Journal of Athletic Training 2012;47(4):396–405
doi: 10.4085/1062-6050-47.4.01

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

*original research*

# Quadriceps and Hamstrings Coactivation During Common Therapeutic Exercises

**Rebecca L. Begalle, MS, ATC*; Lindsay J. DiStefano, PhD, ATC†; Troy Blackburn, PhD, ATC*; Darin A. Padua, PhD, ATC***

*Sports Medicine Research Laboratory, Department of Exercise and Sport Science, University of North Carolina at Chapel Hill; †Department of Kinesiology, University of Connecticut, Storrs

***Context:*** Anterior tibial shear force and knee valgus moment increase anterior cruciate ligament (ACL) loading. Muscle coactivation of the quadriceps and hamstrings influences anterior tibial shear force and knee valgus moment, thus potentially influencing ACL loading and injury risk. Therefore, identifying exercises that facilitate balanced activation of the quadriceps and hamstrings might be beneficial in ACL injury rehabilitation and prevention.

***Objective:*** To quantify and compare quadriceps with hamstrings coactivation electromyographic (EMG) ratios during commonly used closed kinetic chain exercises.

***Design:*** Cross-sectional study.

***Setting:*** Research laboratory.

***Patients or Other Participants:*** Twenty-seven healthy, physically active volunteers (12 men, 15 women; age = 22.1 ± 3.1 years, height = 171.4 ± 10 cm, mass = 72.4 ± 16.7 kg).

***Intervention(s):*** Participants completed 9 separate closed chain therapeutic exercises in a randomized order.

***Main Outcome Measure(s):*** Surface electromyography quantified the activity level of the vastus medialis (VM), vastus lateralis (VL), medial hamstrings (MH), and biceps femoris (BF) muscles. The quadriceps-to-hamstrings (Q:H) coactivation ratio was computed as the sum of average quadriceps (VM, VL) EMG amplitude divided by the sum of average hamstrings (MH, BF) EMG amplitude for each trial. We used repeated-measures analyses of variance to compare Q:H ratios and individual muscle contributions across exercises ($\alpha = .05$), then used post hoc Tukey analyses.

***Results:*** We observed a main effect for exercise ($F_{3,79} = 22.6$, $P < .001$). The post hoc Tukey analyses revealed smaller Q:H ratios during the single-limb dead lift (2.87 ± 1.77) than the single-limb squat (5.52 ± 2.89) exercise. The largest Q:H ratios were observed during the transverse-lunge (7.78 ± 5.51, $P < .001$), lateral-lunge (9.30 ± 5.53, $P < .001$), and forward-lunge (9.70 ± 5.90, $P < .001$) exercises.

***Conclusions:*** The most balanced (smallest) coactivation ratios were observed during the single-limb dead-lift, lateral-hop, transverse-hop, and lateral band-walk exercises. These exercises potentially could facilitate balanced activation in ACL rehabilitation and injury-prevention programs. They also could be used in postinjury rehabilitation programs in a safe and progressive manner.

***Key Words:*** anterior cruciate ligament, closed kinetic chain exercises

**Key Points**

- Exercises that use a quadriceps-dominant activation might negatively affect the knee by increasing strain on the anterior cruciate ligament.
- The hamstrings muscles can counteract the deleterious effect of the quadriceps except when activation is minimal.
- The most balanced quadriceps-to-hamstrings coactivation ratios were produced during the single-limb dead-lift, lateral-hop, transverse-hop, and lateral band-walk exercises.
- Exercises with a more balanced quadriceps-to-hamstrings coactivation ratio may benefit anterior cruciate ligament rehabilitation and injury-prevention programs.

Investigators have estimated that roughly 250 000 physically active young adults sustain anterior cruciate ligament (ACL) injuries annually.[1,2] Noncontact mechanisms, such as decelerating, cutting, and landing from a jump account for about 70% of all ACL injuries.[3–5] Even more daunting are the high rates of recurrent ACL injury to either the repaired or contralateral (previously uninjured) ACL after the athlete returns to full activity.[6–8] Salmon et al[6] reported that 12% of patients had sustained recurrent injury to the ACL of one of their knees within 5 years of the original ACL reconstruction. Similarly, Wright et al[7] found 6% of patients reported recurrent ACL injury to either knee within 2 years after reconstruction. Young adults[8] and individuals who return to sports incorporating lateral side stepping, cutting, jumping, and contact have up to a 10-fold increased likelihood of repeated ACL injury.[6] However, these movements are necessary to successful participation in recreational and competitive sports, and

---

The *Methods* section of this article was adapted with permission from DiStefano LJ, Blackburn JT, Marshall SW, Padua DA. Gluteal muscle activation during common therapeutic exercises. *J Orthop Sports Phys Ther.* 2009;39(7):532–540.

advising young, otherwise healthy adults to avoid these activities is not practical. Instead, the high rates of recurrent injury highlight the need to improve rehabilitation techniques to better prepare individuals for these activities and improve long-term outcomes.

Rehabilitation of the ACL focuses on restoring normal range of motion and strengthening leg musculature, such as the quadriceps and hamstrings, while minimizing excessive loading of the ACL graft.[9] *Closed kinetic chain (CKC) exercise*, which is defined as having the foot fixed against a stationary or moving resistance, has been emphasized as a method to facilitate strengthening while minimizing ACL loading. The weight-bearing nature of these exercises produces a compressive joint load that forces the articular surfaces together, resulting in less anteroposterior displacement of the tibia relative to the femur.[10] Authors of cadaveric studies have demonstrated decreased knee laxity when compressive loads were applied to the joint.[11,12] Beynnon et al[10] demonstrated that added resistance during a CKC knee flexion-extension exercise (squat) did not increase ACL loading, whereas added resistance during open chain knee flexion-extension (seated extension) increased ACL strain. Open chain exercises lack joint compression, which could result in greater anteroposterior displacement of the tibia relative to the femur[10] and thereby place strain on the ACL. Furthermore, the quadriceps-dominant nature of the open chain flexion-extension exercise also could contribute to the increased load observed on the ACL, particularly with added resistance.

