Ultrasound Imaging of the Gluteal Muscles During the Y-Balance Test in Individuals With or Without Chronic Ankle Instability

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Context: Impairments in dynamic postural control and gluteal muscle activation have been associated with the development of symptoms related to long-term injury, which are characteristic of chronic ankle instability (CAI). Ultrasound imaging (USI) provides a visual means to explore muscle thickness throughout movement; however, USI functional-activation ratios (FARs) of the gluteal muscles during dynamic balance exercises have not been investigated.

Objective: To determine differences in gluteus maximus and gluteus medius FARs using USI, Y-Balance Test (YBT) performance, and lower extremity kinematics in individuals with or without CAI.

Design: Cross-sectional study.

Setting: University laboratory.

Patients or Other Participants: Twenty adults with CAI (10 men, 10 women; age = 21.70 ± 2.32 years, height = 172.74 ± 11.28 cm, mass = 74.26 ± 15.24 kg) and 20 adults without CAI (10 men, 10 women; age = 21.20 ± 2.79 years, height = 173.18 ± 15.16 cm, mass = 70.89 ± 12.18 kg).

Intervention(s): Unilateral static ultrasound images of the gluteal muscles during quiet stance and to the point of maximum YBT reach directions were obtained over 3 trials. Hip, knee, and ankle sagittal-plane kinematics were collected with motion-capture software.

Main Outcome Measure(s): Gluteal thickness was normalized to quiet stance to yield FARs for each muscle in each YBT direction. We averaged normalized reach distances and obtained average peak kinematics. Independent *t* tests, mean differences, and Cohen d effect sizes were calculated to determine group differences for all outcome measures.

Results: The CAI group had anterior-reach deficits compared with the control group (mean difference = 4.37%, Cohen d = 0.77, *P* = .02). The CAI group demonstrated greater anterior gluteus maximus FARs than the control group (mean difference = 0.08, Cohen d = 0.57, *P* = .05).

Conclusions: The CAI group demonstrated YBT reach deficits and alterations in proximal muscle activation. Increased reliance on the gluteus maximus during dynamic conditions may contribute to distal joint dysfunction in this population.

Key Words: dynamic balance, functional ankle instability, modified Star Excursion Balance Test, musculoskeletal ultrasound

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Key Points

- Ultrasound imaging revealed altered muscle-activation patterns during a common clinical dynamic-balance test in individuals with chronic ankle instability (CAI).
- Individuals with CAI exhibited decreased anterior-reach performance on the Y-Balance Test and increased gluteus maximus thickness compared with healthy individuals.
- Increased reliance on proximal global mover muscles as a compensatory mechanism should be addressed clinically through neuromuscular education. Ultrasound imaging is a potential feedback aid.

Ankle sprains are prevalent musculoskeletal injuries, with an injury rate of up to 11.96 per 10 000 athlete-exposures among high-risk collegiate athletes and most categorized as lateral ligament injuries.[1] Approximately 30% to 40% of patients with ankle sprains go on to subjectively report that the ankle joint feels unstable and describe episodes of "giving way" and recurrent sprains for 1 year or more after injury, which the International Ankle Consortium has characterized as *chronic ankle instability* (CAI).[2–4] Patients with CAI present with a spectrum of mechanical and sensorimotor impairments that have been collectively modeled as the CAI paradigm.[3,5]

The sensorimotor impairments included in the CAI model are decreased proprioception and muscle strength of the ankle joint and altered postural balance and neuromuscular control of the surrounding structures.[3,5] Although sensorimotor impairments at the ankle joint have been widely investigated, the ankle is not an isolated joint, and movement patterns are also influenced by proximal static and dynamic stabilizers.[6,7] Therefore, the function of the proximal structures in the kinetic chain needs to be explored in this patient population.

The gluteus maximus (GMAX) and gluteus medius (GMED) muscles of the lumbopelvic-hip complex control the position of the pelvis in the frontal plane to help

maintain a stable base of support during weight bearing.[8] Gluteal muscle activity during functional tasks, such as single-legged squatting and other loaded conditions, has been shown to influence lower extremity mechanics and alignment down the kinetic chain. Furthermore, hip-muscle function and lower extremity injury appear to be connected. Although this has been widely explored in a population with patellofemoral pain, emerging evidence has suggested that hip-muscle weakness is a risk factor for lateral ankle sprains in youth athletes and that hip-muscle impairments persist in patients with CAI.[6,9,10] Therefore, gluteal muscle function has been investigated during a variety of functional tasks, such as rotational lunges and squats.[11]

One such task that involves muscles throughout the lower extremity is the modified Star Excursion Balance Test, otherwise known as the *Y-Balance Test* (YBT). This clinical tool is commonly used to assess sensorimotor adaptations, and multiple researchers[12,13] have suggested that individuals with CAI present with impairments in YBT performance. This task involves multiple lower extremity structures for successful performance and specifically requires dynamic single-limb stabilization while participants maintain a semi-squatting position and reach outside the base of support in the anterior, posteromedial, and posterolateral directions.[12,14,15] As such, proximal kinematics and muscle activity have been postulated to influence task performance.

