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ORIGINAL RESEARCH REPORT

Effect of Gender on the Quadriceps-to-Hamstrings Coactivation Ratio During Different Exercises

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Context: Coactivation ratio of quadriceps to hamstring muscles (Q:H) and medial to lateral knee muscles (M:L) contributes to the dynamic stability of the knee joint during movement patterns recommended during rehabilitation and important for daily function. ***Objective:*** To compare the quadriceps-to-hamstring and medial-to-lateral knee muscles' coactivation ratios between men and women during the following closed kinetic chain exercises performed on a balance board: forward lunge, side lunge, single-leg stance, and single-leg squat. ***Design:*** Cross-sectional. ***Participants:*** 20 healthy subjects (10 female and 10 male). ***Main Outcome Measures:*** Surface electromyography was used to measure the activation level of quadriceps (vastus lateralis and medialis) and hamstrings (biceps femoris and medial hamstrings) during forward- and side-lunge, single-leg-stance, and single-leg-squat exercises. Subjects were instructed during each exercise to move into the test position and to hold that position for 15 s. EMG was recorded during the 15-s isometric period where subjects tried to maintain a "set" position while the foot was on a balance board. Analysis of variance was used for statistical analysis. ***Results:*** There was a significant exercise-by-gender interaction for Q:H ratio ($F_{3,48} = 6.63$, $P = .001$), but the exercise-by-gender interaction for M:L ratio was not significant ($F_{3,48} = 1.67$, $P = .18$). Women showed larger Q:H ratio in side-lunge exercises than men ($P = .002$). Both genders showed larger M:L and lower Q:H ratio in a single-leg-stance exercise than in the other exercises. ***Conclusions:*** The results indicate that the forward- and side-lunge and single-leg-squat exercises should not be recommended as exercise where a balanced coactivation between quadriceps and hamstring muscles is warranted. Single-leg-stance exercise could be used when seeking an exercise where the ratio is balanced for both women and men.

Keywords: EMG, knee joint, balance, muscle activation

Muscle coactivation is a simultaneous activity of the muscles acting around a joint. It is important for joint stability and an important factor contributing to the efficiency of human movement.[1] Muscle coactivation assists the ligamentous static stabilizers and also helps balance articular surface pressure distribution.[2] In the knee joint, quadriceps-to-hamstring coactivation plays an important role, especially in the loads place on the anterior cruciate ligament (ACL), which can increase when the knee is stressed in multiplanar movement patterns.[3]

The higher incidence rate of ACL injury in female athletes is well documented, and it was shown that female athletes are more likely to sustain ACL injuries than males playing the same sport.[4,5] The unbalanced coactivation between quadriceps and hamstrings is one of the potential factors that places female athletes at risk.[6,7] Female athletes have repeatedly demonstrated a quadriceps dominance in muscle activity compared with males during movements that have been determined to be risk patterns for ACL injuries.[6,8–10] In addition, females primarily activate the lateral quadriceps and hamstrings while concomitantly showing less medial thigh and hamstring muscle activation during squat and when landing from a jump. An increase in lateral quadriceps and hamstrings activation and a decrease in medial quadriceps and hamstrings may lead to an increase in knee valgus.[11,12]

To promote muscular coactivation ratio, closed kinetic chain (CKC) exercises are widely used in training programs.[13,14] CKC exercises are defined as exercises where the feet are fixed on the ground and that typically involve partial or full weight bearing and movement occurring at several joints.[13–16] On the other hand, open kinetic chain (OKC) exercises are typically non–weight bearing, with movement occurring at a single joint, and the distal segment is free to move. While CKC exercises cause cocontraction of the agonist and antagonist muscle, OKC exercises result in isolated movement at a given joint. OKC exercises are effective for isolated strengthening of selected muscle groups. Some studies have indicated that CKC exercises encourage the quadriceps and hamstring coactivation to provide knee-joint stability, causing minimal tension to ACL or other ligaments of the knee joint in comparison with OKC exercises.[17–19]

