Gluteal Muscle Forces during Hip-Focused Injury Prevention and Rehabilitation Exercises

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ABSTRACT

COLLINGS, T. J., M. N. BOURNE, R. S. BARRETT, E. MEINDERS, B. A. M. GONÇALVES, A. J. SHIELD, and L. E. DIAMOND. Gluteal Muscle Forces during Hip-Focused Injury Prevention and Rehabilitation Exercises. *Med. Sci. Sports Exerc.*, Vol. 55, No. 4, pp. 650–660, 2023. **Purpose:** This study aimed to compare and rank gluteal muscle forces in eight hip-focused exercises performed with and without external resistance and describe the underlying fiber lengths, velocities, and muscle activations. **Methods:** Motion capture, ground reaction forces, and electromyography (EMG) were used as input to an EMG-informed neuromusculoskeletal model to estimate gluteus maximus, medius, and minimus muscle forces. Participants were 14 female footballers (18–32 yr old) with at least 3 months of lower limb strength training experience. Each participant performed eight hip-focused exercises (single-leg squat, split squat, single-leg Romanian deadlift [RDL], single-leg hip thrust, banded side step, hip hike, side plank, and side-lying leg raise) with and without 12 repetition maximum (RM) resistance. For each muscle, exercises were ranked by peak muscle force, and k-means clustering separated exercises into four tiers. **Results:** The tier 1 exercises for gluteus maximus were loaded split squat (95% confidence interval [CI] = 495–688 N), loaded single-leg RDL (95% CI = 500–655 N), and loaded single-leg hip thrust (95% CI = 505–640 N). The tier 1 exercises for gluteus medius were body weight side plank (95% CI = 338–483 N), loaded single-leg squat (95% CI = 278–422 N), and loaded single-leg RDL (95% CI = 283–405 N). The tier 1 exercises for gluteus minimus were loaded single-leg RDL (95% CI = 267–389 N) and body weight side plank (95% CI = 272–382 N). Peak gluteal muscle forces increased by 28–150 N when exercises were performed with 12RM external resistance compared with body weight only. Peak muscle force coincided with maximum fiber length for most exercises. **Conclusions:** Gluteal muscle forces were exercise specific, and peak muscle forces increased by varying amounts when adding a 12RM external resistance. These findings may inform exercise selection by facilitating the targeting of individual gluteal muscles and optimization of mechanical loads to match performance, injury prevention, or rehabilitation training goals.

Key Words: EXERCISE SELECTION, MUSCULOSKELETAL MODELING, MECHANICAL TENSION, MUSCLE STRENGTH AND HYPERTROPHY

The gluteal muscles are among the largest and strongest muscles crossing the hip joint. Gluteus maximus primarily produces a hip extension moment (1), and gluteus medius and minimus primarily generate hip abduction and internal/external hip rotation depending on the hip flexion angle (2). Together, the gluteal muscles are critical for human movement, providing support and producing propulsion during locomotion (3), stabilizing the hip joint (4), and controlling the orientation of the pelvis during single-leg stance (5). Gluteal muscle weakness is associated with a number of hip and knee pathologies, such as femoroacetabular impingement syndrome (6), hip osteoarthritis (7), patellofemoral pain (8), and risk of anterior cruciate ligament injury (9). Increasing gluteal muscle strength is often a successful treatment for reducing knee pain (10), improving self-reported physical function (11), and is critical for the development of running speed and power (3).

Resistance training is an effective method for increasing strength and promoting muscle hypertrophy (12). Applying mechanical tension to a muscle is one of the most important stimuli for promoting neuromuscular adaptations (13). For example, frequently exposing muscles to mechanical tension can result in radial and longitudinal growth of muscle fascicles,

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changes in fiber pennation angle, fiber type, muscle/tendon stiffness, motor unit behavior, and agonist versus antagonist muscle activation (14,15). For some muscle adaptations to occur, adequate mechanical tension is required, and the intensity of the stimulus may relate to the magnitude of the tissue's response (14). Previous studies have shown that, training that produces greater muscle loading, such as performing exercises with greater external resistance or at long muscle lengths, results in greater maximal strength gains (16) and hypertrophy (17), respectively. External resistance is generally added to increase mechanical loading of a muscle group, although this is not always possible in field-based or clinical environments. Despite many structured training programs prescribing specific external resistance (e.g., %RM), it is unknown how much individual muscles are loaded. An improved understanding of muscle loading in common exercises, performed with and without external resistance, may help guide exercise selection choices and improve targeted injury risk reduction training and rehabilitation programs.

Given the difficulties of measuring muscle forces *in vivo*, many studies have investigated the contribution of the gluteal muscles to resistance exercises using surface electromyography (EMG) (18,19). Based on recent meta-analyses, high levels of muscle excitation can be achieved with step-up exercises for the gluteus maximus (18) and hip hike for gluteus medius and minimus (19). There are several considerations when using EMG amplitude alone as a basis for exercise selection. Interpretation of amplitude is highly dependent on the normalization tasks and methods (20), and the signal is susceptible to cross-talk (21) and movement artifacts. Further, EMG is not an accurate proxy for muscle force because of the force–length and force–velocity relationships (22), and there is no evidence to support EMG amplitude as a predictor for longitudinal muscle adaptation (23). Alternatively, neuromusculoskeletal modeling may be used to estimate individual muscle forces, where the relationships between muscle force, fiber length, fiber velocity, and muscle activation are accounted for using a Hill-type muscle model (24). Compared with simplified methods of determining muscle forces, such as static optimization, that are based on assumptions regarding muscle recruitment, EMG-informed methods consider individual muscle activation strategies. As such, incorporating an individual's EMG signals into a model with more personalized musculotendon parameters has been shown to estimate hip and knee joint contact forces comparable with data from instrumented implants (25,26). Therefore, neuromusculoskeletal modeling may overcome some of the limitations of analyzing exercises with EMG alone. A further benefit of neuromusculoskeletal modeling is the ability to better understand the mechanical behavior of individual muscles during different exercises, such as the muscle fiber lengths, fiber velocities, and muscle activations. Such findings can contribute to informing exercise selection for individual muscles of interest, rather than entire muscle groups, which may be comprised of many smaller muscles with varying contributions to movement, that may differ significantly between exercises.

