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Electromyographical Analysis of Selected Lower Extremity Muscles During 5 Unilateral Weight-Bearing Exercises

Clinicians regularly prescribe unilateral weight-bearing (WB) exercises in an attempt to simulate functional muscle recruitment patterns required for activities of daily living, recreation, and sports.[10] The use of unilateral WB exercises in the rehabilitation of knee dysfunction is supported by extensive analysis of the electromyographic (EMG) signal amplitude of the thigh muscles.[2,5,6,9,10,11,14,17,23,30] These studies support the use of the lateral step-up, maximal 1-legged squat, and forward step-up exercises for improving or targeting quadriceps activation in rehabilitation. More recently, hip muscle weakness has been implicated as a risk factor for knee dysfunction.[13,16,18,20,21,23] However, research documenting the EMG signal amplitude of the hip musculature during unilateral WB exercises is limited.

STUDY DESIGN: Prospective single-group repeated-measures design.

OBJECTIVES: To quantify electromyographic (EMG) signal amplitude of the gluteus maximus, gluteus medius, vastus medialis oblique, and biceps femoris during 5 unilateral weight-bearing exercises.

BACKGROUND: Using normalized EMG (NEMG) signal amplitude as a measure of muscle activation and, therefore, an estimate of exercise intensity, the relative contributions and interaction of the hip and thigh muscles during unilateral weight-bearing exercise can be examined. With regard to potential efficiency for strengthening, data on the amount of EMG signal amplitude for these 4 muscles during commonly used exercises are limited.

METHODS AND MEASURES: Twenty-three healthy, asymptomatic subjects (16 men, 7 women; mean ± SD age, 31.2 ± 5.8 years) participated. A repeated-measures analysis was conducted using general linear models. The percent maximum voluntary isometric contraction was measured within each subject across 4 muscles during 5 exercises for 2 separate trials. Effect sizes of pairwise comparisons were computed.

RESULTS: Statistically significant differences were noted in the amount of mean NEMG signal amplitude for the 4 muscles across the 5 exercises. A similar recruitment pattern between muscles was observed across all exercises.

CONCLUSION: Even though all muscles except the biceps femoris demonstrated mean NEMG signal amplitudes sufficient for strengthening, the wall squat produced the highest levels of activation and should be considered the most efficient for targeting any of the 4 muscles or for training a cooperative effort among the muscles. *J Orthop Sports Phys Ther 2007;37(2):48-55 doi:10.2519/jospt.2007.2354*

KEY WORDS: gluteus maximus, gluteus medius, lower extremity, step-up, wall squat

Bolgla et al[4] reported that WB exercises (left-sided pelvic drop and WB left hip abduction with the hips at 0° and 20° of flexion) demonstrated significantly greater right gluteus medius (GMed) EMG signal amplitude when compared to non–weight-bearing exercises (sidelying right-hip abduction and standing right-hip abduction, with the hip at 0° and 20° of flexion), except for sidelying hip abduction. Few studies have reported on the relative activations of the gluteus maximus (GMax) and GMed either alone or in cooperation with the thigh muscles. The GMax and GMed contribute significantly to postural and functional abilities such as normal gait. Weakness of these muscles may interfere with several phases of the gait cycle, affecting not only movement at the hip joint, but also at the knee and ankle joints.[28,29] Because unilateral WB exercises recruit multiple muscles across multiple joints, resulting in varying activations of different lower extrem-

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ity muscles, a thorough understanding of muscle recruitment patterns is needed.

EMG is a measure of muscle activation, so it is assumed that exercises producing higher EMG signal amplitudes also produce greater strengthening effects. Because there is limited direct evidence of the contribution and interaction of the GMax, GMed, vastus medialis oblique (VMO), and biceps femoris (BF) during unilateral WB exercise, the purpose of this study was to quantify muscle activation patterns of these 4 muscles using EMG during 5 unilateral, WB exercises: the wall squat, mini-squat, forward step-up (FSU), lateral step-up (LSU), and retro step-up (RSU). Our hypothesis was that there would be no differences in EMG signal amplitude for any of the muscles across the 5 unilateral WB exercises.

METHODS

Subjects

Twenty-three physically active Department of Defense beneficiaries (16 males, 7 females; mean ± SD age, 31.2 ± 5.8 years; mean ± SD height, 173.1 ± 10.1 cm; mean ± SD body mass, 77.0 ± 13.9 kg) volunteered for this study. All subjects gave their written consent before participating in this study. A brief medical history and physical examination were performed by a licensed physical therapist. Inclusion and exclusion criteria are listed in **TABLE 1**. This study was approved by the Institutional Review Board, Tripler Army Medical Center, Honolulu, HI.

Orientation

On the day of testing each subject received a brief screening examination, signed the informed consent, and was oriented to the testing protocol. All testing was performed on the dominant leg, defined as the leg used to kick a ball (22 right, 1 left). The protocol was sequenced as follows: warm-up, electrode placement, practice and familiarization, maximum voluntary isometric contraction (MVIC) testing, and exercise testing.

