Electromyographic Analysis of the Squat Performed in Self-Selected Lower Extremity Neutral Rotation and 30° of Lower Extremity Turn-Out From the Self-Selected Neutral Position

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During the last several years, the concept of closed kinetic chain exercises has become an integral part of lower extremity rehabilitation programs. The term “kinetic chain” was originally defined by Steindler as "a combination of several successively arranged joints constituting a motor complex" (21). He further subdivided this concept into open and closed kinetic chains. A closed kinetic chain is considered to be one “in which the terminal joint meets with some considerable resistance which prohibits or restrains its free motion” (21). An example of a closed kinetic chain exercise would be the squat or step-up.

Several authors have reasoned that the apparent reduction in strain on the anterior cruciate ligament (ACL) during closed kinetic chain exercises is derived in part by the co-contraction of the quadriceps and hamstring muscle groups (2,11,13). Others have shown that joint compressive forces add stability to the tibiofemoral joint and also reduce ACL strain (6,9,19,22). Yack et al (23) found that an insignificant amount of anterior tibial displacement occurred during the squat and lunge compared with open chain knee extension. Ohkoshi et al (11) found that a posterior shear force existed at all tested angles of knee and trunk flexion during the performance of a static squat. Wilk et al (22) also found the presence of a posterior shear force at the tibiofemoral joint during all angles of
knee flexion when performing a squat or leg press activity. Panariello et al (14) found no significant increase in the anterior-posterior tibiofemoral translation in athletes using the squat for exercise training purposes.

During the performance of a squat, several authors have recommended various positions for placement of the foot (4,10,12,15,16). A previous open kinetic chain study by Hanten and Schulthies (3) found no significant changes in activity of the vastus medialis oblique with medial tibial rotation when the knee was positioned in 50° of flexion. However, Signorile et al (20) found that when tested at −5° of extension, both the vastus medialis and vastus lateralis produced significantly greater electromyographic activity with the foot in an internally rotated position than with the foot externally rotated. A review of literature failed to demonstrate how foot placement and lower extremity turn-out during closed kinetic chain exercises affect the activity of lower extremity muscles.

The purpose of this study was to investigate the effect of lower extremity positioning on electromyographic patterns of the vastus medialis, vastus lateralis, semimembranosus/semitendinous, and biceps femoris muscle groups during the performance of a squat against a resistance of 25% of body weight. Activity patterns of the muscles were examined with the lower extremity in self-selected neutral and 30° of lower extremity external rotation from the self-selected neutral position. Motion was analyzed in 10° intervals from 10–60° of knee flexion during both the ascending and descending phases of the squat. The null hypotheses investigated in this study were that: 1) no differences in muscle activity occurred with changes in lower extremity position; 2) no differences in muscle activity patterns occurred with changes in the angle of knee flexion; and 3) no interactions occurred between the angle of knee flexion and lower extremity rotation on muscle activity patterns.

METHODS

Subjects

Twenty-five (N = 25) untrained subjects (11 females and 14 males), ages 18–35 years, participated in the study. The experiment was reviewed and approved by the Institutional Review Board for Biomedical Research, University of Pittsburgh, Pittsburgh, PA. All subjects signed a written voluntary consent form prior to participation.

Past medical history was reviewed for all subjects prior to their participation in this study. Subjects were excluded from participating in the study if they had a history of: 1) surgery to the neck, shoulder, back, or lower extremity; 2) injury to the neck, shoulder, back, or lower extremity that restricted activity for greater than 1 month; and 3) participation in an exercise program that incorporated squatting exercises within the last 3 months. A physical examination was performed to rule out injury to the anterior and posterior cruciate ligaments as well as patellofemoral pain and dysfunction. Q-angles were measured in the standing position, and all subjects were required to be within ±5° of normal values. For this study, normal Q-angles were defined as 18° for females and 13° for males (8). Subjects were enrolled in this study only if they met all of the above criteria.

