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Hypertrophic Effects of Single- versus Multi-Joint Exercise: A Direct Comparison Between Knee Extension and Leg Press

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Running Title: KNEE EXTENSION VS. LEG PRESS FOR MUSCLE GROWTH

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ABSTRACT

Introduction: Single-joint knee extension (KE) and multi-joint leg press (LP) are commonly used exercises to train the quadriceps femoris (QF), the largest muscle group in humans. However, their comparative effectiveness for inducing QF hypertrophy remains unclear. Furthermore, the specific muscles hypertrophied by LP are not well characterized. This study compared the hypertrophic effects of KE and LP on the QF and other lower-limb muscles. **Methods:** Seventeen untrained adults performed KE with one leg and LP with the contralateral leg at 70% of one-repetition maximum, 10 reps/set, 5 sets/session, 2 sessions/week for 12 weeks. MRI was used to assess pre- and post-training muscle volumes of 17 individual muscles, including the four QF heads, gluteus muscles, hamstrings, and adductors. **Results:** Muscle volumes of the individual and whole QF significantly increased in both conditions ($P \leq 0.026$), except for the rectus femoris in the LP condition ($P = 0.379$). Rectus femoris volume gains were greater for KE than LP (+13.2% vs. +1.1%, $P \leq 0.001$), but gains in the vasti muscles (+5.0–7.2% vs. +4.4–6.2%) and whole QF (+7.1% vs. +4.9%) were comparable between conditions ($P \geq 0.319$). LP, but not KE, increased volumes of the gluteus maximus (+15.4%) and the adductor magnus (+6.2%) ($P \leq 0.001$). A follow-up experiment using surface electromyography showed that muscle excitation patterns during KE and LP generally mirrored the between-condition hypertrophic differences and similarities observed after the training intervention. **Conclusions:** LP induces significant hypertrophy in the gluteus maximus and adductor magnus while producing similar vasti and overall QF growth as KE, indicating that LP is a highly time-efficient exercise. However, KE is essential for effectively targeting the rectus femoris, which may have clinical relevance given its high susceptibility to strain injuries.

Key Words: QUADRICEPS FEMORIS, GLUTEUS MAXIMUS, ADDUCTOR MAGNUS

INTRODUCTION

Skeletal muscle plays a crucial role in maintaining overall health (1), as low muscle mass is associated with an increased risk of cardiovascular disease and diabetes (2-4), as well as higher mortality rates (5). Accordingly, the World Health Organization recommends resistance training to increase or maintain muscle mass (6). In general, lower-limb muscles are larger than upper-limb muscles (7), and greater lower-limb muscle size is associated with superior locomotive and fundamental physical performance, such as sprinting and jumping (8, 9). Therefore, identifying effective training methods to increase lower-limb muscle size, particularly that of the quadriceps femoris (QF), the largest and functionally essential muscle group in the human body (1, 10), could benefit a wide range of populations.

Resistance training exercises can be categorized into single-joint and multi-joint exercises; single-joint exercises involve movement around one joint and are commonly performed to target a specific muscle (or muscle group), whereas multi-joint exercises involve multiple joint actions and activate several muscles (muscle groups) simultaneously (11). To train the QF, single-joint knee extension (KE) and multi-joint leg press (LP) or squat are often adopted (12-15). A recent meta-analysis (16) reported similar hypertrophic effects between single- and multi-joint training; however, most included studies targeted upper-limb muscles and often relied on suboptimal muscle size measures (e.g., arm circumference). Using MRI-based muscle volume, the gold standard for assessing muscle size (17), previous studies found that KE training preferentially induced hypertrophy of the rectus femoris compared with the vasti muscles (12, 13), whereas squat training primarily increased the size of the vasti muscles (18). However, these studies examined either single- or multi-joint exercises in isolation rather than directly comparing their effectiveness. More recent studies (14, 15) compared KE and LP or squat within the same experimental design and suggested that KE and LP/squat may preferentially train the rectus femoris and vastus lateralis, respectively. However, these studies (14, 15) were limited by relatively short intervention durations (5–8 weeks) and by their reliance on ultrasound-based muscle thickness, which may fail to detect regional hypertrophy that MRI can capture, as highlighted by poor correlations between training-induced changes in muscle thickness at limited regions and MRI-derived total muscle volume (19). Consequently, it remains unclear whether KE or LP is more effective for inducing hypertrophy of individual QF constituents and the whole QF. Furthermore, although LP theoretically engages multiple muscle groups, the specific muscles trained/hypertrophied by LP are not fully understood. Clarifying these points would provide valuable evidence for selecting optimal exercises to maximize lower-limb muscle hypertrophy.

The main purpose of this study was to compare the hypertrophic effects of KE and LP on the QF and other lower-limb muscles around the hip and thigh. To this end, we conducted a 12-week training intervention using a within-subject comparison design (Experiment 1), which effectively controls for individual-level confounders such as genetic factors, diet, and sleep, making it well-suited for comparing hypertrophic responses (20, 21). In addition, we assessed lower-limb muscle excitation during KE and LP using surface electromyography (EMG) (Experiment 2) to determine whether differences in hypertrophic responses could be explained by muscle excitation during the exercises. For Experiment 1, given that KE primarily targets the QF and often results in preferential hypertrophy of the rectus femoris (12, 13), we hypothesized that (i) hypertrophy of the QF, particularly the rectus femoris, would be greater after KE than after LP. Furthermore, because LP involves multiple joints and muscles, we hypothesized that (ii) LP would induce hypertrophy not only in the QF but also in other lower-limb muscles (e.g., hip extensors), leading to greater overall lower-limb muscle size gains compared with KE. For Experiment 2, we hypothesized that (iii) muscle excitation during exercise would broadly support and explain the hypertrophic effects found in Experiment 1 (e.g., rectus femoris excitation would be greater during KE than LP).

METHODS

Participants

Seventeen untrained healthy young adults (11 males and 6 females, age: 23.3 ± 4.0 yrs, height: 1.67 ± 0.1 m, body mass: 60.3 ± 6.0 kg) who had not performed KE, LP, or similar exercise (e.g., squat) training in the past 12 months participated in Experiment 1. A separate cohort of eleven healthy males (24.0 ± 5.4 yrs, 1.71 ± 0.1 m, 67.8 ± 9.9 kg) participated in Experiment 2. No participant had a history of competitive strength-sport participation (e.g., powerlifting or bodybuilding). Written informed consent was obtained from all participants. This study was approved by the Ethics Committee of Ritsumeikan University (BKC- LSMH-2022-093). Participants in Experiment 1 were instructed to refrain from any additional lower-limb resistance exercise during the 12-week intervention and to maintain their habitual physical activity otherwise.

Experiment 1

Training program

Each leg was assigned to KE or LP, with dominant and non-dominant legs counterbalanced across participants. Exercises were performed unilaterally using KE (HS-LE, Life Fitness, USA) and LP (HS-SLP, Life Fitness, USA) machines (Figure 1). A backrest for KE and a pad for LP was inserted between the participant's back and the machine to ensure a starting hip joint angle of 90° in both conditions (0° = anatomical position). For LP, participants placed their feet hip-width apart, with the toes aligned at the top edge of the footplate. The knee joint range of motion during exercise was 90–0° for both conditions, and the hip joint range for the LP condition was 90–60°.

The training protocol followed our previous studies (22, 23). Briefly, participants performed a warm-up consisting of 10 repetitions at 50% and 5 repetitions at 80% of the session's target load. Thereafter, KE or LP was performed for 5 sets of 10 repetitions, with each concentric (lifting) and eccentric (lowering) phase lasting 2 s, guided by a metronome (60 bpm). A 2-min rest interval was provided between sets. After completing one leg, the contralateral leg was trained. The starting leg in the first session was counterbalanced across participants and alternated in subsequent sessions.

Training was conducted twice per week on non-consecutive days for 12 weeks. The load was progressively increased during the first three sessions (50%, 60%, and 70% of pre-training one-repetition maximum [1RM]). At least one examiner supervised all sessions, provided verbal encouragement, and ensured correct joint positions and movement speed. Spotting was provided if participants could not complete the prescribed repetitions. When participants completed all sets without assistance in the third and subsequent sessions, the training load was increased by 5% of 1RM in the following sessions. This progression typically resulted in failure or near-failure in sessions three and later, especially in the latter sets (sets ≥ 3). In untrained individuals, meta-analytic evidence indicates little to no difference in hypertrophy between training to failure and not to failure (24).

