Journal of Athletic Training 2012;47(5):525–536
doi: 10.4085/1062-6050-47.5.10

www.nata.org/journal-of-athletic-training

original research

Neuromuscular Characteristics of Individuals Displaying Excessive Medial Knee Displacement

Darin A. Padua, PhD, ATC*; David R. Bell, PhD, ATC†; Micheal A. Clark, DPT, MS, PES, CES‡

*Department of Exercise and Sport Science, University of North Carolina at Chapel Hill; †Departments of Kinesiology and Orthopedics and Rehabilitation, University of Wisconsin–Madison School of Medicine and Public Health; ‡National Academy of Sports Medicine, Chandler, AZ

Context: Knee-valgus motion is a potential risk factor for certain lower extremity injuries, including anterior cruciate ligament injury and patellofemoral pain. Identifying neuromuscular characteristics associated with knee-valgus motion, such as hip and lower leg muscle activation, may improve our ability to prevent lower extremity injuries.

Objective: We hypothesized that hip and lower leg muscle-activation amplitude would differ among individuals displaying knee valgus (medial knee displacement) during a double-legged squat compared with those who did not display knee valgus. We further suggested that the use of a heel lift would alter lower leg muscle activation and frontal-plane knee motion in those demonstrating medial knee displacement.

Design: Descriptive laboratory study.

Setting: Research laboratory.

Patients or Other Participants: A total of 37 healthy participants were assigned to the control (n = 19) or medial-knee-displacement (n = 18) group based on their double-legged squat performance.

Main Outcome Measure(s): Muscle-activation amplitude for the gluteus maximus, gluteus medius, adductor magnus, medial and lateral gastrocnemius, and tibialis anterior was measured during 2 double-legged squat tasks. The first task consisted of performing a double-legged squat without a heel lift; the second consisted of performing a double-legged squat task with a 2-in (5.08-cm) lift under the heels.

Results: Muscle-activation amplitude for the hip adductor, gastrocnemius, and tibialis anterior was greater in those who displayed knee valgus than in those who did not ($P < .05$). Also, use of heel lifts resulted in decreased activation of the gluteus maximus, hip adductor, gastrocnemius, and tibialis anterior muscles ($P < .05$). Use of heel lifts also eliminated medially directed frontal-plane knee motion in those displaying medial knee displacement.

Conclusions: Medial knee displacement during squatting tasks appears to be associated with increased hip-adductor activation and increased coactivation of the gastrocnemius and tibialis anterior muscles.

Key Words: lower extremity, hip, heel lifts

Key Points

- Activation amplitudes of the hip adductor, gastrocnemius, and tibialis anterior muscles were greater in the medial-knee-displacement group than in the control group.
- Activation amplitude was decreased for the tibialis anterior muscle during the heel-lift condition compared with the no–heel-lift condition.
- Medially directed frontal knee displacement was greater in the medial-knee-displacement group than in the control group. Medial knee displacement was corrected in the former group with the use of a heel lift.

Knee-valgus motion is frequently hypothesized as a risk factor for multiple lower extremity injuries.[1,2] Prospective research[3] demonstrated knee valgus to be an important risk factor for lower extremity injury involving the anterior cruciate ligament (ACL). Knee valgus has also been described as associated with other lower extremity conditions, such as patellofemoral pain,[4,5] knee osteoarthritis,[6] medial collateral ligament sprains,[7] and knee cartilage and meniscus damage.[8] To successfully decrease knee-valgus motion, it is important to understand those neuromuscular characteristics (eg, muscle activation, muscle strength, flexibility) associated with it. Different neuromuscular characteristics (eg, decreased gluteal activation or strength, increased hip-adductor activation, decreased ankle-dorsiflexion range of motion) may be associated with knee-valgus motion; thus, we need to develop a systematic assessment process to help clinicians identify which neuromuscular characteristics are involved.

Clinical assessment of knee-valgus movement patterns is operationally defined as the visual appearance of excessive medial knee displacement (MKD).[9] It is not clear whether the knee valgus reported to occur during ACL injuries is an isolated frontal-plane motion that results in medial joint-space opening (ie, true knee valgus) or the combined motions of hip internal rotation and adduction as the foot is fixed on the ground (ie, apparent knee valgus).[10] Therefore, knee valgus and MKD may not represent identical movement patterns. Regardless, excessive MKD is a commonly reported movement pattern observed during noncontact ACL injury events and is believed to be associated with increased lower extremity injury risk.[11–13] The hip abductor, extensor, and external-rotator muscles are frequently hypothesized as being important for controlling against excessive MKD.[14,15] Surprisingly, few authors[16–18] have investigated the role of proximal muscle activation in dynamic knee-valgus motion. Given this limited body of evidence, the relationship between MKD and hip muscle activation is unclear and requires further study.

Recent research indicates that the neuromuscular characteristics of lower leg musculature may contribute to MKD by influencing ankle dorsiflexion, pronation, and eversion. Specifically, tightness or overactivity of the gastrocnemius and soleus musculature can limit ankle dorsiflexion, which is described as resulting in compensatory increases in calcaneal eversion, foot pronation, and tibial internal rotation that may facilitate MKD.[19] We[9] have previously reported, in a separate study of the same participants, a 20% decrease in ankle dorsiflexion range of motion in those with MKD. This finding suggests a possible relationship between ankle muscle-activation patterns that limit ankle dorsiflexion and MKD. However, the previous authors did not report whether muscle-activation differences existed in those participants with MKD. We were also unable to locate any studies investigating lower leg muscle activation as a factor associated with dynamic knee-valgus motion. Thus, the association between lower leg muscle activation and dynamic knee-valgus motion is not well understood.

Exercise interventions that improve MKD may need to differentiate between the hip and lower leg musculature as primary contributing factors to MKD. Heel lifts are recommended as a clinical tool to help distinguish between the lower leg and hip musculature as primary factors contributing to MKD during a double-legged squat.[9] The lower leg musculature is believed to be the primary factor when MKD is present during a double-legged squat but not present after 2-in (5.08-cm) lifts are placed under the heels.[9] A recent investigation[9] has partially validated this concept by comparing hip and lower leg muscle strength and flexibility between individuals with MKD (MKD present without heel lift but not with heel lift) and control (no presence of MKD) participants. In this study,[9] those with MKD displayed decreased lower leg flexibility and strength compared with the control group, but no such deficits in hip muscle flexibility and strength were noted.

Hip and lower leg muscle activation may be associated with MKD, but researchers have not investigated these neuromuscular characteristics. Therefore, the primary purpose of our study was to compare hip and lower leg muscle-activation amplitude in control participants who did not show excessive MKD during the descent and ascent phases of a double-legged squat with that of participants who visually exhibited excessive MKD during a double-legged squat that was corrected by a heel lift. We hypothesized that the MKD group would demonstrate increased lower leg muscle activation during the descent phase but no difference in hip muscle activation during either the descent or ascent phase. A secondary purpose was to investigate the effects of a 2-in (5.08-cm) heel lift on hip and lower leg muscle activation during a double-legged squat. We hypothesized that use of a 2-in (5.08-cm) heel lift would alter lower leg muscle activation and decrease frontal-plane (medial direction) displacement of the knee in the MKD group but that there would be no change in hip muscle activation in either the MKD or control participants.

METHODS

Participants

A total of 37 participants (30 women, 7 men) who were healthy and free from lower extremity injury within 3 months of the time of testing and between the ages of 18 and 25 years volunteered for the study. The participants were assigned to either the MKD or control (CON) group based on their performance of the double-legged squat test, which was evaluated in real time by a single investigator. Participants whose knees stayed over their toes (Figure 1A) were placed in the CON group (n = 19 [15 women, 4 men], age = 21.3 ± 2.3 years, height = 166.8 ± 9.6 cm, mass = 65.9 ± 13.7 kg). Participants who displayed MKD (ie, the midpoint of the patella moved medial to the great toe[9]) during the double-legged squat but not once a 2-in (5.08-cm) lift was positioned under the heels (Figure 1B) were placed in the MKD group (n = 18 [15 women, 3 men], age = 20.2 ± 1.9 years, height = 167.0 ± 7.4 cm, mass = 64.9 ± 9.8 kg). Individuals displaying MKD during both the heel-lift and no–heel-lift conditions were excluded from testing.

