EFFECT OF SQUAT DEPTH AND BARBELL LOAD ON RELATIVE MUSCULAR EFFORT IN SQUATTING

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ABSTRACT

Bryanton, MA, Kennedy, MD, Carey, JP, and Chiu, LZF. Effect of squat depth and barbell load on relative muscular effort in squatting. *J Strength Cond Res* 26(10): 2820–2828, 2012—Resistance training is used to develop muscular strength and hypertrophy. Large muscle forces, in relation to the muscle's maximum force–generating ability, are required to elicit these adaptations. Previous biomechanical analyses of multi-joint resistance exercises provide estimates of muscle force but not relative muscular effort (RME). The purpose of this investigation was to determine the RME during the squat exercise. Specifically, the effects of barbell load and squat depth on hip extensor, knee extensor, and ankle plantar flexor RME were examined. Ten strength-trained women performed squats (50–90% 1 repetition maximum) in a motion analysis laboratory to determine hip extensor, knee extensor, and ankle plantar flexor net joint moment (NJM). Maximum isometric strength in relation to joint angle for these muscle groups was also determined. Relative muscular effect was determined as the ratio of NJM to maximum voluntary torque matched for joint angle. Barbell load and squat depth had significant interaction effects on hip extensor, knee extensor, and ankle plantar flexor RME ($p < 0.05$). Knee extensor RME increased with greater squat depth but not barbell load, whereas the opposite was found for the ankle plantar flexors. Both greater squat depth and barbell load increased hip extensor RME. These data suggest that training for the knee extensors can be performed with low relative intensities but require a deep squat depth. Heavier barbell loads are required to train the hip extensors and ankle plantar flexors. In designing resistance training programs with multi-joint exercises, how external factors influence RME of different muscle groups should be considered to meet training objectives.

KEY WORDS resistance exercise, muscle strength, multi-joint, biomechanics

INTRODUCTION

Inverse dynamics is a procedure used in biomechanics to estimate the mechanical effort required to perform a task. Because direct measurement of muscle force is seldom feasible, motion analysis techniques are combined with the equations of motion to solve for the net joint moment (NJM) acting on a segment. Net joint moment provides an estimate of the minimum muscular torque required at a joint. These procedures have been used to investigate the mechanical effort of a muscle group across different tasks or to compare the mechanical effort between muscle groups performing the same task. For example, Flanagan and Salem (6) compared the contribution of ankle plantar flexor, knee extensor, and hip extensor NJMs during the barbell back squat. This investigation found that the squat exercise required large mechanical efforts from the hip and knee extensors; however, because barbell load increased, hip extensor NJM increased more than knee extensor NJM (6). Thus, increasing barbell load increased the mechanical effort of the hip extensor musculature to a greater extent than for the knee extensor musculature.

A common broad purpose of investigations using inverse dynamics is to provide an estimate of the mechanical loading, such as that on muscles, imposed during a task. In resistance exercise, high muscle forces are required to recruit high-threshold motor units (17), which are necessary to stimulate adaptations, including muscle hypertrophy and increased muscle strength (7). Therefore, calculating NJM in different exercises is useful to determine which exercise places the most stress on a target muscle group or to identify which muscle group may be the limiting factor in a multi-joint task (4,6). However, determining the stress imposed on a muscle group requires more than simply estimating the absolute mechanical effort required of the muscle group. It is also important to consider the strength of the muscle group (2,11).

Muscular strength is defined as the maximum force that can be generated by a muscle (14). In practice, strength is determined as the heaviest weight that can be lifted successfully for one repetition, meaning a heavier weight would cause failure (14). One method in which training weights may be determined is as a percentage of one repetition maximum (1RM), which is known as relative intensity. Analyses

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Table 1. Participant descriptive statistics ($n = 10$).

Descriptive	Mean	*SD*
Height (m)	1.68	0.09
Body mass (kg)	62.5	6.5
Age (y)	22.5	2.1
Weight training age (y)	4.2	3.1
Squat 1RM (kg)	80.5	10.1
Squat 1RM: body mass	1.3	0.2

of resistance exercise training programs suggest that a relative intensity of 85% 1RM or greater is optimal to stimulate muscular strength and hypertrophy adaptations (7). Similar to relative intensity, relative muscular effort (RME) may be determined, where RME is the muscle force required to perform a task relative to the maximum force the muscle can produce (2). In a single-joint exercise, RME and relative intensity should be the same. That is, if an 85% 1RM load is used, the muscle group should be generating 85% of its maximum force. However, in multi-joint exercise, many muscle groups contribute, and it is not known whether all muscle groups involved have the same RME. Because increasing barbell load increases hip extensor NJM more than the knee extensor NJM during squatting (6), it may be hypothesized that these muscle groups operate at different RMEs during squatting, which is dependent on barbell load. If each muscle group in a multi-joint task uses a different percentage of its maximum force–generating ability, the strengthening effect for each muscle group will be different.

