Journal of Electromyography and Kinesiology 63 (2022) 102643

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Activation training facilitates gluteus maximus recruitment during weight-bearing strengthening exercises

Jordan Cannon, Beverly A. Weithman, Christopher M. Powers *

Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory, Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, USA

ARTICLE INFO

Keywords:
Gluteus maximus
Isometric training
Activation training
Recruitment
Electromyography
Neuromuscular adaptation

ABSTRACT

Given its tri-planar action at the hip, strengthening of gluteus maximus (GMAX) has been advocated as part of rehabilitation and injury prevention protocols for various musculoskeletal conditions. However, recruitment of GMAX during weight-bearing strengthening exercises can be challenging owing to the muscular redundancy at the hip for a given joint motion. The current study sought to determine if a 1-week activation program could result in greater GMAX recruitment during functional strengthening exercises. Pre- and post-training surface electromyography were collected from 12 healthy participants as they performed double- and single-leg squats. Between testing sessions, participants completed a GMAX activation training program consisting of isometric exercises with band resistance (twice per day for 7 days). Following the 1-week activation program, GMAX recruitment was found to increase by 57% during the double-leg squat ($p = 0.005$, Cohen's $r = 0.73$) and 53% during the single-leg squat ($p = 0.006$, Cohen's $r = 0.70$). Implementation of an initial GMAX activation program should be considered to facilitate neuromuscular adaptations that facilitate utilization of GMAX during hip strengthening exercises.

1. Introduction

Altered hip mechanics owing to inadequate use of the gluteal musculature has been linked to several musculoskeletal conditions. Specifically, excessive hip adduction and internal rotation during dynamic tasks have been identified as being contributory to femoroacetabular impingement (Bagwell and Powers, 2017; Cannon et al., 2020; Jorge et al., 2014), patellofemoral pain (Liao et al., 2015; Powers et al., 2003; Powers, 2010; Reiman et al., 2009; Souza and Powers, 2009), iliotibial band syndrome (Powers, 2010; Reiman et al., 2009), and tears of the anterior cruciate ligament (Hewett et al., 2005; Powers, 2010; Reiman et al., 2009). Additionally, reduced hip flexion angles and diminished hip extensor moments during landing tasks have been reported to increase loading and energy absorption at the knee (Kulas et al., 2012; Pollard et al., 2010; Stearns et al., 2013). Therefore, optimizing recruitment and strengthening of the gluteal muscles to prevent aberrant lower extremity motions is desirable from a clinical standpoint.

Given its role as a hip extensor, abductor, and external rotator, weakness and/or insufficient use of gluteus maximus (GMAX) has been identified as a potential contributor to abnormal lower extremity kinematics (Hewett et al., 2010; Powers, 2010; Powers and Fisher, 2010). This premise is supported by the findings of previous investigations that have reported greater use of GMAX during dynamic tasks is associated with a reduction in aberrant motions at the hip and knee (Atkins et al., 2021; Barton et al., 2013; Cannon et al., 2021, 2019; Hollman et al., 2020, 2014; Souza and Powers, 2009; Zazulak et al., 2005). As a result of its tri-planar action at the hip, strengthening of gluteus maximus has been advocated as part of rehabilitation and injury prevention protocols for various musculoskeletal conditions.

Targeted and isolated muscle training has been recommended prior to complex multi-joint strengthening tasks to elicit balanced increases in muscle strength among synergists and enable desired changes in movement patterns (Stastny et al., 2016; Stronska et al., 2020). Specific to GMAX, recruitment during weight-bearing strengthening exercises can be challenging owing to the muscular redundancy at the hip for a given joint motion. For example, hip extension exercises may not provide a sufficient strengthening stimulus for GMAX if other synergists such as the hamstrings or adductor magnus are recruited to a greater degree to meet the demands. This potentially is problematic as the hamstrings and adductor magnus also function as hip adductors and

* Corresponding author at: Musculoskeletal Biomechanics Research Laboratory, Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, USA.

E-mail address: powers@pt.usc.edu (C.M. Powers).

https://doi.org/10.1016/j.jelekin.2022.102643
Received 24 August 2021; Received in revised form 2 November 2021; Accepted 30 November 2021
Available online 9 February 2022
1050-6411/

internal rotators, and if recruited without adequate activation of GMAX, may contribute to the hip motions known to be contributory to the aforementioned musculoskeletal conditions. For this reason, it has been proposed that preparatory activation training of the GMAX may be necessary to ensure adequate recruitment while performing hip strengthening exercises (Fisher et al., 2016).

In a previous publication, our group evaluated whether activation training could be used to increase neural drive of GMAX (Fisher et al., 2016). Specifically, transcranial magnetic stimulation (TMS) was used to evaluate whether corticomotor excitability of GMAX could be enhanced following a 1-week activation program. Input-output curves (IOC) were assessed for motor evoked potential (MEP) amplitude and cortical silent period (CSP) duration across varying stimulation intensities and compared pre-training and post-training. Following the activation program, the IOC slope was found to be significantly greater for MEP amplitude and CSP duration, indicating enhanced capability to recruit GMAX via both excitatory and inhibitory mechanisms (Fisher et al., 2016).