This study aims to 1) compare and rank gluteal muscle forces (gluteus maximus, medius, and minimus) in eight hip-focused exercises, 2) determine the effect of adding 12RM resistances on gluteal muscle forces, and 3) describe the main differences in muscle fiber lengths, velocities, and activations between hip-focused exercises.

METHOD

Participants. Participants were 14 female footballers (Table 1), recruited from local soccer, Australian Rules Football, rugby league, or rugby union teams. To be included in the study, participants were required 1) to have played competitive football in the last 2 yr, 2) to have no current lower limb injuries, 3) to have no history of lower limb surgery, 4) to have no lower limb time-loss injuries in the previous 12 months, 5) to be 18 and 35 yr old, and 6) to have a minimum of 3 months lower body strength training experience. An *a priori* power analysis was performed using the *pwr* package in R based on the smallest expected effect size ($d = 1.13$) observed for peak gluteus maximus muscle forces between good morning and deadlift exercises in a previous study (27). A minimum of 14 participants were required to achieve 80% power at an $\alpha = 0.05$ for a dependent t test comparison of group means. Participants were compensated with an AUD50 gift card for their time. This study was approved by the University Human Ethics Research Committee (ethics number 2021/082), and all participants provided written informed consent before data collection.

Study design. This study was a within-participant cross-sectional comparison of eight hip-focused exercises performed with and without external resistance (i.e., dumbbells or loaded barbell). Exercises were performed with body weight only as this is applicable to settings where equipment may not be available (e.g., at home or in the field) or loaded as this is more relevant for a gym setting and enables exercises to be compared at a relative intensity (e.g., % of repetition maximum). Participants attended two sessions on two separate days approximately 1–2 wk apart (median = 12 d, interquartile range = 7 d): 1) exercise familiarization and strength testing session (1.5 h) and 2) biomechanical data collection (2.5 h).

Hip-focused exercises. Exercises included a single-leg squat, split squat, single-leg Romanian deadlift (RDL), single-leg hip thrust, banded side step, hip hike, side plank, and side-lying leg raise (Fig. 1; see Table, Supplemental Digital Content 1, for descriptions of exercise technique, http://links.lww.com/MSS/C750). Exercises were selected based on those commonly used in injury prevention and rehabilitation programs (28) and/or reported to generate high levels of gluteal muscle activation (19).

TABLE 1. Participant characteristics, strength training experience, and health status ($n = 14$).

	Median	IQR	Range
Age (yr)	24.1	6.5	18.4–31.6
Weight (kg)	62.6	9.3	55.9–84.3
Height (cm)	169	8	162–181
Total strength training experience (yr)	6.0	3.5	0.8–15.0
Strength training in previous year (months)	11.5	4.8	3.0–12.0
Strength training per week (times per week)	2	1	1–4
SF-12 physical health (Z score)[a]	55.6	4.0	43.8–59.7
SF-12 mental health (Z score)[a]	56.9	3.1	43.4–58.7

[a] The 12-item Short Form Survey (SF-12) scores relative to U.S. population, where 50 indicates the average person and 10-U change equates to 1 SD.

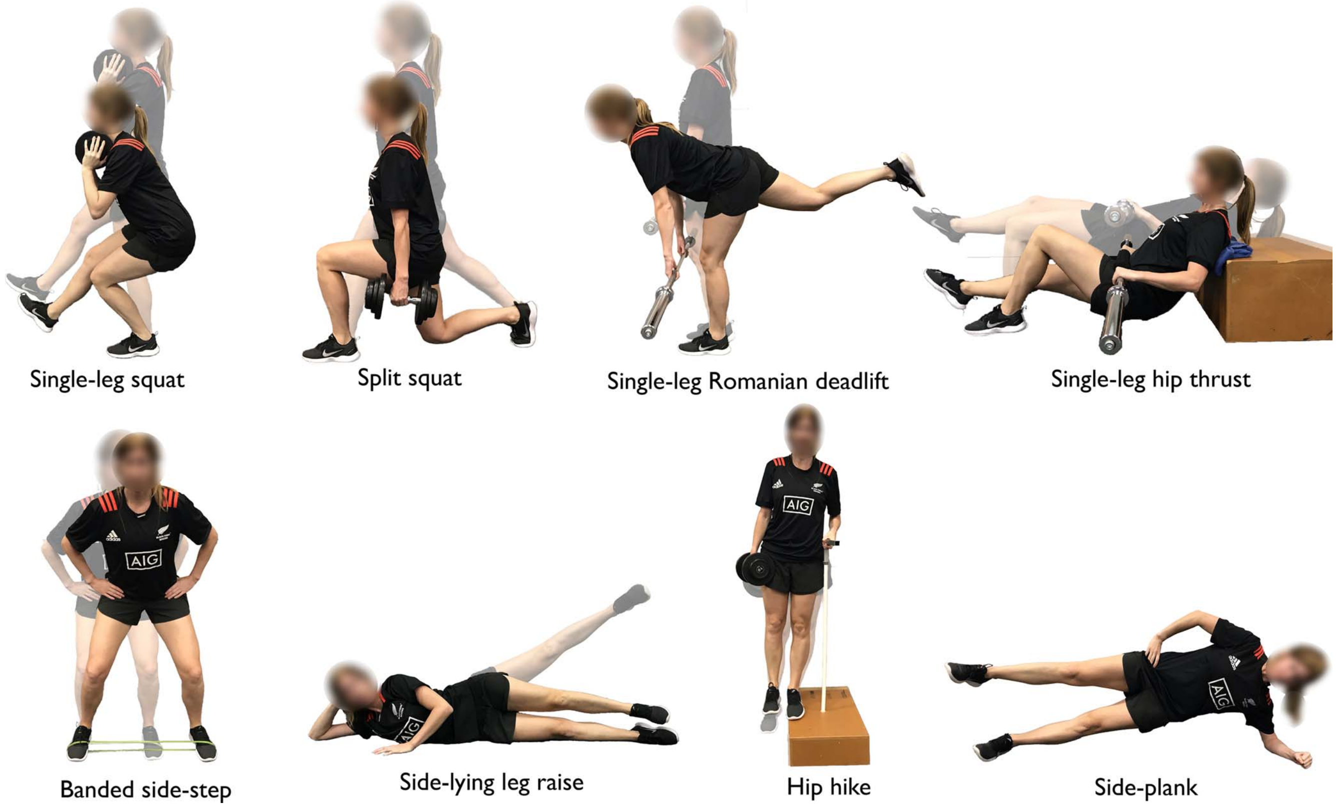

FIGURE 1—Demonstration of the eight hip-focused exercises assessed. The start and end positions of the concentric phase are shown (see Table, Supplemental Digital Content 1, http://links.lww.com/MSS/C750, for descriptions of exercise technique).