1RM

1RM for both exercises (KE-1RM and LP-1RM) was assessed unilaterally in each leg before and after the intervention, always following the MRI measurement. The order of 1RM testing (KE vs LP) was randomized. For each testing, participants completed a warm-up of 5 and 3 repetitions at 50% and 80% of the estimated 1RM, respectively, alternating legs for the unilateral tests. The load was then incrementally increased until 1RM was achieved, with at least 1 minute of rest between attempts (thus at least 2 minutes between attempts on the same leg). After completing testing for one exercise, the other exercise was tested.

MRI

MRI scans were obtained 2–7 days before and after the 12-week training intervention to assess lower-limb muscle volume using a 3-T MRI system (MAGNETOM Skyra, Siemens Healthineers, Germany). Prior T2-MRI work found no evidence of edema in scans acquired 2–5 days after the final training session (25), indicating that acute post-exercise swelling is unlikely to confound the present measurements. T1-weighted cross-sectional images were acquired for each leg using body array and spine coils (Body 18 and CP Spine Array Coil; Siemens Healthineers, Germany) with the following parameters: field of view, 275 × 275 mm; slice thickness, 5 mm; interslice gap, 5 mm; voxel size, 0.54 × 0.54 × 5 mm; repetition time, 700 ms; echo time, 10 ms; and 22 slices per block × 3 blocks. Participants lay in the supine position with legs extended and muscles relaxed, ensuring no compression of the thigh muscles (26).

Images were analyzed using image analysis software (Horos, v3.3.6, Horos Project). All MRI data were anonymized, and investigators were blinded to training conditions. Seventeen individual muscles were analyzed: rectus femoris, vastus lateralis, vastus medialis, vastus intermedius, gluteus maximus, gluteus medius, gluteus minimus, adductor magnus, adductor longus, adductor brevis, pectineus, gracilis, sartorius, biceps femoris short head, biceps femoris long head, semitendinosus, and semimembranosus, (Figure 2).

Anatomical cross-sectional areas (ACSAs) were manually outlined on every other image from the most proximal to the most distal slice in which the muscle was visible. ACSAs for skipped slices and gaps were estimated using linear interpolation. Individual muscle volumes were calculated by summing all ACSAs and multiplying by slice thickness. Group volumes for the QF, gluteal muscles (GLUT), hamstrings (HAM), and adductors (ADD), as well as total muscle volume (ALL), were computed by summing the respective individual muscle volumes.

Experiment 2

EMG during KE and LP

To estimate muscle excitation during KE and LP, surface EMG signals were recorded from the rectus femoris, vastus lateralis, vastus medialis, gluteus maximus, biceps femoris long head, and semitendinosus on the dominant leg. After skin preparation (shaving, light abrasion, and cleaning with ethanol), dual electrodes (EM-272S, Noraxon, USA; interelectrode distance: 20 mm) were placed according to SENIAM guidelines at the following sites: 50% between the anterior superior iliac spine (ASIS) and the superior patellar border for the rectus femoris; 2/3 between the ASIS and the lateral patella for the vastus lateralis; 80% between the ASIS and the medial joint line of the knee for the vastus medialis; 50% between the sacrum and greater trochanter for the gluteus maximus; 50% between the ischial tuberosity and the lateral epicondyle of the tibia for the biceps femoris long head; 50% between the ischial tuberosity and the medial epicondyle of the tibia for the semitendinosus. Signals were amplified (×1,000; MEG-6108MMG, Miyuki Giken, Japan), band-pass filtered at 5–1,000 Hz, and sampled at 2,000 Hz (27, 28). Knee and hip joint angles were recorded simultaneously using electrogoniometers

(SG150; Biometrics, UK). Data acquisition was performed using an A/D converter (PowerLab 16/35, Australia) and software (LabChart v7, ADInstruments, Australia).

Upon arrival, participants completed a warm-up of 10 repetitions at 50% and 5 repetitions at 80% of estimated 1RM. Subsequently, 1RM for KE and LP was assessed in a randomized order (22, 23, 29). Thereafter, participants performed one set of 10 repetitions at 50% 1RM for both KE and LP, replicating the first training session in Experiment 1. A rest interval of ≥ 2 min was provided between exercises. Isometric maximal voluntary contractions (MVCs) were then performed for unilateral KE, knee flexion, and LP for EMG normalization. MVCs were conducted on the same machines using supramaximal loads. Participants gradually increased force over 3 s and held maximal effort for an additional 3 s. The postures during MVC of KE and LP matched the training start positions (hip and knee joint angles at 90°). For knee flexion MVC, the KE machine was adjusted to allow hip and knee angles at 90°. Two MVC trials per task were performed in randomized order with 2 min rests between trials.

EMG during KE and LP (50% 1RM) was analyzed as root mean square (RMS) values from the 3rd to 8th repetitions, averaged across six repetitions. For MVCs, the highest 500-ms RMS window was defined as EMGmax for each muscle across all MVC tasks (i.e., EMG normalization was muscle-specific, using the highest MVC for each muscle). Exercise EMG data were expressed as %EMGmax for each muscle to estimate relative excitation during KE and LP.

Statistical analysis

Descriptive data are presented as mean ± SD unless otherwise stated. For Experiment 1, a two-way linear mixed model (time [pre, post] × exercise condition [KE, LP]) was used to compare unilateral 1RM (KE-1RM, LP-1RM) and muscle volumes for each individual muscle, muscle group, and total lower-limb muscles. When a significant interaction was detected, post hoc analyses were performed as follows: (i) paired *t*-tests comparing pre- and post-training values within each condition and (ii) paired *t*-tests comparing absolute changes between conditions. To assess within-subject associations between changes in muscle volume (by muscle group) and 1RM, matching the training and 1RM conditions, we performed repeated-measures correlation analyses (30). Specifically, we examined associations between changes in volumes of muscle groups trained by KE and KE-1RM, and between those trained by LP and LP-1RM. The strength of correlation was interpreted as follows: < 0.40 weak; 0.40 – 0.60 moderate; 0.60 – 0.80 strong; > 0.80 very strong.

To examine whether regional hypertrophy patterns differed between KE and LP, we first generated pre- and post-training ACSA profiles sampled at 1% intervals across the entire muscle length (1-100%) using cubic spline interpolation (100 points; Origin 2021, OriginLab Corporation) for muscles that showed a significant volume increase in at least one condition. We then aggregated slices into three longitudinal regions: proximal (1-33%), middle (34-66%), and distal (67-100%), and computed regional muscle volumes. Regional hypertrophy was tested with a within-subject linear mixed-effects model with factors condition (KE, LP) and region (proximal, middle, distal), using post-training regional volume as the dependent variable, pre-training regional volume as a covariate (ANCOVA-type adjustment) (31), and a random intercept for subject.

For Experiment 2, paired *t*-tests were used to compare muscle excitation levels (%EMGmax) between KE and LP. Statistical significance was set at $P < 0.05$. P values were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate procedure, applied separately within each family of tests addressing the same question: 1RM (2 exercises); individual muscle volumes (17 muscles); muscle-group volumes and their correlations with 1RM

(4 muscle groups, excluding ALL); regional muscle volumes (3 regions); and muscle excitation levels (6 muscles). All statistical analyses were conducted using IBM SPSS Statistics (version 29; IBM Corp., Armonk, NY, USA) except for the repeated-measures correlations, which were performed with the rmcorr package in R.

RESULTS

Experiment 1

All participants completed the 24 scheduled training sessions. Significant time × condition interactions ($P < 0.001$) were observed for KE-1RM and LP-1RM. Both measures increased significantly after KE training (KE-1RM: 47.4 ± 12.3 kg to 69.8 ± 21.2 kg; LP-1RM: 77.6 ± 25.0 kg to 113.4 ± 41.2 kg) and LP training (47.4 ± 12.9 kg to 55.9 ± 16.7 kg; 76.9 ± 23.9 kg to 146.6 ± 41.9 kg) ($P < 0.001$). Increases in KE-1RM were greater after KE than LP training (22.4 ± 11.9 kg vs. 8.5 ± 7.1 kg), whereas increases in LP-1RM were greater after LP than KE training (69.7 ± 24.4 kg vs. 35.7 ± 24.9 kg) ($P < 0.001$).