Although targeted activation training of GMAX has been shown to elicit greater corticomotor excitability, it is not known whether these neuroplastic changes result in greater activation during weight-bearing exercises. If it can be shown that activation training increases GMAX recruitment during weightbearing hip strengthening exercises, this may result in greater potential for strengthening and utilization of GMAX during movement in the later stages of preventative or rehabilitative training programs. As such, the purpose of the current study was to determine if an activation program can increase recruitment of GMAX during functional weight-bearing exercises. We hypothesized that following the 1-week activation program, GMAX recruitment would be increased during double-leg and single-leg squat exercises.

2. Methods

2.1. Participants

Twelve healthy volunteers (5 female, 7 male) were recruited for this study (Table 1). The number of participants was based on the sample size of Fisher et al. (2016) who demonstrated that 12 participants was sufficient to demonstrate a significant change in corticomotor excitability of GMAX following a 1-week activation training program. Participants were included if they were physically active (regularly engaged in some form of exercise 3–4 days per week) but not currently taking part in a lower extremity strengthening program. Exclusion criteria included current or chronic pain in the low back or lower extremity joints, a history of injury, trauma, or surgery to the low back or lower extremities, pregnancy, and an inability to adhere to the 7-day intervention program. Prior to the beginning of the study, participants provided written informed consent as approved by the Institutional Review Board of the Health Sciences Campus at the University of Southern California.

2.2. Study overview

The current investigation was a pre-post test design. Participants visited the laboratory for instrumented data collection (EMG and lower extremity kinematics and kinetics) on two separate occasions, 7 days apart. Between the data collection sessions, participants completed the gluteal activation training protocol twice per day (see '*GMAXactivationtraining*' section below for details).

Table 1
Participant information (mean ± standard deviation).

	Female (n = 5)	Male (n = 7)	Total (n = 12)
Age (years)	25.2 ± 1.8	26.1 ± 2.7	25.8 ± 2.3
Height (m)	1.65 ± 0.06	1.73 ± 0.06	1.70 ± 0.07
Weight (kg)	56.2 ± 8.0	73.2 ± 10.2	66.1 ± 12.5 kg

2.3. Pre-training data collection

Surface electromyography (EMG) signals were collected from the gluteus maximus of the right hip using a Noraxon wireless EMG system (Noraxon USA inc., Scottsdale, AZ, USA). Raw EMG signals were pre-amplified with a double-differential input design (baseline noise < 1uV, base gain = 400, common mode rejection ratio > 100 dB, input impedance = 100 MΩ), transferred to a 16-bit analog-to-digital converter, and digitally sampled at a rate of 3000 Hz using Qualisys Track Manager (version 2.14, Qualisys Motion Capture Systems, Gothenburg, Sweden). Prior to electrode placement, the skin was shaved with a new disposable razor, lightly abraded with Nuprep^{TM} (Weaver and Company, Aurora, CA, USA) prepping gel, and cleaned with alcohol. A pre-jelled bipolar Norotrode (Norotrode 20, Myotronics Inc., Kent, WA) rectangular disposable electrode consisting of two 9-mm Ag/AgCl discs with an inter-electrode distance of 20 mm was secured over the muscle belly of GMAX (midway between the mid-sacrum and greater trochanter), parallel to the direction of the gluteus maximus muscle fibers.

Following placement of the EMG electrode, each participant performed a maximum voluntary isometric contraction (MVIC) and a submaximal reference voluntary contraction (RVC) using a motor driven dynamometer (Cybex with HUMAX NORM; Computer Sports Medicine Inc., Stoughton, MA). The RVC was collected for the purposes of EMG normalization to avoid the potential confound of increased neural drive during the MVIC task following completion of the activation program. Participants were positioned prone with the pelvis at the edge of the testing table with the right hip and knee joints flexed to 30° and 90°, respectively. The axis of the dynamometer was aligned with the greater trochanter of the right femur and the resistance pad positioned on the posterior and distal thigh (just proximal to the knee joint) and secured with a strap around the thigh.

At least two MVICs were performed in which participants pushed with maximum effort against the resistance pad for 5 s. A one-minute rest period was provided between trials to minimize muscle fatigue. Peak hip extension torque was recorded as the largest magnitude of the two MVIC trials. For the RVC procedure, participants remained in the same position and were instructed to produce a hip extension torque equal to 75% of the magnitude of the peak hip extensor torque for 5 s. Participants were provided visual feedback with a horizontal line indicating the target magnitude. The absolute torque of the target magnitude was recorded for each participant to be used in the post-training data collection (see below). Utilization of peak EMG amplitude from a submaximal RVC task with a relative resistance that is consistent within participants has been recommended for normalization purposes to compare EMG amplitudes pre- and post-training (Besomi et al., 2020).