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Youdas et al[20] reported that Q:H ratio was larger in females than males during single-leg-squat exercise. They also compared the Q:H ratio between unstable and stable surfaces and found no difference between the 2 surfaces in terms of Q:H ratio for either gender. There have been several studies that examined quadriceps and hamstring activation in more advanced maneuvers. For example, several studies examined muscle activation during cutting, landing, and OKC exercises.[10,17,21–25] Assessments of movement strategies that are more commonly used in the midphase of rehabilitation are not available. There has been no study comparing the coactivation ratio of quadriceps (vastus medialis and lateralis) to hamstrings (biceps femoris and medial hamstrings) and medial (vastus medialis and medial hamstring) to lateral (vastus lateralis and biceps femoris; M:L) muscles between genders during different type of exercises on unstable platforms. Therefore, the aim of this study was to compare the quadriceps-to-hamstring and medial-to-lateral knee muscles' coactivation ratios between men and women during different CKC exercises such as forward lunge, side lunge, single-leg stance, and single-leg squat on an unstable platform. We hypothesized that women would demonstrate larger Q:H and/or lower M:L ratio during at least 1 of the exercises.

Methods

Design

We used a cross-sectional design with repeated measures in which the subjects performed 4 different CKC exercises on a balance board while the activation levels of the quadriceps and hamstring muscles were measured by surface electromyography (EMG). The coactivation ratio of the muscles including Q:H and M:L were calculated for forward-lunge, side-lunge, single-leg-stance, and single-leg-squat exercises to determine if there was a gender effect on Q:H and/or M:L ratio. A ratio closer to 1.0 indicates more balanced coactivation. A ratio smaller than 1.0 indicates more hamstrings or more lateral thigh muscle activation, and a ratio larger than 1.0 indicates quadriceps or medial thigh musculature dominance.

Participants

Eighteen healthy subjects (8 men, 10 women) voluntarily participated in this study (Table 1). The inclusion criteria were no history of lower-extremity injuries or surgery at least for the past year and no systematic and neurological disease affecting balance ability during the exercises. The local ethics committee of Hacettepe University approved the protocol for the study. All participants provided informed consent before study enrollment.

Table 1 Physical Characteristics of the Subjects, Mean ± SD

Characteristic	Men	Women
Age (y)	22.6 ± 2.1	23.6 ± 1.8
Weight (kg)	78.1 ± 11.9	57.9 ± 7.1
Height (cm)	177 ± 6.3	161.4 ± 7.2
Body-mass index (kg/m^2)	24.8 ± 2.2	22.2 ± 2.6

Procedures

EMG System. A surface EMG system (Myomonitor, Delsys Inc, Boston, MA) was used to measure the activation levels of the vastus lateralis, vastus medialis, biceps femoris, and medial hamstrings muscles. The characteristics of bipolar Ag/AgCl surface electrodes were as follows: Interelectrode distance was 1 cm, and electrode width was 2 mm. The bandwidth of the processed EMG signal was 20 to 450 Hz, the common-mode rejection ratio was greater than 80 dB, and the input impedance was greater than 10 MΩ. Sampling rate for EMG data was 1000 Hz.

Before electrode placement, the subjects warmed up for 5 minutes on a treadmill at a self-selected velocity. Electrode sites on the body were prepared by shaving any hair on the skin and cleaning the skin with 70% isopropyl alcohol to minimize skin impedance. The placement of electrodes for each muscle was done according to European recommendations for the noninvasive assessment of muscles for surface electromyography.[26] For the vastus medialis muscle, the electrodes were placed at 80% on the line between the anterosuperior iliac spine (ASIS) and the joint space in front of the anterior border of the medial collateral ligament, starting from the ASIS. For the vastus lateralis muscle, the electrodes were placed at 60% on the line from the ASIS to the lateral side of the patella. The placement of the electrodes for medial hamstrings was at 50% on the line between the ischial tuberosity and the medial epicondyle of the tibia. For the biceps femoris, the electrodes were placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. After the placement, the electrodes were fixed on the skin with athletic tape to prevent any displacement during the exercises.