In addition, CKC exercises facilitate coactivation of the leg muscles to provide stability at the knee for stance and movement.[10] In particular, hamstrings coactivation with the quadriceps greatly influences ACL loading in multiple planes (sagittal, frontal, transverse).[2,13–16] The hamstrings function synergistically with the ACL to prevent anterior displacement of the tibia, which can be produced by quadriceps contraction.[17] Decreased hamstrings activation relative to the quadriceps has been implicated as a potential mechanism for increased lower extremity injury.[18] Imbalances in muscle activation can be evaluated with coactivation ratios, which are calculated as mean quadriceps activation divided by mean hamstrings activation during movement. A resulting ratio equal or close to 1.0 is more desirable because this indicates equal or more balanced muscle activation. However, when calculated in this manner, a ratio greater than 1.0 indicates quadriceps-dominant activation. Quadriceps-dominant activation increases anterior tibial shear force and magnifies ACL loading,[9,15,19,20] whereas concomitant hamstrings coactivation provides dynamic joint stabilization that protects the knee during sport-related tasks.[14,15,21] However, not all CKC exercises have the same amount of hamstrings muscle coactivation. This notion is supported by Wilk et al,[22] who found minimal hamstrings activation during a seated leg press and a greater amount of hamstrings activation during a standing squat exercise. Therefore, 2 apparently similar CKC exercises use much different levels of muscle activation, which should be considered in exercise prescription.

Given the importance of hamstrings coactivation during CKC exercise, clinicians need to understand the effects of commonly used CKC exercises on quadriceps-to-hamstrings (Q:H) coactivation ratios. Therefore, the purpose of our investigation was to quantify and compare Q:H coactivation ratios during commonly used CKC therapeutic exercises. We hypothesized that (1) differences in Q:H coactivation ratios would exist among the exercises and (2) we would identify exercises that encourage more balanced activation, thereby enhancing clinical decision making.

## METHODS

### Study Design

We used a cross-sectional design with repeated measures in which all participants performed 9 exercises while we recorded electromyographic (EMG) measurements for the quadriceps and hamstrings muscles and calculated coactivation ratios. The order of exercises was counterbalanced.

### Participants

Twenty-seven healthy individuals (12 men, 15 women; age = 22.1 ± 3.1 years, height = 171.4 ± 10 cm, mass = 72.4 ± 16.7 kg) volunteered to participate in this study. All participants were *recreationally active*, which was defined as 60 minutes of physical activity at least 3 days per week. They had no history of ACL injury, had no history of lower extremity surgery within the 2 years before the study, reported no symptoms of injury at the time of testing, and could perform the exercises without pain. All data were collected in a single testing session on the *dominant limb*, which was defined as the limb used to kick a ball for maximal distance. All participants provided written informed consent, and the Institutional Review Board of the University of North Carolina at Chapel Hill approved the study.

### Procedures

Upon arrival at the research laboratory, participants prepared for exercise by performing a 5-minute jogging warm-up at submaximal speed. All participants wore their own comfortable shorts, T-shirts, and athletic shoes. Before testing, participants were taught the proper technique for all exercises and given time to practice until they felt comfortable performing the exercises correctly.

This study was part of a previously published manuscript investigating gluteal muscle activation for these common therapeutic exercises.[23] Our testing procedures were the same as those described by DiStefano et al,[23] and our study focused on quadriceps and hamstrings coactivation in the closed chain exercises only. We chose closed chain exercises that are used in ACL rehabilitation at different periods, whether accelerated or nonaccelerated protocols are implemented.[24,25] In addition, progressions into lateral and transverse movements, and functional and sport-specific activities, including plyometrics (hopping), were incorporated.[24] Therefore, exercises selected for this study replicated those typically used in ACL rehabilitation. The EMG data were collected while participants completed 8 repetitions each of 9 therapeutic CKC exercises in a randomized order with a 2-minute rest between exercises.

Exercises were chosen for this study because of their common use in lower extremity rehabilitation and injury-prevention programs. The single-limb squat,[26–30] single-limb dead-lift,[31,32] lunge,[30,33,34] and hopping[35] tasks have

Figure 1. Single-limb squat exercise.

Figure 3. Forward lunge.

been studied in relation to ACL and knee injury. These CKC exercises require activation of lower extremity muscles and create a challenge to all 3 planes of motion, particularly frontal-plane stability. All exercises are described in detail.

**Single-Limb Squat.** Participants began by balancing on the dominant lower extremity, with their knees and hips flexed approximately 30° and their hands on their hips. Participants slowly lowered themselves toward the ground using their ankle, knee, and hip joints until they could touch the contralateral middle finger to the outside of the dominant foot without reaching with their shoulders. Next, they returned to the starting position and were instructed to keep their knees over their toes to prevent a knee valgus position (Figure 1).

**Single-Limb Dead Lift.** Participants began by balancing on the dominant limb, with their knees and hips flexed approximately 30° and their hands on their hips. They slowly flexed their hips and trunks, touched the contralateral middle finger to the ground beside the support foot, and returned to the starting position. We instructed them to keep their knees flexed to 30° when reaching for the desired level to enable primarily trunk and hip flexion and to keep their knees over their toes (Figure 2).