Exercise familiarization and strength testing. During the exercise familiarization and strength testing session, participants were given a demonstration and opportunity to practice each exercise while a researcher provided verbal feedback. All exercises were performed on a self-selected leg nominated by the participant based on comfort performing a single-leg squat. Participants underwent a 12-repetition maximum (12RM) ramp testing protocol to determine a relative intensity load for each exercise. For each participant, an initial resistance was selected that was close to their 12RM (estimated by the researcher and participant). The participant then attempted to perform 12 repetitions. If successful, the resistance was increased by approximately 1.25–2.5 kg increments for dumbbell and barbell exercises and repeated after 1–2 min rest. The final resistance was determined when 12 repetitions could not be performed or strict technique could not be maintained. A 12RM intensity was selected because it is a moderate intensity, based on a typical training repetition range used in injury prevention and rehabilitation programs, and for many of the exercises was more practical to conduct than a lower number of repetitions (i.e., 1RM or 5RM). Participants also completed a questionnaires on injury history, sport history, gym experience, and the 12-item Short Form Survey assessing physical and mental health (29).

Biomechanical data collection. Participants were equipped with a full-body marker set consisting of 55 retroreflective markers, including *T*-shaped marker clusters on the shanks, thighs, pelvis, and upper arms (see figure, Supplemental Digital Content 2, for location of markers, http://links.lww.com/MSS/C751). Marker coordinates were recorded using a three-dimensional 12-camera motion capture system (Vicon Nexus, Oxford, UK) at 200 Hz. Ground reaction forces were obtained from one to two force plates embedded in the laboratory floor (AMTI BMS600900, Advanced Mechanical Technology, USA) at 2000 Hz. Muscle excitations were recorded using surface EMG (Atkos classic, Myon AG, Schwarzenberg, Switzerland) from the following 12 muscles: anterior gluteus medius, upper gluteus maximus, tensor fascia latae, rectus femoris, vastus lateralis, vastus medialis, semitendinosus, biceps femoris long head, tibialis anterior, gastrocnemius medial, gastrocnemius lateral, and soleus. Bipolar electrodes were placed following the Surface EMG for the Non-Invasive Assessment of Muscles project guidelines (30).

After performing a 5-min standardized dynamic warm-up, participants performed seven maximal voluntary isometric contraction tasks to elicit maximal muscle activation of each recorded muscle for use in signal normalization. Tests included seated knee extension (70° knee flexion), prone knee flexion (30° knee flexion) (31), supine dorsiflexion (32), prone plantar flexion (33), seated plantar flexion, supine straight-leg hip abduction (34), and standing glute squeeze. Two repetitions of 4-s contractions were performed for each test while strong verbal encouragement was provided.

Hip-focused exercises were performed in a randomized order, beginning with two sets of five body weight only repetitions, followed by two sets of five loaded repetitions with participant-specific 12RM external resistance. All exercises were performed on the participant's preferred single-leg squat leg with an approximate hip joint angular velocity of $30°\cdot s^{-1}$. This speed was selected as a controlled speed that suited both large (e.g., RDL) and small (e.g., hip hike) range of motion exercises during pilot testing. To control movement speed, a metronome was used to indicate the start, middle, and end of each repetition, with tempos ranging from 26 to 60 bpm depending on the exercise hip range of motion. Participants were given a minimum of 30–60 s rest between sets.

Neuromusculoskeletal modeling. Biomechanical data were processed in MATLAB R2018a (MathWorks, Natick, MA) using the Motion Data Elaboration Toolbox for Neuromusculoskeletal apps (MOtoNMS, version 2.2) (35). Marker coordinates and ground reaction forces were filtered using a low-pass, second-order, zero-lag Butterworth filter at 6 Hz. Muscle EMG signals were filtered using a band-pass, second-order, zero-lag Butterworth filter between 30 and 300 Hz, full-wave rectified, and filtered again using a low-pass second-order Butterworth filter at 6 Hz to form a linear envelope. Linear envelopes were normalized to the maximum amplitude acquired during either a maximal voluntary isometric contraction or a selection of loaded exercises. This approach was necessary because muscle EMG signals during dynamic tasks often exceed those measured under isometric or isokinetic conditions (20).

Neuromusculoskeletal modeling was performed in OpenSim version 3.3 (36), using a generic full-body model (37) with 40 Hill-type musculotendon units per leg, and modified wrapping surfaces to allow deep knee (up to 145°) and hip (up to 138°) flexion (38). For each participant, a musculoskeletal model was linearly scaled to segment lengths determined from markers attached to the skin surface during a static standing trial. Following model scaling, muscle optimal fiber lengths and tendon slack lengths of each musculotendon unit were adjusted to preserve the angle of maximum force defined by the unscaled model (39). Muscle volumes, and thus maximum isometric strength, of each musculotendon unit were scaled based on participant height and weight using previously published regression equations (40) using a specific muscle tension of $57.3\ N\cdot cm^{-2}$ for adult females (41). Maximum contraction velocity was set to $10\ m\cdot s^{-1}$ (42). Joint angles, internal joint moments, and musculotendon kinematics were calculated in OpenSim using inverse kinematics, inverse dynamic, and muscle analysis tools, respectively. Inverse dynamics were calculated using all external forces acting on the analyzed leg (i.e., ankle to hip). Models were not made dynamically consistent by measuring torso and upper body external forces (if present) or running a residual reduction algorithm.

For the banded side-step exercise, the force produced by the resistance band was determined before testing by using a load cell and developing a regression equation to predict force based on band length (see document, Supplemental Digital Content 2, for protocol, http://links.lww.com/MSS/C751). No change in band properties was evident between testing of the first and last participant. The predicted force produced by the resistance band was applied to the foot near the distal end of the fifth metatarsal, which was indicated by a marker on both ends of the band, that also defined the orientation of the force vector. For the side-lying leg raise, the external resistance was modeled by applying an additional downwards force ($F_{\text{weight}} = -9.81 \times \text{kg}_{\text{weight}}$) to the tibia superior to the ankle malleoli at a point 20% of tibia length. For the hip hike, a rigid wooden box was placed on the force plate, and ground reaction forces and center of pressure were translated upward to the foot by a distance equal to the box height.