TABLE 1 Inclusion and Exclusion Criteria for Participation in the Study

INCLUSION
◉ Age range, 18-65 y
◉ Bilateral lower extremity range of motion within normal limits
◉ Bilateral lower extremity strength with manual muscle testing 5/5
◉ Able to perform single-limb balance with eyes open for 30 seconds
◉ Department of Defense beneficiary
EXCLUSION
◉ History of surgery for spine or lower extremities
◉ History of disease affecting the spine or lower extremities, such as diabetes, peripheral neuropathy, stroke, arthritis, or fibromyalgia
◉ Unresolved lower extremity pathology or current pain in the spine or lower extremities
◉ Taking any medications

Setup Procedures

After a 10-minute warm-up on a cycle ergometer at a submaximal speed, each subject was prepared for surface EMG electrode placement. The skin was debrided and cleansed with an isopropyl alcohol pad to help reduce skin impedance. EMG recording electrodes were placed according to referenced muscle placement for the most effective measurement.[22] For the GMax the electrode was placed 34% of the distance from the second sacral vertebra to the greater trochanter, starting from the second sacral vertebra.[22] For the GMed the electrode was placed 33% of the distance from the iliac crest to the greater trochanter, starting from the greater trochanter.[22] For the VMO the electrode was placed 52 mm from the superior medial side of the patella, along a line medially oriented at an angle of 50° from a line joining the anterior superior iliac spine and the superior medial side of the patella. For the BF the electrode was placed 35% of the distance from the ischial tuberosity to the lateral side of the popliteal fossa, starting from the ischial tuberosity.[22] Differential electrodes were used with an interelectrode distance of 30 mm in line with the orientation of the muscle fibers. Ground electrode sites were prepared on the proximal fibular head and the iliac crest in the same manner as the other placements. To ensure consistency with electrode placement, the same investigator placed all electrodes. After electrode placement, each subject was instructed in how to perform each of the 5 unilateral WB exercises. The exercises were first demonstrated by a research member. Then the subject practiced and demonstrated each exercise, receiving corrective feedback as needed.

EMG Equipment and Processing

Muscle activity of the GMax, GMed, VMO, and BF was recorded using Ag/AgCl NuTab disposable electrodes and clear adhesive hydrogel. The same EMG equipment and processing were used for both MVIC and specific exercises. The Nicolet Viking IV EMG system (Nicolet Biomedical, Madison, WI), with a 4-channel remote amplifier, was used for data collection with a sampling frequency of 20 kHz. Raw data were band pass filtered at 30 Hz to 10 kHz using Nicolet MultiMode Plus program software (Version 5.1; Nicolet Biomedical, Madison, WI). The common-mode rejection ratio was greater than 110 dB at 50 to 60 Hz. The signal was full-wave rectified then integrated over the period of 1.5 seconds, and amplitude was normalized by the muscle-specific values obtained during the MVICs. Data were therefore expressed as a percentage of the MVIC.[25]

MVIC Testing

The Biodex System 2 isokinetic dynamometer (Biodex Corporation, Shirley, NY) was used to test MVIC for each of the 4 muscles in accordance with testing procedures listed in the Biodex System 2 instruction manual. For GMax testing the subject was placed supine and secured with chest and pelvic straps. The hip was placed in 30° of flexion, with the fixed resistance pad placed just proximal to the popliteal fossa (**FIGURE 1**). For GMed testing the subject was placed in sidelying, tested side up, with the hip in 0° abduction and neutral flexion/extension with the fixed resistance pad over the lateral femoral condyle. The hip and knee of the nontested leg were flexed for support. A strap was placed over the pelvis for proximal stabilization (**FIGURE 2**). For VMO and BF testing the subject was seated with the hip in 90° of flexion. The tested knee was placed in 60° of flexion, with the fixed resistance pad placed at the distal tibia. Straps were used to improve reliability for generating a MVIC.[19] The order of muscle testing was randomized. Standardized verbal encouragement, a proven technique for eliciting a maximum contraction, was given to each subject for all MVIC testing.[6]

FIGURE 1. Maximum voluntary isometric contraction testing of the gluteus maximus.

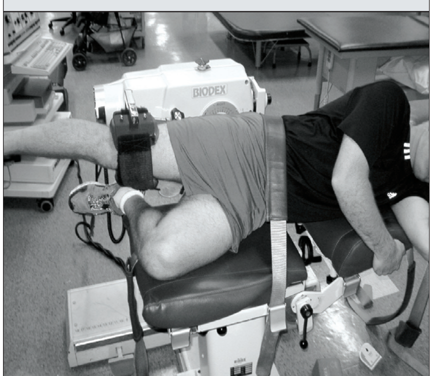

FIGURE 2. Maximum voluntary isometric contraction testing of the gluteus medius.

Each subject completed 3 trials of a maximal contraction, holding each contraction for a period of 3 seconds. The middle 1.5 seconds of that testing period was recorded. An average of each of the 3 trials was calculated to determine the MVIC for each muscle. A 60-second rest was taken between each repetition, with at least a 2-minute rest between each different muscle group.

Exercise Testing Protocol

After MVIC testing, each subject had a 5-minute rest. Muscle activity was measured while doing a randomized series of 5 unilateral WB exercises: wall squat, mini-squat, FSU, LSU, and RSU. Each exercise was standardized to require a 15.24-cm vertical motion, because 15.24 cm is the standard height of a step when negotiating stairs.