In biomechanics research, RME is measured as the ratio of a muscle group's NJM during a task relative to the muscle group's NJM during the maximal voluntary isometric contraction (MVC). Relative muscular effect has not been studied during resistance exercise tasks; however, Bieryla et al. (2) reported RME for the sit-to-stand, which is similar to an unloaded squat. In the sit-to-stand, the knee extensors have the highest RME (78 ± 32% MVC), whereas hip extensor (26 ± 14% MVC) and ankle plantar flexor (28 ± 14% MVC) RMEs are considerably lower (2). Whereas the barbell back squat involves the same joint actions and muscle groups as the sit-to-stand, barbell back squat exercise may be varied by modifying the squat depth and barbell load. If an unloaded squat requires similar RME to the sit-to-stand, knee extensor RME can increase to a smaller extent than hip extensor and ankle plantar flexor RME with these modifications. This may explain why Flanagan and Salem (6) observed a greater increase in hip extensor NJM than the knee extensor NJM as barbell load increased. Because maximum knee extensor strength was not studied, it is not known whether knee extensor RME approached maximum force–generating ability. In contrast, Wretenberg et al. (23) found knee extensor NJM to increase more than hip extensor NJM with increasing squat depth. Taken together, these studies suggest that squat depth and barbell load have unique effects on the absolute mechanical effort, and therefore RME, required of different muscle groups.

If squat depth and barbell load have different effects on each muscle groups' RME, these variations in exercise performance will affect how these muscle groups are trained during the squat exercise. Therefore, the purpose of this investigation was to investigate the effects of barbell load and squat depth on hip extensor, knee extensor, and ankle plantar flexor RME during the squatting exercise. Based on the previous research, we hypothesize that knee extensor RME will be higher with increasing squat depth (6), whereas hip extensor and ankle plantar flexor RME will be higher with increasing barbell load (23).

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Figure 1. High-bar back squat at parallel A) and full B) squat depths. Markers on participant are tracking markers used for dynamic squat trials.

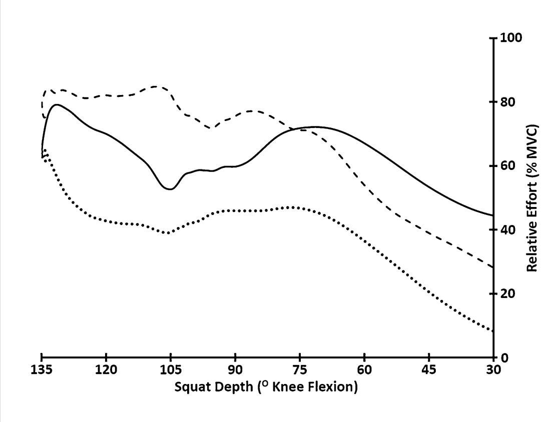

Figure 2. Plots of ankle plantar flexor (solid line), knee extensor (dotted line), and hip extensor (dashed line) relative muscular effort vs. squat depth (knee flexion angle) for a representative participant with a barbell load of 90% 1RM.

METHODS

Experimental Approach to the Problem

Hip extensor, knee extensor, and ankle plantar flexor RMEs were determined for loaded barbell squats by calculating the ratio of torque generated by each muscle group during the squat to the maximum torque the muscle group could produce (2,11). Torque during the squat was calculated by determining the NJM produced by the hip extensors, knee extensors, and ankle plantar flexors using inverse dynamics. Maximum muscular torque was determined using isometric strength testing as it is well known that maximum active muscle force is generated during isometric actions (1). Torques generated during squatting and strength testing were matched for joint angle, making estimates of RME joint angle specific (2). This allowed the effect of squat depth on RME to be examined, which was done at 15° intervals from 119° to 30° knee flexion during the concentric phase of the squat. The effect of barbell load on RME was examined by performing squats at 50 to 90% 1RM in increments of 10% 1RM.