Instrumentation

A surface electromyography (EMG) system (model Bangoli-8; DelSys Incorporated, Boston, MA: interelectrode distance = 10 mm, amplification factor = 1000 (20–450 Hz), common mode rejection ratio at 60 Hz > 80 dB, input impedance > 10^{15}//0.2 Ω//picofarad [pF]) was used to record muscle activity of the gluteus maximus (GMAX), gluteus medius (GMED), adductor magnus (ADD), medial gastrocnemius (MG), lateral gastrocnemius (LG), and tibialis anterior (TA) using differential surface electrodes (Delsys). The EMG data were sampled at a rate of 1440 Hz during testing.

A Flock of Birds electromagnetic motion-analysis system (version 8.0; Ascension Technology Corporation, Burlington, VT) was controlled by MotionMonitor software (Innovative Sports Training Inc, Chicago, IL) at a sampling rate of 144 Hz. These data were used both to identify the descending and ascending phases of the squat task for data-reduction purposes and to quantify the magnitude of frontal-plane knee displacement. Kinematic data were sampled at a rate of 144 Hz during testing and then were synchronized with EMG data during data reduction by resampling via linear interpolation.

Testing Procedures

Participants reported to a research laboratory for a single testing session wearing athletic shoes, shorts, and shirt. Upon arrival, all read and signed an informed consent form approved by the University of North Carolina at Chapel Hill Institutional Review Board, which also approved the study. Demographic information was collected for each participant, and a health questionnaire was used to confirm inclusion and exclusion criteria. Participants then complet-

Figure 1. A, Participants assigned to the control group maintained knee alignment over the great toe during the descent phase of the double-legged squat task without a heel lift. B, Participants with medial knee displacement demonstrated medial displacement of the patella over the great toe without a heel lift, which C, was subsequently corrected when using a heel lift.

ed a 5-minute warm-up on a stationary cycle ergometer at a self-selected pace for 5 minutes.

The *dominant leg* was defined as the leg used to kick a ball for maximum distance and was used for EMG and knee-flexion data collection for each person. The EMG electrodes with a fixed center-to-center electrode distance of 2 cm were applied to each of the 6 muscles of interest on the test leg. For EMG preparation, the skin was shaved, abraded, and cleaned with isopropyl alcohol before the surface electrodes were applied. The electrodes for the MG and LG were placed at 20% of the distance of the total shank from the joint line to the lateral malleolus.[20] The TA electrode was placed 20% of the distance of the total shank from the joint line to the lateral malleolus.[20] The GMED electrode was placed at 50% of the distance between the iliac crest and the greater trochanter, and the GMAX electrode was placed at 20% of the distance from S2 to a point 10 cm distal to the greater trochanter.[20] Finally, the ADD electrode was placed at 50% of the distance from the greater trochanter to the medial joint line.[20] Electrode placements were confirmed by inspecting the muscle activity of each muscle with manual muscle tests. Once electrode placement was confirmed, the electrodes and leads were secured with prewrap and athletic tape to minimize movement artifact.

Electromagnetic sensors were placed on the participant's skin over the lateral aspect of the thigh and anteromedial aspect of the proximal tibia. Data indicating the orientation and position of each sensor relative to a standard range transmitter were conveyed back to a personal computer. Each sensor was placed over the area of least muscle mass to minimize potential sensor movement and was secured using double-sided tape, prewrap, and athletic tape. The medial and lateral malleoli and femoral condyles were digitized to determine the ankle- and knee-joint centers, respectively.

The EMG and kinematic data were collected as participants performed 5 double-legged squat repetitions while positioned with their feet shoulder-width apart, toes pointed straight ahead, and arms extended over the head. All testing was performed in bare feet. Participants were instructed to squat as if they were sitting in a chair. We controlled squat speed via a metronome set at 80 beats per minute and squat depth by placing a tripod behind the participant that gave tactile feedback when he or she reached 80° of knee flexion. We selected this squat depth based on previous research[21] demonstrating that peak knee flexion during jump-landing tasks is approximately 80°. Also, this squat depth was shown to be challenging yet achievable for all participants based on pilot testing. Before testing, participants squatted to 80° of knee flexion, which was confirmed using a manual goniometer. We then set the tripod height and position so that the posterior thigh of the participant would touch the tripod upon reaching 80° of knee flexion. Therefore, the tactile feedback provided by the tripod during testing controlled for the range of knee-flexion motion during the squat tasks. Participants were instructed to descend for 2 beats of the metronome, ascend for 2 beats, pause for 1 beat between squats, and then repeat. Before testing, participants were required to perform at least 5 consecutive practice trials of squatting at the appropriate depth cadence. A 1-minute rest period was allowed between completion of the practice trials and data collection.

Two separate double-legged squat conditions were evaluated: heel lift and no heel lift. During the no–heel-lift condition, participants performed 5 consecutive repetitions of the double-legged squat task while maintaining their heels on the floor. All were able to keep their heels on the floor and reach the desired knee-flexion angle during the squat tasks. They were then allowed a 1-minute rest period before they performed the 5 double-legged squat repetitions with a heel lift. The conditions were identical except that for the latter, a 2-in (5.08-cm) wood block was placed under the heels to position the ankle in relative plantar flexion. Testing order of the no–heel-lift and heel-lift conditions was not randomized because this is the way the test is usually performed clinically.

After the data-collection trials, each participant performed three 5-second maximum voluntary isometric contractions (MVICs) for the GMAX, GMED, ADD, gastrocnemius (MG and LG), and TA. For the GMAX MVIC, the participant was prone on a table with the knee flexed to 90°, hip positioned at 0° of flexion (neutral), and a

Table. Normalized Muscle Activation Amplitude (% Maximal Voluntary Isometric Contraction) for Medial-Knee-Displacement (MKD) and Control (CON) Groups During the Descending and Ascending Phases of the Double-Legged Squat

		No Heel Lift				Heel Lift			
		Descending		Ascending		Descending		Ascending	
Muscle	Group	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval
Gluteus medius	MKD	10.7 ± 5.1	7.8, 13.5	11.5 ± 5.1 ±	8.8, 14.2	9.4 ± 4.9	5.7, 13.1	10.3 ± 5.8	6.1, 14.6
	CON	11.1 ± 6.3	8.2, 14.0	12.4 ± 5.7 ±	9.6, 15.2	12.7 ± 9.3	8.9, 16.5	15.3 ± 10.7	10.9, 19.6
Gluteus maximus	MKD	12.8 ± 8.8	9.1, 16.5	14.5 ± 7.5 ±	10.9, 18.1	10.4 ± 7.2	7.0, 13.7	12.1 ± 7.9	8.4, 15.8
	CON	10.4 ± 5.6	6.7, 14.0	14.3 ± 7.1 ±	10.7, 18.0	9.9 ± 6.1	6.5, 13.2	13.4 ± 7.0	9.7, 17.2
Adductor magnus[a]	MKD	35.1 ± 19.8	26.8, 43.4	28.2 ± 16.1 ±	21.7, 34.7	32.2 ± 18.3	23.9, 40.4	28.2 ± 16.1	23.0, 37.9
	CON	22.4 ± 11.9	14.3, 30.4	18.8 ± 8.5 ±	12.5, 25.2	22.6 ± 13.9	14.6, 30.6	19.9 ± 9.8	12.6, 27.1
Medial gastrocnemius[b]	MKD	35.7 ± 18.1	28.5, 43.0	19.9 ± 9.33 ±	15.6, 24.2	25.6 ± 13.2	20.0, 31.2	24.8 ± 12.3	19.3, 30.4
	CON	23.0 ± 11.3	15.8, 30.3	15.6 ± 8.5 ±	11.3, 19.9	16.3 ± 10.0	10.7, 22.0	16.8 ± 10.9	11.2, 22.4
Lateral gastrocnemius[b]	MKD	32.8 ± 16.2	24.2, 41.5	19.2 ± 9.4 ±	12.8, 25.5	21.3 ± 12.9	14.2, 28.3	24.6 ± 14.8	17.7, 31.6
	CON	22.8 ± 17.7	14.4, 31.2	15.6 ± 14.7 ±	9.4, 21.8	15.9 ± 14.5	9.0, 22.7	15.6 ± 12.2	8.9, 22.3
Tibialis anterior[b]	MKD	74.5 ± 23.7	64.3, 84.8	23.0 ± 12.4 ±	18.1, 27.9	34.0 ± 20.0	26.4, 41.6	14.6 ± 9.4	11.0, 18.2
	CON	56.1 ± 17.5	46.1, 66.1	18.7 ± 6.6	13.9, 23.4	26.7 ± 8.9	19.3, 34.1	11.8 ± 4.3	8.3, 15.3