Next, participants were instrumented for motion capture. Kinematic and kinetic data were collected to ensure the squat exercises were performed similarly before and after the activation training program, such that any differences in GMAX recruitment could be attributed to the training program and not differing movement strategies (see data analysis section below for details). Reflective markers were adhered to the skin over the following bony landmarks bilaterally: distal foot, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral condyles, greater trochanters, iliac crests, anterior superior iliac spines, and posterior superior iliac spines, as well as on the L5-S1 junction. Rigid body plates containing a minimum of 3 reflective markers, to track lower extremity segment motion, were adhered bilaterally over the feet, shank, and thigh segments. An 11-camera motion capture system (Qualisys, Gothenburg, Sweden) tracked three-dimensional coordinates of reflective markers at a sampling rate of 250 Hz. Ground reaction forces and moments were recorded from two in-ground force plates (AMTI, Watertown, Mass, USA) oriented adjacent to one another sampled at a rate of 1500 Hz.

A standing calibration trial was collected prior to data collection.

EMG, kinematic, and kinetic data were collected during a double-leg squat and single-leg squat. These exercises were selected since they are commonly prescribed exercises in lower extremity rehabilitation programs (Boren et al., 2011; McCurdy et al., 2018; Reiman et al., 2012). The double-leg squat was performed with the feet pelvis width apart, parallel to one another, with one foot on each force plate. A metronome was used to control movement speed and was set at 80 BPM. Participants were instructed to descend and ascend at a rate such that the squat cycle was 1.5 s. The single-leg squat task was performed with the right limb on the force plate and the non-weightbearing knee joint (left) flexed to 90°. Participants squatted at a self-selected speed to maintain balance and perform the task in a controlled manner. Participants were instructed to descend as deep as possible for both the double- and single-leg squat conditions. Three sets of 3 repetitions (9 total repetitions) were performed for each squat task.

2.4. GMAX activation training

Immediately following the initial data collection session, participants were instructed in the performance of 3 isometric exercises with band resistance: 1) side-lying clam shell, 2) side-lying hip abduction, and 3) quadruped fire-hydrant (Fig. 1). Each of these exercises has been reported to elicit substantial activation of GMAX (Boren et al., 2011; Distefano et al., 2009; Selkowitz et al., 2016, 2013). The quadruped fire-hydrant was the exercise utilized in the activation program that previously demonstrated increased corticomotor excitability of GMAX (Fisher et al., 2016). The side-lying clam and side-lying hip abduction exercises were included based on the work of Selkowitz et al. (2013) who reported high gluteus maximus activation for dynamic versions of these exercises. For all exercises, resistance bands (mini exercise bands, 9″ x 2″; Perform Better, Cranston, RI, USA) were positioned around the distal thigh just proximal to the knee joints.

For the side-lying clamshell exercise, participants were positioned in side-lying with their legs together and hips flexed to 45°, and knees flexed to 90°. Participants were instructed to raise the top knee towards the ceiling via hip external rotation as much as they could while keeping the feet together. Care was taken to ensure that there was no backward roll of the pelvis or rotation of the spine.

For the side-lying hip abduction exercise, participants also were positioned in side-lying with their legs together and the head, shoulders, hips, knees, and feet aligned. The top leg was then raised (with the knee extended) up towards the ceiling and slightly backwards via hip abduction and extension. Care was taken to ensure there was no backward rolling or rotation of the pelvis or spine.

For the quadruped fire-hydrant exercise, participants began on their hands and knees in a neutral spine posture with the hands directly below the shoulders and knees directly below the hips. Participants were instructed to lift one leg backwards, to the side, and to rotate the knee towards the ceiling such that the hip was in a position of approximately 20° of flexion, 45° of abduction, and 30° of external rotation. Again, care was taken to avoid any rotation in the pelvis or spine and without leaning towards the contralateral side.

Two resistance bands of increasing resistance levels were provided to each participant at the beginning of the training program. Each participant started at either the lowest (yellow) or middle (green) resistance level, depending on how challenging the first session was and how long they could hold the position at the lowest resistance level. If participants could not hold each exercise for a full minute at the lowest resistance level, they started the training program at the lowest resistance level (yellow) for all exercises. If participants could comfortably hold each exercise for one minute at the lowest resistance level, they started the training using the middle resistance level (green) for all exercises. Once participants could comfortably hold each exercise for one minute with the assigned resistance band they progressed to the more advanced level of middle (green) or highest (blue) resistance for the remainder of the training program.

For each exercise, participants were instructed to move into the desired position with a focus on form and posture. After verbal confirmation from each participant that the exercise was targeting the GMAX (based on what muscle they felt working), participants were instructed to hold the position for 1 min. A static isometric hold was chosen over a dynamic motion for consistency with the training program that previously demonstrated increased corticomotor excitability of GMAX (Fisher et al., 2016). Participants who could not hold the position for 1 min were told to hold the position for as long as possible.