Alterations in hip kinematics,[13] hip-muscle fatigue,[16,17] and decreased hip-extension strength[18,19] have been identified and shown to be related to decreased YBT performance, particularly in the posterior-reach directions. Although all of these aspects have been explored, little information is available about the functional-activation patterns of the gluteal muscles during the YBT as they influence task performance in the population with CAI. Using surface electromyography (EMG) in healthy participants, authors[13,20] have found increased gluteal activation in select YBT directions that have been frequently reported as impaired in cohorts with CAI. Therefore, proximal alterations may contribute to dysfunction in this patient population. However, more research is warranted to determine how the gluteal muscles functionally activate in individuals with CAI during this dynamic postural-control test. This information could aid in developing targeted clinical interventions to improve postural-control outcomes in this population.

Ultrasound imaging (USI) is a noninvasive means to observe muscle-thickness changes through a visual interface and allows for individual muscle patterns to be distinguished, as muscle layers can be identified. Instead of electrical muscle activity, which can be determined using EMG, USI allows muscle-thickness changes to be identified throughout activity. Muscle thickness has been found to be correlated with gluteal muscle torque during isometric testing ($r = 0.80$) and has been upheld against fine-wire EMG analyses.[21] Ultrasound imaging may be favorable, as it is a more clinically applicable but noninvasive tool.[21] Furthermore, USI may be superior to surface EMG, as it is not subject to cross-talk.[21] The use of USI under static conditions has expanded to quantifying muscles of the lumbopelvic-hip complex, and functional-activation ratios (FARs) have been used to describe the extent of muscle-thickness changes from resting to exercise conditions.[22]

Ultrasound imaging has excellent intrarater reliability for gluteal muscle measures during static and dynamic conditions (intraclass correlation coefficient [3,3] = 0.98).[23] Therefore, assessing gluteal muscle activation using USI would provide valuable information about the hip stabilizers during a dynamic postural task. In addition, analyzing gluteal muscle activation in lower extremity kinematics in patients with CAI would help to provide a more global picture of the functional and balance strategies used by this population for task performance. Therefore, the purpose of our study was to determine differences in GMAX and GMED FARs using USI, YBT performance, and lower extremity kinematics in individuals with or without CAI. We hypothesized that the CAI group would demonstrate less gluteal muscle thickness at the maximum reach of the YBT reach directions, particularly posteriorly, than the group without CAI (control group). Furthermore, we anticipated that the CAI group would preferentially activate the GMAX over the GMED and would display decreased reach distances and different reach strategies, manifesting in altered lower extremity kinematics at the pinnacle of YBT reach distances compared with the control group.

METHODS

Unilateral muscle activation of the GMAX and GMED and lower extremity kinematics during the YBT for the affected CAI limb and the matched limb of individuals without CAI were examined using a cross-sectional study design. Static individual B-mode USI of the GMAX and GMED muscles was obtained during quiet double-limb stance for normative measures and over 3 trials of the YBT in the anterior, posterolateral, and posteromedial directions. Vicon (version 1.8.5; Vicon Motion Systems, Inc, Lake Forest, CA) and MotionMonitor (version 9.32; Innovative Sports Training, Chicago, IL) software was used to record sagittal-plane hip, knee, and ankle kinematics for all YBT trials. A single examiner with 2 years of USI experience (A.F.D.) obtained all ultrasound data during a single session for each participant. Figure 1 illustrates a flowchart of the study procedures.

Participants

Participants aged 18 to 35 years were recruited through convenience sampling in a university setting. Inclusion and exclusion criteria for the CAI group followed the International Ankle Consortium guidelines.[24] Potential participants in the CAI group were screened to ensure that they had sustained at least 1 substantial ankle sprain 12 months or more before enrollment and no ankle injuries within 3 months of the study. These prospective participants also had to score >11 on the Identification of Functional Ankle Instability, <90% on the Foot and Ankle Ability Measure–Activities of Daily Living subscale, <80% on the Foot and Ankle Ability Measure–Sport subscale, and <24 on the Cumberland Ankle Instability Tool questionnaire. Individuals were included in the control group if they were recreationally active and had no history of ankle sprain. We defined *recreationally active* as participating in at least 30 minutes of physical activity at least 3 days per week.[25] Exclusion criteria consisted of any lower extremity or back injury or surgery, neuropathy, use

Participant recruitment and screening for inclusion and exclusion criteria (n = 48)

Excluded (n = 8)
• Did not meet inclusion criteria

Consent, questionnaires, and patient-reported outcomes (n = 40)
• Healthy group (n = 20)
• Chronic ankle instability group (n = 20)