Subjects

A convenience sample of 10 strength-trained women were recruited from the university community to participate in this investigation. To be included, prospective participants were required to (a) have a minimum of 1 year of experience performing the high-bar back squat and (b) be able to perform a deep squat with a minimum barbell load of 1.0 times their body weight. Prospective participants were excluded if they had current or previous musculoskeletal injuries that would prevent them from performing squatting exercise or strength tests safely. A sample size of 10 participants allows detection of within-subject effect size differences of 0.2 *SD*s while minimizing type I error to 5%

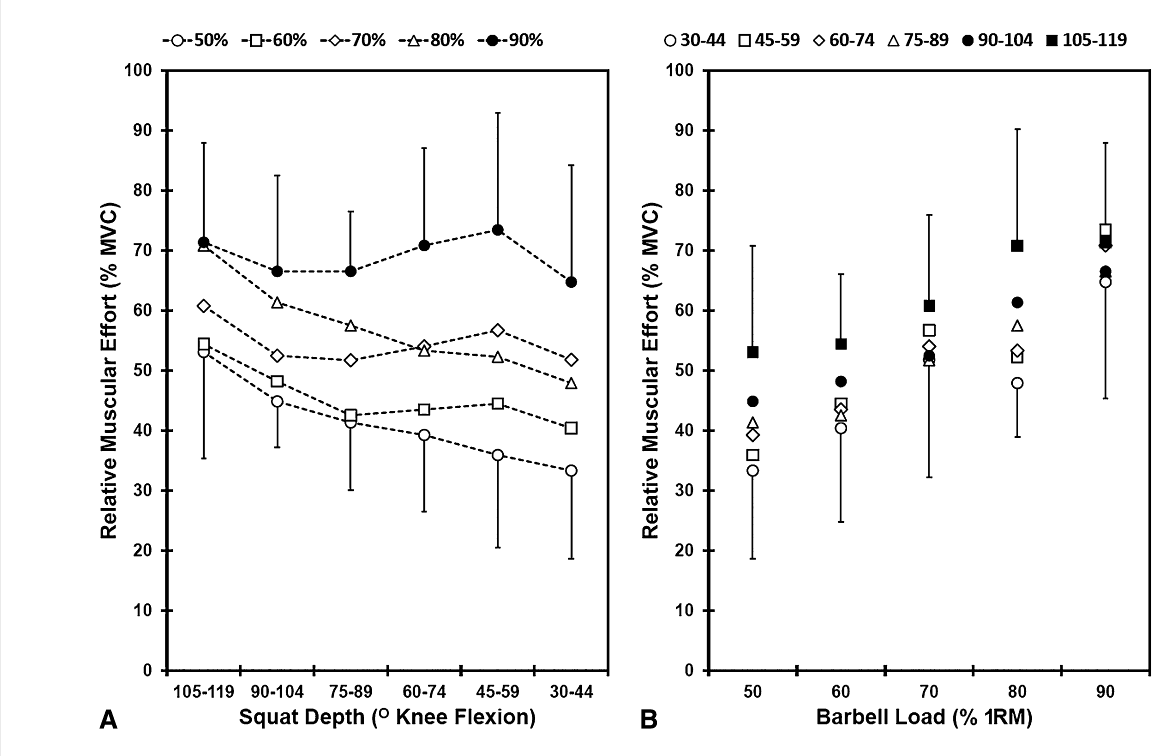

Figure 3. The effects of barbell load at varying squat depths A) and squat depth at varying barbell loads B) on ankle plantar flexor relative muscular effort.

Table 2. Effects of barbell load on relative muscular effort.*

Relative effort	Squat depth	50% 1RM	60% 1RM	70% 1RM	80% 1RM	90% 1RM
Ankle plantar flexor	30°–44°			A	A	A; B; C; D
	45°–59°			A	A	A; B; C; D
	60°–74°			A	A	A; B; C; D
	75°–89°				A; B; C	A; B; C
	90°–104°				A; B; C	A; B; C
	105°–119°				A; B	A; B
Knee extensor	30°–44°				A; B; C	A; B; C
	45°–59°				A; B; C	A
	60°–74°				A	
	75°–89°					
	90°–104°					
	105°–119°				A	
Hip extensor	30°–44°			A; B	A; B	A; B; C; D
	45°–59°		A	A; B	A; B	A; B; C; D
	60°–74°		A	A; B	A; B	A; B; C; D
	75°–89°			A; B	A; B	A; B; C; D
	90°–104°		A	A	A; B; C	A; B; C
	105°–119°			A; B	A; B	A; B; C

*Barbell load in column has significantly ($p \leq 0.05$) greater relative muscular effort than barbell load indicated by alphabets.

and type II error to 20% (power = 80%). Study procedures, approved by a Research Ethics Board at the authors' institution, were explained to participants who provided written informed consent. Participant characteristics are provided in Table 1. Participants completed 3 sessions spaced approximately 1 week apart. During the course of the investigation, participants were instructed to refrain from any strenuous lower-extremity activities outside the laboratory sessions.