Pre- and post-training muscle volumes are presented in Table 1, and volume changes in individual muscles and muscle groups are depicted in Figures 3–7. Significant time × condition interactions ($P \leq 0.029$) were observed for muscle volumes of the rectus femoris, gluteus maximus, adductor magnus, GLUT, ADD, and ALL (Table 1). Rectus femoris volume increased after KE (+13.2%, $P < 0.001$) but not after LP (+1.1%, $P = 0.379$) (Figure 3). Conversely, volumes of the gluteus maximus (+15.4%), adductor magnus (+6.2%), GLUT (+12.0%), and ADD (+4.1%) increased after LP ($P < 0.001$) but not after KE (ranging from –0.9% to +0.2%, $P \geq 0.641$). Between-condition differences in change values for these muscles/groups were significant ($P < 0.001$; Figures 4, 5, 7). Total muscle volume (ALL) increased after both KE and LP (+2.8% and +6.3%, $P \leq 0.003$), with a greater increase for LP ($P < 0.001$) (Figure 7).

Significant main effects of time ($P \leq 0.026$) without interactions ($P \geq 0.301$) were observed in the muscle volumes of the vastus lateralis (KE vs LP: 6.4% vs. 6.2%), vastus medialis (7.2% vs. 6.0%), vastus intermedius (5.0% vs. 4.4%), QF (7.1% vs. 4.9%), biceps femoris long head (2.0% vs. 5.3%), and HAM (1.5% vs. 3.1%) (Table 1), indicating similar volume increases in these muscles/groups regardless of condition. No significant main effects of time or interactions were found in the muscle volumes of the remaining muscles/groups.

Repeated-measures correlation analyses showed that changes in KE-1RM were very strongly associated with changes in QF volume ($r = 0.820$, $P < 0.001$) but not with GLUT ($r = 0.064$, $P = 0.800$), HAM ($r = 0.480$, $P = 0.092$), or ADD ($r = -0.173$, $P = 0.656$). Changes in LP-1RM were strongly associated with changes in each muscle-group volume: QF ($r = 0.630$, $P = 0.005$), GLUT ($r = 0.767$, $P < 0.001$), HAM ($r = 0.700$, $P = 0.002$), and ADD ($r = 0.719$, $P = 0.002$).

Baseline-adjusted regional volume change analyses identified a significant condition × region interaction ($P \leq 0.008$) and main effects of condition ($P < 0.001$), with no main effects of region ($P \geq 0.078$), in the rectus femoris, gluteus maximus, and adductor magnus. However, post hoc analyses showed no significant regional differences in these muscles in either condition ($P \geq 0.075$) (Supplemental Fig. 1 and Supplemental Table 2, Supplemental Digital Content, http://links.lww.com/MSS/D369). The vastus lateralis showed a significant main effect of region ($P = 0.004$) with no effect of condition ($P = 0.765$) or interaction ($P = 0.846$); post hoc tests indicated greater volume change in the middle region than in the proximal and distal regions ($P \leq 0.024$). No significant effects of condition ($P \geq 0.063$), region ($P \geq 0.210$), or interactions ($P \geq 0.546$) were observed in the vastus medialis, vastus intermedius, and biceps femoris long head.

Experient 2

EMG analysis revealed that %EMGmax values during KE were significantly higher than LP for the rectus femoris (38.0 ± 7.6%EMGmax vs. 21.7 ± 10.4%EMGmax, $P < 0.001$), similar for the vastus lateralis (36.9 ± 12.0%EMGmax vs. 37.1 ± 12.9%EMGmax, $P = 0.944$) and vastus medialis (32.4 ± 13.3%EMGmax vs. 35.0 ± 10.7%EMGmax, $P = 0.653$), and significantly lower for the gluteus maximus (8.8 ± 7.1%EMGmax vs. 41.2 ± 20.7%EMGmax, $P < 0.001$), biceps femoris long head (7.3 ± 4.3%EMGmax vs. 13.9 ± 6.7%EMGmax, $P = 0.004$), and semitendinosus (8.1 ± 4.0%EMGmax vs. 18.9 ± 8.4%EMGmax, $P = 0.005$).

DISCUSSION

The main findings of this study were: (i) hypertrophy of the rectus femoris was greater after KE than after LP, whereas hypertrophy of the vasti muscles and overall QF was similar between conditions; (ii) LP, but not KE, induced significant hypertrophy of the gluteus maximus and adductor magnus, resulting in greater overall lower-limb muscle volume gains with LP; and (iii) between-condition differences and similarities in muscle excitation levels measured during exercise were generally consistent with the hypertrophic responses observed after the training period. These findings largely support our hypotheses and indicate that LP is highly time-efficient for inducing hypertrophy across multiple lower-limb muscles, including the QF. However, KE appears to be essential for effectively targeting the rectus femoris. Moreover, although EMG data should be interpreted with caution (32), the observed correspondence between acute EMG-based muscle excitation and training-induced hypertrophy suggests that a single-session EMG assessment may provide a rough indication of which exercise elicits greater hypertrophic effects.

The QF muscles

In the QF, rectus femoris volume increased significantly after KE but not after LP (+13.2% vs. +1.1%; Figure 3). These findings align with previous studies examining the hypertrophic effects of single- or multi-joint exercises on the rectus femoris (12-14, 18). Notably, squat training performed with free weight (18) or on a Smith machine (14), as well as LP training (present study) have consistently failed to induce rectus femoris hypertrophy. This suggests that multi-joint exercises provide minimal, if any, hypertrophic stimulus to the rectus femoris, regardless of exercise or load modality. Supporting this notion, cross-sectional studies have shown that oarsmen and cyclists, who frequently perform simultaneous knee and hip extension, exhibit hypertrophied vasti muscles but rectus femoris sizes comparable to those of untrained individuals (33, 34). Consistent with these morphological observations, our EMG data (Experiment 2) demonstrated significantly lower %EMGmax values for the rectus femoris during LP compared with KE. The rectus femoris is a biarticular muscle that spans not only the knee but also the hip joint and contributes to hip flexion. During LP, which requires simultaneous hip and knee extension, rectus femoris activation may be downregulated because its potential to generate a hip flexion moment (torque) functionally conflicts with the required hip extension (35). Collectively, these findings indicate that the rectus femoris is not effectively activated, and thus not hypertrophied, by multi-joint exercises such as leg press or squats. This phenomenon may extend to other biarticular muscles. For instance, the long head of the triceps brachii (a biarticular muscle) exhibited minimal hypertrophy after multi-joint bench press or dumbbell press training (36, 37), but showed substantial hypertrophy after single-joint elbow extension training (23, 36, 38). Although these studies did not explicitly address this issue, it is plausible that limited hypertrophic adaptation of biarticular muscles in response to multi-joint exercises is a generalizable phenomenon, particularly when a biarticular muscle's action at one joint conflicts with the required action at the other joint.

Interestingly, changes in vasti muscle volumes were similar after KE and LP training (+5.0–7.2% vs. +4.4–6.2%, Figure 3). Likewise, %EMGmax values showed no significant differences in vasti muscle excitation between the two exercises (32.4–36.9%EMGmax vs. 35.0–37.1%EMGmax). These findings suggest that the monoarticular vasti muscles are similarly activated during single-joint KE and multi-joint LP, in contrast to the biarticular rectus femoris, resulting in comparable hypertrophic responses for both exercises. In addition, QF volume changes were also similar between KE and LP training (+7.1% vs. +4.9%, Figure 7), which contradicted our initial hypothesis. This result may seem unexpected given the markedly greater rectus femoris hypertrophy after KE than LP. However, this discrepancy can be explained by the relative contribution of each muscle to total QF volume: the three vasti muscles constitute the majority (~85%) of the QF (Table 1), whereas the rectus femoris accounts for only a small proportion. Consequently, overall QF volume changes are primarily driven by adaptations in the vasti muscles.

The present findings provide valuable practical insights for exercise selection. If the goal is to increase overall lower-limb muscle size, including the QF for general health (2) or athletic conditioning (9), LP may be preferable; it induces comparable hypertrophy in the vasti and whole QF as KE, while also promoting growth in other muscles (as discussed below). Conversely, for individuals aiming to specifically target the rectus femoris (e.g., for injury prevention (39, 40), sport-specific performance enhancement (41), or aesthetic purposes (42)), KE is essential, as LP and other multi-joint exercises do not sufficiently activate this muscle. This consideration is particularly important given that the rectus femoris is the most frequently injured muscle within the QF and is highly susceptible to re-injury (39, 43, 44). Furthermore, marked rectus femoris atrophy has been reported following anterior cruciate ligament reconstruction (40, 45). Thus, the present results provide practical guidance for designing individualized training programs tailored to specific rehabilitation or performance objectives.