Systems setup and calibration

Ultrasound imaging placement

Anterior

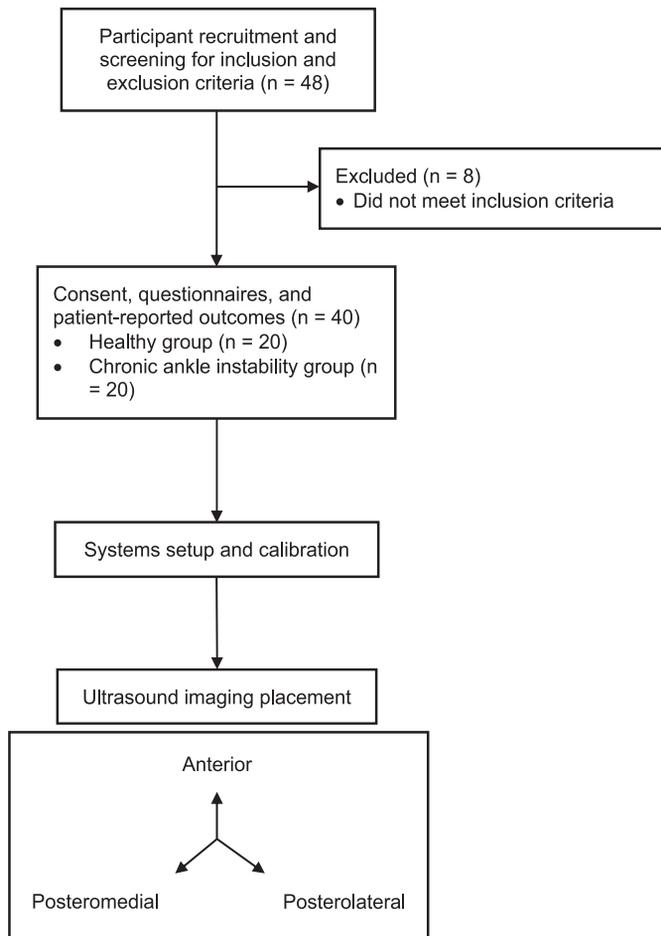Posteromedial   Posterolateral

Figure 1.   Flowchart of the study procedures.

of a biomedical device, muscular abnormality, or pregnancy at the time of the study. Based on the current USI literature, the minimal detectable change for gluteal muscle thickness between groups was, on average, 0.16 cm, with a 0.17-cm standard error of measure to detect a substantial effect (Cohen d > 0.60).[23] An a priori sample-size estimate with an α level set at ≤.05 and 80% power indicated the need for a total of 40 participants. The involved limb in participants with unilateral CAI (n = 8) or the limb that was self-reported as *worse* and confirmed through the Cumberland Ankle Instability Tool in participants with bilateral ankle sprains (n = 12) was designated as the *affected limb*.

The limbs of the control-group participants were matched to the limbs of the CAI-group participants based on sex and height to ensure equal comparisons.

After reporting for testing, participants completed additional questionnaires, including a general health history form, the Tegner Activity Level Scale, the Tampa Scale for Kinesiophobia, Fear-Avoidance Beliefs Questionnaire, and the Patient-Specific Functional Scale. Participant demographic information is presented in Table 1. All participants provided written informed consent, and the study was approved by the University of Virginia Institutional Review Board for Health Sciences Research (No. 18267).

Instrumentation

A portable ultrasound system (model ACUSON Free-style; Siemens Medical Inc, Mountain View, CA) with an 8-MHz linear wireless transducer secured with a custom velcro (Velcro USA Inc, Manchester, NJ) belt that included a foam block was used for USI of the gluteal muscles. A custom YBT was created with 3 tape measures secured at 45° angles from a reference horizontal position to form the reach directions.[12] We used a 12-camera motion-capture system (Vicon Motion Systems, Inc) sampling at 250 Hz and MotionMonitor software to collect lower extremity kinematics.

Procedures

Participants reported to the laboratory for a single session and were prepared for data collection by having 8 clusters of retroreflective markers secured bilaterally on the dorsum of the foot, lateral leg, and lateral thigh and on the lower and upper back.[26] We calibrated the Vicon system using the MotionMonitor software and used a stylus with retroreflective markers in a fixed orientation to indicate specific anatomic landmarks as a reference for the cluster markers for participant digitization in the MotionMonitor system.[26] Participants were outfitted with the ultrasound belt and transducer setup on the affected or matched stance limb. The transducer was secured midway between the posterior-superior iliac spine and greater trochanter, which has been shown to be a valid orientation of the ultrasound probe for GMAX and GMED visualization (Figure 2A).[27] The USI positioning and depth of penetration were adjusted until a clear image of the superior and inferior fascial borders of both the GMAX and GMED was visible on the monitor.

Table 1.   Participant Demographics (Mean ± SD)

| Characteristic	Control	Chronic Ankle Instability	t_{42} Value	P Value
		Group		
Age, y	21.20 ± 2.79	21.70 ± 2.32	−1.46	.61
Height, cm	173.18 ± 15.16	172.74 ± 11.28	−1.25	.93
Mass, kg	70.89 ± 12.18	74.26 ± 15.24	−1.56	.40
Tegner Activity Level Scale score	5.50 ± 1.32	6.00 ± 1.91	−6.58	.19
Tampa Scale for Kinesiophobia score	20.75 ± 5.71	37.65 ± 5.29	−7.15	<.001[a]
Fear-Avoidance Beliefs Questionnaire score	1.45 ± 3.07	15.50 ± 9.84	−6.40	<.001[a]
Identification of Functional Ankle Instability score	1.00 ± 1.00	21.20 ± 4.05	−22.68	<.001[a]
Foot and Ankle Ability Measure score				
Activities of Daily Living subscale	100.00 ± 0.00	83.94 ± 4.57	3.01	<.001[a]
Sport subscale	100.00 ± 0.00	72.83 ± 5.56	3.34	<.001[a]
Cumberland Ankle Instability Tool score	30.00 ± 0.00	17.80 ± 4.43	3.80	<.001[a]