Procedures

The 3 sessions, performed in order, were as follows: (a) back squat 1RM test, (b) motion analysis of back squat exercise and (c) maximum isometric strength testing. For sessions 1 and 2, participants performed the high-bar back squat using their preferred technique. A minimum of parallel squat depth, defined as the top of the thigh at the hip was at the same height or below the top of the patella, was required; however,

Table 3. Effects of squat depth on relative muscular effort.*

Relative effort	Barbell load	A. 30°–44°	B. 45°–59°	C. 60°–74°	D. 75°–89°	E. 90°–104°	F. 105°–119°
Ankle plantar flexor	50% 1RM						A; B; C; D; E
	60% 1RM						A
	70% 1RM						
	80% 1RM					A	A; B; C
	90% 1RM						
Knee extensor	50% 1RM		A	A; B	A; B	A; B	A; B; C; D; E
	60% 1RM		A	A; B	A; B	A; B	A; B; C; D; E
	70% 1RM		A	A	A; B	A; B	A; B; C; D; E
	80% 1RM		A	A; B	A; B	A; B	A; B
	90% 1RM		A	A; B	A; B	A; B	A; B
Hip extensor	50% 1RM		A	A; B	A; B	A; B; C; D	A; B; C; D; E
	60% 1RM		A	A; B	A; B	A; B; C	A; B; C; D
	70% 1RM		A	A; B	A; B	A; B	A; B; C; D; E
	80% 1RM		A	A; B	A; B	A; B; C; D	A; B; C; D; E
	90% 1RM		A	A; B	A; B	A; B	A; B

*Squat depth in column has significantly ($p \leq 0.05$) greater relative muscular effort than squat depth indicated by alphabets.

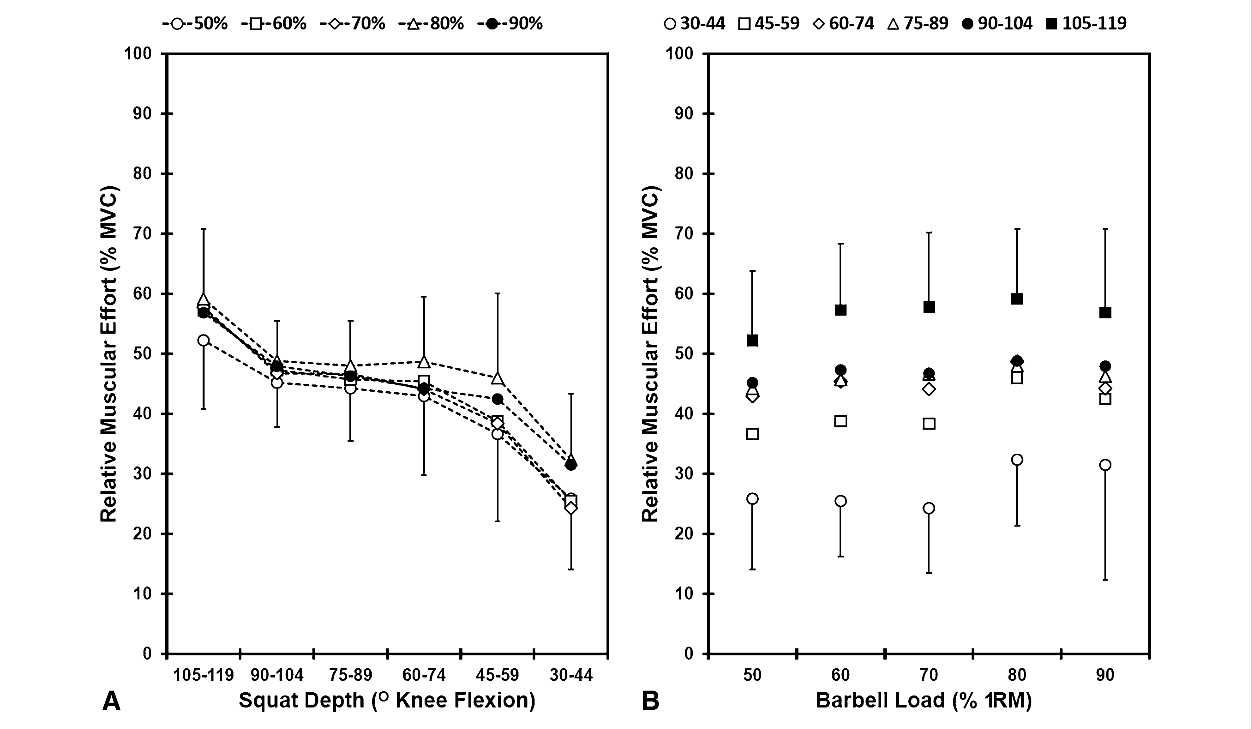

Figure 4. The effects of barbell load at varying squat depths A) and squat depth at varying barbell loads B) on knee extensor relative muscular effort.

participants were instructed to squat to the maximum depth possible (Figure 1). Therefore, each participant performed a full range of motion squat using their normal technique. For 1RM testing, the procedures of Kraemer and Fry (15) were used, where barbell load was increased incrementally until the participants reached a load where failure (i.e., inability to lift the weight) occurred. Thus, 1RM was the heaviest barbell load that was successfully lifted. Loud verbal encouragement was provided during maximum attempts.