Other lower-limb muscles

Gluteus maximus volume increased significantly after LP (+15.4%) but not after KE (+0.2%) (Figure 4), consistent with %EMGmax data showing substantially greater excitation of this muscle during LP (41.2%EMGmax vs. 8.8%EMGmax). These results are expected given that the gluteus maximus is a primary hip extensor, not a knee extensor. In addition, LP induced significant hypertrophy in the ADD (+4.1%, Figure 7), specifically the adductor magnus (+6.2%). Although the adductor muscles are traditionally viewed as hip adductors, each muscle within the group may serve distinct functional roles (46, 47). For instance, Kato et al. (47) reported that the adductor magnus and adductor longus are preferentially activated during hip extension and flexion, respectively. Similarly, Takahashi et al. (48) suggested that the anatomical structure of the adductor magnus is adapted to function as a hip extensor rather than solely as an adductor. While a previous study reported significant hypertrophy of the whole adductor muscle group after squat training (18), the present study is the first to demonstrate selective hypertrophy of the adductor magnus, contributing significantly to the overall growth in the adductor muscle group.

The biceps femoris long head, and consequently the HAM, exhibited slight but significant hypertrophy in both conditions (+1.5% to +5.3%), with no significant difference between KE and LP (Table 1, Figures 6–7). These modest changes, particularly those observed after LP, may be explained by the biarticular nature of the HAM, which spans the hip and knee joints and acts as a hip extensor and knee flexor, through a mechanism similar to that of the rectus femoris; during LP, knee extension occurs concurrently with hip extension, potentially limiting the HAM's net contribution to hip extension because its potential to generate a knee flexion moment can conflict with the required knee extension. The difference between the absence of significant hypertrophy in the rectus femoris and the presence of significant (albeit modest) hypertrophy in the biceps femoris long head after LP, despite a similar mechanical dilemma, may reflect the inherent hypertrophic responsiveness of these muscles. Indeed, literature in young adults suggests that the HAM is more prone to hypertrophy than the QF under resistance training (49, 50), possibly due to differences in their habitual functional roles during everyday locomotor and postural activities.

Furthermore, it is well established that some degree of antagonist coactivation occurs during both single- and multi-joint exercises in upper and lower-limb muscles, likely serving to enhance joint stability, protect ligaments, and improve movement precision (51). The HAM is no exception, and their coactivation is reportedly greater in the biceps femoris long head (~30%) than in the semitendinosus (~10%) during maximal isokinetic knee extensions (52). However, our EMG results (Experiment 2) did not reflect this pattern, likely due to differences in load intensity. Specifically, Experiment 2 used a moderate load (50% 1RM) to ensure all participants could complete 10 repetitions, whereas Experiment 1 involved 70% 1RM, and the referenced EMG study (52) employed maximal efforts. Taken together, these findings suggest that the biceps femoris long head is the primary contributor to hamstring coactivation, especially under high intensity conditions during KE and LP, leading to its modest hypertrophy, and consequently to small but significant HAM volume increases. Nevertheless, the degree of HAM hypertrophy observed here (+1.5% to +5.3%) was far smaller than that reported in studies targeting the HAM as agonists (12–19% with leg curl exercises) (53, 54). Thus, although KE and LP may induce slight HAM hypertrophy via antagonist coactivation, they should not be considered as effective primary exercises for HAM development.

Regional hypertrophy

Significant regional differences were observed only in the vastus lateralis, where the middle region showed greater volume change than the proximal and distal regions (Supplemental Fig. 1, Supplemental Digital Content, http://links.lww.com/MSS/D369). This aligns with Wakahara et al. (55), who reported no regional differences in hypertrophy of the vastus medialis and vastus intermedius, but contrasts with reports of greater distal than proximal hypertrophy in the rectus femoris (12, 55) and in the vastus lateralis (12) after KE training. Two classic studies also suggested regional differences, although they did not statistically test them (56, 57).

One likely reason for these discrepancies is methodological differences. Unlike the above studies (12, 55–57), which compared percent changes in ACSA at selected locations, we first computed regional muscle volume within three bins along the muscle length (proximal 1–33%, middle 34–66%, distal 67–100%) by sampling ACSA at 1% intervals. This approach leverages the full dataset while reducing the influence of large errors in regions near proximal and distal ends where ACSA is very small (see Supplemental Fig. 1, Supplemental Digital Content, http://links.lww.com/MSS/D369). We then compared post-training regional volumes across regions (and conditions), with pre-training regional volume included as a covariate in an ANCOVA-type linear mixed model, rather than analyzing percent change, as recommended on statistical grounds (31).

A second possibility is the comparatively modest hypertrophy of each QF head in the present study. After 12 weeks of KE training, whole-muscle volume increased by ~13% in the rectus femoris and ~6% in the vasti muscles, whereas Wakahara et al. (55) reported increases of ~24% and ~10%, respectively. This difference likely reflects, at least in part, the higher weekly training frequency (3 vs. 2 sessions per week), and consequently greater training volume, in that study. Differences in hip joint position during training, specifically the smaller hip flexion angle (70° vs 90°) used by Wakahara et al. (55), may also have contributed to the larger hypertrophic response (58), as discussed later. However, as noted in the limitations, our study was designed primarily to compare whole-muscle volume responses to KE and LP while minimizing confounding factors, rather than to maximize muscle hypertrophy after each exercise individually; an exhaustive mapping of regional hypertrophy therefore falls beyond its scope. Nevertheless, our methods, results, and rationale should provide a useful framework for future studies specifically targeting training-induced regional muscle hypertrophy.

1RM strength

After KE training, changes in KE-1RM were very strongly associated with changes in QF volume ($r = 0.820$, $P < 0.001$), but not with other muscle groups ($r \leq 0.480$, $P \geq 0.092$). After LP training, changes in LP-1RM were strongly associated with changes in each muscle-group volume ($r = 0.630$–767, $P < 0.005$). These patterns are consistent with the training stimulus: KE primarily targeted and hypertrophied the QF (aside from a small but significant change in HAM), whereas LP induced hypertrophy across all muscle groups. Although we did not measure neural adaptations, the present associations support the view that muscle hypertrophy is a major contributor to strength gains over several months (e.g., > 12 weeks) of resistance training (30).

We also note that the within-participant (contralateral-leg) design raises the possibility of cross-education (20, 59), whereby strength gains in one limb partially transfer to the contralateral limb. Although this effect cannot be completely excluded, we observed exercise-specific strength increases (KE-1RM increased more after KE, and LP-1RM increased more after LP), suggesting that any cross-education was likely minimal. Importantly, we selected this design because the primary aim was to compare hypertrophic adaptations, which show no transfer between limbs (20, 21).

Limitations

There are some limitations to this study. First, the posture used in this study, specifically the hip joint angle that was standardized at 90° in the starting position for both KE and LP (Figure 1), may have influenced the hypertrophic responses of certain muscles. Growing evidence suggests that training at longer muscle lengths enhances hypertrophy (22, 23, 29, 53); thus, the observed changes in muscle volume might have differed if the exercises had been performed without this hip angle adjustment. For example, KE training at a smaller hip flexion angle (e.g., 70°), where the rectus femoris is at a longer length due to its biarticular nature, may have further augmented its hypertrophy (58). Conversely, LP training at a greater hip flexion angle (e.g., 110°) in the bottom/starting position, where the gluteus maximus and adductor magnus are more stretched as hip extensors (regardless of their bi- or mono-articular nature), could have increased their growth (18). Nevertheless, standardizing the hip joint angle minimized the influence of muscle length as a confounding factor, particularly for the rectus femoris, and our main findings would likely remain unchanged if these differences had occurred. Future studies and practitioners designing training programs to maximize hypertrophy should take these considerations into account.

Second, all participants were previously untrained; therefore, the generalizability of our findings to resistance-trained individuals is uncertain. In resistance-trained participants, Burke et al. (15) reported greater rectus femoris hypertrophy after KE than LP (consistent with our results) but greater vastus lateralis hypertrophy after LP than KE (in contrast to our findings). This discrepancy for the vastus lateralis may reflect differences in training status, the shorter intervention duration in that study (8 weeks), and reliance on ultrasound-based muscle thickness rather than MRI-derived muscle volume. We remain confident in our findings for untrained adults, given the longer training duration (12 weeks), MRI-based volumetry, and EMG assessments during exercise used here. Nevertheless, further studies in resistance-trained individuals and athletes, employing longer interventions, MRI-derived muscle volume, and standardized EMG protocols, are warranted to clarify the effects of KE versus LP and other single-joint and multi-joint exercises.