Muscle forces were determined using an EMG-assisted approach using the Calibrated EMG-Informed Neuromusculoskeletal Modelling Toolbox (43) via two steps: 1) model calibration and 2) model execution. During model calibration participants' musculotendon parameters were personalized by minimizing an objective function during one repetition of each exercise with and without external resistance (14 trials in total) (43,44). The objective function sought to minimize error between predicted and measured joint moments, with a penalty for normalized fiber lengths less than 0.6 or greater than 1.4. See Table, Supplemental Digital Content 3, for a summary of the resulting muscle model parameters (http://links.lww.com/MSS/C752). For execution, calibrated models were used to determine muscle forces for the remaining trials by solving the following objective function:

$$F_{\text{objective}} = \alpha E_{\text{TrackMoment}} + \beta E_{\text{SumExcitations}} + \gamma E_{\text{TrackExcitations}}, \quad [1]$$

where TrackMoment and TrackExcitation are the sum of the squared difference between model-predicted and experimentally measured joint moments and muscle excitations, respectively; SumExcitations is the sum of squared model excitations for all muscles; and α, β, and γ are weighting factors. Weighting factors were determined by setting α and β to 1, and varying γ between 1 and 1,000, to determine the optimal parameters for each participant and each exercise that minimized the normalized RMSE between model-predicted and measured knee and hip joint torques (45).

Model verification. To verify the accuracy of the neuromusculoskeletal model muscle force solutions, model-predicted joint moments and muscle excitations were compared with joint moments calculated from inverse dynamics and surface EMG, respectively (see Figure, Supplemental Digital Content 4, for tracking error, http://links.lww.com/MSS/C753). The joint moments and muscle excitations predicted by the neuromusculoskeletal model showed good agreement with joint moments from inverse dynamics (median RMSE <2.4–3.5 N·m, median $R^2 > 0.93$–0.99) and measured EMG signals (median RMSE <2.6%–16%, median $R^2 > 0.34$–1.00).

Data analysis. Analysis of muscle forces was limited to gluteus maximus, medius, and minimus. Each gluteal muscle force was determined by taking the average force of the three muscle segments included in the model (e.g., glmax1, glmax2, and glmax3). Muscle force time series data were normalized to each muscle's maximum isometric force to allow comparison between muscles of different size. Muscle force data were also time normalized to one repetition, defined from minimum to maximum hip flexion/extension or abduction/adduction angles, depending on the predominant plane of movement. Peak muscle forces were extracted from each repetition and presented in absolute force (N) and percentage of maximum peak muscle force observed for any exercise (% of observed maximum) for each muscle including both body weight and loaded conditions. Muscle fiber lengths were normalized to optimal fiber length. Fiber velocities were normalized to optimal fiber length multiplied by maximum contraction velocity.

Statistical analysis. Data and statistical analyses were performed in R Studio (version 4.0.5, Boston, MA). Gluteal muscle forces for each exercise were expressed over time using ensemble averages ±1 SE. Exercises were ranked from highest to lowest based on mean peak muscle force with 95% confidence intervals (CI) and classified into one of four tiers using *k*-means clustering. Four tiers were selected as a sensible number that did a good job of partitioning exercises with similar peak muscle force in to groups. The effect of external resistance on peak gluteal muscle force was expressed using mean differences and corresponding 95% CI between loaded and body weight exercise conditions. Muscle fiber lengths, velocities, and activations are presented for each exercise and muscle using descriptive statistics, including minimum, maximum, and value at peak muscle force.

RESULTS

External resistance for 12 RM loads. For loaded exercises, the mean ± 1 SD 12RM external resistance was 18.0 ± 2.0 kg for hip hike, 4.6 ± 1.1 kg for side-lying leg raise, 8.2 ± 6.0 kg for single-leg hip thrust, 19.3 ± 6.1 kg for single-leg RDL, 13.6 ± 3.3 kg for single-leg squat, and 30.0 ± 6.2 kg for split squat. For the banded side step, 12 of 14 participants used a moderate stiffness band, and 2 of 14 participants used a high stiffness band.

Gluteal muscle force rank and tiers. Gluteal muscle force magnitude and patterns were exercise and muscle specific (Fig. 2). The exercises with the highest peak gluteus maximus muscle force (tier 1) were loaded split squat (95% CI = 495–688 N), loaded single-leg RDL (95% CI = 500–655 N), and loaded single-leg hip thrust (95% CI = 505–640 N) (Fig. 3). The exercises with the highest peak gluteus medius muscle force (tier 1) were body weight side plank (95% CI = 338–483 N), loaded single-leg squat (95% CI = 278–422 N), and loaded single-leg RDL (95% CI = 283–405 N) (Fig. 3). The exercises with the highest peak gluteus minimus muscle force (tier 1) were single-leg RDL (95% CI = 267–389 N) and body weight side plank (95% CI = 272–382 N) (Fig. 3).

Effect of external 12 RM load on gluteal muscle forces. Peak gluteal muscle forces significantly increased for all exercises performed with 12RM external resistance compared with body weight only (Fig. 4). The mean increase in muscle force ranged from 48 N (side-lying leg raise, 95% CI = 3–98 N) to 150 N (single-leg squat, 95% CI = 118–182 N) for gluteus maximus, 62 N (single-leg hip thrust, 95% CI = 42–82 N) to 121 N (hip hike, 95% CI = 98–144 N) for gluteus medius, and 28 N (split squat, 95% CI = 6–49 N) to 88 N (hip hike, 95% CI = 49–126 N) for gluteus minimus (Fig. 4).