Motion Analysis

In the second session, participants performed the back squat with barbell loads of 50, 60, 70, 80, and 90% 1RM, starting with the lightest and progressing to the heaviest. One set of 3 repetitions was performed at each load, and 3 to 5 minutes of rest were allowed between each set of exercise. Sets of exercise started with the lightest barbell load (50% 1RM) and progressed to the heaviest barbell load (90% 1RM), which is consistent with how the exercise may be performed in a resistance exercise session. All trials were performed in a motion analysis laboratory with 9 optoelectronic cameras (ProReflex MCU240; Qualisys, Gothenburg, Sweden) and 2 force platforms (AMTI OR6-6; AMTI, Watertown, MA, USA). Participants performed squats with one foot on each force platform. All data were collected simultaneously using a personal computer with Qualisys Track Manager (version 2.3.510, Qualisys). Optoelectronic camera data were captured at 120 Hz. Force platform data were collected through an analog-to-digital board (USB-1616FS; Measurement Computing, Norton, MA, USA) at 1200 Hz. Retroreflective markers were placed on participants using a 6 degree of freedom model (see Chiu and Salem (4) for details).

Motion analysis data were processed and analyzed in Visual 3D software (version 4.82; C-Motion, Germantown, MD, USA) using standard 3D rigid body linked segment modeling procedures. Segment anthropometric characteristics were based on geometric shapes where segments were modeled as truncated cones. Motion and force platform data were digitally low-pass filtered using a fourth-order recursive Butterworth with a 6 Hz cutoff frequency. Joint angles were defined as the motion of the leg relative to the foot (ankle), thigh relative to the leg (knee), and pelvis relative to the thigh (hip), bilaterally, using a XYZ Cardan sequence. Net joint moment was expressed in the coordinate system of the distal segment (i.e., ankle to foot; knee to leg; hip to thigh). The primary variables of interest were NJM and joint angles at the hip, knee, and ankle in the sagittal plane during the concentric phase of the squat.

Isometric Strength Testing

In the third session, MVC were performed to determine the maximum strength of participant's hip extensors, knee extensors, and ankle plantar flexors. Procedures for strength testing were modified from Anderson et al. (1). Maximum isometric