Maximum Voluntary Isometric Contractions. Maximum voluntary isometric contractions (MVICs) of the muscles were recorded before the exercise testing. Quadriceps MVIC testing was performed with the subjects seated on an isokinetic machine (ISOMED 2000, D&R GmbH. Germany) in which their hips were positioned in 90° of flexion and knee in 60° of flexion. For hamstring MVIC testing, the subjects were positioned in prone with the knee flexed at 90°. The trunk was fixed with the straps on the machine, and the subjects were warned verbally when compensation mechanisms of the trunk occurred. The subjects performed 1 trial to understand the task, and after that they performed 3 repetitions of 5-second duration. During the test, the subjects received standardized verbal encouragements to produce maximum effort. A 2-minute rest was given between contractions.

Exercises. All exercise testing procedures were explained, and 4 CKC exercises performed on a balance board (Wobble

Board, Hygenic Corp, OH, USA) were shown to all the subjects. Exercises were performed on the dominant limb only, defined as the leg preferred to kick a ball.[16,27,28] Each individual had a 5-repetition trial to learn the exercises.

For the forward lunge and side lunge, subjects performed a front step or side step onto the balance board with their dominant leg. During the exercises, the angle of the dominant knee was set at 60° of flexion while the trunk was maintained in an upright position (Figures 1 and 2). The subjects were instructed to keep their knees over the toes and to place their weight (as much as possible) on the dominant leg.

Figure 1 — Forward-lunge exercise.

Figure 2 — Side-lunge exercise.

Figure 3 — Single-leg-stance exercise.

Figure 4 — Single-leg-squat exercise.

For single-leg stance, subjects maintained balance on their dominant limb while standing on the balance board, keeping their stance leg in full extension and nonstance knee slightly flexed (Figure 3).

For single-leg squat, subjects kept their balance on the dominant limb while performing a squat by flexing their knee to 45° (Figure 4).

While EMG data were being collected during the exercises, the subjects completed 3 sets of 4 CKC exercises in a computer-based randomized order. The exercises were performed with no change in body posture and knee-joint angle. The subjects were instructed to hold the knee position at the preferred angle for 15 seconds, and a 2-minute rest was given between exercises. A digital goniometer (Baseline, Aurora, IL, USA) was used to determine the knee angle before performing the exercises: Knee-flexion angle for the lunge exercises was 60° and for single-leg-squat exercises was 45°. The posture while performing the exercises was visually checked.

EMG-Signal Processing

All EMG signals were normalized to the maximum EMG signal recorded during MVICs and referred to as %MVIC. EMG-data processing was done using MatLab (MathWorks R2012a). The EMG signals were band-pass filtered (20–450 Hz) and smoothed using root-mean-square and a 100-millisecond moving-window function. For each of the MVIC trials, the maximum value obtained over the 5-second maximum effort was recorded and the maximum values of 3 MVIC trials were used for normalization of the EMG data obtained during the exercises. For each trial of each exercise (3 trials), the maximum signal amplitude of the middle 5 seconds of the 15-second data-collection period was divided by MVIC value. Then, the average of the 3 trials, expressed as %MVIC, was used for data analysis. The average %MVIC for each muscle was used to calculate the 2 separate ratios: Q:H ratio = (sum of average M + L Q/sum of average M+L H) and M:L ratio = (medial Q + medial H/lateral Q + lateral H)].[27]

Statistical Analysis

SPSS version 15.0 (SPSS Inc, Chicago, IL) was used for all statistical analyses. Two-way repeated-measures ANOVA with 1 between-groups (gender) and 1 within-group (exercise) at 4 levels (forward lunge, side lunge, single-leg stance, single-leg squat) was used to determine whether Q:H and M:L coactivation ratio differed between genders during the exercises. The significant interactions or main effects were analyzed with Bonferroni post hoc tests. Intraclass correlation coefficient ($ICC_{3,1}$) and standard error of measurement (SEM) were used to determine the reliability of %MVIC values of the muscles. Statistical significance was set at $P < .05$.

Results

Reliability was calculated across the 3 sets for each muscle during the 4 exercises. Reliability ($ICC_{3,1}$) values ranged from .65 to .92, with SEM of 1.72% to 10.98% MVIC (Table 2). The percentages of muscle activation relative to MVIC for each muscle and exercise are presented in Table 3.