[a] Indicates difference (P ≤ .05).
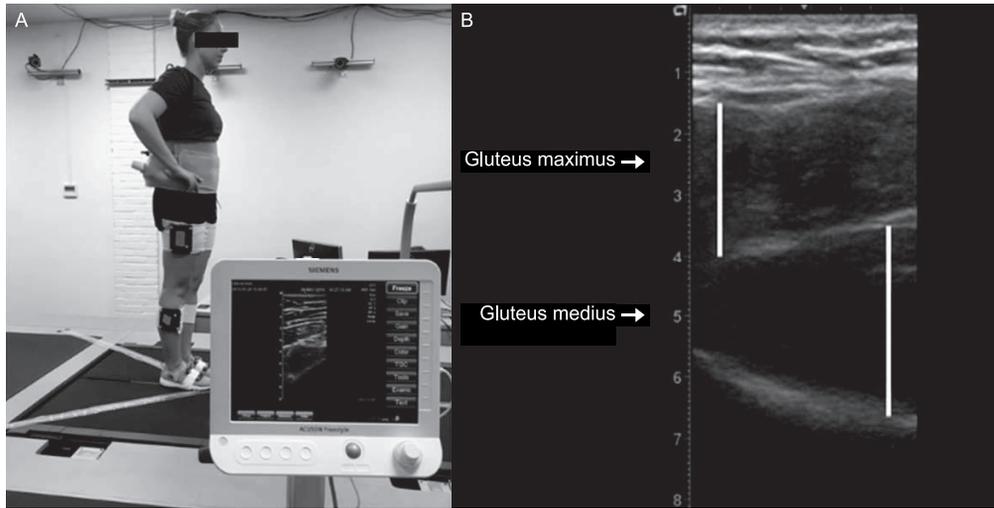
Figure 2. Ultrasound imaging. A, Systems and participant setup. B, Measured image at quiet stance.

Participants were instructed to stand with equal weight on both feet and their upper extremities by their sides during 3 quiet-standing ultrasound images for normalization of the test images[22] and for resting kinematic measures.

Before YBT administration, participants received oral test instructions to maintain the toe immediately posterior to the start of the tape measure, keep their hands on their hips and full foot contact on the stage, reach as far as possible down the length of the anterior tape measure, lightly tap down, lift the toe, and return to the standing position without losing balance.[28] Participants practiced until they successfully performed 3 trials, and data collection began when they were comfortable with the test. Three trials were recorded in the anterior direction, and a static image of the gluteal muscles was taken at the pinnacle of the reach when the reach toe was lifted from the ground to avoid weight transference to the contralateral limb. Reach distances were also recorded in centimeters for all trials. These procedures were repeated for the posteromedial and posterolateral reach directions, with the heel now placed at the start of the tape measure. After YBT collection, an examiner (A.F.D.) measured anatomic *limb length*, which was defined as the distance between the anterior-superior iliac spine and the medial malleolus of the affected or matched limb in order to normalize the reach distances.[14] Participants were then dismissed.

Data Processing

Ultrasound images were processed using ImageJ software (version 1.52a; National Institutes of Health, Bethesda, MD). An investigator (A.F.D.) blinded to participant information at the time of data processing measured GMAX and GMED thickness from the inferior portion of the superior fascial border to the superior portion of the inferior fascial border for each muscle and position (Figure 2B). Average YBT reach distances were calculated for the anterior, posteromedial, and posterolateral reach directions and normalized to limb length (Equation 1).[14] The average GMAX and GMED muscle thicknesses from the 3 images for each position were calculated and normalized to the quiet-standing measures to determine the FAR (Equation 2).[22] The GMAX-to-GMED ratios were obtained for all

positions to determine the preferential-activation ratio (Equation 3).[29]

$$\text{Normalized Reach Distance}$$
$$= \left(\frac{\text{Average Reach Distance}}{\text{Leg Length}} \right) \times 100. \quad (1)$$

$$\text{FAR} = \frac{\text{Average Thickness During Task}}{\text{Average Quiet-Standing Thickness}}. \quad (2)$$

$$\text{Preferential-Activation Ratio} = \frac{\text{Average GMAX FAR}}{\text{Average GMED FAR}}. \quad (3)$$

Kinematic data were filtered with a zero-lag, fourth-order Butterworth filter at 14.5 Hz using MotionMonitor software. Peak sagittal-plane ankle-dorsiflexion, knee-flexion, and hip-flexion kinematics were obtained for all YBT trials, and the average of the 3 trials for each position was calculated. All kinematic measures were normalized to quiet-standing kinematics to determine the extent of motion beyond stance.