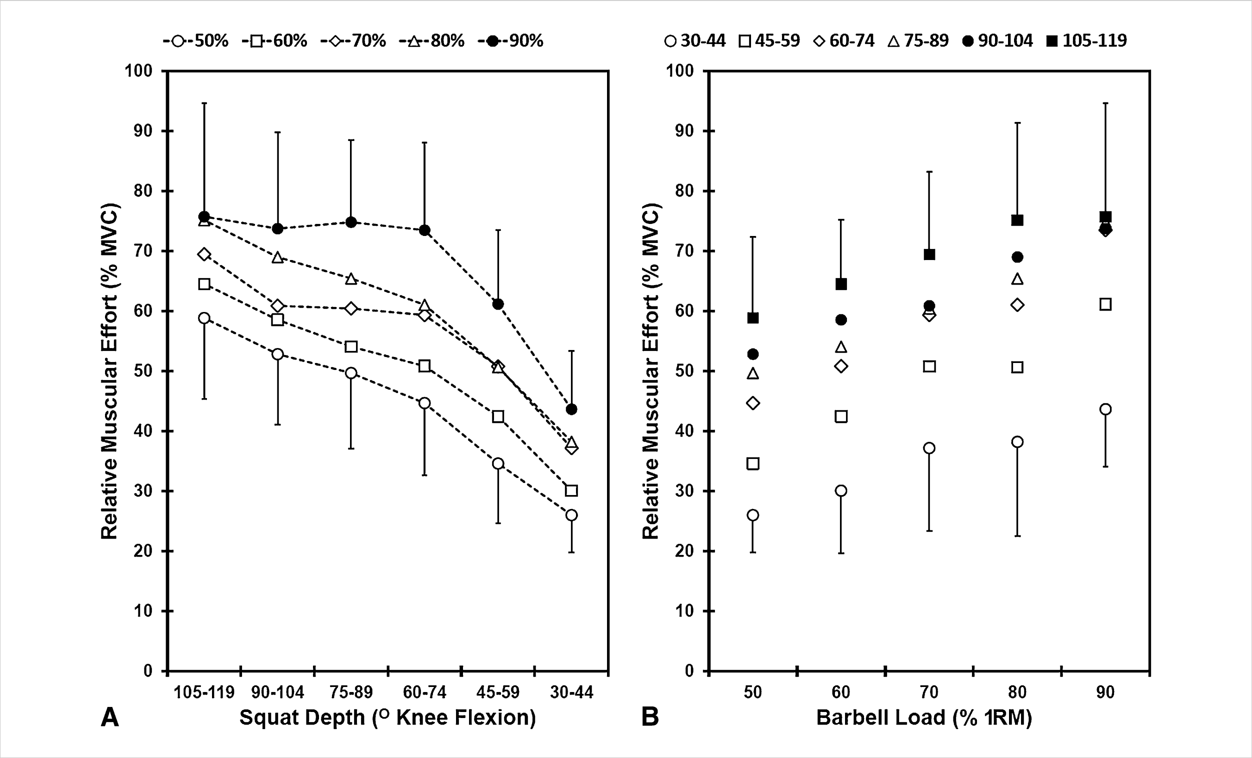

Figure 5. The effects of barbell load at varying squat depths A) and squat depth at varying barbell loads B) on hip extensor relative muscular effort.

contractions were measured at 30°, 60°, and 90° joint angles at the hip and knee (0° equals full extension; positive values are flexion) and 5°, 15°, and 25° joint angles at the ankle (0° equals neutral; positive values are dorsiflexion). All strength testings were performed using a custom-built dynamometer based on the leg extension apparatus described in Schilling et al. (21). The dynamometer consisted of a simple pulley system with a tension-calibrated load cell (MLP-350; Transducer Techniques, Temecula, CA, USA) placed in line with the cable. The load cell was calibrated by hanging objects of known mass and measuring the voltage output. A linear regression was fit to the calibration data to calculate the force from the measured voltage.

A lever arm was attached to the pulley that, in combination with a bench, could be configured for hip extensor, knee extensor, and ankle plantar flexor efforts. Hip extensor testing was performed with the participant lying supine. Knee extensor and ankle plantar flexor testing was performed with the participant sitting upright. Participants performed 2 maximal efforts at each angle for each joint. In each trial, they were instructed to contract as hard as possible for 4 seconds and loud verbal encouragement was provided.

The analog signal from the load cell was channeled through a signal conditioner (TMO-1-2200, Transducer Techniques), digitally converted using a 16-bit analog-to-digital board (PCI-DAS 120/JR; Measurement Computing), and recorded to a personal computer. Data were sampled at 500 Hz using APAS software (Ariel Dynamics, Temecula, CA, USA). Moment was calculated by multiplying force with the radius of the pulley and corrected to account for the inertial characteristics of the lower extremity during the hip extensor testing and of the leg and foot during the knee extensor testing. For this correction, the same segment anthropometric characteristics were used as in the inverse dynamics procedures. Data were digitally low-pass filtered using a fourth-order recursive Butterworth with a 10-Hz cutoff frequency. The maximum moment was determined and only the highest maximum value from the 2 trials at each joint and angle was used for analysis. The relationship between strength and joint angle was determined by plotting maximum moment against joint angle. Data were fit with regression equations to determine the participant-specific relationship between maximum strength and joint angle. All relationships could be fit with a power function or second-order polynomial and matched with the previously reported relationships in the literature.

Statistical Analyses

Relative muscular effect was determined as the ratio of NJM during the squat to the maximum moment from the strength curve matched for joint angle (2). Relative muscular effect was expressed as a percentage (i.e., % MVC). Squat depth was defined as knee flexion angle, and RME was determined in 15° intervals (30°–44°, 45°–59°, 60°–74°, 75°–89°, 90°–104°, and 105°–119°) using software code written in MATLAB (MathWorks, Natick, MA, USA). The minimum depth reached by all participants was 119°; however, some participants squatted to greater knee flexion angles. Data for knee angles greater than 119° were not analyzed because not all participants squatted below this depth. Data from 0° to 30° knee angles were not analyzed because knee and hip flexor moments were present during these squat depths and were not of interest for this investigation.

To assess the effects of barbell load (50, 60, 70, 80, 90% 1RM) and squat depth (30°–44°, 45°–59°, 60°–74°, 75°–89°, 90°–104°, and 105°–119° knee angles) on RME, 5 × 6 (load by depth) analyses of variance (ANOVAs) were used. Individual ANOVAs were performed for the hip extensors, knee extensors, and ankle plantar flexors. Tukey's Honestly Significant Difference (HSD) was used for subsequent post hoc comparisons of load and depth where ANOVAs were significant. Alpha was set a priori at 0.05.