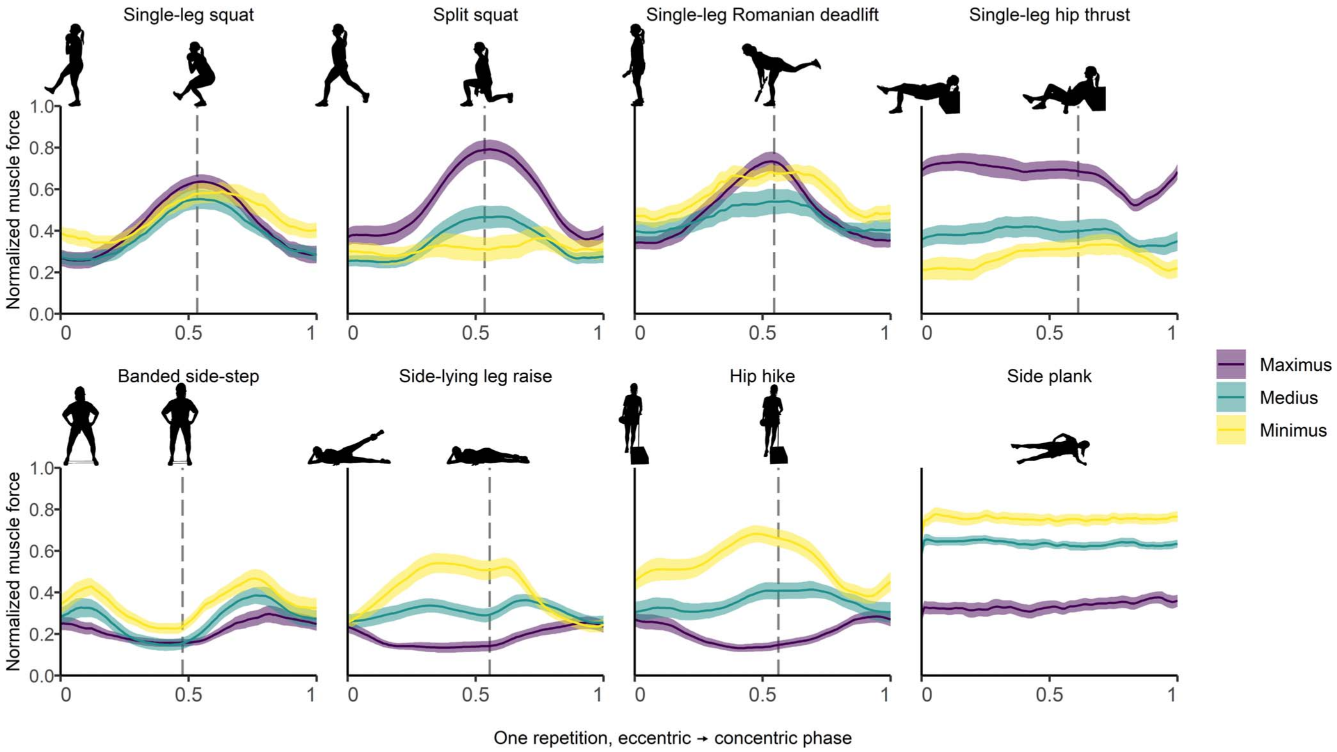

FIGURE 2—Normalized gluteal muscle forces during 12RM-loaded exercises time normalized to one repetition (0 to 1). *Lines* indicate mean muscle force across participants (n = 14), *shaded area* indicates ±1 SE, and the *vertical dashed line* indicates transition from the eccentric to concentric phase defined by hip joint angle (note: transition offset from 0.5 indicates faster or slower concentric vs eccentric phase).

