an instrument to assess this outcome, it may not wholly encompass the relevance to task specificity; the self-efficacy questionnaire used was not specific to the barbell back squat exercise. This study investigated recreationally active college students, not powerlifters or Olympic lifters, and therefore, cannot be extrapolated to such populations, as squat kinematics differ (53) and because such populations are more homogenous. Finally, participants were not allowed to wear a weight belt or knee wraps/sleeves during testing, which may have impacted their self-efficacy.

PRACTICAL APPLICATIONS

After examining psychological, anthropometric, and biomechanical factors, it was found that squat strength is primarily predicated on anthropometric variables (fat-free mass relative to height), and in a heterogeneous population, biomechanical and psychological variables seem to play secondary roles. Scientists can apply these exploratory findings in hypothesis-driven research; that is, to understand if these cross-sectional measures hold longitudinally. Practically, these results confirm the importance of weight classes in strength sports and also provide practitioners with an improved understanding of the emergent nature of back squat strength.

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