Figure 2. Single-limb dead-lift exercise.

**Multiplanar Lunges.** Lunges were performed in the sagittal (forward lunge), frontal (lateral lunge), and transverse (transverse lunge) planes. All 3 lunges started with the participants standing with their feet near each other and hands on their hips. All lunges were performed with the dominant limb taking the step and lowering into 90° of hip and knee flexion while the trunk was maintained in an upright position. This prevented the knee from moving anterior to the foot, and the knee of the nondominant limb did not touch the ground. Participants were instructed to keep their knees over the toes for all lunges. They lunged forward, sideways (toward the dominant side), and rotated toward the dominant side (Figures 3 through 5).

**Multiplanar Hops.** Similar to the lunges, hops were performed in the sagittal (forward hop), frontal (lateral hop), and transverse (transverse hop) planes. Participants started in the same position as the lunges and hopped in the

Figure 4. Lateral lunge.

Figure 5. Transverse lunge.

Figure 7. Lateral band-walk exercise.

desired direction: forward, sideways, and rotated 135° toward the ipsilateral side. All jumps were performed off the participants' nondominant limb, landing on the dominant limb, and participants jumped a distance of half of their body heights in the appropriate direction. They were instructed to land "as softly as possible" with their knees flexed and to keep their knees over their toes. They also were instructed to stabilize their bodies and balance upon landing for 3 seconds (Figure 6).

**Lateral Band Walks.** An elastic band (resistance = 2.04 kg/30.5 cm of expansion) was tied around the participants' ankles while they stood upright with their feet together. They maintained their hips and knees in 30° of flexion and their hands on their hips during the exercise. Leading with the dominant limb, participants sidestepped a distance of 130% of their shoulder width (indicated by markings on the floor), assumed a single-limb stance on the dominant limb, and adducted the nondominant limb to replicate the starting position. They were instructed to keep their toes pointed straight ahead and their knees over their toes (Figure 7).

Figure 6. Landing position for multiplanar hop-to-balance exercises.

With the exception of the multiplanar hops, participants used a metronome to perform each exercise at a standardized repetition speed of 60 beats per minute. Both the eccentric and concentric phases of these exercises lasted 2 seconds. During the multiplanar hops, participants were required to stabilize in the landing position for 3 seconds (equivalent of 3 beats of the metronome). They were observed during all practice and recorded repetitions to ensure correct performance of the exercise.

Five minutes after completion of the 9 exercises, 3 separate 5-second maximal voluntary isometric contractions (MVICs) were performed for both the quadriceps and hamstrings to normalize muscle activation data recorded during the exercises. Quadriceps MVIC testing was performed with the participant seated in a chair with the hips and knees flexed to 90° and the trunk supported by the chair back while the investigator (L.J.D.) manually resisted knee extension. Hamstrings MVIC testing was performed with the participant lying prone with the hip positioned in neutral, tibial rotation in neutral, knees flexed to 90°, and the investigator manually resisting knee flexion.

### Data Sampling and Reduction

Preamplified active surface EMG electrodes (Bagnoli-8; Delsys Inc, Boston, MA) with an interelectrode distance of 10 mm, an amplification factor of 10 000 (20–450 Hz), and a common mode rejection ratio of more than 80 dB at 60 Hz were used to measure activation of the quadriceps and hamstrings. All electrodes were placed over the midsection of the muscle belly as outlined by Rainoldi et al.[36] The vastus medialis (VM) electrode was placed 52 mm from the superomedial side of the patella along a line medially oriented at an angle of 50° with respect to the anterosuperior iliac spine, and the vastus lateralis (VL) electrode was placed 94 mm from the superolateral side of the patella to the anterosuperior iliac spine, starting from the patella. The placement of the electrodes for the biceps femoris (BF) was 35% of the distance between the ischial tuberosity and the lateral side of the popliteus cavity, whereas the electrodes for the medial hamstrings (MH) were placed 36% of the distance between the ischial tuberosity and the medial side of the popliteus cavity, starting from the ischial tuberosity. A single reference electrode was positioned over the tibial tuberosity of the dominant limb. Before placement, electrode sites were prepared by shaving hair from the immediate vicinity of the muscle belly and cleansing the skin with isopropyl alcohol applied with a sterile gauze pad to reduce impedance to the EMG signal and to allow proper electrode fixation. Electrodes were secured with prewrap and athletic tape. Proper location of the electrodes was confirmed by viewing the EMG signals on an oscilloscope while the participant activated the muscles against manual resistance. The EMG data were sampled at 1000 Hz.

A dual-axis electrogoniometer (Biometrics, Inc, Ladysmith, VA) was secured to the dominant limb to monitor sagittal-plane knee kinematics. A foot switch was placed directly on the plantar aspect of the first metatarsal to identify foot contact. These data were sampled at 1000 Hz and time synchronized with the EMG data.

Data were collected and exported using MotionMonitor software (Innovative Sports Training, Inc, Chicago, IL). Raw EMG data were band-pass filtered at 20 to 350 Hz and smoothed using a root mean square sliding-window function with a time constant of 20 milliseconds (MATLAB; The MathWorks, Inc, Natick, MA). The customized software program was used to identify the beginning and end of the middle 4 repetitions for each exercise, and the mean EMG signal amplitudes for the quadriceps and hamstrings were calculated and averaged.