Similar to Fisher et al. (2016), participants completed three isometric holds of each exercise, on each limb, twice a day for seven days. Participants were encouraged to space the two sessions into morning and evening each day to avoid muscle fatigue. Of the 14 training sessions performed, at least 4 were supervised by a research assistant. During supervised sessions participants were manually cued if they showed compensatory motions such as considerable rotation of the pelvis or spine. Participants kept training logs that tracked each session and progression to greater resistance which were submitted upon completion of the study.

2.5. Post-training data collection

Following the completion of the 1-week activation program, participants returned to the lab for follow-up EMG, kinematic, and kinetic assessment. EMG data were first collected as participants performed the RVC task to the target magnitude established in the initial data collection session (75% of the maximum hip extensor torque elicited during pre-training data collection session). Following the RVC assessment, participants performed the double-leg squat and single-leg squat exercises using the same experimental procedures described above.

2.6. Data processing and analysis

Marker coordinate and analog force plate data were low-pass second order Butterworth filtered (dual-pass) to produce a final cut-off frequency of 6 Hz and 12 Hz, respectively. Using Visual 3D software (C-Motion, Rockville, MD), three-dimensional joint kinematics were calculated for the ankle, knee, and hip using Cardan rotation sequences of X-Y-Z, corresponding to sagittal-frontal-transverse planes at the joint. Force plate data were down sampled to 250 Hz for time synchronization with kinematic data. Internal net joint moments were calculated at the right ankle, knee, and hip using inverse dynamics. Net joint moments

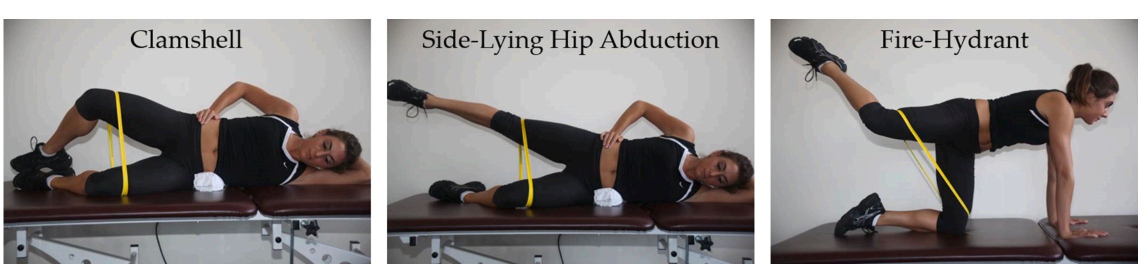

Fig. 1. Isometric exercises included in the gluteus maximus activation training protocol.

were normalized to body mass.

Digital processing of the EMG signals included removing the direct current bias before being bandpass filtered between 30 and 500 Hz using a second-order dual-pass Butterworth filter. EMG signals were then full wave rectified and low-pass filtered using a second-order single-pass Butterworth filter with a 2.5 Hz cut-off frequency to produce a linear envelope (Winter, 2009). EMG signals from the pre- and post-training sessions were normalized to the peak magnitude during the corresponding day's RVC task.

The primary variable of interest was the mean GMAX EMG during the descent phase of each squat. The decent phase was defined as the period from upright standing position to peak hip flexion and was the period of interest given that eccentric action of the GMAX is important for controlling the motions of flexion, adduction, and internal rotation during the deceleration phase of athletic movements (Cannon et al., 2021; Hollman et al., 2020; Robertson et al., 2008; Zazulak et al., 2005). To ensure squat exercises were performed similarly between testing days peak hip flexion angles, peak hip extensor moments, and descent times for both squat tasks were calculated.

2.7. Statistical analysis

The Shapiro-Wilk test was conducted to determine the normality of the data. When data were normally distributed, comparison of variables pre- and post-training were conducted using one-tailed paired t-tests. When normality was not satisfied, one-tailed Wilcoxon signed-rank tests for paired samples were used. Post-hoc Bonferroni correction for multiple comparisons were applied to p-values. Effect size estimates were performed using Cohen's r (z-statistic divided by the square root of the sample size) and reported with 95% confidence intervals. Interpretation of effect sizes were as follows: small ($r = 0.1$–0.29), moderate ($r = 0.3$–0.49), or large ($r \geq 0.5$) (Fritz et al., 2012). All statistical analyses were performed in (R Core Team, 2021) with statistical significance set to $p < 0.05$.

3. Results

Peak hip flexion angles, peak hip extensor moments, and descent times for both squat exercises did not differ between testing days (Table 2). Following the 1-week activation program GMAX recruitment was found to significantly increase during each task (Fig. 2). The mean EMG of GMAX during the double-leg squat task increased from 14 ± 6% to 22 ± 11% RVC ($p = 0.005$, Cohen's $r = 0.73$ [0.32, 0.89]). During the single-leg squat task, GMAX EMG increased from 49 ± 21% to 75 ± 34% RVC ($p = 0.006$, Cohen's $r = 0.70$ [0.27, 0.89]).

Table 2
Squat kinematics and kinetics pre-training and post-training.