Statistical Analysis

Patient-reported outcomes were compared using independent t tests with the α level set a priori at $\leq.05$ to determine the difference in patients' activity levels, kinesiophobia, and self-reported ankle function. Independent t tests with an α level set a priori at $\leq.05$ were also used to compare the YBT reach distances, lower extremity kinematics, GMAX and GMED FARs, and gluteal preferential-activation ratios of the CAI and control groups. Mean differences and Cohen d effect sizes with 95% confidence intervals were used to determine the magnitude of differences, with effect sizes interpreted as *small* (Cohen d $\leq$ 0.2), *moderate* (Cohen d = 0.6), or *large* (Cohen d $\geq$ 0.8). All statistical analyses were performed using Excel (version 2016; Microsoft Corp, Redmond, WA) and SPSS (version 24.0; IBM Corp, Armonk, NY).

Table 2. Between-Groups Y-Balance Test Reach Distances, Kinematics, and Gluteal-Activation Patterns

Reach Direction	Group, Mean ± SD		Mean Difference (95% Confidence Interval)	Effect Size (95% Confidence Interval)
	Control	Chronic Ankle Instability		
Anterior				
Reach distance, % limb length	70.22 ± 5.22[a]	65.85 ± 6.16[a]	4.37 (0.72, 8.02)	0.77 (0.12, 1.41)
Sagittal-plane kinematics, °				
Ankle dorsiflexion	31.26 ± 5.37	29.08 ± 4.52	2.18 (−1.00, 5.36)	0.44 (−0.19, 1.07)
Knee flexion	75.65 ± 16.06	69.51 ± 13.28	6.14 (−3.29, 15.57)	0.42 (−0.21, 1.04)
Hip flexion	33.62 ± 11.45	34.62 ± 17.45	−1.00 (−10.45, 8.45)	0.07 (−0.69, 0.55)
Functional-activation ratio				
Gluteus maximus	1.08 ± 0.14[a]	1.16 ± 0.14[a]	0.08 (0.01, 0.17)	0.57 (−0.06, 1.26)
Gluteus medius	1.04 ± 0.24	1.05 ± 0.19	−0.01 (−0.15, 0.13)	0.05 (−0.67, 0.57)
Preferential-activation ratio	1.10 ± 0.31	1.14 ± 0.41	−0.06 (−0.31, 0.19)	0.16 (−0.78, 0.47)
Posteromedial				
Reach distance, % limb length	78.02 ± 11.07	78.27 ± 10.21	−0.25 (−7.07, 6.57)	0.02 (−0.64, 0.60)
Sagittal-plane kinematics, °				
Ankle dorsiflexion	24.48 ± 6.61	25.22 ± 4.46	−0.74 (−5.60, 4.12)	0.10 (−0.72, 0.52)
Knee flexion	74.88 ± 13.92	69.44 ± 14.19	5.44 (−3.56, 14.44)	0.39 (−0.24, 1.01)
Hip flexion	79.34 ± 11.99	81.84 ± 20.33	−2.50 (−13.18, 8.18)	0.15 (−0.77, 0.47)
Functional-activation ratio				
Gluteus maximus	1.09 ± 0.15	1.09 ± 0.15	0.00 (−0.10, 0.10)	0.00 (−0.62, 0.62)
Gluteus medius	0.96 ± 0.27	0.94 ± 0.24	0.02 (−0.17, 0.21)	0.07 (−0.55, 0.69)
Preferential-activation ratio	1.19 ± 0.24	1.33 ± 0.63	−0.11 (−0.45, 0.23)	0.21 (−0.83, 0.42)
Posterolateral				
Reach distance, % limb length	79.90 ± 7.62	79.11 ± 10.44	0.79 (−5.06, 6.64)	0.09 (−0.52, 0.71)
Sagittal-plane kinematics, °				
Ankle dorsiflexion	21.38 ± 5.65	21.28 ± 3.71	0.10 (−3.54, 3.74)	0.02 (−0.60, 0.64)
Knee flexion	65.95 ± 19.48	60.54 ± 17.48	5.41 (−6.44, 17.26)	0.29 (−0.33, 0.92)
Hip flexion	83.27 ± 15.90	80.53 ± 21.23	2.74 (−9.27, 14.75)	0.15 (−0.47, 0.77)
Functional-activation ratio				
Gluteus maximus	1.08 ± 0.18[a]	1.06 ± 0.12	0.02 (−0.10, 0.14)	0.11 (−0.51, 0.73)
Gluteus medius	0.98 ± 0.19	0.94 ± 0.26	0.04 (−0.11, 0.19)	0.18 (−0.45, 0.80)
Preferential-activation ratio	1.13 ± 0.25	1.25 ± 0.35	−0.11 (−0.40, 0.18)	0.24 (−0.87, 0.38)

[a] Indicates group difference ($P \leq .05$).

RESULTS

The groups were similar in terms of anthropometric measures and activity levels (Table 1). The CAI group presented with greater kinesiophobia than the control group for the subjective outcomes of the Tampa Scale for Kinesiophobia (mean difference = 16.90, Cohen d = 3.07, $P < .001$) and the Fear-Avoidance Beliefs Questionnaire (mean difference = 14.05, Cohen d = 1.93, $P < .001$). On the Patient-Specific Functional Scale, the CAI group designated activities in which they believed they were limited based on their ankle function and frequently reported problems with running (n = 17), field and court sports (n = 15), cutting (n = 6), and jumping (n = 5), whereas few participants reported limitations in balancing (n = 2).