Procedures

Prior to data collection, each subject’s body weight was determined. Twenty-five percent of his/her body weight was used as the weight to be lifted by the subject during this study. This weight was selected to give the subject some level of resistance without creating excessive fatigue or risking injury. It was felt that this weight would also be a realistic level of resistance for resistance training during a rehabilitation program.

During data collection, a shoulder-width stance was assumed by each subject. Shoulder width was determined by measuring the distance anteriorly across the chest from the lateral aspect of the right acromion to the lateral aspect of the left acromion. All electromyographic and motion data were collected from the dominant extremity. The dominant extremity was defined as the leg he/she would use to kick a ball.

The subject’s position of self-selected neutral lower extremity turn-out was determined by having him/her march in place five times on a piece of paper. When the subject came to rest, a mark was drawn that bisected the calcaneus and the web space between the first and second toes. A line connecting the two marks was drawn to represent his/her self-selected neutral position of lower extremity turn-out. The 30° turn-out position was determined by placing the axis of a goniometer at the mark bisecting the calcaneus and measuring an arc 30° lateral to the self-selected neutral position. A line was drawn between these two points to indicate the 30° position of lower extremity turn-out. This procedure was performed for both lower extremities. A line was also drawn to...
connect the marks that bisected the right and left calcanei. This line was used to mark the subject’s frontal body plane.

After lower extremity positions had been determined, the subject was positioned for application of surface electromyographic electrodes (Therapeutics Unlimited, Iowa City, IA). The skin was prepared by rubbing it lightly with fine sandpaper and cleaning it with alcohol to reduce impedance of the signal. Electrodes were placed over the largest bulk of the muscle belly while the subject performed an isometric contraction. All electrodes were applied by the same experimenter to avoid intertester variability in placement sites. The ground electrode was placed over the most bony portion of the tibia.

Raw electromyographic data were collected using the EMG-67 system (Therapeutics Unlimited, Iowa City, IA). This system uses silver-silver chloride surface electrodes and on-site preamplifiers. The raw electromyographic (EMG) signal was preamplified with a gain of 35, filtered with a 75 Hz high-pass filter to decrease low frequency and 60 cycle noise, further amplified, and then converted to root mean square (RMS) voltage using a time constant of 55 msec. This RMS voltage is a measure of the power of the EMG signal. The RMS voltage was then sampled at 100 Hz. Electromyographic and motion data were collected simultaneously and automatically synchronized using computer software.

The muscles examined in this study were the vastus medialis, vastus lateralis, semimembranosus/semitendinosus, and biceps femoris. Three 2-second maximum volitional isometric contractions (MVIC) were performed for each muscle group. A MVIC for each muscle group was used as a reference for comparisons of electromyographic data. The MVIC for the vastus medialis and vastus lateralis was determined by having the subject contract the quadriceps with the knee in full extension. The maximum contraction for the semimembranosus/semitendinosus and biceps femoris was performed in the prone position with the knee flexed to 45° and in neutral rotation. The motion of knee flexion, not hip extension, was resisted. The vastus medialis and vastus lateralis were tested simultaneously as were the semimembranosus/semitendinosus and biceps femoris.

A computer program was used to calculate the maximum 1/2-second average of the processed electromyographic signal for each muscle. This voltage was then used as the reference voltage for that muscle and individual during the squatting exercises. All subsequent muscle activity levels were converted to a percentage of this maximum voluntary isometric contraction reference voltage for each muscle group and each individual.

Once the maximum volitional contraction for each muscle group was determined, the subject was pre-
FIGURE 3. Muscle activity patterns of the vastus medialis (VM) during the descending and ascending phases of the squat. Values are percentages of maximal volitional isometric contractions. One standard of deviation is noted.

The angle of knee flexion was then calculated from these three-dimensional coordinates.