\It was found that there was a significant interaction between exercise and gender in Q:H ratio ($F_{3,48} = 6.63$, $P = .001$). During the side lunge, Q:H ratio was larger for women than for men ($P = .002$). There was a significant exercise main effect for Q:H ratio ($F_{3,48} = 28.61$, $P < .001$). The Q:H ratio during single-leg stance was lower when compared with the side-lunge, forward-lunge, and single-leg-squat exercises ($P < .001$), and the Q:H ratio during side-lunge exercise was higher than during single-leg-squat exercise for both genders ($P = .003$)

There were no significant interactions between exercise and gender for M:L ratio ($F_{3,48} = 1.67$, $P = .18$). The exercise main effect was not found to be significant ($F_{3,48} = 2.05$, $P = .11$; Figure 5).

Discussion

The main objective of this study was to compare the coactivation ratios of quadriceps-to-hamstrings and medial-to-lateral knee muscles between genders during different CKC exercises on a balance board. The only gender difference that was found was in the side-lunge exercise, in which case women had a larger Q:H ratio than men. On the other hand, the medial-to-lateral coactivation ratio did not differ according to gender during exercises.

Table 2 Intrarater Reliability for Testing of Muscle Activation

	Forward Lunge		Side Lunge		Single-Leg Stance		Single-Leg Squat	
Muscle	$ICC_{3,1}$	SEM (%MVIC)	$ICC_{3,1}$	SEM (%MVIC)	$ICC_{3,1}$	SEM (%MVIC)	$ICC_{3,1}$	SEM (%MVIC)
Vastus lateralis	.88	5.40	.82	7.64	.83	10.98	.82	5.70
Vastus medialis	.76	5.83	.76	6.19	.72	8.86	.91	4.79
Medial hamstring	.75	3.84	.92	1.72	.67	8.31	.66	5.67
Biceps femoris	.65	3.37	.71	4.64	.78	6.11	.82	2.80

Abbreviations: ICC, intraclass correlation coefficient; SEM, standard error of measurement; MVIC, maximum voluntary isometric contraction.

Table 3 The Percentage of Muscle Activation Relative to Maximum Voluntary Isometric Contraction for Each Muscle and Exercise, Mean ± SD (Range)

Muscle	Gender	Forward lunge	Side lunge	Single-leg stance	Single-leg squat
Vastus medialis	Female	32.5 ± 16.1 (51.3)	39.4 ± 22.5 (73.8)	3.6 ± 3.4 (8.1)	29.7 ± 6.7 (18.5)
	Male	31.2 ± 10.8 (35.7)	35.0 ± 11.7 (37.9)	5.7 ± 3.1 (8.6)	34.2 ± 16.5 (58.9)
Vastus lateralis	Female	38.6 ± 19.3 (59.7)	43.7 ± 15.1 (44.8)	3.5 ± 2.9 (7.8)	37.1 ± 9.4 (27.2)
	Male	29.6 ± 16.5 (56.6)	34.5 ± 14.7 (39.9)	6.2 ± 4.7 (12.1)	34.0 ± 13.9 (45.3)
Medial hamstrings	Female	11.2 ± 6.7 (18.3)	7.5 ± 4.6 (11.5)	20.4 ± 11.9 (33.1)	14.3 ± 7.6 (21.5)
	Male	15.6 ± 6.7 (23.5)	14.3 ± 6.1 (18.6)	25.4 ± 12.8 (40.4)	18.4 ± 7.2 (25.8)
Biceps femoris	Female	13.0 ± 4.5 (14.1)	8.1 ± 3.5 (10.4)	25.8 ± 8.7 (26.3)	17.0 ± 8.8 (24.8)
	Male	13.7 ± 4.5 (13.1)	13.6 ± 8.3 (24.7)	16.8 ± 7.7 (26.9)	16.5 ± 10.2 (31.5)