A series of 3 repetitions, consisting of a concentric (up) and eccentric (down) phase, were recorded for each exercise. A metronome set at 40 beats per minute was used to control exercise speed such that the concentric and eccentric phase took 1.5 seconds each. The subject was instructed to begin each exercise at the command, "ready, set, go." Once the subject could keep pace with the metronome, recording was initiated manually by the investigator at the beginning of the concentric phase of a repetition. The subject continued with the exercise until the EMG system recorded 10 seconds of data. The first 3 seconds were not used and the following 6 seconds were divided into 2 repetitions. Each repetition consisted of a 1.5-second concentric phase and a 1.5-second eccentric phase. The EMG signal for the 1.5-second concentric phase was recorded and represented the integrated EMG over the entire concentric movement. The EMG signal measured during each movement was full-wave rectified and then integrated over a period of 1.5 seconds. An average of the 2 concentric repetitions was calculated. This average amplitude was normalized by the specific value obtained during the MVIC testing of the respective muscle. Data were therefore expressed as a percentage of the MVIC.

Unilateral Wall Squat

For the unilateral wall squat (**FIGURE 3A**) the subject stood with his/her back resting against a wall and maintained a single-limb stance with the dominant leg. The subject was instructed to keep the trunk and head in an upright vertical position with the pelvis level throughout the exercise. The nondominant knee was fully extended and the hip was flexed enough so that the nondominant leg did not touch the ground during testing. The heel of the dominant leg was placed 30.48 cm from the wall. Repetitions were standardized by the use of a metronome, as described in the exercise testing protocol.

Unilateral Mini-Squat

The subject initiated this exercise (**FIGURE 3B**) with the dominant knee and hip moving into a flexed position while the nondominant knee remained flexed with the hip in neutral so as not to touch the ground during testing. The subject was instructed to keep the trunk and head in an upright vertical position with the pelvis level throughout the exercise. For this exercise the subject lowered his/her body 15.24 cm in a vertical descent using the wall guide to control the depth of the movement. The subject was allowed to lightly touch, but not to hold the wall to remain upright and balanced. Repetitions were standardized by the use of a metronome, as described in the exercise testing protocol section.

Forward Step-up

The height of the step used was 15.24 cm (**FIGURE 3C**). The subject stood in front of the step with feet parallel and then placed the foot of the dominant leg on the step, while keeping the nondominant knee extended with the foot dorsiflexed and hip slightly extended. The subject was instructed to maintain an upright and vertical position of the head and trunk with the pelvis level throughout the exercise. The subject was allowed to lightly touch, but not hold, the wall to remain upright and balanced. Repetitions were standardized by the use of a metronome, as described in the exercise testing protocol.

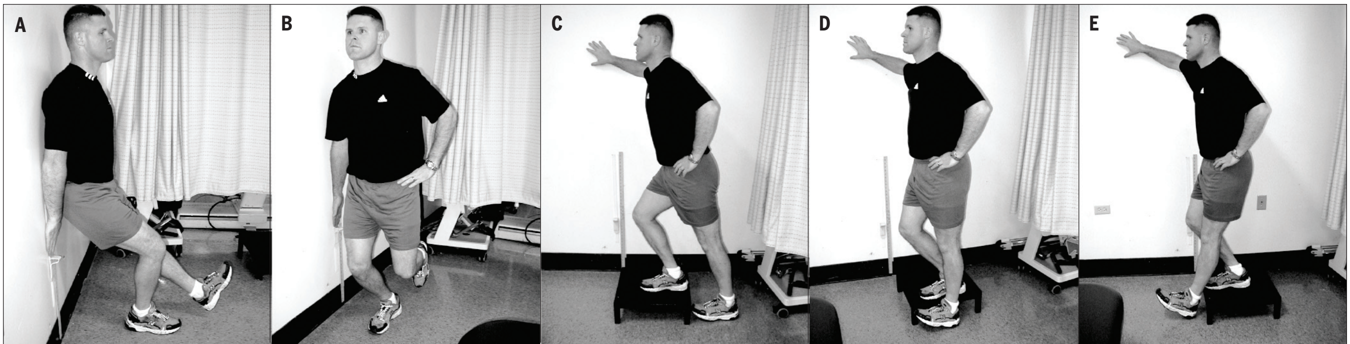

FIGURE 3. (A) Test position for the unilateral wall squat. (B) Test position for the unilateral mini-squat. (C) Test position for the forward step-up. (D) Test position for the lateral step-up. (E) Test position for the retro step-up. Note: The object on the wall at the subject's right hand served as guide to standardize the lowering height of 15.24 cm.

Lateral Step-up

The height of the step used was 15.24 cm (**FIGURE 3D**). The subject stood at the side of the step and placed the dominant leg on the step. The nondominant knee remained extended with the foot dorsiflexed and hip in neutral. The subject was instructed to maintain an upright and vertical position of the head and trunk, with the pelvis level throughout the exercise. The subject was allowed to lightly touch, but not hold, the wall to remain upright and balanced. Repetitions were standardized by the use of a metronome, as described in the exercise testing protocol.