Y-Balance Test Performance and Kinematics

When we compared YBT performances, the CAI group had smaller anterior-reach distances than the control group (mean difference = 4.37%, Cohen d = 0.77, $P = .002$). However, we observed no differences in the posteromedial or posterolateral reach direction (Table 2; Figure 3). We also identified no group differences in ankle dorsiflexion, knee flexion, or hip flexion for any reach direction (Table 2).

Gluteal Activation

We noted a group difference for the GMAX FAR in the anterior direction; the CAI group had a greater GMAX FAR than the control group (mean difference = 0.08, Cohen d = 0.57, $P = .02$; Table 2, Figure 4A). However, these differences were not accompanied by differences in the preferential-activation ratios between groups (Figure 4B).

No group differences were found for the GMED FARs in any reach direction. In the anterior-reach direction, both groups demonstrated thickness measures greater than the quiet-stance measures (Table 2; Figure 4A). However, in the posteromedial and posterolateral directions, both groups displayed smaller values than the quiet-stance measures.

DISCUSSION

Our hypotheses were partially confirmed; the CAI group presented with decreased performance in the anterior-reach direction of the YBT compared with the control group. Unlike previous investigators who found dynamic-balance deficits in conjunction with arthrokinematic restrictions in patients with CAI,[30] we demonstrated no between-groups differences for ankle dorsiflexion, knee flexion, or hip flexion. Also, no differences occurred in other reach directions, which contradicts previous findings.[12,15]

The variance in gluteal muscle activation was greater than we anticipated,. The CAI group exhibited greater GMAX
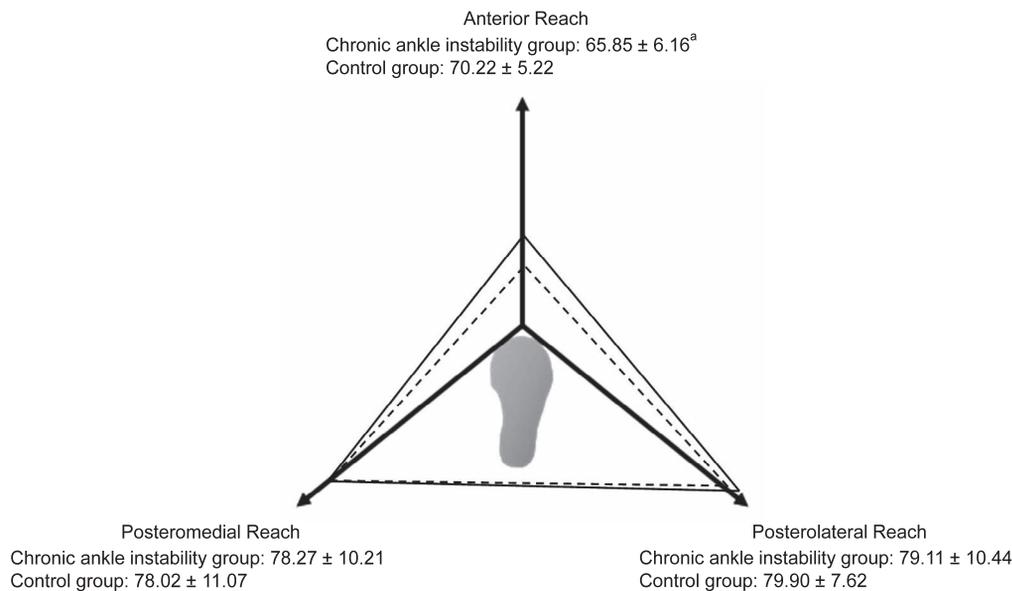
Anterior Reach
Chronic ankle instability group: 65.85 ± 6.16[a]
Control group: 70.22 ± 5.22

Posteromedial Reach
Chronic ankle instability group: 78.27 ± 10.21
Control group: 78.02 ± 11.07

Posterolateral Reach
Chronic ankle instability group: 79.11 ± 10.44
Control group: 79.90 ± 7.62

Figure 3. Reach distances (cm) for the chronic ankle instability (dashed line) and control (solid line) groups. [a] Indicates difference ($P \leq$ .05).

FARs than the control group in the anterior-reach direction, which was contrary to our hypothesis. The average GMED FARs for both groups were also less than the quiet-stance thickness values in the posterior-reach directions. This decrease in thickness during the task does not mean that the muscles were not activating; many factors could have influenced the gluteal muscle thickness measures. In a previous USI muscle-thickness investigation, Dieterich et al[31] found that the deeper muscles decrease in muscle thickness due to compression from synergistic muscle activation and paired fine-wire EMG reflected motor recruitment. Given that the GMAX FARs were greater than the quiet-stance thickness values in the posterior directions, the GMED muscles may have been compressed by this larger muscle. In addition, specifically in the posteromedial- and posterolateral-reach directions, the task required participants to move their center of mass anteriorly by leaning the trunk forward and rotating the hips, movements that are known to be exaggerated in the population with CAI.[32] Although we did not collect hip-rotation or trunk kinematics, the positioning of the iliac crest may have changed and, therefore, lengthened the gluteal muscles, as they would be stretched from the resting position.[8] Further explorations of the trunk strategy and different kinematic components in conjunction with muscle function during the YBT are warranted to better explain this relationship.