The electrogoniometer data were used to determine the start and stop points for the single-limb squat and single-limb dead-lift exercises. Both the electrogoniometer and foot switch were used to select the middle 4 trials for the multiplanar hops and lunges. *Muscle activity during the landing phase*, which was defined as the 3-second period after foot contact, was used for the multiplanar hops. Data from the foot switch and the processed EMG signal established the middle 4 trials for the lateral band walks. Lateral band-walk trials began when the participant lifted the dominant foot from the ground to begin the abduction sidestepping motion and continued as he or she assumed a single-limb stance on the dominant limb and adducted the nondominant limb to replicate the starting position. The end of the trial was the instant immediately before the start of the subsequent trial. Therefore, data include both weight-bearing and non–weight-bearing components of this exercise.

Raw MVIC EMG data were filtered and smoothed in the same manner as the exercise data. Visual inspection was used to identify the middle of each MVIC trial, and the computer algorithm selected 100 milliseconds before and after this point, resulting in a 200-millisecond window. The mean amplitude during this 200-millisecond window was calculated for the 3 MVIC trials per muscle. One MVIC value was obtained for each muscle by averaging the 3 means. The mean EMG amplitudes for each exercise were normalized to these reference values and expressed as percentages of MVICs.

Normalized EMG amplitude levels were used to derive Q:H coactivation ratios for each of the 9 CKC therapeutic exercises. Ratios were calculated by dividing the average quadriceps activity (VM, VL) by the average hamstrings activity (MH, BF). Balanced or equal coactivation calculated by this method would result in a coactivation ratio of 1.0, whereas ratios greater than 1.0 would indicate greater quadriceps than hamstrings activation. Similarly, ratios less than 1.0 would indicate greater hamstrings than quadriceps activation.

### Statistical Analysis

A 1-way repeated-measures analysis of variance (ANOVA) was used to identify differences in Q:H coactivation ratios among exercises. In addition, 2 separate repeated-measures ANOVAs with 2 factors (exercise, muscle side [medial or lateral]) were used to identify differences in medial or lateral and pooled quadriceps and hamstrings activation within the dominant limb during the exercises. The Tukey post hoc analysis was used to calculate minimum differences (MDs) for pairwise comparisons when differences were observed. The $\alpha$ level was set a priori at .05. We used SPSS (version 19.0; IBM Corporation, Armonk, NY) to perform all statistical analyses.

## RESULTS

Calculated Q:H coactivation ratios with standard deviations and 95% confidence intervals are displayed in Table 1 for each therapeutic exercise. Overall means and standard deviations for quadriceps (VM, VL) and hamstrings (MH, BF) activation also are included. We observed an exercise main effect for the Q:H ratio ($F_{3,79} = 22.6$, $P < .001$). Tukey post hoc analysis revealed larger Q:H coactivation ratios for the lunge exercises (forward lunge = 9.70 ± 5.90, $P < .001$; lateral lunge = 9.30 ± 5.53, $P < .001$; transverse lunge = 7.78 ± 5.51, $P < 0.001$) than the single-limb dead lift (2.87 ± 1.77, $P < .001$), lateral hop (3.83 ± 3.51, $P < .001$), transverse hop (3.77 ± 3.51, $P < .001$), and lateral band walk (3.64 ± 1.57, $P < .001$). The Q:H coactivation ratios were greatest (quadriceps-dominant activation pattern) during the 3 lunge exercises, displaying nearly 10 times more quadriceps than hamstrings activation in the forward and lateral lunges. The Q:H coactivation ratios were smaller during the single-limb dead lift, lateral hop, transverse hop, and lateral band walk. The single-limb dead lift (2.87 ± 1.77, $P < .001$) resulted in the smallest Q:H coactivation ratio (most balanced quadriceps and hamstrings activation).

An exercise main effect for pooled quadriceps activation ($F_{4,98} = 40.14$, $P < .001$) was observed; however, no exercise-by-side interaction ($F_{3,84} = 1.42$, $P = .24$) was detected. The Tukey post hoc analysis revealed that the single-limb squat and all 3 lunge exercises had greater quadriceps activation than all other exercises (MD = 37.80, $P < .01$; Table 2).

Normalized EMG amplitudes for pooled quadriceps (VM, VL) and pooled hamstrings (MH, BF) with standard deviations and 95% confidence intervals for all therapeutic exercises are displayed in Table 2. An exercise main effect for pooled hamstrings activation ($F_{8,200} = 14.35$, $P < .001$) was observed. However, no exercise-by-side interaction ($F_{3,69} = 2.58$, $P = .07$) was detected for hamstrings activation. The Tukey post hoc analysis revealed the single-limb dead lift used greater hamstrings activation than the lateral band-walk, forward-hop, lateral-lunge, and forward-lunge exercises (MD = 8.64, $P < .01$).

**Table 1. Calculated Quadriceps:Hamstrings Coactivation Ratios with 95% Confidence Intervals for Each Therapeutic Exercise (Mean ± SD)**

| Exercise | Quadriceps-to-Hamstrings Coactivation Ratio | 95% Confidence Interval |
|---|---|---|
| Single-limb dead lift[a] | 2.87 ± 1.77 | 2.17, 3.57 |
| Transverse hop[a] | 3.77 ± 3.51 | 2.39, 5.17 |
| Lateral hop[a] | 3.83 ± 3.51 | 2.45, 5.23 |
| Lateral band walk[a] | 3.64 ± 1.57 | 3.02, 4.26 |
| Forward hop | 5.26 ± 4.43 | 3.51, 7.01 |
| Single-limb squat | 5.52 ± 2.89 | 4.36, 6.66 |
| Transverse lunge | 7.78 ± 5.51 | 5.60, 9.96 |
| Lateral lunge[b] | 9.30 ± 5.53 | 7.13, 11.49 |
| Forward lunge[b] | 9.70 ± 5.90 | 7.36, 12.03 |

[a] Indicates exercise was different from all 3 lunge exercises (minimum difference = 3.93, $P < .01$).