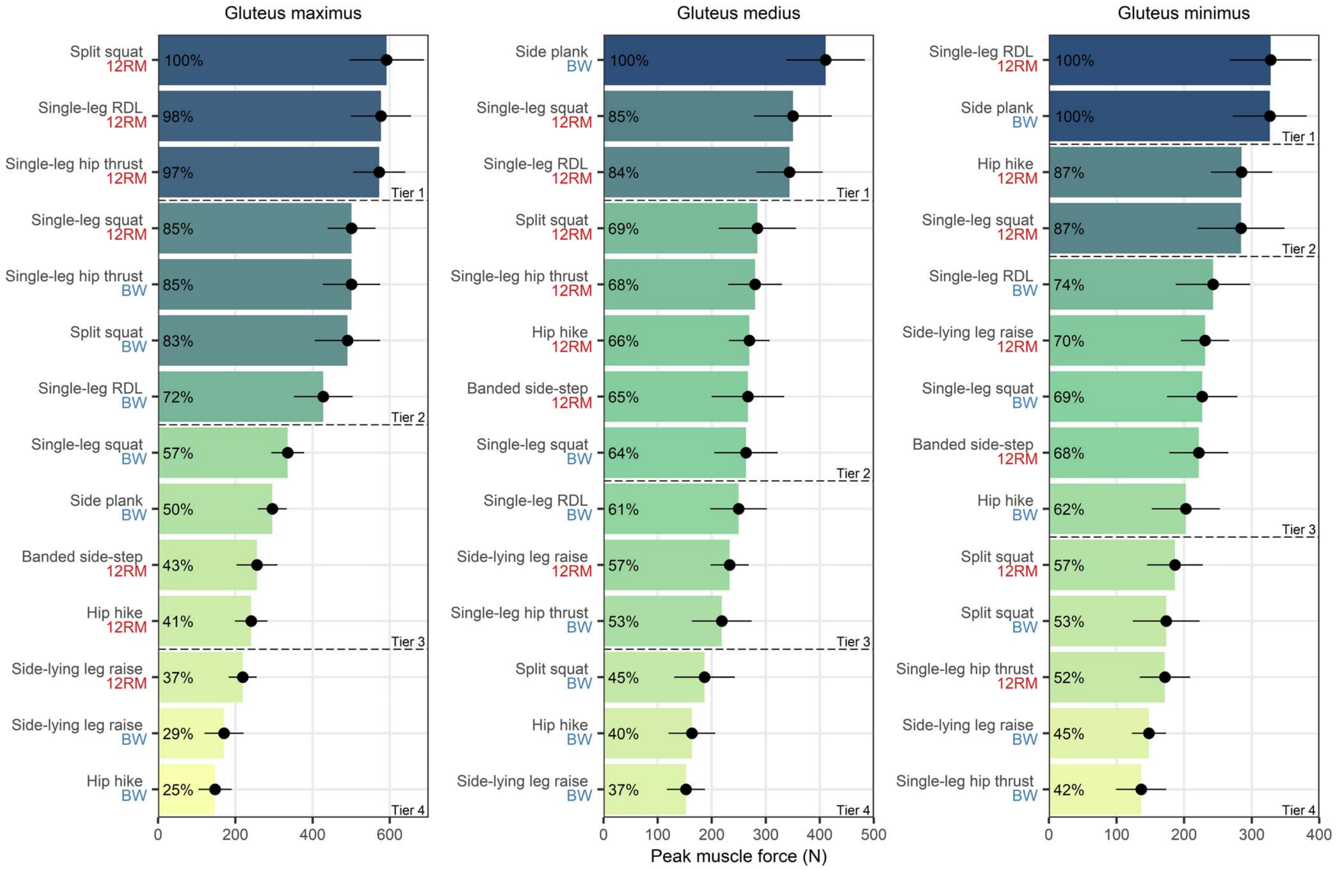

FIGURE 3—Peak gluteal muscle forces during exercises performed with body weight only (BW) and loaded at 12RM ranked from highest to lowest. *Dashed line* indicates four tiers determined using *k*-means clustering. *Bars/points* indicate mean peak muscle force across participants (n = 14), and *lines* indicate the 95% CI. Percentages on each bar represent peak muscle force as a percentage of the maximum peak muscle force observed for each muscle.

Gluteal muscle activations, fiber lengths, and fiber velocities. Exercises that reached long fiber lengths and, as such, had substantial contributions from passive force (>1.2 optimal fiber lengths) included the split squat (maximus = 1.39, medius = 1.26), single-leg RDL (maximus = 1.35, medius = 1.21), single-leg hip thrust (maximus = 1.32), single-leg squat

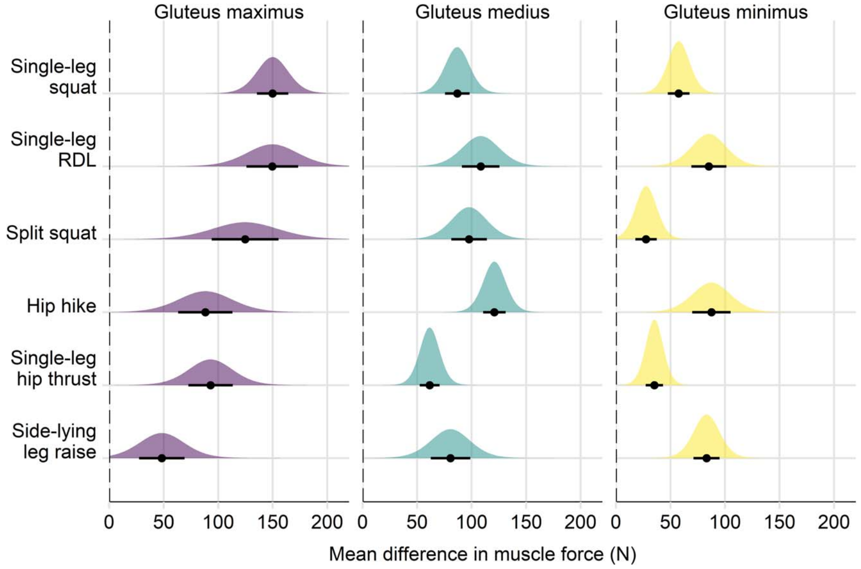

FIGURE 4—Mean difference in peak gluteal muscle force between 12RM-loaded and body weight only conditions. The *points* indicate the mean difference (loaded—body weight) across participants (n = 14), the *density plot* indicates the Student's *t* distribution, and the *line* indicates the 95% CI of the mean difference.