		Pre	Post	Mean Difference [95% CI]	p-value
Double-Leg Squat	**Descent Time (s)**	0.72 ± 0.03	0.72 ± 0.04	−0.001 [-0.019, 0.016]	0.88
	Peak Hip Flexion Angle (°)	95 ± 12	99 ± 11	3.36 [-0.34, 7.06]	0.07
	Peak Hip Extensor Moment (Nm/kg)	1.52 ± 0.21	1.57 ± 0.24	0.05 [-0.07, 0.17]	0.39
Single-Leg Squat	**Descent Time (s)**	1.16 ± 0.32	1.23 ± 0.24	0.07 [-0.14, 0.29]	0.46
	Peak Hip Flexion Angle (°)	86 ± 15	89 ± 17	2.95 [-1.39, 7.30]	0.16
	Peak Hip Extensor Moment (Nm/kg)	1.68 ± 0.42	1.72 ± 0.50	0.04 [-0.08, 0.16]	0.49

4. Discussion

Consistent with our hypothesis, the results of the current study demonstrated that a 1-week activation training program increased GMAX recruitment during weight-bearing hip strengthening exercises. GMAX EMG was observed to increase significantly post-training during the double-leg squat and single-leg squat by 57% and 53%, respectively. Given the large effect sizes observed for each task (Cohen's $r = 0.73$ and 0.70), we consider the observed changes to be clinically relevant. Peak hip flexion, peak hip extensor moment, and descent times for both squat exercises did not differ pre- and post-training, suggesting that the observed increases in GMAX EMG post-training were not the result of differing movement strategies.

We previously have reported that a 1-week activation training program resulted in heightened corticomotor excitability of GMAX (Fisher et al., 2016). However, functional carry over of the observed neuroplastic changes with respect to improved muscle recruitment during functional tasks was not evaluated. The current study extends the previous work in this area by demonstrating that GMAX activation training improves recruitment during weight-bearing hip strengthening exercises. Although TMS measures were not obtained in the current study, our findings suggest that targeted GMAX activation training elicits neuroplastic adaptations that provide a foundation to increase GMAX utilization during weight-bearing exercises. Future investigations should confirm that activation training both increases corticomotor excitability and recruitment of GMAX during weight-bearing exercises in the same group of participants.

Our finding of improved GMAX recruitment following activation training is in contrast to the findings of Cochrane et al. (2017) who reported no change in GMAX recruitment during a hip extension test following 6 weeks of activation training. It should be noted however, that the activation exercises implemented by Cochrane et al. (2017) were used as a warm-up to a traditional strengthening program as opposed to being evaluated as a stand-alone intervention. Furthermore, direct comparison of the current study to Cochrane et al. (2017) is limited owing to differences in the nature of the activation program (duration, frequency, intensity), the population studied (professional athletes vs. healthy volunteers), and the method of EMG normalization (RVC vs. MVIC). Additional studies have evaluated the influence of GMAX activation exercises and/or warm-up protocols on sprinting, jumping, and landing performance with mixed results (Barry et al., 2016; Comyns et al., 2015; Healy and Harrison, 2014; Parr et al., 2017; Pinfold et al., 2018). However, comparisons to the current study also are limited owing to the varied outcome measures of interest (performance variables vs. muscle activation).

High variability was observed in GMAX EMG in response to the activation training. In general, it appears that individuals with greater GMAX recruitment pre-training were the participants who demonstrated the greatest increase in GMAX recruitment following the activation training (Fig. 2). This suggests that the activation training augmented activation in those with higher GMAX recruitment to begin with and is counter to the premise that those with the lowest pre-training GMAX recruitment are likely to benefit most from the training program. It is possible one week of activation training was not of sufficient duration for participants with low baseline GMAX. Optimal dosing to increase GMAX corticomotor excitability and facilitate transfer to recruitment during weight-bearing exercises currently is unknown and should be the focus of future investigations.

When using EMG, the process of normalization is required to assess changes in muscle activation between days. Typically, EMG signals during a given task are expressed as a percentage of the EMG signal obtained during a reference activity such as a MVIC. The use of a MVIC