CONCLUSIONS

In summary, this study demonstrated that the rectus femoris exhibited significant hypertrophy after KE but not after LP training, supporting the notion that biarticular muscles undergo minimal hypertrophy when trained with multi-joint exercises in which their action at one joint conflicts with the required action at the other joint. In contrast, LP elicited similar hypertrophic responses in the vasti muscles and overall QF as KE, while inducing substantial hypertrophy in the gluteus maximus and adductor magnus, two of the largest individual muscles in the human body (10). Consequently, LP produced greater overall lower-limb muscle volume gains than KE. Given that lack of time is a common barrier to exercise participation (60), LP may be recommended as a highly time-efficient exercise for increasing general lower-limb muscle mass, including the QF, in untrained individuals. However, KE appears essential for specifically targeting the rectus femoris, which may be clinically relevant due to its high susceptibility to strain injuries.

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FIGURE LEGENDS

Figure 1. Illustrations of the knee extension (A) and leg press (B) exercises.

Figure 2. Example axial MRI images and anatomical cross-sectional areas (ACSA) of the analyzed individual muscles.

Figure 3. Muscle volumes of the quadriceps femoris before and after training and their changes. In each subfigure, raw data for the knee extension (KE) and leg press (LP) conditions are plotted on the upper axes; each pair of pre- and post-training observations is connected by a line. On the lower axes, paired mean differences are plotted as bootstrap sampling distributions (5,000 samples, bias-corrected and accelerated) (61). Mean differences are shown as dots with horizontal dashed lines, and 95% confidence intervals are indicated by the ends of the vertical error bars. *$P < 0.05$, pre vs post. †$P < 0.05$, KE vs. LP.

Figure 4. Muscle volumes of the gluteus femoris before and after training and their changes. In each subfigure, raw data for the knee extension (KE) and leg press (LP) conditions are plotted on the upper axes; each pair of pre- and post-training observations is connected by a line. On the lower axes, paired mean differences are plotted as bootstrap sampling distributions (5,000 samples, bias-corrected and accelerated) (61). Mean differences are shown as dots with horizontal dashed lines, and 95% confidence intervals are indicated by the ends of the vertical error bars. *$P < 0.05$, pre vs post. †$P < 0.05$, KE vs. LP.

Figure 5. Muscle volumes of the adductor muscles and sartorius before and after training and their changes. In each subfigure, raw data for the knee extension (KE) and leg press (LP) conditions are plotted on the upper axes; each pair of pre- and post-training observations is connected by a line. On the lower axes, paired mean differences are plotted as bootstrap sampling distributions (5,000 samples, bias-corrected and accelerated) (61). Mean differences

are shown as dots with horizontal dashed lines, and 95% confidence intervals are indicated by the ends of the vertical error bars. **P* < 0.05, pre vs post. †*P* < 0.05, KE vs. LP.

Figure 6. Muscle volumes of the hamstrings before and after training and their changes. In each subfigure, raw data for the knee extension (KE) and leg press (LP) conditions are plotted on the upper axes; each pair of pre- and post-training observations is connected by a line. On the lower axes, paired mean differences are plotted as bootstrap sampling distributions (5,000 samples, bias-corrected and accelerated) (61). Mean differences are shown as dots with horizontal dashed lines, and 95% confidence intervals are indicated by the ends of the vertical error bars. **P* < 0.05, pre vs post. †*P* < 0.05, KE vs. LP.

Figure 7. Muscle volumes of each muscle group before and after training and their changes. In each subfigure, raw data for the knee extension (KE) and leg press (LP) conditions are plotted on the upper axes; each pair of pre- and post-training observations is connected by a line. On the lower axes, paired mean differences are plotted as bootstrap sampling distributions (5,000 samples, bias-corrected and accelerated) (61). Mean differences are shown as dots with horizontal dashed lines, and 95% confidence intervals are indicated by the ends of the vertical error bars. *P < 0.05, pre vs post. †P < 0.05, KE vs. LP. QF, quadriceps femoris; GLUT, gluteus muscles; ADD, adductor muscles; HAM, hamstring muscles; ALL, all analyzed muscles.

SUPPLEMENTAL DIGITAL CONTENT

SDC 1: Supplemental Digital Content.pdf

Table 1. Muscle volume of individual muscles and muscle groups pre and post knee extension (KE) and leg press (LP) interventions.

	KE			LP			Interaction	Time effect
	Pre	**Post**	***g***	**Pre**	**Post**	***g***	***P***	***P***
Volume of individual muscles (cm³)								
Rectus femoris	233.3 ± 54.5	264.2 ± 70.3 *	0.48	236.8 ± 55.2	239.5 ± 56.1	0.05	< 0.001	< 0.001
Vastus lateralis	584.8 ± 140.2	622.2 ± 149.4 *	0.25	581.3 ± 136.8	617.4 ± 145.2 *	0.25	1.000	0.004
Vastus medialis	398.5 ± 91.4	427.0 ± 106.0 *	0.28	404.9 ± 96.4	429.1 ± 107.3 *	0.23	1.000	0.004
Vastus intermedius	473.3 ± 153.8	496.7 ± 164.0 *	0.14	468.9 ± 129.1	489.5 ± 140.9 *	0.15	1.000	0.026
Gluteus maximus	831.0 ± 157.1	832.6 ± 137.7	0.01	850.8 ± 153.9	981.9 ± 175.6 *	0.78	< 0.001	< 0.001
Gluteus medius	290.3 ± 51.5	289.8 ± 51.2	-0.01	290.8 ± 54.7	305.1 ± 58.6	0.25	0.387	0.197
Gluteus minimus	83.9 ± 17.9	85.9 ± 17.2	0.11	83.1 ± 19.4	85.0 ± 15.9	0.11	1.000	0.564
Biceps femoris short head	84.6 ± 18.5	87.6 ± 18.5	0.16	84.6 ± 22.7	86.8 ± 22.0	0.10	1.000	0.164
Biceps femoris long head	173.3 ± 37.4	176.8 ± 38.9 *	0.09	168.8 ± 37.4	177.7 ± 38.8 *	0.23	0.588	0.010
Semitendinosus	166.5 ± 57.6	166.9 ± 56.6	0.01	171.3 ± 55.5	175.4 ± 56.5	0.07	1.000	0.564
Semimembranosus	218.0 ± 51.2	220.9 ± 51.4	0.06	216.4 ± 50.0	221.3 ± 50.5	0.10	1.000	0.197
Adductor magnus	568.7 ± 128.5	563.5 ± 123.7	-0.04	567.5 ± 129.9	602.8 ± 133.5 *	0.26	0.029	0.083
Adductor longus	161.5 ± 40.4	160.8 ± 39.5	-0.02	160.6 ± 45.9	160.7 ± 42.2	0.00	1.000	0.866
Adductor brevis	104.2 ± 23.4	104.6 ± 22.6	0.02	107.5 ± 24.2	108.0 ± 23.6	0.02	1.000	0.863
Pectineus	43.3 ± 18.4	43.3 ± 18.5	0.00	45.4 ± 18.7	47.8 ± 18.2	0.13	1.000	0.564
Gracilis	81.1 ± 23.1	80.0 ± 24.4	-0.04	82.0 ± 26.4	83.8 ± 25.9	0.06	0.822	0.863
Sartorius	125.4 ± 36.0	126.2 ± 37.6	0.02	125.3 ± 35.5	126.3 ± 33.0	0.03	1.000	0.689
Volume of muscle groups (cm³)								
QF	1689.9 ± 415.2	1810.2 ± 461.9 *	0.27	1691.9 ± 394.2	1775.5 ± 425.1 *	0.20	0.319	< 0.001
GLUT	1205.2 ± 202.3	1208.2 ± 183.6	0.01	1224.8 ± 200.1	1372.0 ± 227.0 *	0.67	< 0.001	< 0.001
HAM	642.4 ± 151.1	652.2 ± 151.8 *	0.06	641.0 ± 152.7	661.2 ± 153.0 *	0.13	0.301	< 0.001
ADD	958.8 ± 216.5	952.1 ± 211.6	-0.03	963.1 ± 227.6	1003.0 ± 228.5 *	0.17	0.014	0.049
ALL	4621.7 ± 984.6	4748.9 ± 1010.6 *	0.12	4646.1 ± 970.3	4938.0 ± 1017.5 *	0.29	0.025	< 0.001

Data are mean ± SD. ***g*** = Hedge's ***g*.** * Significant increases from pre to post ($P < 0.05$). QF, quadriceps femoris; GLUT, gluteus muscles; HAM, hamstrings; ADD, adductors; ALL, all muscles analyzed. *P* values were adjusted using the Benjamini–Hochberg method for the individual muscles (17) and muscle groups (4) except for ALL.