[a] Indicates main effect for group ($P < .05$).
[b] Indicates group × heel lift × phase interaction ($P < .05$).

strap placed over the midbelly of the hamstrings. He or she was then instructed to contract isometrically into hip extension. For the GMED MVIC, the participant was side lying with a strap placed over the knee joint of the upper leg. He or she was instructed to lift up by moving the hip into abduction while keeping the knee extended and the hip in neutral rotation. The ADD MVIC was also assessed in a side-lying position with the bottom leg serving as the test leg. The top leg (nontest leg) was positioned in 45° of hip and knee flexion as the participant placed the top leg on the table's surface. With the participant in this position, the stabilization strap was placed around the test leg just proximal to the medial knee joint line above the epicondyle, and the participant lifted the leg off the table into the strap with maximum force. For the LG and MG MVICs, the participant lay prone on a table with the knees fully extended and the ankle in neutral sagittal-plane position over the edge of the table. A strap was placed around the metatarsal heads of the foot, and he or she was instructed to push into the strap with maximum force. The TA MVIC was assessed with the participant lying supine on a table with the knees fully extended and the ankle in neutral sagittal-plane position over the edge of the table. A strap was placed over the dorsal aspect of the metatarsal head, and he or she was instructed to pull up into the strap with maximum effort. The participant's body was not strapped to the table during gastrocnemius and TA MVIC assessments; however, we ensured that the body did not slide on the table surface during MVIC testing through visual observation. These testing positions are similar to the manual muscle tests described by Hislop and Montgomery.[22]

Data Reduction

The raw EMG data were exported into a custom MATLAB program (The MathWorks, Inc, Natick, MA) and then passively demeaned, bandpass (10 to 350 Hz) and notch (59.5 to 60.5 Hz) filtered, and smoothed using a 25-millisecond root mean square sliding window. Mean EMG amplitudes were calculated during each trial of the descending and ascending phases of the double-legged squat tasks. The *descending phase* was defined as the time from initiation of knee flexion until peak knee flexion as measured with the electromagnetic tracking system. The *ascending phase* was defined as the time from initiation of knee extension until return to the original starting position. We investigated both the descending and ascending phases because we believed that it was clinically important to understand whether differences in muscle-activation strategies existed between groups as they lowered (descending phase) and raised (ascending) the body's center of mass. The EMG data were normalized to the mean amplitude during the middle 3 seconds of each MVIC trial averaged across the 3 MVIC trials.

Three-dimensional coordinates of lower extremity bony landmarks were estimated using MotionMonitor software (version 8.0). All kinematic data were filtered using a 4th-order, low-pass Butterworth filter at 14.5 Hz. Frontal-plane knee-joint displacement data were reduced using custom MATLAB software. We quantified frontal-plane knee-joint displacement as the linear motion (m) of the knee-joint center along the y-axis of the global reference system relative to the starting position for each squat repetition. Frontal-plane knee-joint displacement data were time normalized to each squat repetition (from initiation of knee flexion [0%] to the return to the starting position [100%]) using a cubic spline function. The 5 trials for each participant were ensemble averaged across the whole squat repetition. Ensemble-averaged data for the CON and MKD groups separately were then averaged, and corresponding 95% confidence intervals were determined across each of the 101 discrete data points.

Statistical Analysis

All dependent variables were averaged separately over the 5 trials of the double-legged squat task. Dependent variables were average EMG amplitudes of the GMAX, GMED, ADD, MG, LG, and TA. These EMG data were

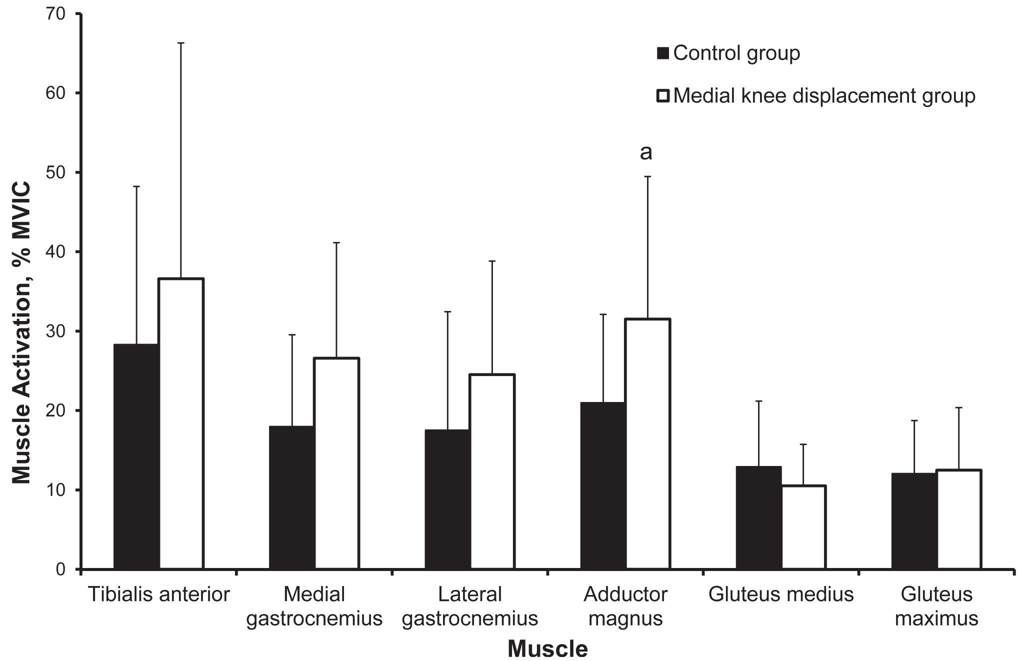

Figure 2. Normalized muscle-activation amplitude (% MVIC) for medial knee displacement and control groups collapsed across squat phase (descending, ascending) and condition (no heel lift, heel lift). Abbreviation: MVIC, maximal voluntary isometric contraction. [a] Indicates difference between medial knee displacement and control groups ($P < .05$).

analyzed during both the descending and ascending phases and the no–heel-lift and heel-lift conditions. We calculated Pearson product moment correlations to assess the relationships between all EMG variables during the no–heel-lift condition due to the possibility of the EMG variables being related and the risk of committing a type II error. Significant correlations were observed between the MG and LG during the descending ($r = 0.52$, $P = .002$) and ascending ($r = 0.74$, $P < .001$) phases. Similarly, the GMED and GMAX were significantly correlated during the descending ($r = 0.45$, $P = .01$) and ascending ($r = 0.36$, $P = .04$) phases. No other significant relationships were observed ($P > .05$).

Based on the correlation analyses, we performed 4 separate mixed-model repeated-measures analyses of variance to compare muscle activation between the MKD and CON groups. Separate analyses were performed for the TA, ADD, gastrocnemius (MG and LG), and gluteal (GMED and GMAX) muscles. Each analysis involved 1 between-subjects factor (group, 2 levels: MKD, CON), and the number of within-subject factors varied. For the TA and ADD muscles, there were 2 within-subject factors: squat condition (no heel lift, heel lift) and squat phase (descending, ascending). Due to the significant relationships between the MG and LG as well as the GMED and GMAX, we included muscle (2 levels: GMED, GMAX or MG, LG) as a third within-subject factor for these variables. Significant interactions were assessed using Tukey honestly significant difference post hoc analysis procedures. Statistical significance was set a priori at $\alpha < .05$. The SPSS for Windows software (version 17.0; SPSS Inc, Chicago, IL) was used for all statistical analyses.