RESULTS

Hip extensor, knee extensor, and ankle plantar flexor RME for a representative participant squatting a barbell load of 90% 1RM are presented in Figure 2. Note that this participant squatted below 119°; however, because not all participants squatted to this knee flexion angle, data beyond 119° were not statistically analyzed. ANOVA revealed significant interactions between barbell load and squat depth ($p < 0.01$) on hip extensor, knee extensor, and ankle plantar flexor RME.

Ankle Plantar Flexor Relative Muscular Effect

The effects of barbell load and squat depth on ankle plantar flexor RME are plotted in Figures 3A,B, respectively, and significant differences are shown in Tables 2 and 3, respectively. In general, barbell load had a greater effect on ankle plantar flexor RME than squat depth. However, the effect of barbell load was not consistent for all squat depths. The 90% 1RM condition had the highest ankle plantar flexor RME, and this high RME was observed at all squat depths. At shallow squat depths (30°–74°), ankle plantar flexor RME was lowest for 50% 1RM and not different from 60% 1RM, 70% 1RM, and 80% 1RM. At deeper squat depths (75°–119°), ankle plantar flexor RME was lower for 50% 1RM, 60% 1RM, and 70% 1RM than 80% 1RM and 90% 1RM.

Knee Extensor Relative Muscular Effect

The effects of barbell load and squat depth on knee extensor RME are plotted in Figures 4A,B, respectively, and significant differences are shown in Tables 2 and 3, respectively. In contrast to the ankle, barbell load had minimal effects on knee extensor RME, whereas squat depth had greater effects. In general, knee extensor RME was lowest at 30° to 44° and greatest at 105° to 119°. Knee extensor RME was not significantly different at intermediate squat depths (60°–74° to 90°–104°).

Hip Extensor Relative Muscular Effect

The effects of barbell load and squat depth on hip extensor RME are plotted in Figures 5A,B, respectively, and significant differences are shown in Tables 2 and 3, respectively. Both barbell load and squat depth had significant effects on hip extensor RME. In general, because barbell load increased, hip extensor RME also increased. Similarly, RME was greater at the largest squat depth and least at the shallowest squat depth.

DISCUSSION

This study examined the RME of the hip extensors, knee extensors, and ankle plantar flexors throughout a typical range of barbell loads and squat depths during the squatting exercise. In resistance exercise, muscular strength and hypertrophy adaptations are stimulated by imposing tension on active muscles (7). As a function of the size principle, large tensions, approximately 80% MVC or higher, are required to recruit, and therefore train, all high-threshold motor units (17). We determined how barbell load and squat depth affected RME, which is an estimate of muscle tension in relation to maximum muscle force. The key findings show that barbell load has a more pronounced effect than squat depth on ankle plantar flexor RME, whereas the opposite is observed for the knee extensors. Hip extensor RME is influenced by both barbell load and squat depth. Previous investigations of lower-extremity NJM in squatting have reported similar findings, notably that knee extensor NJM increases with squat depth (23) and hip extensor and ankle plantar flexor NJM increase with barbell load (6). These findings are important for using the squat exercise in practice because load and range of motion will have different influences on the mechanical effort of the hip extensors, knee extensors, and ankle plantar flexors. Specifically, to maximize the mechanical effort required of the knee extensors, greater squat depths are required, whereas ankle plantar flexor effort is increased by increasing the barbell load.

Although squat depth did influence the hip and knee extensor RME, this influence was not linear. The largest and smallest hip and knee extensor RMEs were found in the deepest (105°–119°) and shallowest (30°–44°) portions, respectively. However, RME was constant in the mid-range (60°–74° to 90°–104°). Wretenberg et al. (23) similarly reported knee extensor NJM to be greater in full vs. parallel squats. Furthermore, in the sit-to-stand task, which requires the same muscle and joint actions as the concentric phase of the squat, lowering chair height increases knee extensor RME (12). Thus, the effect of depth on knee extensor RME seems to be uniform for squat-type movements, regardless of whether they are performed for exercise or as an activity of daily living, and across different populations.

In concert with previous research (12,23), our findings relating to squat depth may be applied to the debate over how deep an individual should squat in training. Many sources in the exercise literature suggest that squats be performed to a “parallel” depth, which is approximately 105° of knee flexion (5). From our findings, it would seem that squatting to an end point between 59° and 104° may limit recruitment of the hip and knee extensors compared with squatting below 105°. Thus, if the goal is to maximize mechanical loading and, therefore, activation of the hip and knee extensors, squat depths greater than 105° are required. Moreover, given that increasing barbell load from 50% to 90% 1RM has virtually no effect on knee extensor RME, this strategy would be ineffective for training the knee extensors. Thus, partial depth and parallel squats with greater loads will preferentially stress the hip extensors and ankle plantar flexors over the knee extensors.