Figure 1

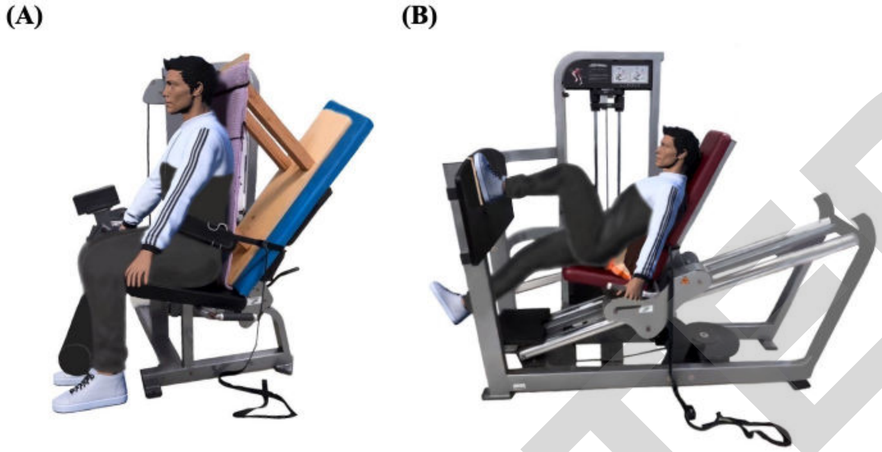
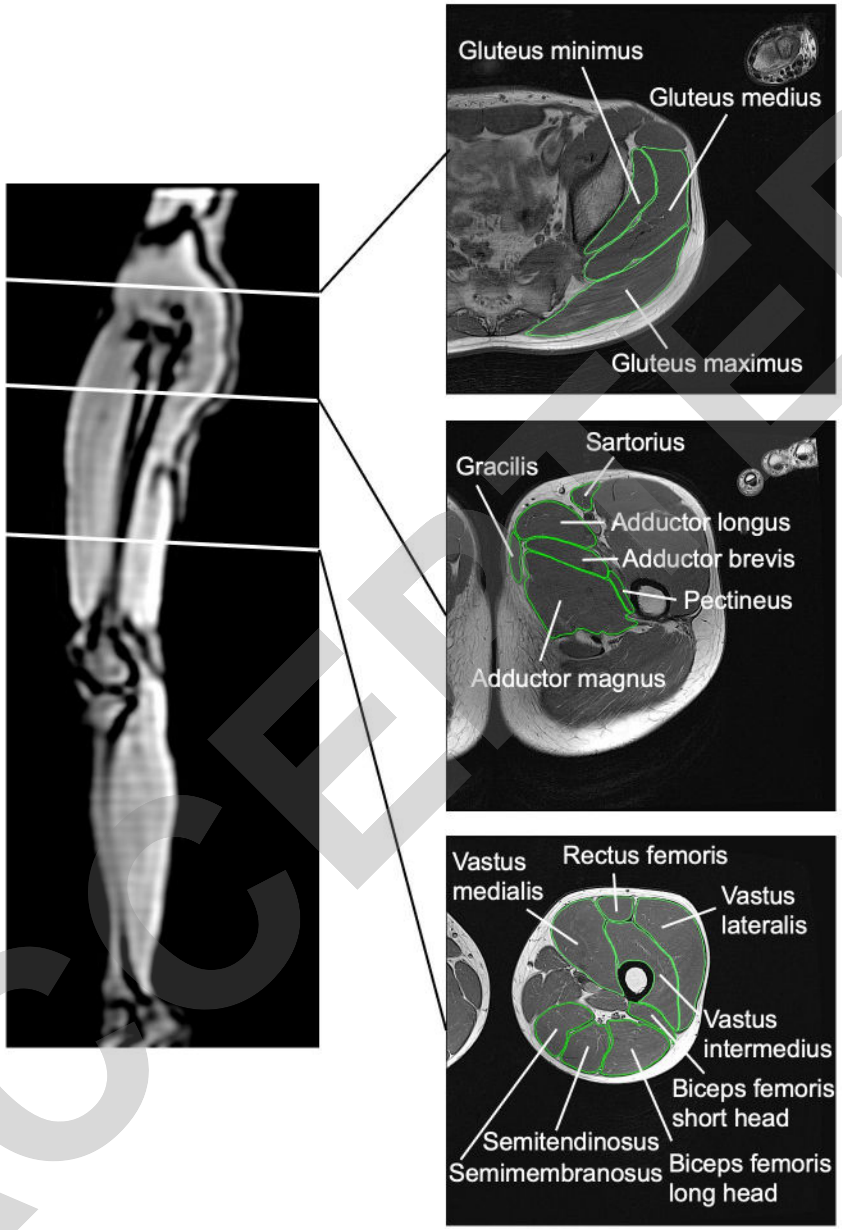
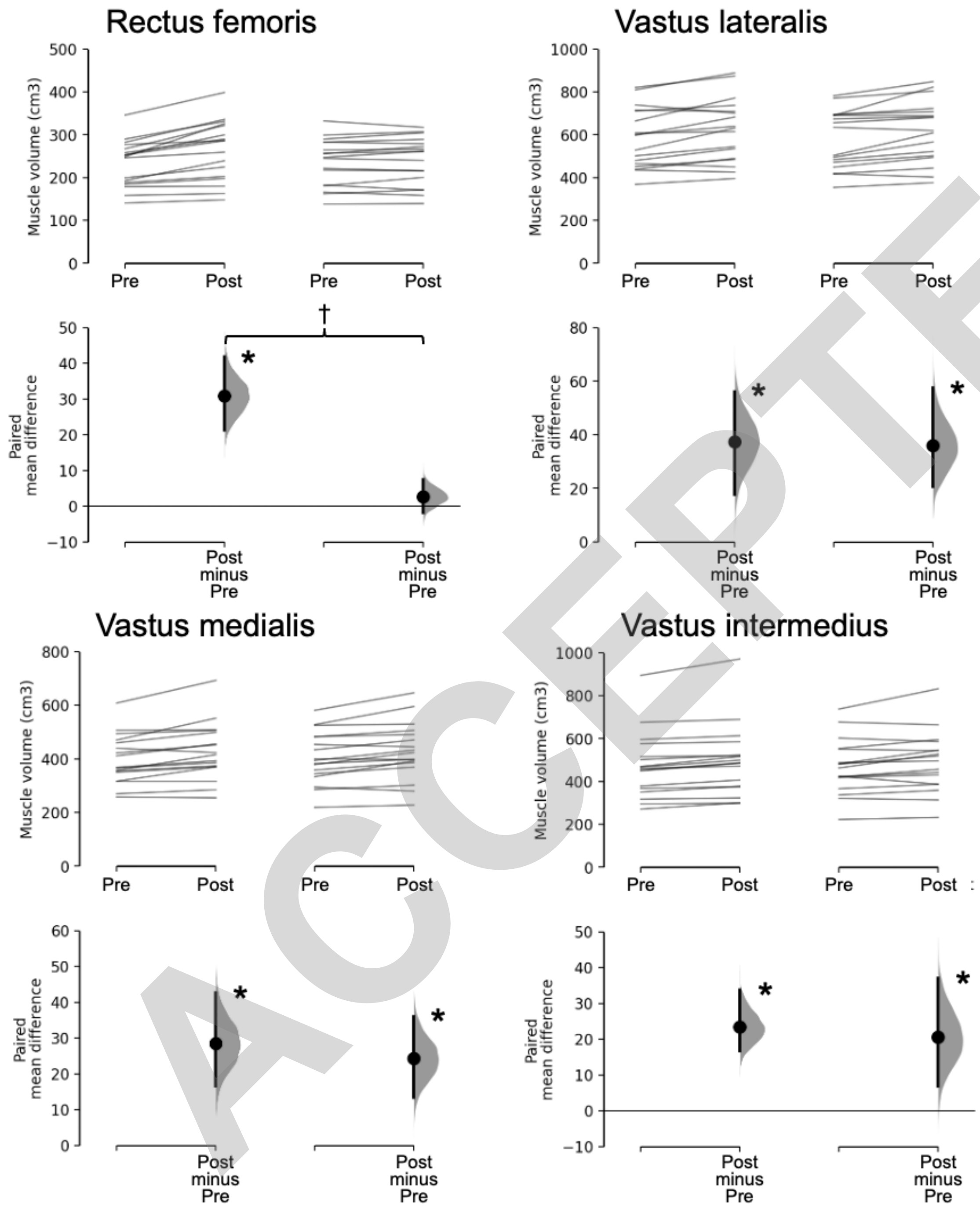