Retro Step-up

The height of the step used was 15.24 cm (**FIGURE 3E**). The subject stood in front of the step, facing away from it, with feet parallel. The subject placed the foot of the dominant leg on the step behind him/her. The nondominant knee remained extended with the foot dorsiflexed and the hip in slight flexion. The subject was instructed to maintain an upright and vertical position of the head and trunk throughout the exercise. The subject was allowed to lightly touch, but not hold, the wall to remain upright and balanced, with the pelvis level throughout the exercise. Repetitions were standardized by the use of a metronome.

Statistical Analysis

A repeated-measures analysis was conducted using general linear models (SAS Version 9.1; SAS Institute Inc, Cary, NC). The ratio of EMG signal amplitude to MVIC was measured within each subject across 4 muscles (GMax, GMed, VMO, and BF) during 5 exercises (wall squat, mini-squat, FSU, LSU, and RSU) for 2 separate trials, providing 40 repeated measures per subject. Preliminary analyses indicated that there were no significant differences in the outcome across trials; therefore, measures from the 2 trials were averaged.

The model consisted of 2 within-subjects factors, muscle and exercise, and the interaction between the 4 muscles and 5 exercises. An unstructured covariance structure was used to account for the dependent measures between muscles and exercise within a person. A 12-degrees-of-freedom F test of the interaction between muscle and exercise was used to evaluate whether there was a statistically significant difference in the activation of the 4 muscles during the 5 exercises. If the F test was significant, then pairwise post hoc comparisons were performed to test for differences between and within each muscle and each exercise. To protect against inflated type I error, which may result from multiple comparisons, significant differences between and within each muscle and each exercise were determined using the simulation method proposed by Edwards and Berry,[12] as implemented by the LSMEANS statement in SAS Proc Mixed.[27] Consequently, all pairwise statistical tests report the *P* values after adjusting for multiple comparisons.

Effect sizes of pairwise comparisons between exercises within each muscle were computed as the difference between the 2 mean ratios of NEMG signal amplitude of the compared exercises, divided by the standard deviation of the specific muscle. For the effect sizes of pairwise comparisons between muscles within each exercise, the difference in means was divided by the standard deviation of the specific exercise. The effect sizes and 95% confidence intervals were reported as Cohen *d*.[8] Cohen[8] designated an effect size of 0.2 as small, 0.5 as medium, and 0.8 as large. An effect size of 0.5 or greater was considered clinically significant.

RESULTS

The interaction between the 2 within-subjects factors, muscle and exercise, was significant ($F_{12,22} = 7.92$, $P<.0001$). This provides evidence that the responses across the 4 muscles under the 5 exercises were significantly different. Furthermore, the main effects of muscle ($F_{3,22} = 103.5$, $P<.001$) and exercise ($F_{4,22} = 26.5$, $P<.001$) were significant.

TABLE 2 lists the mean normalized EMG (NEMG), standard deviations, and standard errors of measurements for each muscle under each exercise. Pairwise comparisons tested the differences between and within each muscle for each exercise. Significant differences from the pairwise comparisons between the 5 exercises for each of the 4 muscles are reported as footnotes, with their corresponding *P* values, an estimate of the effect size, and the 95% confidence interval of this effect size.

TABLE 3 lists the NEMG, standard deviations, and standard errors of measurements for each exercise under each muscle. Pairwise comparisons tested the differences between and within each exercise for each muscle. Significant differences from the pairwise comparisons between the 4 muscles for each of the 5 exercises are reported as footnotes, with their corresponding *P* values, an estimate of the effect size, and the 95% confidence interval of this effect size.

TABLE 2 NEMG Signal Amplitude for Each Muscle*

EXERCISE†	GMAX‡	GMED§	VMO‖	BF¶
1. Wall squat	86 ± 43 (9)	52 ± 22 (5)	66 ± 16 (3)	15 ± 8 (2)
2. Mini-squat	57 ± 44 (9)	36 ± 17 (4)	60 ± 17 (3)	11 ± 6 (1)
3. FSU	74 ± 43 (9)	44 ± 17 (4)	65 ± 17 (4)	12 ± 6 (1)
4. LSU	56 ± 29 (6)	38 ± 18 (4)	55 ± 12 (3)	9 ± 4 (1)
5. RSU	59 ± 35 (7)	37 ± 18 (4)	57 ± 17 (4)	10 ± 5 (1)

Abbreviations: BF, biceps femoris; FSU, forward step-up; GMax, gluteus maximus; GMed, gluteus medius; LSU, lateral step-up; RSU, retro step-up; VMO, vastus medialis oblique.
* *Expressed as mean ± SD (SEM) percent MVIC for 5 unilateral WB exercises.*
† *A repeated-measures model with an unstructured within-person covariance revealed a significant main effect across exercise (F = 26.52, P<.001). Significant differences for each muscle across exercises are listed below: d = effect size (95% confidence interval).*
‡ *Exercise 1 significantly greater than exercises 2 (P<.001, d = 0.72 [0.56-0.89]), 4 (P<.001, d = 0.74 [0.58-0.91]), and 5 (P<.001, d = 0.69 [0.52-0.85]); exercise 3 significantly greater than exercises 2 (P = .019, d = 0.42 [0.26-0.59]), 4 (P = .003, d = 0.44 [0.28 -0.61]), and 5 (P = .039, d = 0.39 [0.22-0.55]).*
§ *Exercise 1 significantly greater than exercises 2 (P = .001, d = 0.82 [0.74-0.89]), 4 (P = .011, d = 0.75 [0.67-0.83]) and 5 (P = .002, d = 0.80 [0.72-0.87]).*
‖ *Exercise 1 significantly greater than exercise 4 (P = .006, d = 0.70 [0.63-0.76]); exercise 3 significantly greater than exercise 4 (P = .033, d = 0.61 [0.54-0.67]).*
¶ *Exercise 1 significantly greater than exercises 4 (P = .008, d = 0.88 [0.85-0.90]) and 5 (P = .047, d = 0.67 [0.65-0.70]); exercise 3 significantly greater than exercise 4 (P = .0012, d = 0.41 [0.39-0.44]); exercise 5 significantly greater than exercise 4 (P = .0157, d = 0.20 [0.18-0.23]).*