Another potential explanation for the decreased gluteal FARs could be attributed to an eccentric muscle contraction. The gluteal muscles eccentrically contract to limit the rate of hip flexion,[8] which is necessary during the YBT due to the controlled dynamic movement in the posterior-reach directions and is reflected in current EMG explorations of the gluteal muscles during dynamic single-limb tasks.[33] The GMED is specifically designed to contract eccentrically to prevent pelvic drop and hip rotation during single-limb tasks[8] and, thus, helps to explain the decreased FARs seen during the YBT.

To our knowledge, USI during an eccentric muscle contraction has not been explicitly studied. The FAR was originally designed to detect transverse abdominis activation during an abdominal draw-in maneuver and other targeted abdominal exercises.[22,29] This concept has been expanded to other tasks, such as loaded functional positions, and to other muscle groups, including the gluteals.[22,27] Given the unique geometry and broad nature of the gluteal muscles, the interpretation of the muscle activation shifts slightly and is task dependent. For example, in several cases, we found that the gluteal muscle thickness of both participant groups decreased during the YBT task in relation to quiet standing, but, in their EMG study, Jaber et al[33] observed increased electrical gluteal activity in other populations during dynamic balance. Therefore, we suggest that decreases in the FAR during a task that requires eccentric control should be interpreted with caution and do not imply muscle disuse. The results should instead be considered in the context of the movement demands and contextualized to a reference contraction. In our investigation, we designated the control group without CAI as the reference population to draw inferences about the CAI group. Further work pairing EMG techniques with USI would also be beneficial to elucidate these relationships.

The CAI group presented with greater average functional activation of the GMAX in the anterior direction than the control group. Instead of relying on muscles closer to the center of hip rotation for eccentric control during activity,[8] a bracing effect of the hip global mover occurred during this task. Given the known limitations at the ankle in individuals with CAI, it is plausible that these patients shifted their strategy to rely more heavily on the GMAX to maintain stability. This altered recruitment pattern may reflect a reluctance to call on the peroneals, tibialis anterior, or other muscles of the lower extremity due to impairments associated with CAI.[3] Although the patients had an increased GMAX FAR, this finding coincided with decreased YBT performance in the anterior direction. This may be an inefficient and ineffective strategy for dynamic stabilization. Our findings highlight an opportunity for
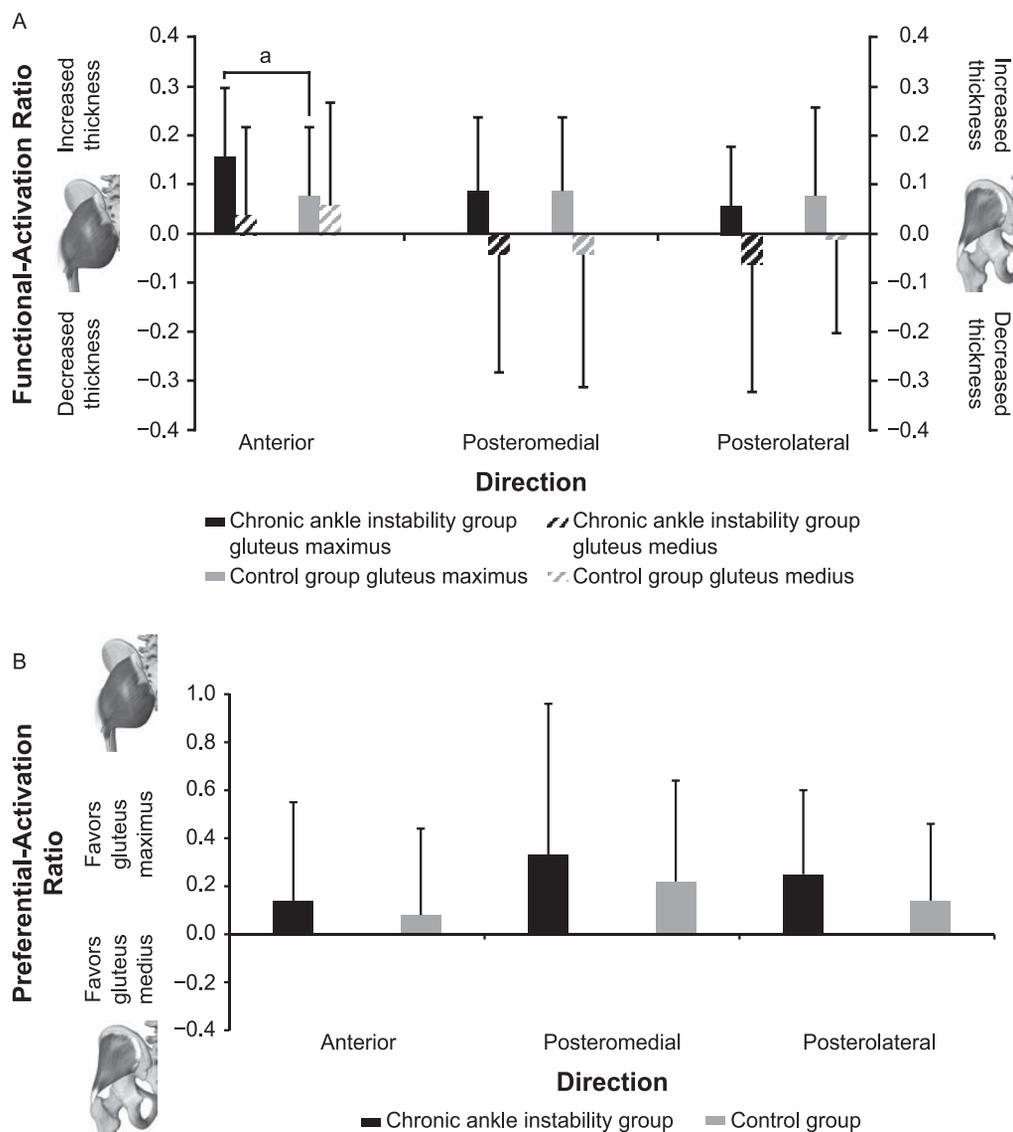
Figure 4. A, Functional-activation ratios of the gluteus maximus and gluteus medius. B, Preferential-activation ratios of the gluteal muscles. [a] Indicates difference ($P \leq .05$).