Figure 2



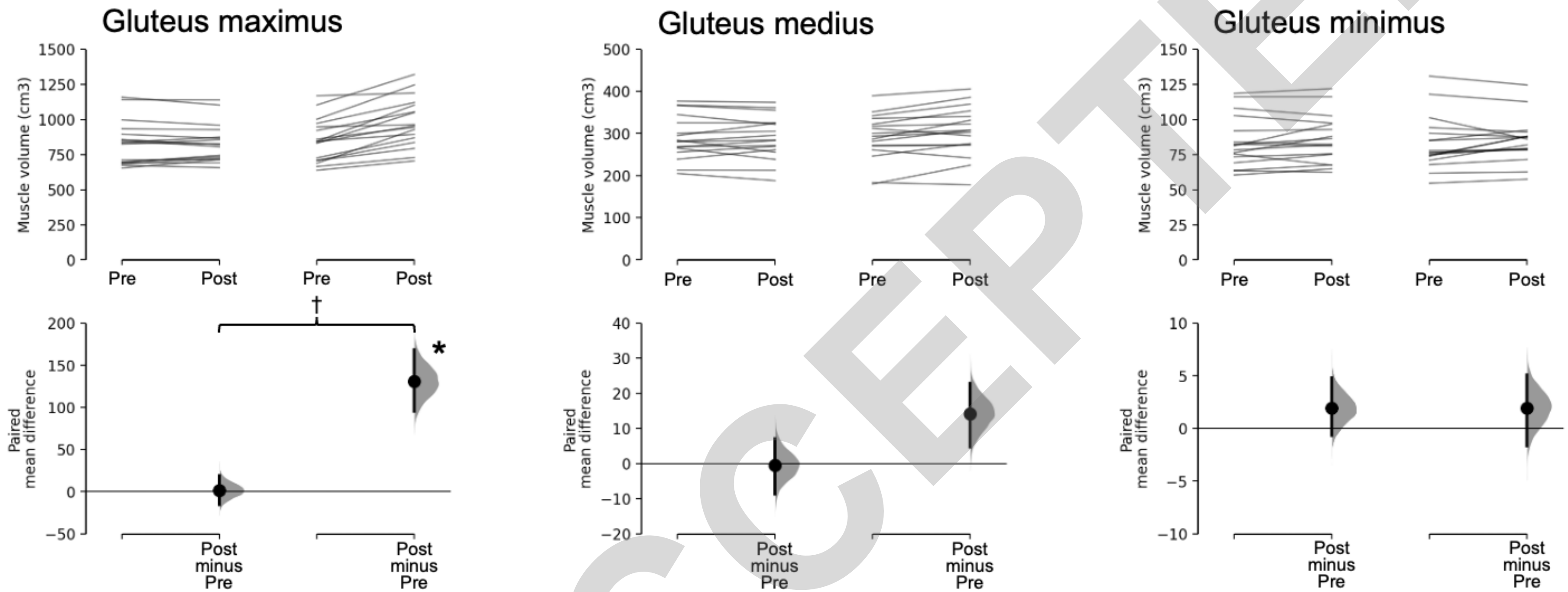
Gluteus minimus
Gluteus medius
Gluteus maximus
Sartorius
Gracilis
Adductor longus
Adductor brevis
Pectineus
Adductor magnus
Vastus medialis
Rectus femoris
Vastus lateralis
Vastus intermedius
Biceps femoris short head
Semitendinosus
Semimembranosus
Biceps femoris long head

Figure 3



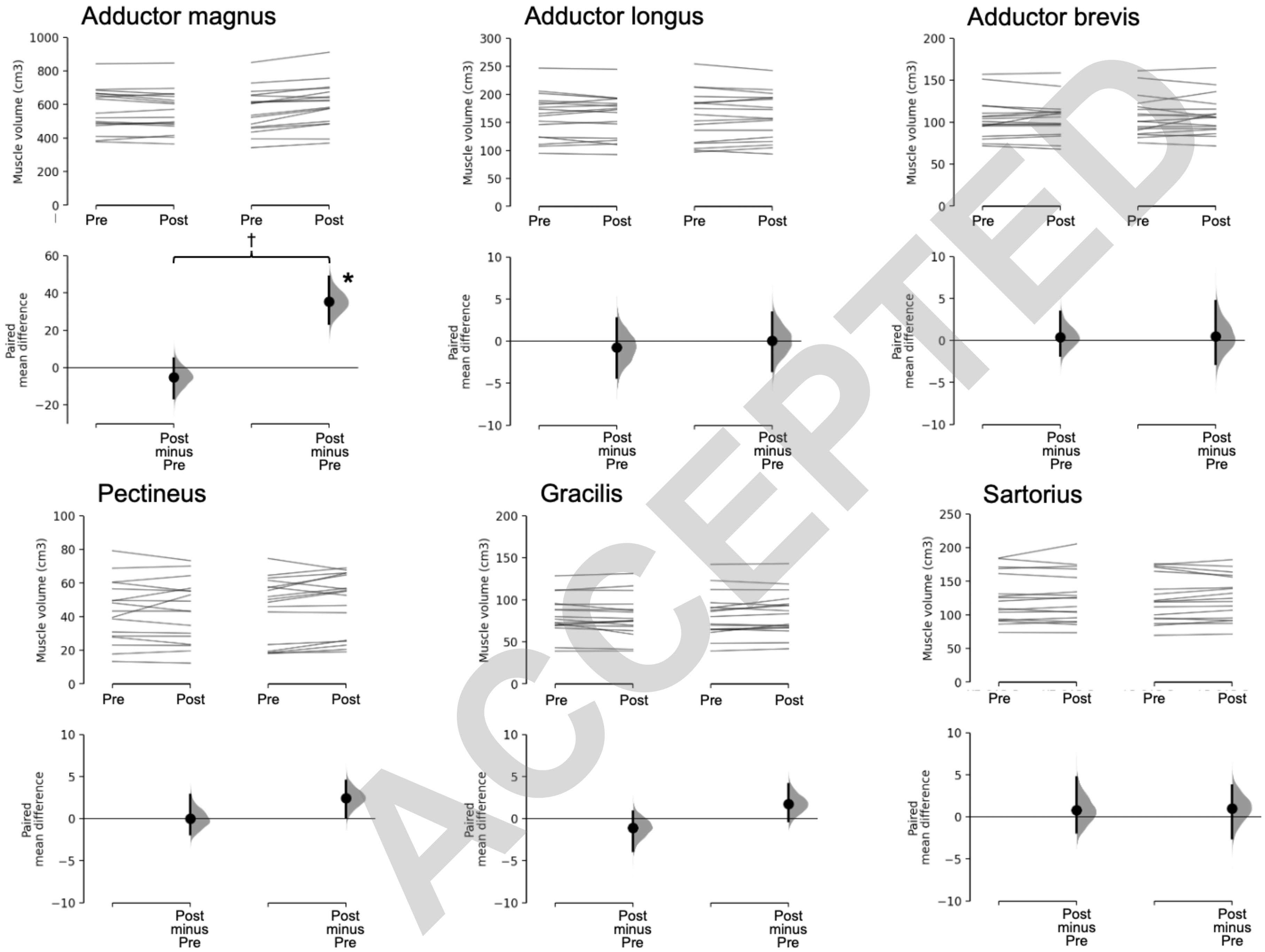
Rectus femoris
Vastus lateralis
Vastus medialis
Vastus intermedius
Muscle volume (cm3)
Paired mean difference
Pre
Post
Post minus Pre
†
*