After the infrared light-emitting diodes were applied, the subject was positioned on the experimental platform (Figure 1). Electromyographic and motion data were collected simultaneously during three Olympic squats performed between 0° and 75° of knee flexion (Figure 2). Electromyographic data were averaged over the 10° intervals of motion. Average activity levels were determined and compared with those gathered during the MVIC testing. Data collected during the dynamic squatting activities are expressed as a percentage of the data gathered during isometric testing.

The Olympic squat was performed using a high bar (i.e., bar placed over the upper trapezius muscle) position and shoulder-width stance. Each subject was positioned on the experimental platform with his/her feet shoulder width apart in either the self-selected neutral or 30° turned-out position. Subjects performed the squats without shoes to avoid differences in heel height and shoe stability. The shoulder-width measurement previously determined with a tape measure was used to position the feet. Foot position for the first series of squats was randomly selected for the first subject. Subsequent subjects alternately started with their lower extremity placed in self-selected neutral or 30° of turned-out from the self-selected position. Randomization was used to avoid training effects and fatigue as extraneous variables.

To obtain the proper position of turn-out, the foot was placed so that the line indicating self-selected neutral or 30° turned-out from self-selected neutral bisected the subject's calcaneus and web space of the first and second toes. A board was placed vertically in front of the subject's toes in order to control the amount of forward motion that occurred at the knees (Figure 2). This board was intended to standardize forward movement of the knees during knee flexion in both squatting test positions.

Once positioned on the squatting platform, subjects performed four squats with an unweighted bar. The first squat was used to determine the subject's position at 75° of knee flexion. No restraints were used for marking the squat depth because it was feared that a marker would influence the subject's performance of the squat with undesired periods of acceleration, deceleration, or stopping. The remaining three squats were used to practice the squatting motion. Squatting speed, set at 2 seconds per descending and ascending phase, was paced by a metronome. During these preliminary squats, corrections were made in the subject's squatting technique, speed of the squat, and squatting depth.
FIGURE 4. Muscle activity patterns of the vastus lateralis (VL) during the descending and ascending phases of the squat. Values are percentages of maximal volitional isometric contractions. One standard of deviation is noted.

Following the unweighted practice squats, the bar was weighted to 25% of the subject's body weight and positioned on the subject's back across the upper trapezius muscles. The subject then performed two practice squats with the weighted bar. After completion of both the unweighted and weighted trial lifts, the subject performed three experimental squats with 25% of body weight for data collection. Each squat was separated by a rest interval of 6 seconds. It was used to give subjects time to rest themselves in order to avoid fatigue during the experiment.

After completion of the first series of three experimental squats, the bar was removed from the subject's shoulders and the lower extremity position was altered to the second squatting position. Lower extremity position was changed by having the subject perform an isometric quadriceps contraction in full extension and dorsiflexion of the ankle. In this position, the entire lower extremity was rotated on the heel to the new position. Once the first lower extremity was correctly positioned, the same sequence was followed for repositioning the other lower extremity. Collection of electromyographic and motion data for the second lower extremity squatting position proceeded in the same order as the first with both unweighted and weighted trials and experimental lifts.

Electromyographic and motion data were analyzed at 10° intervals of motion from 10–60° of knee flexion. Collected EMG amplitudes and motion data were analyzed and averaged over 10° intervals (i.e., 10–20°, 20–30°, etc.) and scaled as a percentage of the subject's maximal volitional isometric contraction. The initial 10° and final 15° of motion were not examined. These data points were excluded in order to minimize the variability of muscle activity during the initial acceleration and final deceleration phases of the squatting motion.

Data Analysis

Statistical analysis included a four-way analysis of variance (ANOVA) with repeated measures. The main effects for knee flexion angle, foot positioning, direction of movement, and muscle were investigated (Table 1). A post hoc analysis was performed using the Scheffé procedure.

RESULTS

The mean muscle activity patterns for the vastus medialis, vastus lateralis, semimembranosus/semiten-dinosus, and biceps femoris, expressed as percentages of maximum volitional isometric contractions, are found in Figures 3–6. Percentages of maximal volitional isometric contractions for each muscle group in 10° intervals are found in Table 2.