Frontal-plane knee-joint displacement data were analyzed by comparing the 95% confidence intervals from the ensemble-averaged data between the MKD and control groups during the squat task. Specific comparisons of 95% confidence intervals during the squat task involved the MKD and control groups during the no–heel-lift condition and the MKD and control groups during the heel-lift condition.

RESULTS

Descriptive statistics including means, standard deviations, and 95% confidence intervals are presented in the Table. Group main-effects findings for all muscles tested are displayed in Figure 2.

Hip Muscle Activation

Statistical analyses of group differences revealed no main effects involving group for the gluteal muscles ($F_{1,34} = 0.15$, $P = .69$, $\eta^2 = .006$; Figure 2). Thus, no differences in GMED and GMAX activation amplitude were observed between the MKD and CON groups. However, a group main effect for ADD activation was noted ($F_{1,34} = 4.32$, $P = .04$, $\eta^2 = .12$), with ADD activation 34% greater in the MKD than in the CON group (Figure 2). No interactions were observed for group for gluteal and ADD activation amplitude ($P > .05$).

The heel-lift condition influenced ADD activation amplitude but not gluteal (GMED and GMAX) muscle activation. An interaction involving phase and heel-lift condition was shown for ADD activation ($F_{1,34} = 6.96$, $P = .01$, $\eta^2 = .18$). Tukey post hoc analyses revealed greater ADD activation during the descending phase than during the ascending phase of the no–heel-lift condition, but this difference was no longer significant during the heel-lift condition. However, Tukey post hoc analysis did not reveal differences between the heel-lift and no–heel-lift conditions during either the descending or ascending phases of the squat task (Figure 3). Furthermore, gluteal (GMED and

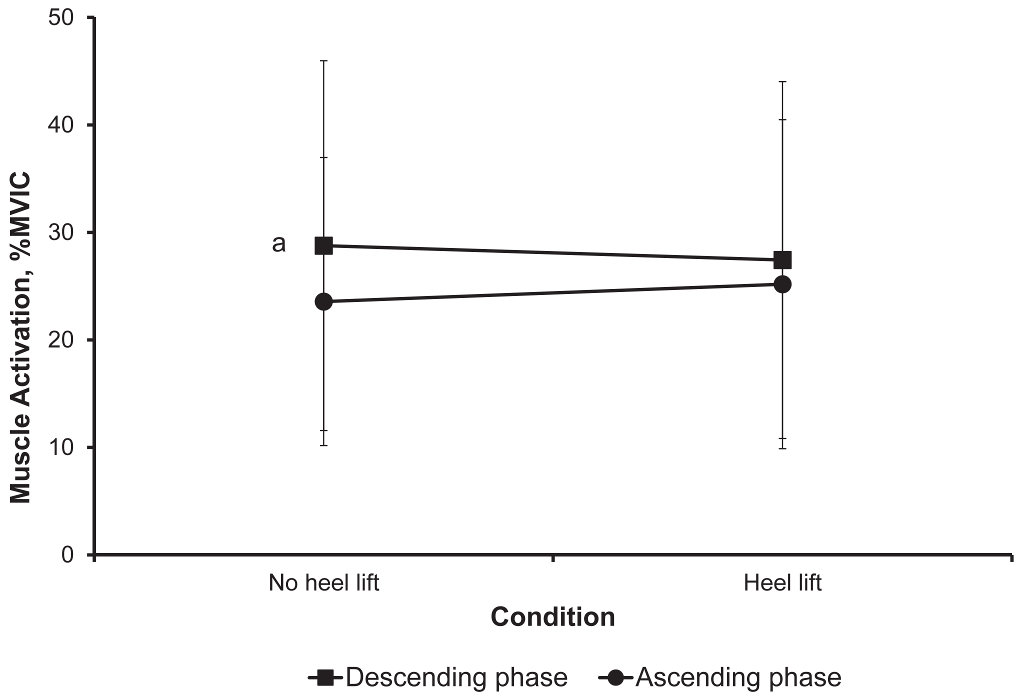

Figure 3. Two-way interaction (squat phase × heel-lift condition) for hip-adductor activation (% MVIC). No change was seen in adductor activation between the no–heel-lift and heel-lift squat conditions during either the descending or ascending phase. Descending-phase activation was greater during the ascending phase only during the no–heel-lift condition. Abbreviation: MVIC, maximal voluntary isometric contraction. [a] Indicates difference between the descending and ascending phases (*P* < .05).

GMAX) activation demonstrated no main effect ($F_{1,28} = 0.13$, $P = .72$, $\eta^2 = .005$) or interactions ($P > .05$) for heel lift. Based on these findings, ADD, GMED, and GMAX activations were not changed during the heel-lift condition compared with the no–heel-lift condition.

Lower Leg Muscle Activation

Three-way interactions involving group-by-phase by heel-lift condition were observed for the TA ($F_{1,34} = 4.46$, $P = .04$, $\eta^2 = .12$; Figure 4) and gastrocnemius (MG and LG: $F_{1,34} = 8.75$, $P = .006$, $\eta^2 = .22$; Figure 5). Tukey

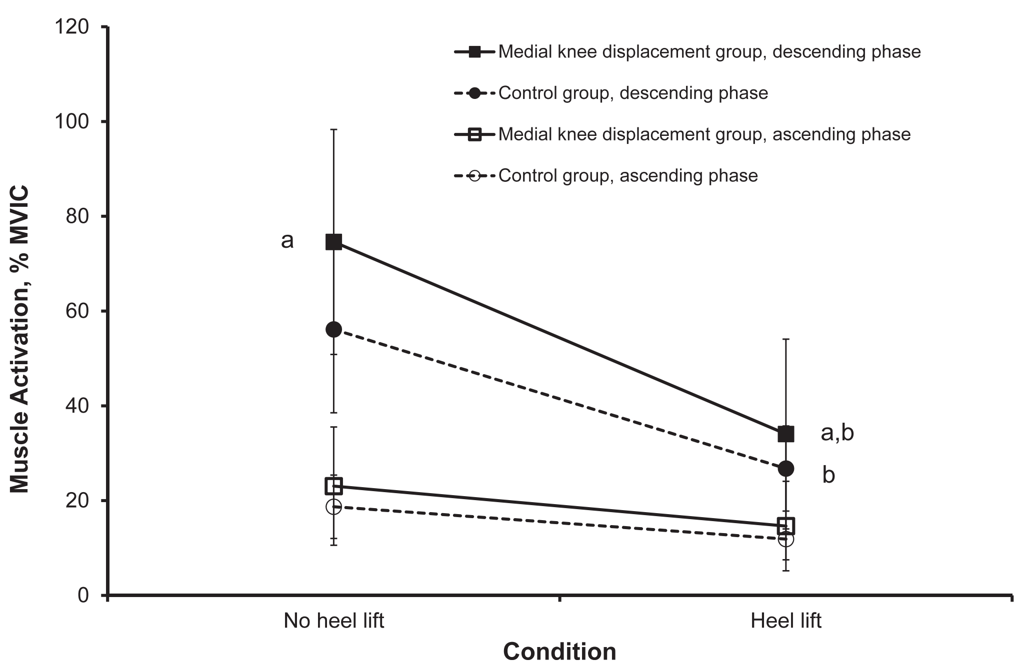

Figure 4. Three-way interaction (group × squat phase × heel-lift condition) for tibialis anterior activation (% maximum voluntary isometric contraction). The medial knee displacement (MKD) group demonstrated greater activation compared with the control group during the descending phase of both the no–heel-lift and heel-lift conditions. Activation during the heel-lift condition was less than during the no–heel-lift condition for both the MKD and control groups. Abbreviation: MVIC, maximal voluntary isometric contraction. [a] Indicates difference between the MKD and control groups (*P* < .05). [b] Indicates difference between the no–heel-lift and heel-lift conditions (*P* < .05).