Figure 4



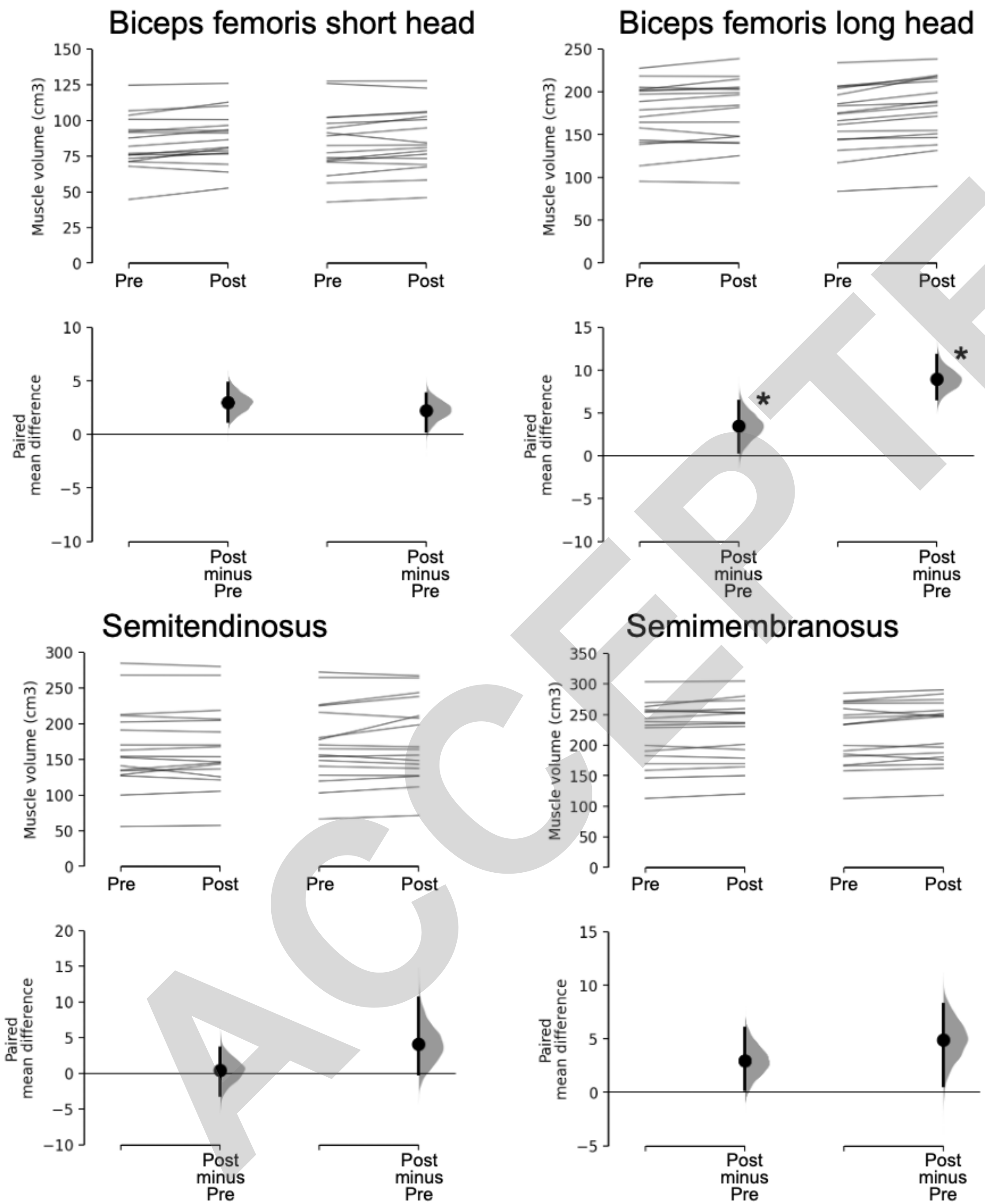
Gluteus maximus
Gluteus medius
Gluteus minimus
Muscle volume (cm3)
Paired mean difference
Pre
Post
Post minus Pre
†
*

Figure 5



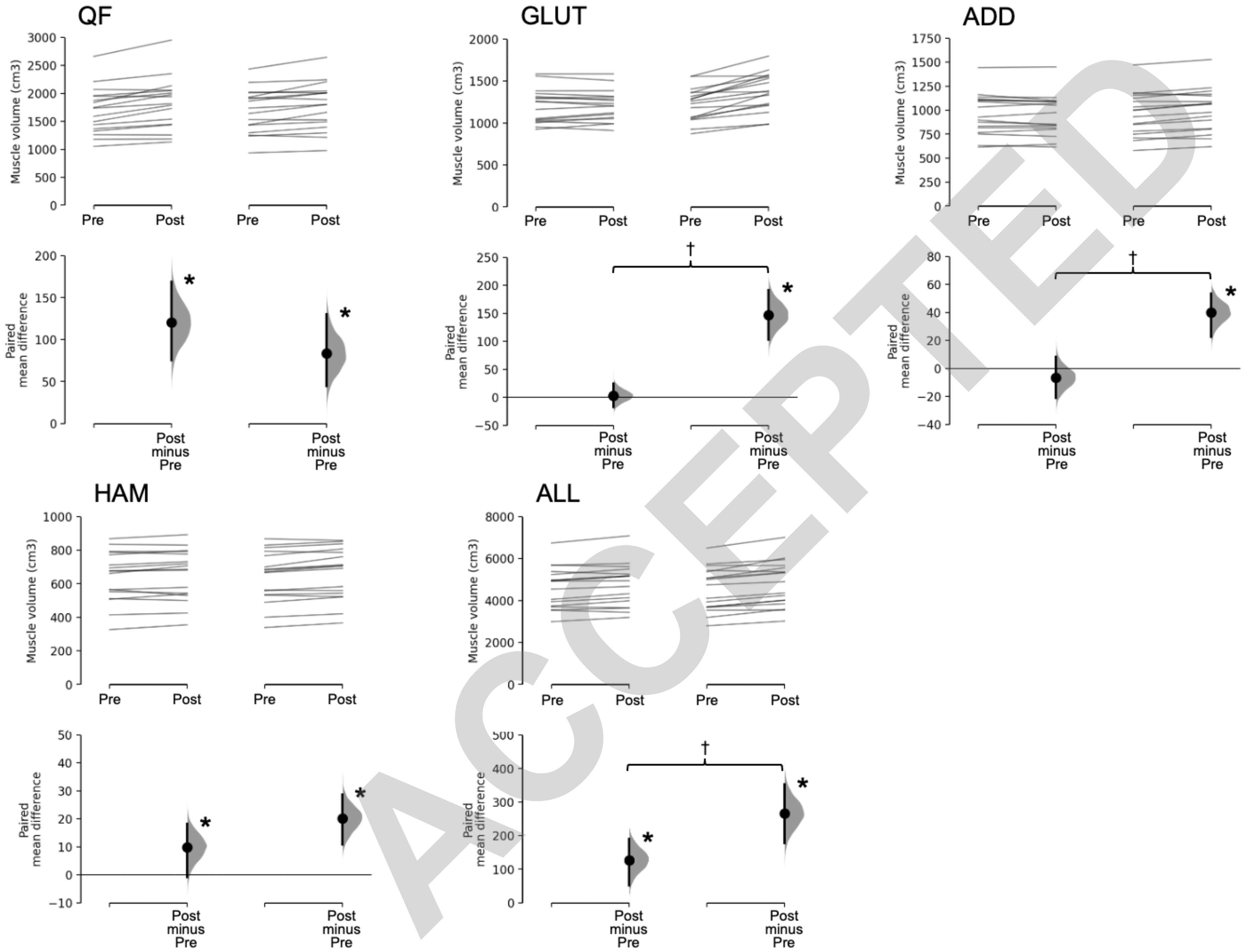
Adductor magnus
Adductor longus
Adductor brevis
Muscle volume (cm3)
Paired mean difference
Pre
Post
Post minus Pre
†
*
Pectineus
Gracilis
Sartorius

Figure 6



Biceps femoris short head
Biceps femoris long head
Semitendinosus
Semimembranosus
Muscle volume (cm3)
Paired mean difference
Pre
Post
Post minus Pre
*

Figure7


QF
GLUT
ADD
HAM
ALL
Muscle volume (cm3)
Pre
Post
Paired
mean difference
Post
minus
Pre
*
†