TABLE 3 NEMG Signal Amplitude for Exercises*

MUSCLE†	WALL SQUAT‡	MINI-SQUAT§	FSU‖	LSU¶	RSU#
1. GMax	86 ± 43 (9)	57 ± 44 (9)	74 ± 43 (9)	57 ± 29 (6)	59 ± 35 (7)
2. GMed	52 ± 22 (5)	36 ± 17 (4)	44 ± 17 (4)	38 ± 18 (4)	37 ± 18 (4)
3. VMO	66 ± 16 (3)	60 ± 17 (3)	65 ± 17 (4)	55 ± 12 (3)	57 ± 17 (4)
4. BF	15 ± 8 (2)	11 ± 6 (1)	12 ± 6 (1)	9 ± 4 (1)	10 ± 5 (1)

Abbreviations: BF, biceps femoris; FSU, forward step-up; GMax, gluteus maximus; GMed, gluteus medius; LSU, lateral step-up; RSU, retro step-up; VMO, vastus medialis oblique.
* *Expressed as mean ± SD (SEM) percent MVIC for 4 muscles.*
† *A repeated-measures model with an unstructured within-person covariance revealed a significant main effect across muscle (F = 103.51, P<.001). Significant differences for each exercise between muscles are listed below: d = effect size (95% confidence interval).*
‡ *Muscle 1 significantly greater than muscles 2 (P = .021, d = 0.95 [0.80-1.10]) and 4 (P<.001, d = 1.96 [1.81 – 2.11]); muscle 2 significantly greater than muscle 4 (P<.001, d = 1.02 [0.87-1.16]); muscle 3 significantly greater than muscles 2 (P = .022, d = 0.39 [0.24-0.54]) and 4 (P<.001, d = 1.40 [1.25-1.55]).*
§ *Muscle 1 significantly greater than muscle 4 (P = .001, d = 1.47 [1.34-1.60]); muscle 2 significantly greater than muscle 4 (P<.001, d = 0.80 [0.68-0.93]); muscle 3 significantly greater than muscles 2 (P<.001, d = 0.74 [0.61-0.87]) and 4 (P<.001, d = 1.55 [1.42-1.68]).*
‖ *Muscle 1 significantly greater than muscle 4 (P<.001, d = 1.82 [1.68-1.96]); muscle 2 significantly greater than muscle 4 (P<.001, d = 0.93 [0.79-1.07]); muscle 3 significantly greater than muscle 2 (P<.001, d = 0.61 [0.47-0.75]) and 4 (P<.001, d = 1.54 [1.40-1.68])*
¶ *Muscle 1 significantly greater than muscle 4 (P<.001, d = 1.81 [1.70-1.91]); muscle 2 significantly greater than muscle 4 (P<.001, d = 1.08 [0.97-1.19]); muscle 3 significantly greater than muscle 2 (P = .005, d = 0.66 [0.55-0.76]) and 4 (P<.001, d = 1.74 [1.63-1.84]).*
\# *Muscle 1 significantly greater than muscle 4 (P<.001, d = 1.68 [1.56-1.80]); muscle 2 significantly greater than muscle 4 (P<.001, d = 0.91 [0.79-1.03]); muscle 3 significantly greater than muscles 2 (P = .003, d = 0.71 [0.60-0.83]) and 4 (P<.001, d = 1.62 [1.50-1.74]).*

GMax

For the GMax, the mean NEMG across the exercises ranged from 86% to 56% MVIC. Across exercises, the GMax percent MVIC ranked as follows in descending order: wall squat, FSU, RSU, mini-squat, and LSU. A greater percent MVIC was generated during the unilateral wall squat, as compared to the mini-squat ($P<.001$, $d = 0.72$), LSU ($P<.001$, $d = 0.74$), and RSU ($P<.001$, $d = 0.69$). Similarly, a statistically greater percent MVIC was generated for the GMax during the FSU as compared to the mini-squat ($P = .019$, $d = 0.42$), LSU ($P = .003$, $d = 0.44$), and RSU ($P = .039$, $d = 0.39$).

GMed

For the GMed, the mean NEMG across the 5 unilateral WB exercises ranged from 52% to 36% MVIC. Across exercises, the GMed percent MVIC ranked as follows in descending order: wall squat, FSU, LSU, RSU, and mini-squat. A greater percent MVIC was generated during the unilateral wall squat as compared to the mini-squat ($P = .001$, $d = 0.82$), LSU ($P = .011$, $d = 0.75$), and RSU ($P = .002$, $d = 0.80$).