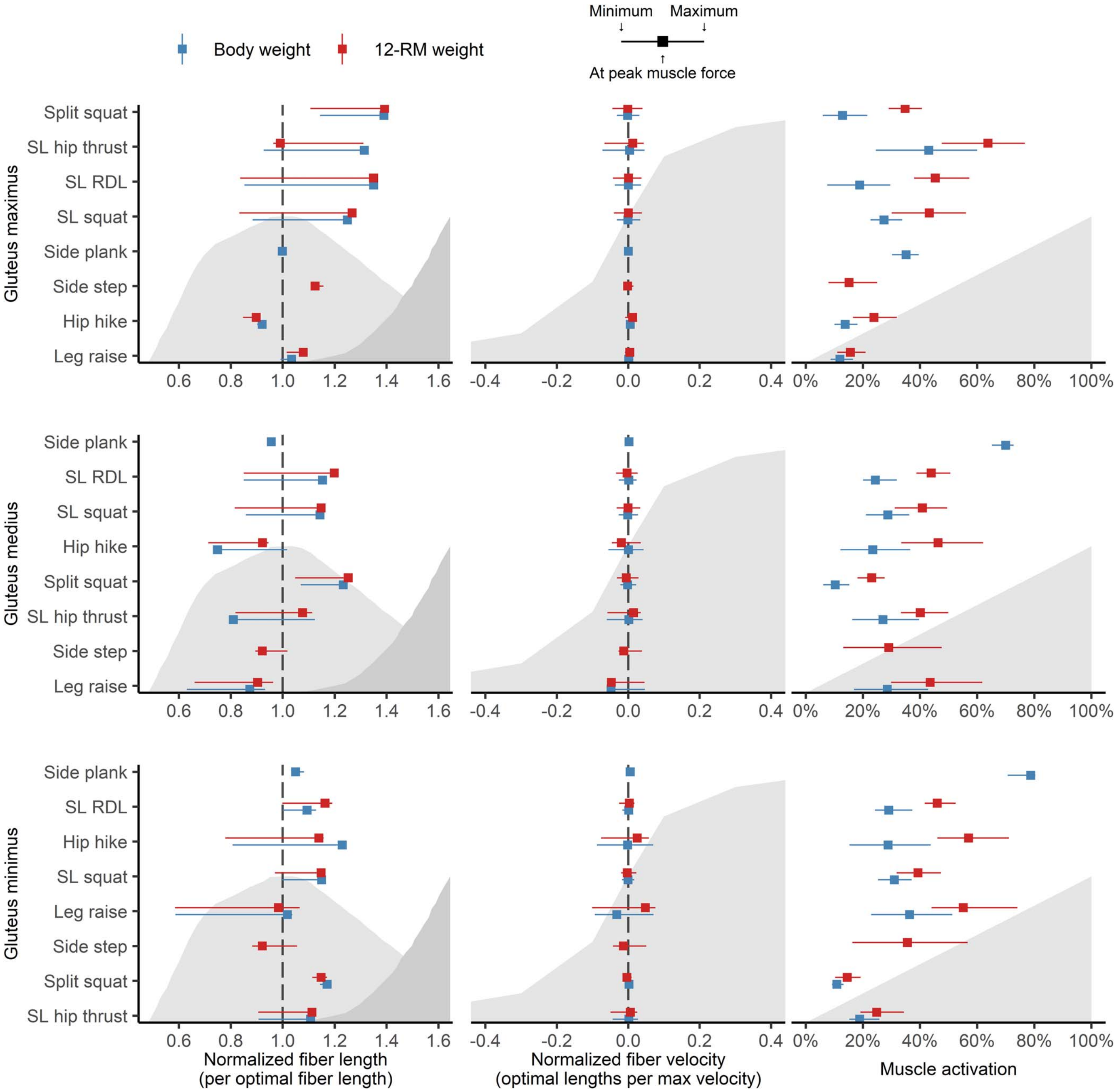

FIGURE 5—Mean-normalized muscle fiber lengths, mean-normalized fiber velocities, and mean muscle activation ranges across all participants (*n* = 14) during one repetition of exercises performed with body weight only (*blue*) and loaded at 12RM (*red*). *Left column:* Muscle fiber length range (*horizontal line* showing minimum to maximum value) normalized to optimal fiber length with fiber length at peak muscle force shown with a square and overlayed on the active and passive force–length relationship curves (*gray shading*). *Middle column:* Fiber velocity range (*horizontal line* showing minimum to maximum value) normalized to optimal fiber length times maximum fiber velocity, with fiber velocity at peak muscle force indicated with a square and overlayed on the force–velocity relationship curve from concentric (−) to eccentric (+). *Right column:* Muscle activation range (*bar* showing minimum and maximum values). SL, single leg.

(maximus = 1.27), and hip hike (minimus = 1.23) (Fig. 5, first column). Peak muscle forces for all gluteal muscles coincided with maximum fiber length for five out of seven of the dynamic exercises (Fig. 5, first column). Fiber velocities were relatively low during all exercises (range, −0.10 to 0.08 times maximum fiber velocity) and therefore had only a small contribution to increasing or decreasing muscle force (Fig. 5, second column). Maximal muscle activations ranged from approximately 5% to 80% depending on exercise and gluteal muscle (Fig. 5, third column).

DISCUSSION

This study demonstrated that common hip-focused exercises impose varying mechanical demands on individual gluteal muscles. The peak gluteus maximus muscle forces were highest during the loaded split squat, single-leg RDL, and single-leg hip thrust, and the peak gluteus medius and minimus muscle forces were highest during the body weight side plank, loaded single-leg squat, and loaded single-leg RDL. Adding 12RM external resistance increased muscle forces for all exercises, although the size of the increase was exercise and muscle specific. Peak muscle force generally coincided with maximum fiber length, indicating that muscle lengthening is a strong predictor of muscle tension. Overall, these results may be used to target individual gluteal muscles and to optimize the mechanical load according to specific performance, injury prevention, or rehabilitation training goals.

Effect of exercise on gluteus maximus muscle force. Tier 1 exercises for gluteus maximus included the loaded split squat, loaded single-leg RDL, and loaded single-leg hip thrust (Fig. 3). These exercises all had peak muscle forces within 3% of each other, indicating very similar loading magnitudes (Fig. 2). Three previous studies have examined gluteus maximus muscle forces in males or mixed-sex cohorts during strength training exercises using musculoskeletal modeling with static and dynamic optimization to calculate muscle forces (27,46,47). Consistent with our results, when performed with a resistance equal to 25% of body mass, previous studies reported the highest gluteus maximus muscle force during split squats, followed by deadlifts and good mornings (27) or bilateral squats (46). When our peak gluteus maximus muscle forces for loaded split squats were normalized to body mass to match previous studies, our data ($29 \pm 10\ \mathrm{N \cdot kg^{-1}}$, average of 30 kg weight and 63 kg body mass) were close to Kipp et al. (46) ($32 \pm 7\ \mathrm{N \cdot kg^{-1}}$, average of 20 kg weight and 82 kg body mass) but substantially lower than Schellenberg et al. (27) ($\sim 39 \pm 10\ \mathrm{N \cdot kg^{-1}}$, average of 17 kg weight and 68 kg body mass). Likewise, lower single-leg RDL gluteus maximus peak muscle force was seen in the current study ($26 \pm 6\ \mathrm{N \cdot kg^{-1}}$) compared with Van Hooren et al. (47) ($49 \pm 12\ \mathrm{N \cdot kg^{-1}}$). Differences between study results may relate, in part, to our all-female cohort, the total amount of external resistance used (e.g., 12RM vs 12% body weight vs 1RM), musculoskeletal modeling parameter choices, and/or the approach used to solve muscle forces (EMG informed vs static optimization vs dynamic optimization).

Effect of exercise on gluteus medius and minimus muscle force. The highest peak gluteus medius muscle forces were observed during the body weight side plank, whereas both the body weight side plank and the loaded single-leg RDL had the highest peak gluteus minimus muscle force (Fig. 3). Previous research has reported higher gluteus medius muscle forces during step-ups than split squats and bilateral squats (46); however, this study is the first to investigate a wide range of hip-focused exercises that also includes isometric and hip abduction exercises. As no equipment is required, the side plank may be a good choice for targeting gluteus medius and minimus within at-home or on-field training programs. In contrast to the other exercises analyzed, the side plank is typically performed isometrically and may promote different strength and/or structural adaptations than if forces are produced isotonically (48). The loaded single-leg RDL provided equally high gluteus minimus muscle force (100% observed maximum), while also producing high gluteus medius (84% observed maximum) and gluteus maximus (98% observed maximum) muscle forces. As such, single-leg RDL may be most suited to targeting all the gluteal muscles simultaneously.