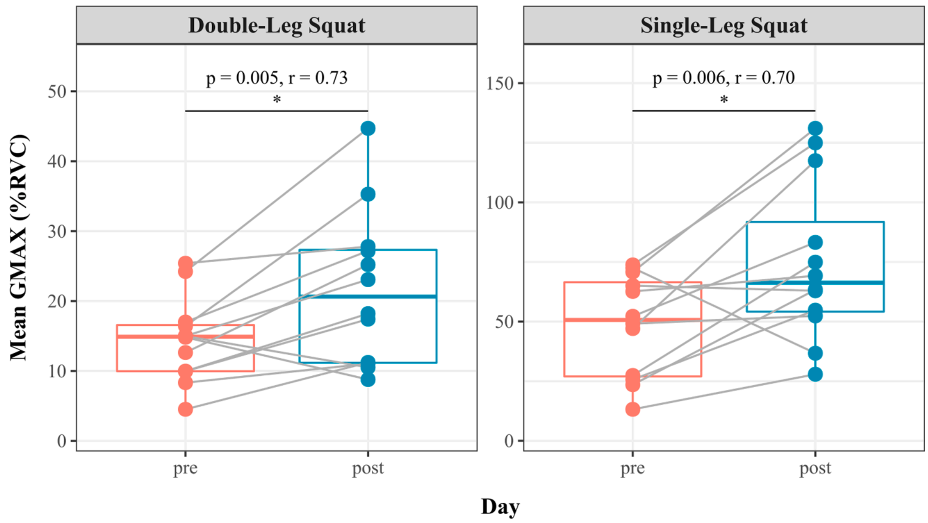

Fig. 2. Boxplots and individual participant changes in gluteus maximus (GMAX) recruitment during the descent phase of double-leg and single-leg squat exercises. The horizontal line of the boxplot indicates median value with the top and bottom boundaries of the box indicating the 25th and 75th percentile.

for normalization purposes presents a challenge when comparing EMG signals before and after an intervention program in which neuromuscular activation is expected to increase. For example, if GMAX neural drive is increased for the post-training MVIC, the effects of the training program could be washed out as the normalized EMG magnitude during the squat exercises could appear the same, or actually decrease, compared to pre-training. To address this issue, we normalized the GMAX EMG data to the same submaximal RVC torque magnitude on both days. However, the possibility exists that GMAX activation during the RVC task also could have increased post-training. If this were the case, an argument could be made that the observed post-training increases in GMAX recruitment during the squat exercises may be underestimated.

The findings of the current study demonstrate the ability of an activation program to enhance GMAX recruitment, and therefore, may improve the capacity for strengthening. While a 1-week activation training program alone would not be expected to elicit muscle hypertrophy, such training may increase the potential to strengthen GMAX through increased recruitment during functional exercises. This is important as muscular redundancy at the hip for joint actions such as hip extension may result in compensatory actions of synergistic muscles (i.e., hamstrings and adductor magnus) that contribute to the undesired motions of hip adduction and internal rotation. Future work should aim to evaluate the long-term effects of GMAX activation training and investigate differences between strengthening programs that include and do not include an initial GMAX activation training component.

The results of the current study should be viewed in light of several limitations. First, only healthy, and active young adults participated. As such, our findings cannot be generalized to older adults or specific patient populations. Second, we did not control for baseline GMAX activation levels or screen for individuals with diminished activation who may benefit most from activation training. Therefore, it is possible that the participants who exhibited the greatest increases in GMAX recruitment were not the participants who would benefit most from activation training. Several other factors may have influenced the response to activation training and transfer to weight-bearing exercises including previous experience with strengthening programs or sporting activities that require high use of GMAX. Lastly, we only evaluated the immediate effects of GMAX activation training. Whether or not such training has long-term carry over remains to be seen.

5. Conclusion

The current study demonstrated that a 1-week GMAX activation program increased GMAX recruitment during functional hip strengthening exercises. Greater GMAX recruitment may increase the availability of the muscle to be utilized during strengthening and movement-based training as part of preventative and rehabilitative training programs. Implementation of initial activation training should be considered to facilitate neuroplastic and neuromuscular adaptations that facilitate strengthening and functional utilization of GMAX.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Atkins, L., James, C., Yang, H., Sizer, P., Brismée, J., Sawyer, S., Powers, C., 2021. Immediate Improvements in Patellofemoral Pain Are Associated with Sagittal Plane Movement Training to Improve Use of Gluteus Maximus Muscle During Single Limb Landing. Phys. Ther. 101 (10), 1–7. https://doi.org/10.1093/ptj/pzab165.

Bagwell, J.J., Powers, C.M., 2017. The Influence of Squat Kinematics and Cam Morphology on Acetabular Stress. Arthrosc. J. Arthrosc. Relat. Surg. 33 (10), 1797–1803. https://doi.org/10.1016/j.arthro.2017.03.018.

Barry, L., Kenny, I., Comyns, T., 2016. Performance effects of repetition specific gluteal activation protocols on acceleration in male rugby union players. J. Hum. Kinet. 54, 33–42. https://doi.org/10.1515/hukin-2016-0033.

Barton, C.J., Lack, S., Malliaras, P., Morrissey, D., 2013. Gluteal muscle activity and patellofemoral pain syndrome: a systematic review. Br. J. Sports Med. 47 (4), 207–214. https://doi.org/10.1136/bjsports-2012-090953.

Besomi, M., Hodges, P.W., Clancy, E.A., Van Dieën, J., Hug, F., Lowery, M., Merletti, R., Søgaard, K., Wrigley, T., Besier, T., Carson, R.G., Disselhorst-Klug, C., Enoka, R.M., Falla, D., Farina, D., Gandevia, S., Holobar, A., Kiernan, M.C., McGill, K., Perreault, E., Rothwell, J.C., Tucker, K., 2020. Consensus for experimental design in electromyography (CEDE) project: Amplitude normalization matrix. J. Electromyogr. Kinesiol. 53, 102438. https://doi.org/10.1016/j.jelekin.2020.102438.