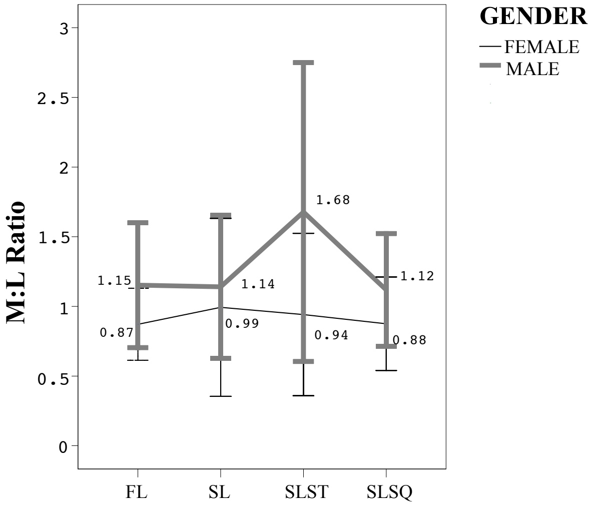

Figure 5 — Coactivation ratio of medial to lateral (M:L) knee muscles during forward-lunge (FL), side-lunge (SL), single-leg-stance (SLST), and single-leg-squat (SLSQ) exercises on balance board between genders.

Before the current study there was no study in the literature comparing the Q:H ratio between genders during side-lunge exercises. Therefore, it is difficult to compare our results with others. However, our findings of a Q:H ratio suggests that women showed greater quadriceps dominance, which could be potentially harmful to the ACL during this movement and could put them at risk for ACL injuries compared with men. This information is in agreement with other studies that found quadriceps dominance in females while performing dynamic movements such as single-leg squat,[11,20] running, and jumping.[6,18] We expected to find a difference for Q:H ratio for gender. Only 1 study in the literature investigated the gender effect on Q:H ratio during CKC exercise, and it showed that females had larger Q:H ratio (1.4) than males (0.4) during single-leg-squat exercise.[20]

Both genders showed lower Q:H ratio during single-leg-stance exercise than all the other exercises, which showed that hamstring muscles were more active than quadriceps muscles during this exercise. On the other hand, they showed larger Q:H ratio during side-lunge exercise when compared with single-leg-stance and -squat exercises. Because Q:H ratio was larger than 1.0 during lunge and squat exercises, these exercises might be beneficial when prescribing exercises that require more quadriceps activation versus hamstring activation for quadriceps strengthening. However, the lunge and squat should not be used if the goal is to promote more balanced coactivation. The Q:H ratio for single-leg stance was the only exercise where the hamstring was more active than the quadriceps. Therefore, this exercise resulted in a more balanced hamstring-to-quadriceps activation because the other exercises required 2 to 6 times more quadriceps activation (Figure 6). Begalle et al[27] reported results similar to those of our study. They investigated the Q:H ratios during common CKC exercises without making a gender comparison. They indicated that the Q:H ratio was larger during forward- and side-lunge exercises compared with single-limb dead lift, lateral and transverse hop, and lateral walk exercises. However, the coactivation ratios of our study were smaller (side lunge 4.6 and front lunge 2.7) than the ratios in their study (side lunge 9.3 and front lunge 9.7). The difference between the 2 studies could be due to the effect of different knee-flexion angle while performing the lunge exercises and the different type of muscle contractions. The subjects of the Begalle et al study performed the lunge exercises with 90° knee flexion, and we used 60° knee flexion in side-lunge exercises. The exercises were performed in a dynamic manner in their study but in an isometric manner in our study. Because during static exercises both quadriceps and hamstrings work together (cocontraction) for stability of the knee joint, Q:H ratio may be found lower in our