[b] Indicates exercise was different from all other exercises (minimum difference = 3.93, $P < .01$).

## DISCUSSION

The objective of this study was to assess Q:H coactivation ratios during CKC exercises that commonly are used in lower extremity rehabilitation and injury-prevention programs. We found differences in the levels of Q:H coactivation during these exercises, which supported our first hypothesis. In support of our second hypothesis, exercises were identified that encouraged more balanced Q:H coactivation. Interpretation of our results also offered insight into the potential effectiveness of these common exercises in terms of neuromuscular reeducation or muscle strengthening, or both. Investigators have suggested that muscle activation greater than 50% to 60% MVIC is necessary to produce gains in muscle strength.[37,38] Surprisingly, none of the exercises incorporated in our study successfully facilitated enough hamstrings activation to promote muscle strengthening using this definition of MVIC. This knowledge of muscle contributions during exercises is vital for devising a rehabilitation program to restore muscle integrity and function. Our study provides information that will assist clinicians in selecting exercises most appropriate for their current rehabilitation goals and throughout their exercise progressions. Exercises and their implications for rehabilitation will be discussed in order of the smallest Q:H coactivation ratios (most balanced) to the largest coactivation ratios (most quadriceps dominant). For ease of discussion, exercises also are grouped loosely into 3 general categories based on similar coactivation ratios.

### Smallest Coactivation Ratios

Exercises in this section of the discussion displayed coactivation ratios ranging from 2.87 ± 1.77 to 3.64 ± 1.57. The most balanced Q:H coactivation ratio was observed during the single-limb dead lift, which appears to be driven by both a lesser amount of quadriceps and greater amount of hamstrings activity than the other exercises. Compared with all other exercises, the single-limb dead lift had the greatest overall mean hamstrings activation (25% ± 8%). If the goal of a rehabilitation program is to promote more balanced activation, the single-limb dead lift with body-mass resistance is a good choice. Our results are in agreement with those of other researchers.[31,32] Ebben[31] investigated hamstrings activation of the BF during lower body resistance training exercises in collegiate athletes and observed 48% MVIC activation during the single-leg (stiff-leg) dead lift and 27% MVIC during a squat. The EMG activity was recorded from a single hamstrings muscle (BF) and a single quadriceps muscle (rectus femoris) in this study. The coactivation ratio was calculated as the mean BF activation divided by the mean quadriceps activation for each exercise. The coactivation ratios in our study and similar studies were calculated with the mean activation of 2 muscles, which could contribute to the differences observed in activation levels. These authors concluded the dead lift was superior to a squat exercise in terms of hamstrings activation.[31] However, this level of activation did not exceed the 50% to 60% MVIC necessary for muscle strengthening, so we do not know if strengthening would occur. Ebben[31] also investigated BF activation during 2 open chain exercises and observed 98% and 81% MVIC, respectively, for the Russian curl and seated leg curl. The combination of results from our study and the study by Ebben[31] suggests the potential benefit of including both open and closed chain exercises, depending on the rehabilitation goals of achieving quadriceps strengthening, hamstrings strengthening, or balanced activation. Similarly, Escamilla et al[32] investigat-

**Table 2. Normalized Mean Signal Amplitudes (% Maximal Voluntary Isometric Contraction) for Pooled Quadriceps (Vastus Medialis, Vastus Lateralis) and Pooled Hamstrings (Medial Hamstrings, Biceps Femoris)**

| | Quadriceps | | Hamstrings | |
|---|---|---|---|---|
| Exercise | Mean ± SD | 95% Confidence Interval | Mean ± SD | 95% Confidence Interval |
| Single-limb dead lift[a,b] | 65.71 ± 29.40 | 54.08, 77.34 | 24.15 ± 8.51 | 20.84, 27.47 |
| Transverse hop | 48.46 ± 40.04 | 33.62, 64.30 | 16.47 ± 10.29 | 12.18, 20.76 |
| Lateral hop | 67.84 ± 42.18 | 51.16, 84.53 | 17.97 ± 8.79 | 14.27, 21.68 |
| Lateral band walk | 45.27 ± 19.01 | 37.75, 52.79 | 10.69 ± 6.05 | 8.22, 13.15 |
| Forward hop | 75.87 ± 58.77 | 52.62, 99.12 | 14.66 ± 7.58 | 11.53, 17.77 |
| Single-limb squat[b,c] | 113.27 ± 38.49 | 98.04, 128.50 | 22.24 ± 8.42 | 18.80, 25.68 |
| Transverse lunge[b,c] | 123.73 ± 51.06 | 103.53, 143.93 | 20.99 ± 9.09 | 17.15, 24.83 |
| Lateral lunge[c] | 141.42 ± 55.07 | 119.63, 163.21 | 15.08 ± 7.37 | 11.98, 18.18 |
| Forward lunge[c] | 128.42 ± 57.32 | 105.75, 151.09 | 15.20 ± 7.98 | 11.95, 18.45 |

[a] Indicates exercise uses greater hamstrings activation than the lateral band walk, forward hop, lateral lunge, and forward lunge (minimum difference = 8.64, $P < .01$).

[b] Indicates exercise uses greater hamstrings activation than the lateral band walk (minimum difference = 8.64, $P < .001$).