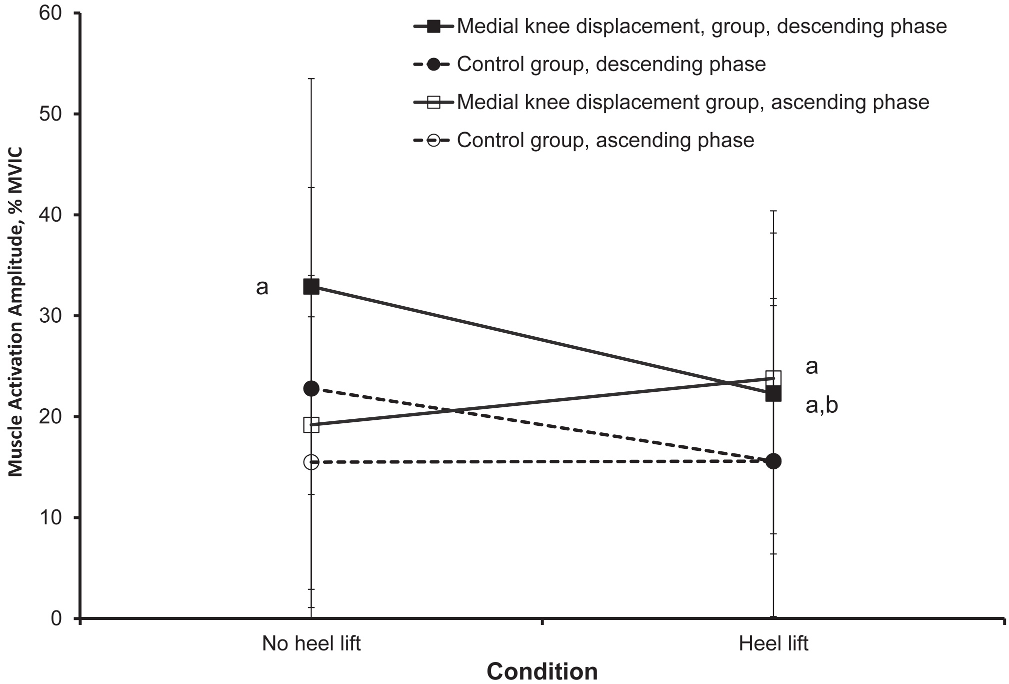

Figure 5. Three-way interaction (group × squat phase × heel lift condition) for gastrocnemius muscle activation (% maximum voluntary isometric contraction). The medial knee displacement (MKD) group demonstrated greater activation compared with the control group during the descending phase of the no–heel-lift and heel-lift conditions and the ascending phase of the heel- lift condition. Decreases were seen in gastrocnemius activation during the heel-lift condition compared with the no–heel-lift condition for the MKD group only. Abbreviation: MVIC, maximal voluntary isometric contraction. [a] Indicates difference between the MKD and control groups ($P < .05$). [b] Indicates difference between the no–heel-lift and heel-lift conditions ($P < .05$).

post hoc analyses demonstrated greater TA activation in the MKD group than in the CON group during the descending phase of the squat task during the no–heel-lift (25% greater) and heel-lift (21% greater) conditions (Table). No differences were observed in TA activation between MKD and CON groups during the ascending phase. During the heel-lift condition, both the MKD and CON groups demonstrated decreased TA activation (MKD: decreased 55%, CON: decreased 52%) compared with the no–heel-lift condition (Table).

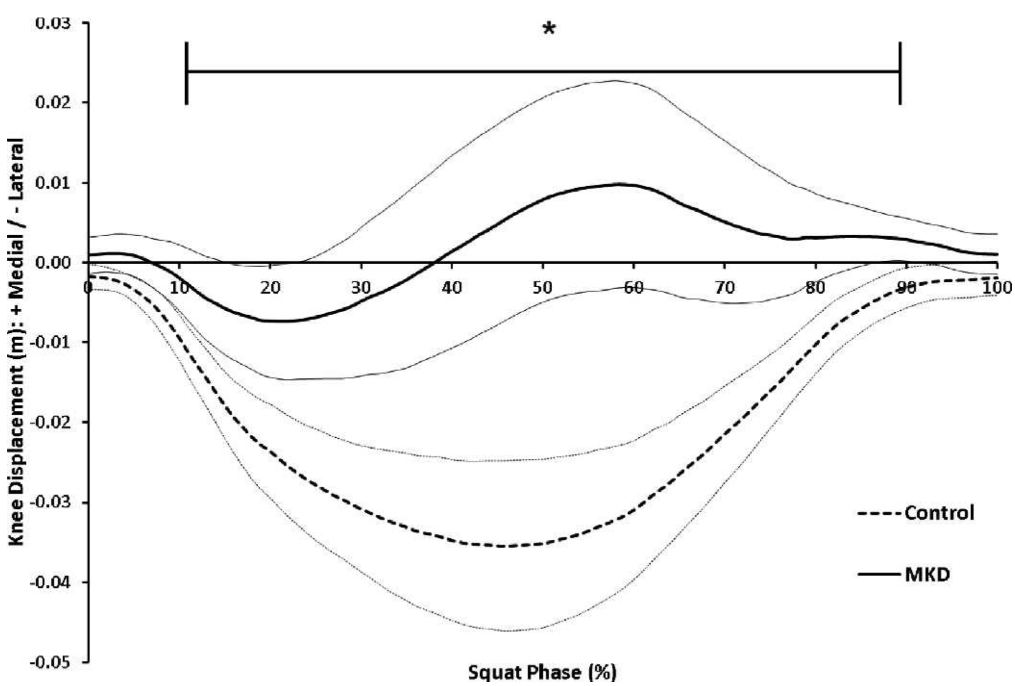

Figure 6. Frontal-plane knee-displacement comparison between the medial knee displacement (MKD) and control groups during the no–heel-lift condition. The MKD group displayed greater medially directed frontal-plane knee motion than the control group. * Indicates difference between the MKD and control groups ($P < .05$).

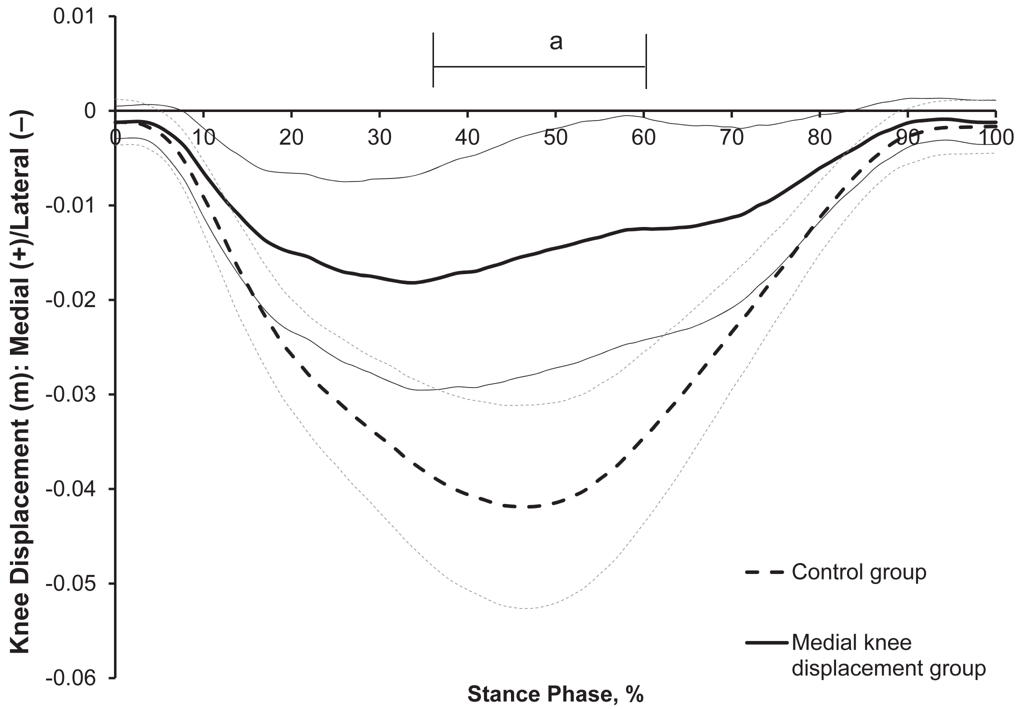

Figure 7. Frontal-plane knee-displacement comparison between the medial knee displacement (MKD) and control groups during the heel-lift condition. The MKD group did not display medially directed frontal-plane knee motion during the no–heel-lift condition. [a] Indicates difference between the MKD and control groups ($P < .05$).