VMO

For the VMO, the mean NEMG across the 5 unilateral WB exercises ranged from 66% to 55% MVIC. Across exercises, the VMO percent MVIC ranked as follows in descending order: wall squat, FSU, mini-squat, RSU, and LSU. A greater percent MVIC was generated during the wall squat as compared to the LSU ($P = .006$, $d = 0.70$) and during the FSU as compared to the LSU ($P = .033$, $d = 0.62$).

BF

For the BF, mean NEMG across the 5 unilateral WB exercises ranged from 9% to 15% MVIC. Across exercises, the BF percent MVIC ranked as follows in descending order: wall squat, FSU, mini-squat, RSU, and LSU. A greater percent MVIC was generated during the wall squat as compared to the LSU (P = .008, d = 0.88) and RSU (P = .047, d = 0.67). Similarly, a statistically greater percent MVIC was generated for the BF during the FSU as compared to the LSU (P = .0012, d = 0.41), and RSU as compared to the LSU (P = .0157, d = 0.20).

Interaction Between Hip and Thigh Muscles

The interaction between the hip and thigh muscles demonstrated a similar muscle recruitment pattern within each exercise. Significant interactions (**TABLE 3**) were noted as follows: GMax greater than BF ($d \geq 1.02$), GMed greater than BF ($d \geq 0.80$), VMO greater than GMed ($d \geq 0.39$), and VMO greater than BF ($d \geq 1.40$). The only exception to this pattern of activation was demonstrated for the wall squat: Gmax greater than GMed ($d \geq 0.95$).

DISCUSSION

This study examined the NEMG signal amplitude during exercises that simulate functional muscle recruitment patterns to strengthen lower extremity muscles. A key observation in our study was that for all 4 muscles, statistically significant differences were noted in the amount of mean NEMG signal amplitude across the 5 exercises. In addition, a consistent pattern of recruitment between the hip and thigh muscles was observed for each exercise. Andersen et al[1] suggest that an adaptive threshold of 40% to 60% of maximal effort is necessary to strengthen muscle during therapeutic exercise. Using NEMG signal amplitude as a measure of muscle activation and therefore, an estimate of exercise intensity, the relative contributions and interaction of the hip and thigh muscles are discussed with respect to the potential efficiency of these exercises during rehabilitation.

Gluteus Maximus

While many exercises are used clinically to strengthen the GMax, little is known about their efficiency. Due to the highest level of recruitment, we recommend the wall squat over the mini-squat (d = 0.72), LSU (d = 0.74), and RSU (d = 0.69). Clinically, the FSU may also be prescribed over the same 3 exercises (d = 0.42, 0.44, 0.39, respectively), but may result in a smaller strengthening effect. The small variation in mean GMax NEMG signal amplitude among the RSU (59% MVIC), mini-squat (57% MVIC), and LSU (56% MVIC) suggests that these exercises may have similar strengthening effects. Mean GMax NEMG signal amplitude was within or above the 40% to 60% threshold for all exercises, indicating that they activate the GMax to a sufficient intensity for strengthening. Clinically, FSU, RSU, mini-squat, and LSU may be considered as a progression towards the wall squat or used earlier in the rehabilitation process, as they require the least amount of muscle activity.

Worrell et al[30] examined the mean NEMG signal amplitude of the GMax and hamstring (HS) muscles during the LSU. The mean NEMG signal amplitude of the GMax (15% to 23% MVIC) and HS (10% to 14% MVIC) were reported. Our study revealed Gmax at 56% MVIC and HS at 9% MVIC. Methodological differences in step height, step-up cadence, and MVIC testing position likely account for the reported differences between studies. Worrell et al[30] recommend that the LSU should not be used to recruit the GMax muscle. Our results do not support their recommendation, given a mean GMax NEMG of 56%.

Blanpied[3] investigated GMax EMG activity during a wall slide squat and squat machine exercise. Placing the foot forward or anterior to the center of mass of the body resulted in a significant increase in GMax, vastus lateralis, and hamstring muscle activity, presumably due to a change in the application of the ground reaction force relative to the body position. Similarly, in this study, placing the foot anterior to the hip during the wall squat resulted in the highest level of GMax recruitment. To our knowledge, no other studies have reported mean GMax NEMG for the wall squat, FSU or RSU that allow direct comparisons to our findings.

Gluteus Medius

In weight bearing the GMed controls the pelvis and the femur in the frontal plane. Clinicians and researchers often cite the importance of strengthening the hip musculature to stabilize the pelvis and decrease valgus alignment at the knee.[12,13,20,21,26] In our study, mean GMed NEMG signal amplitude was highest during the wall squat as compared to the mini-squat (d = 0.82), LSU (d = 0.75), and RSU (d = 0.80), indicating the potential for a moderate to large strengthening effect. The lack of a statistically significant difference in the mean GMed NEMG signal amplitude among the FSU (44% MVIC), LSU (38% MVIC), RSU (37% MVIC), and mini-squat (36% MVIC) suggests that these exercises have similar levels of recruitment. To our knowledge quantification of mean GMed NEMG signal amplitude during unilateral WB exercises has only been described by Bolgla and Uhl.[4] However, due to differences in the WB test positions, direct comparison of results to our study is not possible. Both the wall squat and FSU elicit sufficient mean GMed EMG signal amplitude to strengthen the GMed. But, because of their lower demands, the LSU, RSU, and mini-squat should be considered for use in earlier stages of the rehabilitation process.