Exercises that were primarily hip abduction movements (hip hike, banded side step, side-lying leg raise) did not produce greater gluteus medius and minimus (hip hike exempt) muscle forces than hip extension–dominant movements (split squat, single-leg squat, RDL, and hip thrust). Lower peak muscle forces during hip abduction–dominant exercises were generally explained by short maximum fiber lengths and/or fast concentric fiber velocities, despite having some of the highest muscle activations. Based on EMG analyses, hip abduction–dominant movements are sometimes considered a highly “targeted” exercises for training gluteus medius and minimus (19); however, the mechanical stimulus may be lower than during a movement that can be performed with greater external resistance (i.e., single-leg squat and RDL). For example, Buehler et al. (49) found that the peak hip abductor muscle forces were lower during standing hip abduction with an elastic resistance band than walking. As such, hip abduction exercises performed with an elastic resistance may not provide sufficient amounts of mechanical tension to increase gluteus medius strength and size in active individuals. Broadly, one way to increase the mechanical load on the hip abductor muscles may be to modify exercises to include greater hip adduction, thereby lengthening fibers and increasing passive forces.

When normalized to maximum isometric strength (i.e., to account for muscle volume), gluteus minimus typically produced more force than gluteus medius, particularly for hip hikes, side-lying leg raises, and side planks, which may be compensatory for the smaller moment arm of gluteus minimus (Fig. 2). As such, these exercises may be useful for promoting greater adaptation in gluteus minimus relative to gluteus medius. For example, training gluteus minimus may be beneficial for a range of hip pathologies as it contributes to stabilizing the femoral head within the acetabulum via direct attachments to the joint capsule (50).

Effect of external resistance on gluteal muscle force. As expected, all exercises had greater peak gluteal muscle force when performed with 12RM external resistance compared with body weight only. However, the extent to which peak gluteal muscle force increased with added external load was muscle specific and varied between exercises. A similar conclusion was made in a previous study that compared exercises performed using external resistances equal to 0%, 25%, 50%, and 75% of body mass, which also showed relatively uniform scaling of muscle forces with increasing external resistance (46). Therefore, as widely recognized by resistance training principles, greater muscle loading can be elicited by increasing external resistance. To place this effect into context, tier 1-loaded exercises produced greater peak gluteus maximus muscle force (3.3–3.6 times body weight) than a maximal effort sprint acceleration (1.9–3.3 times body weight) (3). Our study and others (27,46) provide insight into how loading affects individual muscle forces, and importantly, how muscle loading is affected by exercise selection. It is reasonable to suggest that muscle forces may further increase following the same pattern shown in Figure 4 with increasing external loads (e.g., <12RM). We also observed that certain exercises have greater potential to be loaded with heavier weights (e.g., split squat), which may be a key factor in maximizing load of gluteal muscles. Conversely, some exercises performed with a 12RM load led to lower peak muscle forces than other exercise performed with body weight only. For example, body weight single-leg squat has higher peak gluteus medius muscle force than loaded side-lying leg raises.

Muscle fiber length, fiber velocity, and activation. Peak muscle force corresponded with maximum fiber length, and the exercises that generated the greatest peak gluteus maximus muscle force (split squat, single-leg hip thrust, single-leg RDL, and single-leg squat) all had high passive force contributions due to fibers lengths around 1.2 to 1.4 times optimal fiber length. Previous studies suggest that training at long fiber lengths positively influences muscle hypertrophy compared with short fiber lengths (17). Greater hypertrophy may be related to the high peak muscle forces that occur at long fiber lengths because of increased force within the passive components of the muscle, such as titin proteins, that are linked to adaptive signaling pathways (51). Conversely, the single-leg hip thrust achieved peak gluteus maximus muscle force at its optimum length, with no contribution from passive muscle forces, and consequently had the highest gluteus maximus muscle activation (77%) to produce sufficient muscle force. However, peak muscle force generally occurred with muscle activations close to the average value, indicating that peak muscle activation is not necessarily an indicator of peak force due to the interaction with fiber length. For the single-leg hip thrust and hip hike, peak muscle force in loaded and unloaded conditions switched between occurring near maximum fiber length to near minimum fiber length. This is presumably due to the effect of external resistance on the hip joint moment at the start of the repletion compared with the end of the repetition. Notably, in both situations, the peak muscle force occurred closer to the plateau of the force–length relationship, where the maximum amount of active force can be produced. Further, muscle fiber velocities were very close to zero at peak muscle force due to the transition between eccentric and concentric phases, resulting in very small effects on total muscle force. Performing exercises at a greater tempo may influence findings as fiber velocity has a greater effect on muscle forces.

Limitations. The main methodological limitation of this study is the use of a generic musculoskeletal model that is a simplified representation of the human body. As such, several muscle properties were informed by general medical imaging databases (40) and cadaveric data (37). Therefore, where possible, bone lengths, muscle volume, and musculotendon unit parameters were personalized to the participants anthropometric measures. However, moment arms were based on the generic male model and may not accurately represent those of a female, particularly for muscles that attach to the pelvis due to sex-specific variations in anatomy. Muscle force estimates cannot be directly validated against *in vivo* measures without the use of invasive methods. Alternatively, model predictions were verified using experimentally measured joint moments and muscle surface EMG signals (44,52), showing small errors (i.e., <3.5 N·m median error for joint moments and <16% median error for muscle excitation) (see figure, Supplemental Digital Content 4, for tracking error, http://links.lww.com/MSS/C753). Further, our within-participant study design enables exercises to be compared using the same musculoskeletal model for each participant; thereby, any limitations associated with methodology affects all exercises. Performing exercises at the same approximate joint angular velocity ensured exercises were performed at a slow and controlled tempo; however, for exercises with a large range of motion (single-leg RDL and squat), this tempo may have been slower than performed in practice. Exercise familiarity may have influenced the ability to produce force in different exercises. To minimize this, we recruited participants with substantial gym experience (average training age = 6 yr) and performed a dedicated exercise familiarization session (approximately 2 h). Normalization of peak muscle force to body mass ($N \cdot kg^{-1}$) was considered; however, body mass was a weak predictor of peak muscle force (mean exercise $R^2 = 0.16$) and had no effect on the within-participant comparisons or exercise ranking analysis used in this study.

CONCLUSIONS

The split squat, single-leg RDL and single-leg hip thrust produced the highest peak gluteus maximus muscle forces, whereas side plank and single-leg RDL produced the highest peak gluteus medius and minimus muscle forces. Adding 12RM external resistance increased muscle forces for all exercises, although the size of the increase was exercise and muscle specific. For most exercises, peak muscle forces corresponded with maximum fiber length, with fiber velocities close to zero and muscle activation near their average value. These results may be used to target individual gluteal muscles and optimize mechanical load to meet performance, injury prevention, or rehabilitation training goals.

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