No main effect or interactions were seen for muscle side ($P > .05$) for the gastrocnemius; thus, MG and LG activation amplitudes were pooled for analyses. Gastrocnemius activation during the no–heel-lift condition was greater in the MKD group than in the CON group only during the descending phase (30% greater). Use of the heel lift caused decreased gastrocnemius activation compared with the no–heel-lift condition during the descending (32% decrease) phase for the MKD group, but no changes were observed for the CON group. Gastrocnemius activation in the MKD group was still greater than the CON group during the heel-lift condition during both the descending (30% greater) and ascending (34% greater) phases.

Frontal-Plane Knee Displacement

During the no–heel-lift condition, the MKD group displayed greater medially directed frontal-plane knee displacement than did the control group from 10% to 90% of the squat task (Figure 6). When using the heel lift, the MKD group's frontal-plane knee-displacement values were all laterally directed; however, they demonstrated less laterally directed frontal-plane knee displacement than did the CON group for approximately 35% to 60% of the squat task. No change was apparent in the CON group's frontal-plane knee displacement (Figure 7).

DISCUSSION

To our knowledge, this is the first study to compare hip and lower leg muscle activation between individuals presenting with excessive MKD and those without. In summary, our findings revealed that muscle-activation amplitudes of the hip ADD, gastrocnemius, and TA muscles were greater in the MKD group than in the CON group, but no differences were evident in either GMED or GMAX muscle-activation amplitude between groups. Muscle activation was also decreased for the TA muscle during the heel-lift condition compared with the no–heel-lift condition for all participants. Gastrocnemius activation was also decreased during the heel-lift compared with the no–heel-lift condition but only in the MKD group. Use of a heel lift did not affect gluteal or hip ADD muscle activation within either the descending or ascending phases. Our findings also validate the visual observations of greater medially directed frontal-plane knee displacement in the MKD than in the CON group, as well as correction of medial knee displacement by using a heel lift in the MKD group. These results suggest that increased gastrocnemius, TA, and ADD activation may be an important neuromuscular characteristic associated with excessive MKD during a double-legged squat task. Furthermore, our findings indicate that use of a heel lift facilitates a decrease in medially directed frontal-plane knee motion and is associated with decreased gastrocnemius and TA activity during squatting motions.

Perhaps the most intriguing result of this study was increased gastrocnemius muscle activation in the MKD group compared with the CON group. Activation of the gastrocnemius was 42% greater in the MKD group than in the CON group during the descending phase of the no–heel-lift condition. The gastrocnemius is one of the primary muscles that eccentrically resists ankle dorsiflexion.[23] We theorize that increased gastrocnemius activation may have resulted in a larger internal ankle plantar-flexion moment and increased posterior ankle stiffness. We also observed 25% greater TA activity in MKD compared with the CON participants. Increased TA and gastrocnemius activation in the MKD group indicates that these participants demonstrated greater overall coactivation in their lower leg musculature. Previous researchers[24,25] demonstrated that increased coactivation of agonist and antagonist musculature enhanced overall joint stiffness. We theorize that increased ankle joint stiffness may have limited ankle dorsiflexion, and compensatory MKD may have then occurred during the squatting task. It should be noted that differences in joint moments and stiffness between groups are speculative because we did not quantify ankle-joint kinematics or kinetics.

DiGiovanni and Langer[23] suggested that limited dorsiflexion may facilitate excessive rear-foot pronation and subsequent tibial internal rotation given that the subtalar joint's axis of rotation is oblique and calcaneal eversion is a coupled motion with dorsiflexion. Thus, during weight-bearing activities, restricted dorsiflexion may be compensated for by increased pronation. When the subtalar joint pronates during weight-bearing activities, the calcaneus everts as the talar head adducts and plantar flexes.[26,27] Talar movement during pronation causes lower extremity internal rotation, which, during frontal-plane observation, may appear as MKD. We believe that one of the primary factors affecting the presence of MKD in these participants was increased gastrocnemius and TA coactivation, which may have enhanced ankle-joint stiffness and restricted ankle dorsiflexion (Figure 8). However, the conceptual model we propose in Figure 8 requires further study, because we did not quantify the amount of ankle dorsiflexion or calcaneal eversion during the squat task.

Increased gastrocnemius and TA activation as a factor associated with MKD is further demonstrated when considering that during the heel-lift squatting condition, MKD was not apparent, and activation of these muscles was decreased compared with the no–heel-lift squatting condition. Specifically, MKD participants experienced 55% and 33% decreases in gastrocnemius and TA activation, respectively, during the descending phase of the heel-lift squatting condition. The lack of MKD during the heel-lift squatting condition cannot be explained by alterations in hip muscle activation because ADD and GMED activity was unchanged and GMAX activity was decreased between the no–heel-lift and heel-lift squatting conditions. We hypothesize that the lack of medially directed frontal-plane knee motion in the MKD group during the heel-lift condition may be due to decreases in gastrocnemius and TA activation. We theorize that decreased gastrocnemius and TA activation during the heel-lift squatting condition minimized the internal plantar-flexion moment and stiffness of the ankle, thus allowing for less-restricted dorsiflexion and minimizing compensatory pronation (Figure 8). Previous research[28,29] provides some support for this theory because the internal ankle plantar-flexion moment was reduced when performing single-legged squats with the foot on a declined slant board (eg, heel lift, more plantar-flexed position) compared with flat on the floor. However, it is not clear whether the reduced internal ankle plantar-flexion moment while squatting with the heel elevated is due to decreased muscle activation, less passive tension from the gastrocnemius and soleus muscles, a decreased ankle-joint moment arm for the vertical ground reaction force, or some combination of these factors.

Our findings of increased gastrocnemius and TA activation in MKD compared with CON participants, combined with decreased MKD and gastrocnemius and TA activation during the no–heel-lift squatting condition, suggest that these may be key and often overlooked factors influencing MKD. It is important to note that we did not quantify ankle kinematics and kinetics during the squat task; thus, the conceptual model presented in Figure 8 is largely theoretical. We cannot conclude that decreased MKD during the heel-lift condition was due to decreased gastrocnemius and TA activation. Future research investigating dorsiflexion and lower leg kinematics during the squat tasks is needed to support this conceptual model.

Some support of the conceptual model is provided in research demonstrating coupled movement between frontal-plane knee motion and rear-foot pronation and eversion.[30,31] Specifically, runners identified as hyperpronators demonstrate increased knee valgus during running,[31] and women landed from a jump with increased knee valgus and rear-foot pronation and eversion.[32] Therefore, muscle-recruitment strategies that restrict ankle dorsiflexion, such as increased gastrocnemius and TA activation, may facilitate greater apparent knee valgus (MKD) by causing compensatory increases in rear-foot pronation and eversion motion.