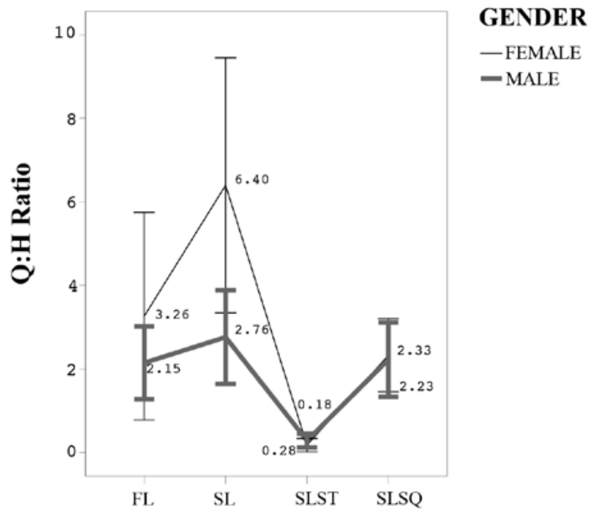

Figure 6 — Coactivation ratio of quadriceps to hamstring (Q:H) muscles during forward-lunge (FL), side-lunge (SL), single-leg-stance (SLST), and single-leg-squat (SLSQ) exercises on balance board between genders.

study compared to the ratios during dynamic exercises in their study. In addition, lunge exercises could make the quadriceps more active compared with the hamstrings, which causes a larger Q:H ratio.

Medial thigh-muscle activity is important to control knee-valgus moment compared with the lateral thigh muscles during athletic activities such as cutting, landing, and squatting.[8,24,29,30] The studies reported that females who showed unbalanced or lower medial-to-lateral coactivation ratio could lose the ability to control the excessive knee-valgus force and anterior shear force, and these forces caused undesirable strain to the ACL during activities.[11,12,25] There has been no study investigating the difference between genders in terms of medial-to-lateral ratio during closed-chain activities. Meyer et al[11] investigated only medial-to-lateral quadriceps muscle-activation ratio, and they found that females showed lower medial-to-lateral quadriceps ratio than males during dynamic single-leg-squat exercise. Palmieri-Smith et al[25] reported that the ratio of medial-to-lateral Q:H cocontraction was lower in women (0.7) than in men (0.9) during landing from a jump. Only in women was the M:L ratio related to a high knee-valgus moment as reported by Palmieri-Smith. They hypothesized that the difference in women only may be because there may be a medial-to-lateral threshold that must be reached before a difference in knee valgus is identified. Therefore, the unbalanced M:L ratio may explain why females are more prone to ACL injuries during sports compared with the males.[5,7,11] In contrast to this finding, we did not find any difference between genders regarding M:L ratio during the CKC exercises, especially during single-leg-squat exercises. Because the exercises in our study were performed in a static manner, they may not result in loads that are great enough to cause excessive knee-valgus moment. On the other hand, both genders showed balanced M:L ratios that were close to 1.0 during the exercises. Hence, these exercises could be beneficial for the balance between medial and lateral knee muscles (Figure 5).

We used a balance board with the exercises because balance boards are the most commonly used unstable platform to make CKC exercises more difficult for subjects during neuromuscular training.[15,18] The balance board is an inexpensive device that patients can easily afford for their home exercise program, and there has been no study in the literature investigating the muscle-coactivation ratio during exercises on a balance board. We aimed to investigate only the gender effects on H:Q and M:L ratio during the exercises performed on a balance board. Therefore, we did not include a control group performing the exercises without a balance board in our study.

The limitation of this study was that it was difficult for us to prevent major changes in the muscle activations because of the compensation mechanisms during the exercises and the difficulty of the exercises. Although we attempted to standardize the subjects' positions by instructing them to keep the pelvis level and the trunk in vertical alignment (verbal and physical cues typically used in a clinical setting), trunk position was not objectively monitored. Therefore, varying trunk postures might have affected our results.

Conclusion

The results of this study demonstrated that women had a larger Q:H ratio than men in side-lunge exercises only. In addition to this, both genders demonstrated lower (<1.0) Q:H ratios during single-leg-stance exercise and larger Q:H ratio during side-lunge exercise than single-leg-stance and single-leg-squat exercise. These larger ratios indicate that forward- and side-lunge and single-leg-squat exercises should not be recommended to improve the balance between quadriceps and hamstring muscles. M:L ratios, for which no gender difference was observed, were found close to 1.0 during all exercises. Therefore, single-leg-stance exercise could be used to promote Q:H, and all 4 exercises could be used for the balance between medial and lateral knee muscles in both women and men.

Acknowledgments

The local ethics committee of Hacettepe University in accordance with the Helsinki II declaration approved the study. All participants gave informed consent before study enrolment.

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