The effect of squat depth on knee extensor RME is particularly important to determine how the exercise is best used in practice. A recent investigation compared the effects of deep vs. partial squat exercise on vertical jump height. Training with deep squats improved countermovement and squat vertical jump performance, whereas partial squat exercise did not (10). Computer modeling studies have found that increasing the strength of the knee extensors have a greater effect on improving vertical jump height than increasing the strength of the hip extensors or ankle plantar flexors (3,18). Because our results find that knee extensor RME was largest at the deep squat depth, it may be theorized that performing deep squats is more effective than partial squats for strengthening the knee extensors, which is why deep squats improved jump height (10). Although it is commonly recommended that squats be performed to a parallel depth (5), this recommendation may preclude a strengthening effect on the knee extensors. Taken together, performing squats beyond 105° knee flexion seems to be necessary to optimally train the knee extensors.

Although our data provide insight into the mechanics of the hip, knee, and ankle with increasing depth and barbell load during the squat exercise, they also raise a question requiring further investigation. The greatest RME for each joint generally occurred at the deepest squat depth analyzed and with the heaviest barbell load. However, these RMEs are less than would be expected for exercise performed at 90% 1RM. At 90% 1RM, the ankle plantar flexors reached 71% MVC, the knee extensors 57% MVC, and the hip extensors 76% MVC. These values cast doubt as to whether the ability to squat maximum loads (i.e., 100% 1RM) is limited by the strength of the lower-extremity muscles. A possible explanation for the submaximal RME observed, particularly for the knee extensors, is provided by a limitation of inverse dynamics, the process used to calculate NJM. Net joint moment represents the forces generated by all muscles acting on a segment, which includes agonist and antagonist muscles (20). Therefore, NJM represents the *minimum* torque required. The *actual* torque and subsequently RME required will increase with increasing antagonist co-contraction (8,20).

The hamstrings have been reported to be active in the concentric phase of loaded squatting tasks (9,25). Co-contraction of the quadriceps and hamstrings would seem to be counterproductive because the hamstrings exert a flexor torque at the knee. However, this co-contraction may be beneficial in the squat as it is a multi-joint task. As the knee extends, the force acting on the co-contracting hamstrings is transferred to the hip, assisting with the hip extension. The hamstrings have a smaller lever arm at the knee than at the hip, and therefore, for the same force in the muscle, the flexor torque at the knee is less than the extensor moment at the hip (19,24). Waters et al. (22) have also reported that the hamstrings contribute 45 to 55% of the maximum torque generated by the hip extensors. Therefore, if the hip extensor RME exceeds 45 to 55% MVC, as was observed in this investigation, it would not be possible to generate hip extensor torque without activating the hamstrings. As the hamstrings co-contract with the quadriceps, the knee extensor NJM will underestimate the torque generated by the quadriceps. Thus, quadriceps RME should be higher than the knee extensor RME during loaded squats (20).

In summary, this investigation reports on the effect of squat depth and barbell load on hip extensor, knee extensor, and ankle plantar flexor RME in the back squat exercise. Barbell load had a greater effect on ankle plantar flexor RME, whereas squat depth influenced the knee extensor RME. The unique effects of squat depth and barbell load on hip extensor, knee extensor, and ankle plantar flexor RME illustrate the importance of each factor in squatting exercise. To maximize loading of the knee extensors to enhance performance, squat depths greater than 105° knee flexion are required. To accurately estimate RME, antagonist co-contraction needs to be accounted for. We hypothesize that quadriceps RME is greatly underestimated during squatting as a result of hamstring co-contraction. Future investigation accounting for hamstring co-contraction will be important to determine the true quadriceps RME. Nevertheless, because barbell load and squat depth have nonuniform effects on lower-extremity RME, these factors should be considered in the design of resistance exercise programs to preferentially stress muscle groups in accordance with specific training objectives.

PRACTICAL APPLICATIONS

Squatting exercise is commonly used in resistance training programs to strengthen the hip extensors, knee extensors, and ankle plantar flexors. This research finds that the RME of each muscle group is dependent on both squat depth and barbell load. Large muscular tensions in relation to the strength of the muscle, which RME is an indicator of, are required to elicit muscle strength and hypertrophy adaptations. Therefore, squat depth and barbell load should be considered as variables when using squatting exercise depending on which muscle groups are important to train. Across a range of populations, including athletes, individuals with lower-extremity injuries, and elderly individuals, strong knee extensors are important for performance (11,13,16,18).

Therefore, because knee extensor RME is highest at deep squat depths, squatting exercise should be performed to deep squat depths to strengthen the knee extensors. Furthermore, because increasing barbell load has little effect on knee extensor RME, strengthening of the knee extensors with deep squats can be performed with relatively light barbell loads. Heavier barbell loads are warranted for strengthening the hip extensors and ankle plantar flexors.

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