All subjects completed the squats with 25% of body weight except for one subject who was able to squat with only 15% of his/her body weight. The subject reported weakness and apprehension as reasoning for not lifting 25% of his/her body weight. Individual comparison of this subject's data found that the data closely paralleled that of the other subjects and were less than one standard deviation from the mean activity level. Therefore, this subject's data results were included in the analysis.

No significant change in muscle activity levels occurred for the main effect of lower extremity rotation. Significant (p < 0.05) changes in
muscle activity were found with changes in knee flexion angle, direction of movement (descending or ascending), and individual muscles. Statistical analysis of the interaction of lower extremity position with knee flexion angle was significant \( (p = 0.0207) \) with initial ANOVA liberal statistical testing. However, further examination of this interaction with more conservative tests (Huynh Feldt and Greenhouse Geisser) revealed the interaction to be insignificant \( (p = 0.0627 \) and \( p = 0.0584 \), respectively). Therefore, the interaction of lower extremity position and knee flexion angle was considered to be insignificant. This insignificant finding allowed for the data from the self-selected neutral and 30° turned-out squatting positions to be combined into one set of data points (Figures 3–6).

A post hoc analysis of individual muscle activity patterns found the vastus medialis and vastus lateralis to be significantly more active \( (p < 0.05) \) during the 50–60° arc of motion than during the 10–20° arc throughout the descending phase of the squat. During the ascending phase, the vastus medialis demonstrated greater activity in the 60–50° and 50–40° arcs of motion compared with the 20–10° arc of motion. During the same phase, the vastus lateralis was significantly more active during the 60–50° arc than during the 20–10° arc of motion. No significant changes in muscle activity were found to occur in the semimembranosus/semitendinosus or biceps femoris muscle groups during either the descending or ascending phases of the squat.

Analysis of muscle activity revealed that peak activity levels in the vastus medialis, vastus lateralis, and biceps femoris muscle groups occurred between the 50–60° and 60–50° arc of knee flexion during the descending and ascending phases, respectively (Table 3). The overall greatest level of activity in these three muscle groups occurred during the ascending phase. Peak activity in the

Results of this study indicate that muscle activity patterns can be affected by changes in knee flexion angles and direction of movement but not lower extremity axial rotation.

**DISCUSSION**

The results of this study indicate that muscle activity patterns can be affected by changes in knee flexion angles and direction of movement but not lower extremity axial rotation. Few studies were identified that investigated the effects of muscle activity in the lower extremity during a squat. Therefore, comparison of these present results to previous studies is difficult.
Ohkoshi et al (11) demonstrated increased levels of quadriceps activity with increased angles of knee flexion during the performance of a static squat. They also found increased hamstring activity with increases in the angle of trunk flexion. Data presented by Wilk et al (22) found that the greatest level of quadriceps activity during the squat occurred when the knee was flexed from 88–102°. Brask et al (1) also found significantly greater muscle activity in the rectus femoris, vastus medialis, biceps femoris, and semimembranosus/semitendinosus during the performance of an 8-inch step-up compared with a 4-inch step-up. These results are in agreement with our findings of increased muscle activity with increased angles of knee flexion.

Our results demonstrated lower levels of muscle activity during the eccentric (descending) phase compared with the concentric (ascending) phase of the squat.

Similar results were reported by Brask et al (1) who demonstrated peak muscle activity during the concentric phase of a 4- and 8-inch lateral step-up. Wilk et al (22) found greater EMG activity levels occurred within the vastus medialis and vastus lateralis during the ascending phase of the squat. The increased muscle activity in the vastus medialis and vastus lateralis during the ascending phase is due to the ability of a muscle to generate greater force during the eccentric phase for a given level of activation than it does during the concentric phase when both are performed at the same speed (5).