Other previous research also supports our conceptual model in suggesting that restricted ankle dorsiflexion is a factor influencing dynamic knee-valgus alignment. In a separate study of the same participants, we[9] reported a 20% decrease in ankle dorsiflexion range of motion in the MKD compared with the CON group. Sigward et al[33] found a negative relationship between ankle dorsiflexion range of motion and MKD during a jump-landing task, such that individuals with less dorsiflexion range of motion had greater MKD. Other investigators have examined ankle dorsiflexion during functional tasks and observed similar relationships. Hagins et al[34] demonstrated that participants landed with more knee-valgus angle on a surface with an anterior incline of 3.6° and less ankle dorsiflexion. Research by Cortes et al[35] also supports this concept: Participants performed rear-foot landings (landing on the heels in a dorsiflexed position) instead of using their preferred landing styles. During rear-foot landings, participants displayed greater knee-valgus angle at initial contact and decreased dorsiflexion motion after landing compared with their preferred landing styles. Our findings, combined with those of previous researchers,[33–35] support the conceptual model that restricted ankle dorsiflexion is associated with MKD. We theorize that this relationship may occur because limited forward tibial progression (limited dorsiflexion) during deceleration results in compensatory pronation and tibial internal rotation that facilitates MKD, but this possibility requires further investigation.

Contrary to our original hypothesis, no differences were seen in GMED and GMAX activation between groups; however, hip-ADD activation was 34% greater in MKD than in CON participants. Thus, the presence of MKD in our participants did not appear to be associated with decreased GMED and GMAX activation but rather with increased ADD activity. We believe these findings indicate that the relative coactivation between the hip adductor (ADD) and abductor-external rotator (GMED and GMAX) muscles may contribute to MKD. Increased hip ADD activity that is not offset by concomitant increases in GMED and GMAX activity may allow a net internal hip-

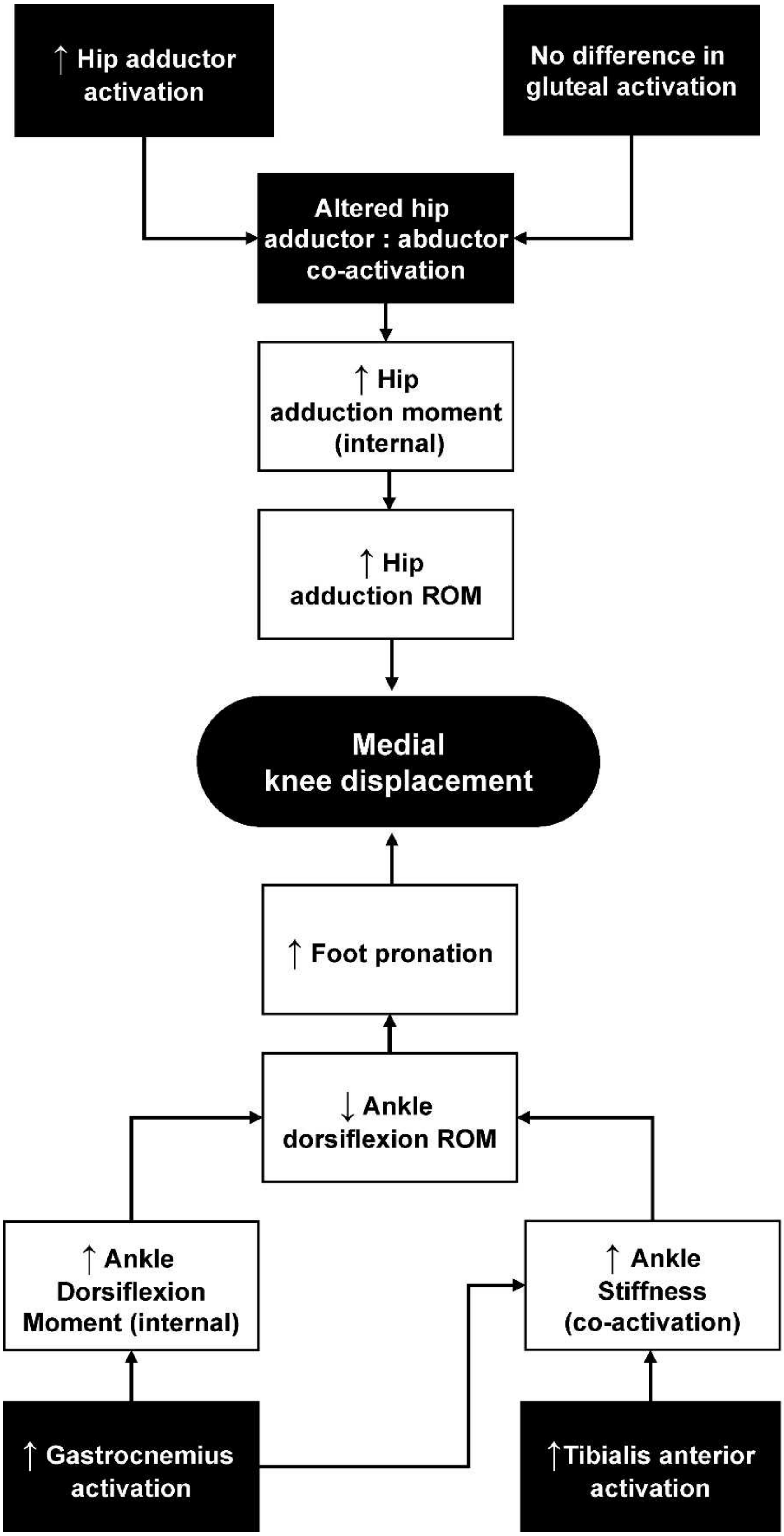

Figure 8. Theoretical model describing the influence of altered hip and lower leg muscle activation in medial-knee-displacement participants during the double-legged squat. Darkened boxes represent findings from the current study. Clear boxes represent theoretical associations of these variables with medial knee displacement. Abbreviation: ROM, range of motion.

adduction moment to pull the hip into a more adducted position. The coactivation ratio of the hip ADD relative to the GMED and GMAX muscles can be calculated by dividing the ADD activation by the average activity of the GMED and GMAX (ADD/average [GMED + GMAX]).[36,37] The coactivation ratios in the MKD and CON groups were 4.0 and 2.3, respectively. Thus, MKD participants displayed 4 times more ADD activation relative to the gluteal muscles. We theorize that increased ADD relative to GMED and GMAX activation was associated with MKD during squatting by increasing the internal hip-adduction moment (Figure 4). However, we did not quantify hip-joint kinetics, so future research is needed.

It is difficult to directly compare these findings with previous results because few authors have examined the influence of hip muscle activation on dynamic knee valgus. Most of the research investigating the influence of hip muscle activation on dynamic knee valgus is limited to sex comparisons of gluteal muscle activity.[38–40] Studies of GMED activation in combination with dynamic knee-valgus measures are in agreement with our findings.[16–18] Russell et al[18] did not observe differences in either knee-valgus angle or GMED activation between men and women during a single-legged drop landing. Palmieri-Smith et al[17] and Hollman et al[16] reported no association between GMED activity and knee-valgus alignment during single-legged landings or step-down tasks, respectively. Therefore, the assumption that GMED-activation amplitude is associated with dynamic knee valgus in healthy participants is not supported by our study or by earlier investigations of both GMED activation and knee-valgus alignment measures.[18]

Our findings of decreased MKD in combination with decreased gastrocnemius and TA activity during the heel-lift condition may have important clinical implications. Multiple neuromuscular strategies could facilitate MKD during a squatting task. Identifying the specific underlying neuromuscular strategy may be a critical aspect of exercise prescription to correct and minimize MKD. We believe that correction of MKD when using heel lifts indicates a lower leg muscle imbalance. Our results agree with those of previous researchers demonstrating decreased gastrocnemius[41,42] and TA[42] activity when using heel lifts. Therefore, use of a heel lift in those demonstrating MKD during an overhead squat may help to identify lower leg muscle imbalances that can be addressed through appropriate exercise interventions and ultimately decreased MKD. However, research validating the conceptual model in Figure 8 is needed before suggesting potential exercises to decrease MKD.