[c] Indicates exercise uses greater quadriceps activation than the lateral band-walk, single-limb dead-lift, and all hopping exercises (minimum difference = 37.90, $P < .01$).

ed EMG activity during 2 styles of dead lifts (sumo and conventional) in National Collegiate Athletic Association Division I football players during the hypertrophy phase of training. Exercises were performed at a maximum intensity of 12 repetitions, and the authors observed moderate to high coactivation ratios among the quadriceps, hamstrings, and gastrocnemius muscles, concluding the dead lift might be an effective CKC exercise to use during knee rehabilitation. Again, the mean amplitude of muscle activation for the medial and lateral hamstrings achieved only between 27% and 29% MVIC during this study, which might not be sufficient for muscle strengthening. The activation levels for this study are similar to the results found in our study, where mean activations of 2 quadriceps and 2 hamstrings muscles were used to calculate coactivation ratios. A possible explanation for the greater hamstrings activation observed during the single-limb dead lift is the inherent nature of the exercise. The lunge and squat exercises use the hamstrings eccentrically to control the hip during the downward movement (knee flexion) phase of the exercise. During the dead-lift exercise, the hamstrings work eccentrically at the hip and knee, building up tension to stabilize the body as the body mass is moved anterior to the hip and knee during the exercise. However, during the lunge and squat exercises, the hamstrings work eccentrically largely at the hip to control the knee flexion caused by gravity, whereas little to no knee flexion occurs during the dead-lift exercise. These results support the potential benefit of incorporating the dead-lift exercise in a knee rehabilitation setting when promoting coactivation is important.

Our results also suggest the lateral hop-to-balance, transverse hop-to-balance, and lateral band-walk exercises are effective in promoting a more balanced Q:H coactivation ratio than the squat and lunge exercises, which had the highest ratios. These exercises had the lowest levels of mean quadriceps activation (45%–68% MVIC) overall with midrange levels of mean hamstrings activation (10%–18% MVIC), which influences the more balanced coactivation ratio. Again, these exercises still could be considered quadriceps dominant and might not produce a sufficient amount of hamstrings activation to promote muscle strengthening. Therefore, the lateral and transverse hop-to-balance and lateral band-walk exercises would not be recommended for strengthening the hamstrings and would be recommended only for minimal strengthening of the quadriceps. However, incorporating these exercises could potentially aid in neuromuscular reeducation and more balanced coactivation of the thigh musculature while moving primarily in the frontal plane. The lunge and hop exercises in the transverse plane appeared to produce greater hamstrings activation than the lunge and hop exercises in the forward and lateral directions. In addition, the transverse hop achieved better coactivation than the transverse lunge. These hop-to-balance exercises have not been evaluated in terms of Q:H coactivation, offering novel information about their beneficial use in a knee rehabilitation program.

## Moderate Coactivation Ratios

Exercises in this section of the discussion displayed coactivation ratios ranging from 5.26 ± 4.43 to 5.52 ± 2.89. The forward hop and single-limb squat exercises demonstrated approximately 5 times greater quadriceps than hamstrings activation. Whereas these 2 exercises had similar Q:H coactivation ratios, it is interesting to interpret the individual muscle contributions influencing these ratios. The single-limb squat used greater mean quadriceps activation (113% MVIC) than the forward hop (75% MVIC). Therefore, although not different, the hamstrings activation also needed to be greater during the single-limb squat to observe similar coactivation ratios.

Quadriceps-dominant activation during the single-limb squat in our study was in agreement with findings reported in the literature.[26–29,31,32] The single-limb squat frequently is used in functional movement screenings designed to identify individuals with faulty neuromechanics and in rehabilitation programs. Beutler et al[29] recommended the use of the single-limb squat exercise for quadriceps strengthening after they observed peak quadriceps activity at 201% MVIC and peak hamstrings activity at 81% MVIC during this exercise. Moreover, Richards et al[28] observed a greater increase in quadriceps EMG amplitude and knee extensor moment as the knee-flexion angle increased during the single-limb squat, resulting in even greater quadriceps dominance. However, modifications have been identified for the single-limb squat that can facilitate more balanced coactivation by adding resistance to both the flexion and extension phases.[27] Shields et al[27] discovered that adding resistance to the single-limb squat increased hamstrings (BF) activation by 12% MVIC and improved Q:H ratios from 3.0 to 2.32 at the highest resistance. Whereas the exercise remained quadriceps dominant overall and might not facilitate hamstrings strengthening, increasing the resistance did result in slightly more balanced activation. This highlights the importance of understanding the neuromuscular makeup of any exercise that a clinician is going to prescribe, as well as possible ways to modify and adapt exercises to meet the needs and goals of the program.

## Largest Coactivation Ratios

Exercises in this section of the discussion displayed coactivation ratios ranging from 9.30 ± 5.53 to 9.70 ± 5.90. Our results demonstrated that multiplanar lunge exercises produced the largest Q:H ratios, which were driven by the largest mean quadriceps activation (123%–141% MVIC) compared with all other exercises and relatively small hamstrings activation (15%–22% MVIC). Therefore, these exercises are largely quadriceps dominant, which is in agreement with findings reported in the literature.[33,34] The very large Q:H coactivation ratios seen in the multiplanar lunge exercises could contribute to anterior tibial translation, resulting in greater ACL loading. The potential for this loading to be injurious is most likely when the knee is in a more shallow knee-flexion angle, such as during weight acceptance or returning to stance. Activation of the quadriceps in shallow knee-lexion angles has been suggested to place greater strain on the ACL because of the anterior tibial translation that occurs with quadriceps contraction.[39] This should be considered when deciding whether to incorporate these exercises into a knee rehabilitation program because the primary goal should be to protect the patient; premature inclusion of these exercises could result in damage to the reconstructed knee.