clinical interventions to target single-legged squatting or other single-limb dynamic strengthening to enhance the hip strategy used by this population or to target neuromuscular-education patterns to shift to a more GMED-focused or deep lateral rotator stabilization tactic during functional activities.

Because we found that individuals with CAI relied more heavily on the GMAX as a probable bracing mechanism, clinicians can use this information to help guide rehabilitative interventions, especially as these results indicated decreased anterior-reach performance. Focusing on single-limb balance or squatting tasks may help patients with CAI adopt a more favorable hip strategy for more effective stabilization and increased reach performance. These interventions would also help address previously identified muscle weaknesses and insufficiencies in this population.[6,7,9] Furthermore, clinicians should consider the specific activities with which patients report difficulty due to their ankle function. The Patient-Specific Functional Scale scores from our study suggested that the patients did not believe their balance was limited due to ankle function;

rather, they reported difficulty during more demanding activities, such as running, cutting, and jumping. Therefore, increasingly demanding tasks may further highlight dysfunction throughout the kinetic chain. This is clinically meaningful, as it may be more beneficial to isolate the activities that patients report having difficulty performing to best identify stabilizing muscle dysfunction for targeted strengthening or neuromuscular-education tactics.

Our findings are clinically meaningful because they add to the growing literature suggesting that proximal adaptations exist during a variety of dynamic activities in individuals with CAI. To our knowledge, we are the first to implement USI as a measurement tool to detect altered gluteal muscle activation during this functional task. Although USI has been used in research settings, this tool should also be considered clinically useful in the athletic training setting. Ultrasound imaging does not require the same level of data processing as traditional EMG measures and allows for a real-time visual interface for both clinicians and patients. As such, USI can potentially be implemented as a form of visual muscle biofeedback during

rehabilitative sessions. This would help clinicians guide muscular education for patients with CAI during dynamic movement, such as the YBT. It could also help patients target muscles closer to the hip center of rotation, such as the GMED, or help increase efficiency in a hip-dominant strategy when performing single-limb activities.

Our study had some limitations. We collected only sagittal-plane ankle-dorsiflexion, knee-flexion, and hip-flexion kinematics and therefore could not examine influences from frontal-plane or transverse-plane motions and trunk kinematics, which may have influenced gluteal muscle-activation patterns and YBT performance. We also focused on the GMAX and GMED muscles; other proximal muscle-group activation patterns could have affected task performance. Our sample was a particularly young and active population due to recruitment in a university and local community setting and, thus, these results cannot necessarily be extrapolated to other groups of patients with CAI. Most of our participants with CAI had a history of bilateral ankle sprains, so we were unable to reasonably perform limb comparisons. Future research is warranted to determine differences in gluteal muscle FARs between limbs in patients with unilateral CAI. Finally, we used USI as the measurement tool and therefore cannot infer the extent of force generation or activation. Ultrasound imaging is a novel tool to investigate muscle thickness during the YBT and, as such, provides a different picture of muscle function during this dynamic task. However, electrical activation cannot be inferred from this measure. Future work is necessary to relate USI findings to other muscle-functioning measures, such as EMG, strength, or muscle-endurance outcomes. The USI probe may have shifted during dynamic movement, which is an inherent limitation of the tool. The same clinicians took measures of securing the probe to the hip to minimize this error and ensure validity of the results.

CONCLUSIONS

The CAI group presented with decreased anterior-reach YBT performance and altered functional GMAX muscle activation compared with the control group. Using USI to measure muscle morphologic changes and estimate muscle-activation patterns during a clinical dynamic-balance test, we identified dynamic-balance deficits and more use of the GMAX during the anterior reach on the YBT. Hip-muscle morphology and increased reliance on GMAX activation during loaded, dynamic conditions may contribute to dysfunction down the kinetic chain in individuals with CAI.

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