The following limitations should be considered when interpreting the findings of our study. First, our results are limited to an overhead squatting task because we neither observed for MKD nor assessed muscle activation during other functional tasks, such as jump landings or cutting maneuvers. Future authors should identify whether findings carry over when individuals perform more demanding tasks, such as cutting and jump landings, and also investigate the influence of other hip and thigh muscles. Second, our findings are limited to those individuals with MKD that is correctable with a heel lift. Individuals who display MKD during both no–heel-lift and heel-lift conditions may demonstrate different muscle-activation patterns. Third, we did not measure the activation of other hip and thigh muscles, such as the hip external rotators or quadriceps and hamstrings. These muscles are also believed to be important for MKD control. Fourth, these findings do not establish a cause-and-effect relationship between increased activation of the ADD, TA, and gastrocnemius and MKD. Finally, we only measured frontal-plane knee displacement during the squat. Research investigating lower extremity kinematics and kinetics during no–heel-lift and heel-lift squatting conditions is needed.

In conclusion, our findings indicate that gastrocnemius, TA, and ADD activation was increased in participants who display MKD compared with those who did not. We believe these represent 2 neuromuscular strategies associated with dynamic knee valgus. Increased gastrocnemius and TA may be associated with ankle-joint stiffness, thus restricting dorsiflexion motion and facilitating compensatory foot pronation and tibial internal rotation. Increased ADD activity without concomitant increases in gluteal activity may increase internal hip adduction moment and position. Both neuromuscular strategies appear to be associated with MKD.

ACKNOWLEDGMENTS

We acknowledge funding support from the National Academy of Sports Medicine.

REFERENCES

1. Huberti HH, Hayes WC. Patellofemoral contact pressures: the influence of Q-angle and tendofemoral contact. *J Bone Joint Surg Am*. 1984;66(5):715–724.
2. 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(11):647–660.
3. Hewett TE, Myer GD, Ford KR, et al. 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*. 2005;33(4):492–501.
4. Elias JJ, Mattessich SM, Kumagai M, Mizuno Y, Cosgarea AJ, Chao EY. In vitro characterization of the relationship between the Q-angle and the lateral component of the quadriceps force. *Proc Inst Mech Eng H*. 2004;218(1):63–67.
5. Mizuno Y, Kumagai M, Mattessich SM, et al. Q-angle influences tibiofemoral and patellofemoral kinematics. *J Orthop Res*. 2001;19(5):834–840.
6. Brouwer GM, van Tol AW, Bergink AP, et al. Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. *Arthritis Rheum*. 2007;56(4):1204–1211.
7. Hull ML, Berns GS, Varma H, Patterson HA. Strain in the medial collateral ligament of the human knee under single and combined loads. *J Biomech*. 1996;29(2):199–206.
8. Senter C, Hame SL. Biomechanical analysis of tibial torque and knee flexion angle: implications for understanding knee injury. *Sports Med*. 2006;36(8):635–641.
9. Bell DR, Padua DA, Clark MA. Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. *Arch Phys Med Rehabil*. 2008;89(7):1323–1328.
10. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW. Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. *BMC Musculoskelet Disord*. 2010;11:265.
11. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female

athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med*. 2009;43(6):417–422.
12. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359–367.
13. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32(4):1002–1012.
14. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech*. 2006;22(1):41–50.
15. Lawrence RK 3rd, Kernozek TW, Miller EJ, Torry MR, Reuteman P. Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clin Biomech (Bristol, Avon)*. 2008;23(6):806–813.
16. Hollman JH, Ginos BE, Kozuchowski J, Vaughn AS, Krause DA, Youdas JW. Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *J Sport Rehabil*. 2009;18(1):104–117.
17. Palmieri-Smith RM, Wojtys EM, Ashton-Miller JA. Association between preparatory muscle activation and peak valgus knee angle. *J Electromyogr Kinesiol*. 2008;18(6):973–979.
18. Russell KA, Palmieri RM, Zinder SM, Ingersoll CD. Sex differences in valgus knee angle during a single-leg drop jump. *J Athl Train*. 2006;41(2):166–171.
19. Hirth CJ, Padua DA. Clinical movement analysis to identify muscle imbalances and guide exercise. *Athl Ther Today*. 2007;12(4):10–14.
20. LeVeau B, Andersson G. Interpretation of the electromyographic signal. In: Soderberg G, ed. *Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives*. Atlanta, GA: US Department of Health and Human Services; 1992:70–95.
21. Padua DA, Marshall SW, Boling MC, et al. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: the JUMP-ACL study. *Am J Sports Med*. 2009;37(10):1996–2002.
22. Hislop HJ, Montgomery J. *Daniels and Worthingham's Muscle Testing: Techniques of Manual Examination*. St. Louis, MO: Saunders Elsevier; 2007.
23. DiGiovanni CW, Langer P. The role of isolated gastrocnemius and combined Achilles contractures in the flatfoot. *Foot Ankle Clin*. 2007;12(2):363–379.
24. Hogan N, Mann RW. Myoelectric signal processing: optimal estimation applied to electromyography, part I: derivation of the optimal myoprocessor. *IEEE Trans Biomed Eng*. 1980;27(7):382–395.
25. Lacquaniti F, Licata F, Soechting JF. The mechanical behavior of the human forearm in response to transient perturbations. *Biol Cyber*. 1982;44(1):35–46.
26. Tiberio D. The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. *J Orthop Sports Phys Ther*. 1987;9(4):160–165.
27. Tiberio D. Pathomechanics of structural foot deformities. *Phys Ther*. 1988;68(12):1840–1849.
28. Richards J, Thewlis D, Selfe J, Cunningham A, Hayes C. A biomechanical investigation of a single-limb squat: implications for lower extremity rehabilitation exercise. *J Athl Train*. 2008;43(5):477–482.
29. Zwerver J, Bredeweg SW, Hof AL. Biomechanical analysis of the single-leg decline squat. *Br J Sports Med*. 2007;41(4):264–268.
30. McClay Davis I. Coupling parameters in runners with normal and excessive pronation. *J Appl Biomech*. 1997;13(1):109–124.
31. McClay I, Manal K. A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals. *Clin Biomech (Bristol, Avon)*. 1998;13(3):195–203.
32. Kernozek TW, Torry MR, H VANH, Cowley H, Tanner S. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Med Sci Sports Exerc*. 2005;37(6):1003–1012.
33. Sigward SM, Ota S, Powers CM. Predictors of frontal plane knee excursion during a drop land in young female soccer players. *J Orthop Sports Phys Ther*. 2008;38(11):661–667.
34. Hagins M, Pappas E, Kremenic I, Orishimo KF, Rundle A. The effect of an inclined landing surface on biomechanical variables during a jumping task. *Clin Biomech (Bristol, Avon)*. 2007;22(9):1030–1036.
35. Cortes N, Onate J, Abrantes J, et al. Effects of gender and foot-landing techniques on lower extremity kinematics during drop-jump landings. *J Appl Biomech*. 2007;23(4):289–299.
36. Padua D, Carcia C, Arnold B, Granata K. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Motor Behav*. 2005;37(2):111–125.
37. Padua DA, Arnold BL, Perrin DH, et al. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train*. 2006;41(3):294–304.
38. Hart JM, Garrison JC, Kerrigan DC, Palmieri-Smith R, Ingersoll CD. Gender differences in gluteus medius muscle activity exist in soccer players performing a forward jump. *Res Sports Med*. 2007;15(2):147–155.
39. Zazulak BT, Ponce PL, Straub SJ, et al. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther*. 2005;35(5):292–299.
40. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med*. 2003;31(3):449–456.
41. Lee KH, Matteliano A, Medige J, Smiehorowski T. Electromyographic changes of leg muscles with heel lift: therapeutic implications. *Arch Phys Med Rehabil*. 1987;68(5, pt 1):298–301.
42. Lee KH, Shieh JC, Matteliano A, Smiehorowski T. Electromyographic changes of leg muscles with heel lifts in women: therapeutic implications. *Arch Phys Med Rehabil*. 1990;71(1):31–33.

Address correspondence to Darin A. Padua, PhD, ATC, University of North Carolina at Chapel Hill, Department of Exercise and Sport Science, 216 Fetzer Gym, CB#8700, Chapel Hill, NC. Address e-mail to dpadua@email.unc.edu.