Clinicians should be mindful of the healing process and how these exercises affect knee joint structures to allow adequate time for healing and an effective progression of exercises. When a patient is ready, multiplanar lunge exercises are great tools to facilitate quadriceps strengthening in a more functional, sport-specific manner. Stuart et al[40] identified the lunge as a "safe" exercise for ACL rehabilitation, but it is affected by direction and magnitude of ground reaction force, knee-flexion angle, muscle activation, and tibial rotation. They analyzed tibiofemoral joint forces and muscle activity during the forward lunge and found that the mean tibiofemoral shear force was actually posterior throughout the full cycle, with magnitude and increased at greater knee-flexion angles that would not load the ACL.[40] They also observed greater quadriceps and less hamstrings activity during the forward lunge than squat exercises. Other researchers investigating the forward and side lunges have found large forces were placed on the posterior cruciate ligament during both exercises, but no quantifiable loads were placed on the ACL.[41] However, researchers have demonstrated increased patellofemoral joint force and stress during the forward and side lunges, with the greatest stress during the side lunge, which could be a factor with some ACL reconstruction procedures.[42] Finally, researchers have demonstrated modifications for the forward lunge that could encourage greater hamstrings activation. Farrokhi et al[33] investigated how trunk position could influence muscle activity in the lead limb during a forward lunge exercise. They found EMG activity of the lateral hamstrings (BF) was greater with a forward trunk posture than with a trunk-erect posture, which was heavily quadriceps dominant. A forward trunk posture increased the hip-extensor impulse and recruitment, improving Q:H coactivation.

### Recommendations and Limitations

Based on our findings, use of the single-limb dead-lift, lateral hop-to-balance, transverse hop-to-balance, and lateral band-walk exercises is encouraged to help facilitate a more balanced Q:H coactivation ratio during rehabilitation. Lunge exercises should be used with care if the goal is to facilitate coactivation but could be desirable when the goal is quadriceps strengthening. A slight forward lean of the trunk potentially could help increase hamstrings activation. All of these exercises could facilitate quadriceps strengthening in a CKC. However, none of the exercises that we investigated could successfully strengthen the hamstrings muscles in a CKC. Exercise prescription depends on knowledge of muscle activation during each exercise, as well as possible modifications to help achieve rehabilitation goals. Dominant quadriceps activation that is not offset by appropriate hamstrings activation will facilitate anterior tibial translation and increase ACL loading.[2,13,14,17] Rehabilitation programs designed to facilitate a more balanced Q:H coactivation ratio potentially could help reduce the risk of reinjury to the ACL-reconstructed limb and injury to the contralateral (previously uninjured) knee. Alarmingly, the risk of reinjury is higher than the risk of initial ACL injury in young, active individuals.[8,43] Reinjury rates as high as 33% have been identified in individuals after ACL reconstruction.[6,44] Researchers and clinicians must identify ways to modify and improve rehabilitation programs to decrease this rate of reinjury.

We examined muscle activation in a healthy, college-aged population. Therefore, a limitation of our study was that the results cannot be generalized to an injured population. It is not clear if the results would be similar in populations with ACL-deficient or ACL-reconstructed knees. In the future, researchers should investigate patterns of muscle activation during common rehabilitation exercises in individuals after ACL reconstruction.

In addition, a possible limitation to our study was the use of the kicking leg as the dominant leg tested during all exercises. Exercises evaluated were closed chain, and typically if a person prefers to kick with the right leg, the left leg would be the preferred stance leg. However, the test limb was consistent across participants, and the goal of the study was to observe changes in muscle activation within participants across a number of exercises. We are confident that the results would have been similar if we had assessed the dominant stance limb instead.

Another limitation was that we analyzed muscle activation during the entire repetition of an exercise and calculated coactivation ratios with this mean muscle activation rather than at distinct points. We acknowledge that if one looked at these exercises at different periods or point by point throughout the movement cycle, one might see different relationships. However, we do not believe this is a limitation because the purpose of our study was to investigate the muscle activity on a more global level throughout the course of each exercise. In addition, full kinematic and kinetic data were not obtained during this study, so identifying phases of each exercise is more difficult. This method of calculating coactivation ratios depicts the overall relationship between quadriceps and hamstrings muscle activation during these 9 exercises. In addition, similar methods have been used in previous research.[45]

Finally, another limitation to our study was the inherent variability of EMG signals and complicated interpretation, particularly when studying dynamic movements with changes in muscle length, as the muscle would move under the skin where the EMG electrodes are positioned. Collecting detailed kinematic and kinetic data along with the EMG data might enhance the interpretation of findings related to the effect placed on the ACL during these exercises. Despite these limitations, we believe EMG still affords useful information in the coactivation patterns used by these individuals performing CKC exercises.

## CONCLUSIONS

We evaluated the Q:H coactivation ratios among 9 commonly used CKC therapeutic exercises. Results of our study identified exercises, such as multiplanar lunges and single-limb squats, that used a quadriceps-dominant activation pattern and thus might negatively affect the knee by increasing strain on the ACL. The hamstrings muscles are capable of counteracting this deleterious effect of the quadriceps except when activation is minimal. Knowledge of coactivation ratios during therapeutic exercises allows for better exercise prescription and progression, demonstrating clear clinical relevance.