Boren, K., Conrey, C., Coguic, J.L., Paprocki, L., Voight, M., Robinson, T.K., 2011. Electromyographic Analysis of Gluteus Medius and Gluteus Maximus During Rehabilitation Exercises. Int. J. Sports Phys. Ther. 6, 206–223.

Cannon, J., Cambridge, E.D.J., McGill, S.M., 2021. Increased core stability is associated with reduced knee valgus during single-leg landing tasks: Investigating lumbar spine and hip joint rotational stiffness. J. Biomech. 116, 110240. https://doi.org/10.1016/j.jbiomech.2021.110240.

Cannon, J., Cambridge, E.D.J., McGill, S.M., 2019. Anterior Cruciate Ligament Injury Mechanisms and the Kinetic Chain Linkage: The Effect of Proximal Joint Stiffness on Distal Knee Control During Bilateral Landings. J. Orthop. Sport. Phys. Ther. 49 (8), 601–610. https://doi.org/10.2519/jospt.2019.8248.

Cannon, J., Weber, A.E., Park, S., Mayer, E.N., Powers, C.M., 2020. Pathomechanics Underlying Femoroacetabular Impingement Syndrome: Theoretical Framework to Inform Clinical Practice. Phys. Ther. 100, 788–797. https://doi.org/10.1093/ptj/pzz189.

Cochrane, D.J., Harnett, M.C., Pinfold, S.C., 2017. Does short-term gluteal activation enhance muscle performance? Res. Sport. Med. 25 (2), 156–165. https://doi.org/10.1080/15438627.2017.1282358.

Comyns, T., Kenny, I., Scales, G., 2015. Effects of a Low-Load Gluteal Warm-Up on Explosive Jump Performance. J. Hum. Kinet. 46, 177–187. https://doi.org/10.1515/hukin-2015-0046.

Distefano, L.J., Blackburn, J.T., Marshall, S.W., Padua, D.A., 2009. Gluteal muscle activation during common therapeutic exercises. J. Orthop. Sports Phys. Ther. 39 (7), 532–540. https://doi.org/10.2519/jospt.2009.2796.

Fisher, B.E., Southam, A.C., Kuo, Y.-L., Lee, Y.-Y., Powers, C.M., 2016. Evidence of altered corticomotor excitability following targeted activation of gluteus maximus training in healthy individuals. Neuroreport 27, 415–421.

Fritz, C.O., Morris, P.E., Richler, J.J., 2012. Effect size estimates: Current use, calculations, and interpretation. J. Exp. Psychol. 141, 2–18. https://doi.org/10.1037/a0024338.

Healy, R., Harrison, A.J., 2014. The effects of a unilateral gluteal activation protocol on single leg drop jump performance. Sports Biomechanics 13 (1), 33–46. https://doi.org/10.1080/14763141.2013.872288.

Hewett, T.E., Ford, K.R., Hoogenboom, B.J., 2010. Understanding and Preventing ACL Injuries: Current Biomechanical and Epidemiologic Considerations - Update 2010. North Am. J. Sport. Phys. Ther. 5, 234–251.

Hewett, T.E., Myer, G.D., Ford, K.R., Heidt, R.S., Colosimo, A.J., McLean, S.G., van den Bogert, A.J., Paterno, M.V., Succop, P., 2005. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am. J. Sports Med. 33 (4), 492–501. https://doi.org/10.1177/0363546504269591.

Hollman, J.H., Beise, N.J., Fischer, M.L., Stecklein, T.L., 2020. Coupled Gluteus Maximus and Gluteus Medius Recruitment Patterns Modulate Hip Adduction Variability During Single-Limb Step-Downs: A Cross-Sectional Study. J. Sport Rehabil. 30 (4), 625–630. https://doi.org/10.1123/jsr.2020-0005.

Hollman, J.H., Galardi, C.M., Lin, I.-H., Voth, B.C., Whitmarsh, C.L., 2014. Frontal and transverse plane hip kinematics and gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat tests in women. Clin. Biomech. 29 (4), 468–474. https://doi.org/10.1016/j.clinbiomech.2013.12.017.

Jorge, J.P., Simões, F.M.F., Pires, E.B., Rego, P.A., Tavares, D.G., Lopes, D.S., Gaspar, A., 2014. Finite element simulations of a hip joint with femoroacetabular impingement. Computer Methods in Biomechanics and Biomedical Engineering 17 (11), 1275–1284. https://doi.org/10.1080/10255842.2012.744398.

Kulas, A.S., Hortobágyi, T., DeVita, P., 2012. Trunk position modulates anterior cruciate ligament forces and strains during a single-leg squat. Clin. Biomech. 27 (1), 16–21. https://doi.org/10.1016/j.clinbiomech.2011.07.009.