Our study found no significant changes in semimembranosus/semitendinosus and biceps femoris activity throughout the range of motion. These findings differ from those of Brask et al (1). Their study found significant changes in semimembranosus/semitendinosus muscle activity during the concentric and eccentric phases of the step-up.

The biarticular nature of the hamstrings makes delineating muscle activity in the hamstrings as concentric or eccentric difficult. During the ascending phase of the squat, the hamstrings contract to extend the hip while they are also lengthened across the knee. While unable to delineate the type of muscle activity present during the squat, our data does show no significant changes in muscle activity within the semimembranosus/semitendinosus and biceps femoris muscle groups during both the descending and ascending phases of the squat. The possible combination of concentric and eccentric activity in the hamstrings during the squat could affect the muscle activity level present during the ascending and descending phases of the motion. It is possible this may be a contributing factor to the overall lower levels of muscle activity in the hamstrings compared with the pure concentric and eccentric activity found within the uniaxial vastus medialis and vastus lateralis during the same motions.

The quadriceps/hamstring co-contraction observed during the squat has been reported by others (1,2,11,18). Several authors have indicated that contraction of the hamstrings during the squat counteracts anterior tibial displacement produced by the quadriceps (11,13,17,23). However, Lutz et al (7) found that the presence of hamstring contraction during the squat may not be enough to reduce the amount of anterior shear forces that occur at the
tibiofemoral joint during closed kinetic chain activities.

CONCLUSION

Recent literature has shown the benefits of using closed kinetic chain exercises during lower extremity rehabilitation programs. Collected data have shown that lower extremity positioning and the interaction of positioning with changes in knee flexion angles caused insignificant changes in the muscle activity patterns of all the investigated muscle groups. The present data were able to show a significant change in muscle activity patterns of the vastus medialis and vastus lateralis with changes in knee flexion angles during a squat. However, significant changes in muscle activity patterns of the semimembranosus/semitendinosus and biceps femoris did not occur with changes in knee flexion angles.

While this data help to educate us on muscle activity patterns during a dynamic closed kinetic chain activity, it does not supply information on force levels present during this muscle activity. Further research is needed to determine the levels of force generated by lower extremity muscle groups during dynamic closed kinetic chain activity.

REFERENCES


TABLE 2. Muscle activity levels with changing knee flexion angles. Values as noted above are the muscle’s percentage of maximal volitional isometric contraction. (Values are averages from both self-selected 0 and 30° turned-out positions.)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Knee Flexion Angles (in degrees)</th>
<th>Activity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-20°</td>
<td>20-30°</td>
</tr>
<tr>
<td>VM</td>
<td>5.43</td>
<td>10.25</td>
</tr>
<tr>
<td>VL</td>
<td>6.85</td>
<td>11.05</td>
</tr>
<tr>
<td>BF</td>
<td>5.01</td>
<td>5.21</td>
</tr>
</tbody>
</table>

VM = Vastus medialis. 
VL = Vastus lateralis. 
BF = Biceps femoris. 
SM/ST = Semimembranosus/semitendinosus.

TABLE 3. Highest and lowest percentages of muscle activity and their respective angle of knee flexion. Values are percentages of maximum volitional isometric contractions.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Highest Activity</th>
<th>Lowest Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM</td>
<td>28.69 (50-60°)</td>
<td>5.43 (10-20°)</td>
</tr>
<tr>
<td>VL</td>
<td>29.66 (50-60°)</td>
<td>6.85 (10-20°)</td>
</tr>
<tr>
<td>BF</td>
<td>13.46 (60-50°)</td>
<td>5.01 (10-20°)</td>
</tr>
<tr>
<td>SM/ST</td>
<td>13.91 (20-30°)</td>
<td>8.09 (10-20°)</td>
</tr>
</tbody>
</table>

VM = Vastus medialis. 
VL = Vastus lateralis. 
BF = Biceps femoris. 
SM/ST = Semimembranosus/semitendinosus.