## REFERENCES

1. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med*. 2006;34(9):1512–1532.
2. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med*. 1999;27(6):699–706.
3. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes, part 2: a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med*. 2006;34(3):490–498.
4. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573–578.
5. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players, part 1: mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(7):705–729.
6. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21(8):948–957.
7. Wright RW, Dunn WR, Amendola A, et al. Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. *Am J Sports Med*. 2007;35(7):1131–1134.
8. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med*. 2009;37(2):246–251.
9. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med*. 1995;23(1):24–34.
10. Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension: a comparison of an open and a closed kinetic chain exercise. *Am J Sports Med*. 1997;25(6):823–829.
11. Markolf KL, Bargar WL, Shoemaker SC, Amstutz HC. The role of joint load in knee stability. *J Bone Joint Surg Am*. 1981;63(4):570–585.
12. Hsieh HH, Walker PS. Stabilizing mechanisms of the loaded and unloaded knee joint. *J Bone Joint Surg Am*. 1976;58(1):87–93.
13. Holcomb WR, Rubley MD, Lee HJ, Guadagnoli MA. Effect of hamstring-emphasized resistance training on hamstring: quadriceps strength ratios. *J Strength Cond Res*. 2007;21(1):41–47.
14. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med*. 2006;34(2):269–274.
15. Li G, Rudy TW, Sakane M, Kanamori A, Ma CB, Woo SL. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech*. 1999;32(4):395–400.
16. More RC, Karras BT, Neiman R, Fritschy D, Woo SL, Daniel DM. Hamstrings: an anterior cruciate ligament protagonist. An in vitro study. *Am J Sports Med*. 1993;21(2):231–237.
17. Draganich LF, Jaeger RJ, Kralj AR. Coactivation of the hamstrings and quadriceps during extension of the knee. *J Bone Joint Surg Am*. 1989;71(7):1075–1081.
18. Hewett TE, Myer GD, Zazulak BT. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. *J Sci Med Sport*. 2008;11(5):452–459.
19. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res*. 2001;19(6):1178–1184.
20. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament: an in vitro study performed with a new experimental technique. *J Bone Joint Surg Am*. 1990;72(4):557–567.
21. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med*. 1986;14(1):83–87.
22. Wilk KE, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am J Sports Med*. 1996;24(4):518–527.
23. Distefano LJ, Blackburn JT, Marshall SW, Padua DA. Gluteal muscle activation during common therapeutic exercises. *J Orthop Sports Phys Ther*. 2009;39(7):532–540.
24. Beynnon BD, Uh BS, Johnson RJ, et al. Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind comparison of programs administered over 2 different time intervals. *Am J Sports Med*. 2005;33(3):347–359.
25. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(8):1128–1144.
26. Youdas JW, Hollman JH, Hitchcock JR, Hoyme GJ, Johnsen JJ. Comparison of hamstring and quadriceps femoris electromyographic activity between men and women during a single-limb squat on both a stable and labile surface. *J Strength Cond Res*. 2007;21(1):105–111.
27. 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(10):1520–1526.
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. 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(1):13–18.
30. Boudreau SN, Dwyer MK, Mattacola CG, Lattermann C, Uhl TL, McKeon JM. Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. *J Sport Rehabil*. 2009;18(1):91–103.
31. Ebben WP. Hamstring activation during lower body resistance training exercises. *Int J Sports Physiol Perform*. 2009;4(1):84–96.
32. Escamilla RF, Francisco AC, Kayes AV, Speer KP, Moorman CT III. An electromyographic analysis of sumo and conventional style deadlifts. *Med Sci Sports Exerc*. 2002;34(4):682–688.
33. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. *J Orthop Sports Phys Ther*. 2008;38(7):403–409.
34. Pincivero DM, Aldworth C, Dickerson T, Petry C, Shultz T. Quadriceps-hamstring EMG activity during functional, closed kinetic chain exercise to fatigue. *Eur J Appl Physiol*. 2000;81(6):504–509.
35. Palmieri-Smith RM, McLean SG, Ashton-Miller JA, Wojtys EM. Association of quadriceps and hamstrings cocontraction patterns with knee joint loading. *J Athl Train*. 2009;44(3):256–263.
36. Rainoldi A, Melchiorri G, Caruso I. A method for positioning electrodes during surface EMG recordings in lower limb muscles. *J Neurosci Methods*. 2004;134(1):37–43.
37. Ayotte NW, Stetts DM, Keenan G, Greenway EH. Electromyographical analysis of selected lower extremity muscles during 5 unilateral weight-bearing exercises. *J Orthop Sports Phys Ther*. 2007;37(2):48–55.

38. Atha J. Strengthening muscle. *Exerc Sport Sci Rev*. 1981;9:1–73.
39. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32(2):477–483.
40. Stuart MJ, Meglan DA, Lutz GE, Growney ES, An KN. Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. *Am J Sports Med*. 1996;24(6):792–799.
41. Escamilla RF, Zheng N, MacLeod TD, et al. Cruciate ligament tensile forces during the forward and side lunge. *Clin Biomech (Bristol, Avon)*. 2010;25(3):213–221.
42. Escamilla RF, Zheng N, MacLeod TD, et al. Patellofemoral compressive force and stress during the forward and side lunges with and without a stride. *Clin Biomech (Bristol, Avon)*. 2008;23(8):1026–1037.
43. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. *Am J Sports Med*. 2009;37(3):471–480.
44. Laboute E, Savalli L, Puig P, et al. Analysis of return to competition and repeat rupture for 298 anterior cruciate ligament reconstructions with patellar or hamstring tendon autograft in sportspeople. *Ann Phys Rehabil Med*. 2010;53(10):598–614.
45. Bennett DR, Blackburn JT, Boling MC, McGrath M, Walusz H, Padua DA. The relationship between anterior tibial shear force during a jump landing task and quadriceps and hamstring strength. *Clin Biomech (Bristol, Avon)*. 2008;23(9):1165–1171.

---

*Address correspondence to Rebecca L. Begalle, MS, ATC, Department of Exercise and Sport Science, University of North Carolina at Chapel Hill, 209 Fetzer Hall, CB #8700, Chapel Hill, NC 27599. Address e-mail to rbegalle@email.unc.edu.*