Vastus Medialis Oblique

For the purposes of this study, the mean NEMG VMO signal amplitude is considered reflective of the knee extensor muscles. Due to the highest levels of muscle recruitment, our data support that the wall squat and FSU should be prescribed over the LSU (d = 0.70 and d = 0.61, respectively) to target the knee extensor muscles. The more anterior position of the foot compared to the hip during the wall squat may account for the higher knee extensor activation.[3]

Mean NEMG VMO signal amplitude activation was within or above the 40% to 60% range for all 5 exercises indicating that they all activate the knee extensors to a sufficient intensity for strengthening. Worrell et al[30] reported that mean VMO NEMG during the LSU ranged from 63% to 80% MVIC.

Several studies have reported VMO EMG analyses during unilateral WB exercises.[2,5,7,9] Brask et al[5] reported a mean peak VMO NEMG signal amplitude of 60% MVIC during the concentric phase of an unweighted LSU. Cook et al[9] reported mean VMO NEMG signal amplitude of 47% MVIC during the concentric phase of an unweighted LSU. Beutler et al[2] observed that at an angle of 30° knee flexion, the 1-legged squat and FSU had relatively low quadriceps activation levels of 69% and 67% MVIC, respectively. Our EMG data are consistent with these findings for the mini-squat at 60% MVIC and the FSU at 65% MVIC.

Biceps Femoris

Our findings indicate greater activation of the BF during the wall squat over the LSU (d = 0.88) and the RSU (d = 0.67), as well as the FSU and RSU over the LSU (d = 0.41, d = 0.20, respectively). However, due to the consistently reported low HS activity during unilateral WB exercises,[5,9,17,24,30] which is consistent with our findings, these exercises would have limited strengthening effects in healthy individuals. If HS strengthening is indicated, exercises such as the HS muscle curl exercise should be considered.[1]

Interaction Between Hip and Thigh Muscles

Unilateral WB exercises recruit multiple muscles across multiple joints, resulting in varying activations of different hip and thigh muscles. A large effect size was demonstrated for the recruitment patterns of the 4 muscles within each exercise such that mean GMax, GMed, and VMO NEMG signal amplitudes were consistently higher than the BF. Clinically, these exercises could be used interchangeably for the purpose of training this cooperative muscle activation potentially as a prerequisite to functional activities. However, a main difference in prescribing each exercise would be the need to determine the best exercise to efficiently target a specific muscle or muscle group. The mean VMO EMG signal amplitudes within each exercise were consistently higher than those of the GMed. The effect size was small and may not be clinically significant.

The only additional interaction occurred during the wall squat between the Gmax and GMed. The effect size was large and may be clinically significant. To perform all other exercises, the pattern of GMax and GMed muscle activations was not significantly different. Only the wall squat elicited a higher GMax as compared to GMed muscle activation possibly related to the foot position forward of the hip necessary to perform the wall squat.

Limitations

Our study has the following limitations. Use of surface EMG electrodes is associated with crosstalk from adjacent muscles. To minimize crosstalk, standardized and optimal electrode placement was used.[22] Advantages of surface electrodes include the ability to obtain a broad sampling of motor units and the noninvasive nature of this technique. Limitations in our EMG equipment allowed collection of data over a small number of trials. However, no differences were found when testing for difference between trials.

The results of our study may be influenced by submaximal effort of subjects during MVIC testing. We attempted to control for this by giving standardized verbal encouragement to each subject, a proven technique for eliciting a maximum contraction.[6]

Varying trunk and pelvic postures may have affected our results due to their influence on the demands of the lower extremity muscles during the unilateral WB exercises. We attempted to standardize the subjects pelvic and trunk posture in vertical alignment through corrective feedback of verbal and physical cueing commonly used in the clinical setting.

The results of the current study are representative of a young, asymptomatic population during the concentric phase of the exercises. Future studies should include examination of EMG signal amplitude to investigate gender differences, quantify the eccentric phase of these exercises, and compare these exercises to others to determine the best exercises to target muscles for strengthening. Additional studies of interactions between hip and thigh muscles might include onset and timing of muscle activations within these exercises and a comparison to functional activities.

CONCLUSION

This study quantified the relative differences in mean NEMG signal amplitudes of 4 muscles between and within 5 unilateral WB exercises. For all 4 muscles, statistically significant differences were noted in the mean NEMG signal amplitude across the 5 exercises. All muscles except the BF demonstrated mean NEMG signal amplitudes within or above the recommended adaptive threshold for strengthening. Considering the high levels of muscle activation for all muscles for the wall squat, this exercise is the most efficient for strengthening a single muscle or for training a cooperative effort between the hip and thigh muscles. Clinicians may use this information when prescribing unilateral WB exercises to target specific lower extremity muscles when patients can safely perform WB exercise. Future studies should focus on the effectiveness of these exercises for rehabilitation purposes.