Liao, T., Yang, N., Ho, K., Farrokhi, S., Powers, C.M., Perry, J., Biomechanics, M., Angeles, L., Vegas, L., 2015. Femur rotation increases patella cartilage stress in females with patellofemoral pain. Med. Sci. Sport. Exerc. 47, 1775–1780. https://doi.org/10.1249/MSS.0000000000000617.

McCurdy, K., Walker, J., Yuen, D., 2018. Gluteus Maximus and Hamstring Activation During Selected Weight-Bearing Resistance Exercises. J. Strength Cond. Res. 32, 594–601.

Parr, M., Price, P.D., Cleather, D.J., 2017. Effect of a gluteal activation warm-up on explosive exercise performance. BMJ Open Sport Exerc. Med. 3, 1–8. https://doi.org/10.1136/bmjsem-2017-000245.

Pinfold, S.C., Harnett, M.C., Cochrane, D.J., 2018. The acute effect of lower-limb warm-up on muscle performance. Res. Sport. Med. 26 (4), 490–499. https://doi.org/10.1080/15438627.2018.1492390.

Pollard, C.D., Sigward, S.M., Powers, C.M., 2010. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. Clin. Biomech. 25 (2), 142–146. https://doi.org/10.1016/j.clinbiomech.2009.10.005.

Powers, C.M., Ward, S., Fredericson, M., Guillet, M., Shellock, F., 2003. Patellofemoral Kinematics During Weight-Bearing and Non–Weight-Bearing Knee Extension in Persons With Lateral Subluxation of the Patella: A Preliminary Study. J. Orthop. Sport. Phys. Ther. 33, 687–1685. https://doi.org/10.1007/s00167-006-0045-6.

Powers, C.M., 2010. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J. Orthop. Sport. Phys. Ther. 40 (2), 42–51. https://doi.org/10.2519/jospt.2010.3337.

Powers, C.M., Fisher, B., 2010. Mechanisms underlying ACL injury-prevention training: The brain-behavior relationship. J. Athl. Train. 45, 513–515. https://doi.org/10.4085/1062-6050-45.5.513.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria https://www.r-project.org/.

Reiman, M.P., Bolgla, L.A., Lorenz, D., 2009. Hip functions influence on knee dysfunction: a proximal link to a distal problem. J. Sport Rehabil. 18, 33–46.

Reiman, M.P., Bolgla, L.A., Loudon, J.K., 2012. A literature review of studies evaluating gluteus maximus and gluteus medius activation during rehabilitation exercises. Physiother. Theory Pract. 28 (4), 257–268. https://doi.org/10.3109/09593985.2011.604981.

Robertson, D.G.E., Wilson, J.M.J., St. Pierre, T.A., 2008. Lower extremity muscle functions during full squats. J. Appl. Biomech. 24, 333–339. https://doi.org/10.1123/jab.24.4.333.

Selkowitz, D.M., Beneck, G.J., Powers, C.M., 2016. Comparison of Electromyographic Activity of the Superior and Inferior Portions of the Gluteus Maximus Muscle During Common Therapeutic Exercises. J. Orthop. Sports Phys. Ther. 46 (9), 794–799. https://doi.org/10.2519/jospt.2016.6493.

Selkowitz, D.M., Beneck, G.J., Powers, C.M., 2013. Which Exercises Target the Gluteal Muscles While Minimizing Activation of the Tensor Fascia Lata? Electromyographic Assessment Using Fine-Wire Electrodes. J. Orthop. Sport. Phys. Ther. 43 (2), 54–64. https://doi.org/10.2519/jospt.2013.4116.

Souza, R.B., Powers, C.M., 2009. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. J. Orthop. Sports Phys. Ther. 39 (1), 12–19. https://doi.org/10.2519/jospt.2009.2885.

Stastny, P., Tufano, J.J., Golas, A., Petr, M., 2016. Strengthening the Gluteus Medius Using Various Bodyweight and Resistance Exercises. Strength Cond. J. 38, 91–101. https://doi.org/10.1519/SSC.0000000000000221.

Stearns, K.M., Keim, R.G., Powers, C.M., 2013. Influence of relative hip and knee extensor muscle strength on landing biomechanics. Med. Sci. Sports Exerc. 45, 935–941. https://doi.org/10.1249/MSS.0b013e31827c0b94.

Stronska, K., Golas, A., Wilk, M., Zajac, A., Maszczyk, A., Stastny, P., 2020. The effect of targeted resistance training on bench press performance and the alternation of prime mover muscle activation patterns. Sport. Biomech. https://doi.org/10.1080/14763141.2020.1752790.

Winter, D.A., 2009. Biomechanics and Motor Control Of Human Movement, Fourth Edition. Wiley, Toronto. https://doi.org/10.1002/9780470549148.

Zazulak, B.T., Ponce, P.L., Straub, S.J., Medvecky, M.J., Avedisian, L., Hewett, T.E., 2005. Gender comparison of hip muscle activity during single-leg landing. J. Orthop. Sports Phys. Ther. 35, 292–299. https://doi.org/10.2519/jospt.2005.1734.