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REFERENCES

1. Andersen LL, Magnusson SP, Nielsen M, Haleem J, Poulsen K, Aagaard P. Neuromuscular activation in conventional therapeutic exercises and heavy resistance exercises: implications for rehabilitation. *Phys Ther. 2006;86:683-697.*
2. Beutler AI, Cooper LW, Kirkendall DT, Garrett WE, Jr. Electromyographic analysis of single-leg, closed chain exercises: implications for rehabilitation after anterior cruciate ligament reconstruction. *J Athl Train*. 2002;37:13-18.
3. Blanpied P. Changes in muscle activation during wall slides and squat-machine exercise. *J Sport Rehab.* 1999;8:125-134.
4. Bolgla LA, Uhl TL. Electromyographic analysis of hip rehabilitation exercises in a group of healthy subjects. *J Orthop Sports Phys Ther.* 2005;35:487-494.
5. Brask B, Lueke RH, Soderberg GL. Electromyographic analysis of selected muscles during the lateral step-up exercise. *Phys Ther.* 1984;64:324-329.
6. Campenella B, Mattacola CG, Kimura IF. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *Isokinet Exerc Sci*. 2000;8:1-6.
7. Caterisano A, Moss RF, Pellinger TK, et al. The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. *J Strength Cond Res*. 2002;16:428-432.
8. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: Lawrence Earlbaum Associates; 1988.
9. Cook TM, Zimmerman CL, Lux KM, Neubrand CM, Nicholson TD. EMG comparison of lateral step-up and stepping machine exercise. *J Orthop Sports Phys Ther.* 1992;16:108-113.
10. DeCarlo M, Porter DA, Gehlsen G, Bahamonde R. Electromyographic and cinematographic analysis of the lower extremity during closed and open kinetic chain exercise. *Isokin Exerc Sci*. 1992;2:24-29.
11. Earl JE, Schmitz RJ, Arnold BL. Activation of the VMO and VL during dynamic mini-squat exercises with and without isometric hip adduction. *J Electromyogr Kinesiol*. 2001;11:381-386.
12. Edwards D, Berry JJ. The efficiency of simulation-based multiple comparisons. *Biometrics*. 1987;43:913-928.
13. Fredericson M, Cookingham CL, Chaudhari AM, Dowdell BC, Oestreicher N, Sahrmann SA. Hip abductor weakness in distance runners with iliotibial band syndrome. *Clin J Sport Med*. 2000;10:169-175.
14. Gryzlo SM, Patek RM, Pink M, Perry J. Electromyographic analysis of knee rehabilitation exercises. *J Orthop Sports Phys Ther*. 1994;20:36-43.
15. Gueorguieva R, Krystal JH. Move over ANOVA: progress in analyzing repeated-measures data and its reflection in papers published in the Archives of General Psychiatry. *Arch Gen Psychiatry*. 2004;61:310-317.
16. Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther*. 2003;33:671-676.
17. Isear JA, Jr., Erickson JC, Worrell TW. EMG analysis of lower extremity muscle recruitment patterns during an unloaded squat. *Med Sci Sports Exerc*. 1997;29:532-539.
18. Jaramillo J, Worrell TW, Ingersoll CD. Hip isometric strength following knee surgery. *J Orthop Sports Phys Ther*. 1994;20:160-165.
19. Kramer JF, Vaz MD, Vandervoort AA. Reliability of isometric hip abductor torques during examiner- and belt-resisted tests. *J Gerontol*. 1991;46:M47-51.
20. Mascal CL, Landel R, Powers C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther*. 2003;33:647-660.
21. Niemuth PE, Johnson RJ, Myers MJ, Thieman TJ. Hip muscle weakness and overuse injuries in recreational runners. *Clin J Sport Med*. 2005;15:14-21.
22. Rainoldi A, Melchiorri G, Caruso I. A method for positioning electrodes during surface EMG recordings in lower limb muscles. *J Neurosci Methods*. 2004;134:37-43.
23. Selseth A, Dayton M, Cordova M, Ingersoll C, Merrick M. Quadriceps concentric EMG activity is greater than eccentric emg activity during the lateral step-up exercise. *J Sport Rehabil*. 2000;9:124-134.
24. Shields RK, Madhavan S, Gregg E, et al. Neuromuscular control of the knee during a resisted single-limb squat exercise. *Am J Sports Med*. 2005;33:1520-1526.
25. Soderberg GL, Knutson LM. A guide for use and interpretation of kinesiologic electromyographic data. *Phys Ther.* 2000;80:485-498.
26. Tyler TF, Nicholas SJ, Mullaney MJ, McHugh MP. The role of hip muscle function in the treatment of patellofemoral pain syndrome. *Am J Sports Med*. 2006;34:630-636.
27. Westfall PH, Tobias RD, Rom D, Wolfinger RD, Hochberg Y. *Multiple Comparisons and Multiple Tests Using the SAS System*. Cary, NC: SAS Institute; 1999.
28. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc*. 2006;38:945-952.
29. Wilson J, Ferris E, Heckler A, Maitland L, Taylor C. A structure review of the role of gluteus maximus in rehabilitation. *NZ J Physiother*. 2005;33:95-100.
30. Worrell TW, Crisp E, Larosa C. Electromyographic reliability and analysis of selected lower extremity muscles during lateral step-up conditions. *J Athl Train*. 1998;33:156-162.