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REPORT

EMG Analysis of Lower Extremity Muscles in Three Different Squat Exercises

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Abstract. The purpose of this study was to come across an exercise that increases the Hamstring contraction levels so that it may protect the anterior cruciate ligament (ACL). Previous studies have postulated that changing the projection of the center of gravity behind the feet will decrease the translation of the tibia, therefore protect the ACL. Muscle activity of the quadriceps, hamstring and soleus muscles in healthy subjects was measured with an EMG during three different squat tasks with differences of support of body weight and the center of gravity. The subjects were nine healthy female recreational athletes with no history of any pathological knee condition or musculoskeletal system disorder. There was no significant difference in the activities of the four muscles (Vastus Medialis; Hamstring: Semitendinosus and Biceps Femoris; and Soleus); and there was a similar pattern in the activity between those muscles in the exercises. In addition, VM values were considerably higher than the Hamstring and soleus activity levels. There was no significant difference between one squat from another and among the phases (0–30°, 30–60° or 60–90°) of knee flexion. These results suggest that even when changing the projection of the center of gravity, the activity of the quadriceps is high compared to the hamstring and soleus muscles.

Key words: anterior cruciate ligament, hamstrings, squat

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Women have a higher incidence rate than men for non-contact anterior cruciate ligament (ACL) injuries in sport activities. Recent studies reported that the incidence for female athletes is estimated as high as eight times than for male athletes[1)2)]. Researchers have shown that the contraction of the quadriceps muscle group applies an anterior shearing force on the tibia through the patella tendon. This shearing force may lead to an ACL injury when the knee flexion angle is less than 30 degrees and the hamstrings do not apply sufficient posterior shearing force[3)]. Moreover, hamstring muscle group contraction in a nearly fully extended knee cannot provide a sufficiently large posterior shearing force on the tibia to resist anterior tibial translation relative to the femur and therefore cannot protects the ACL. This is because the hamstring muscles meet the tibia at a smaller angle with the knee near full extension[4)]. The restriction of the anterior tibial translation by hamstring muscle tension occurred at all knee flexion angles except near full extension. It was also found that during an isolated quadriceps muscle load, forces on the ACL increased from 0 degree (in full extension), to a peak at 15 degree of flexion. This steadily decreased as the knee become more flexed. The addition of hamstring muscle tension did not significantly change the forces on the ACL near full extension, but progressively decreased as the knee was flexed to 15, 30, and 60 degrees[5)].

A parameter commonly used to describe muscle strength properties about the knee joint is the maximal isokinetic hamstring muscle strength to maximal isokinetic quadriceps muscle strength, also called H:Q ratio. It is accepted by previous studies that the H:Q ratio is between 0.6 and 0.8 for an uninjured lower limb[6)]. The H:Q ratio has received great amount of attention in the literature Ghena *et al.*[7)] reported that H/Q ratio was, in isokinetic movements, of 0.6 or greater and universally accepted in the ACL rehabilitation community, but in this early research they did not consider or evaluate the anterior tibial translation. In

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addition, recent study showed another muscle that also restrains the anterior tibial translation acting as an synergist for the ACL was the soleus (SO) muscle[8).

Closed kinetic chain exercises have become increasingly popular and strongly recommended for rehabilitation after ACL injury because they are believed to be safer than other exercises[9)]. Important factors that characterized an exercise as harmful or not to the injured knee are muscle coactivation, shearing forces, tibial translation, and ACL strain. Coactivation of the lower limb muscles is thought to improve the stability of the knee joint[10)]. By placing the projection of the center of gravity over, behind and in front of the feet, it is proposed that the activity of the muscles will change and assist the ACL with the anterior tibial translation preventing the injury of this ligament[11)].

The purpose of this study was to come across a close kinetic chain exercise, three different squat exercises, which increases the hamstring and soleus contraction levels so that it may increase the H/Q ratio. We suggest that placing the projection of the center of gravity behind the feet will stimulate a favorable coactivation that will increase the H/Q ratio and increasing the stability of the knee joint.

Materials and Methods

Subjects

Nine healthy female recreational athletes with no history of any pathological knee condition, musculoskeletal or neurological dysfunction that would otherwise affect motor performance involving either lower extremity, were recruited from students of Hiroshima University. A recreational athlete was defined as a person who plays basketball, soccer, or volleyball up to three times a week, but does not follow a professionally designed training regimen. Subjects with mean age, 22.7 ± 2.3 years old; height, 1.60 ± 0.06 m; weight, 47.7 ± 1.5 kg participated in this study, all values are given as (mean ± standard deviation). All subjects signed an informed consent form before participating in this study.

Experimental protocol

Three different squat tasks were performed according to the method from Kvist *et al.*[11)]. From 0 to 90 degrees of knee joint flexion were performed: 1) a squat where the projection of the center of gravity (CGO) (Fig. 1A) was approximately over the feet, 2) a squat with their hands on a wall and the feet 70 to 80 cm from the wall so the center of gravity was approximately in front of the feet (CGF) (Fig. 1B), and 3) a squat with their back resting against a wall and the feet 30 to 40 cm from the wall so the center of gravity was approximately behind the feet (CGB) (Fig. 1C). All measurements were preceded by a standardized warm-up consisting of pedaling a stationary bicycle for 10 minutes.

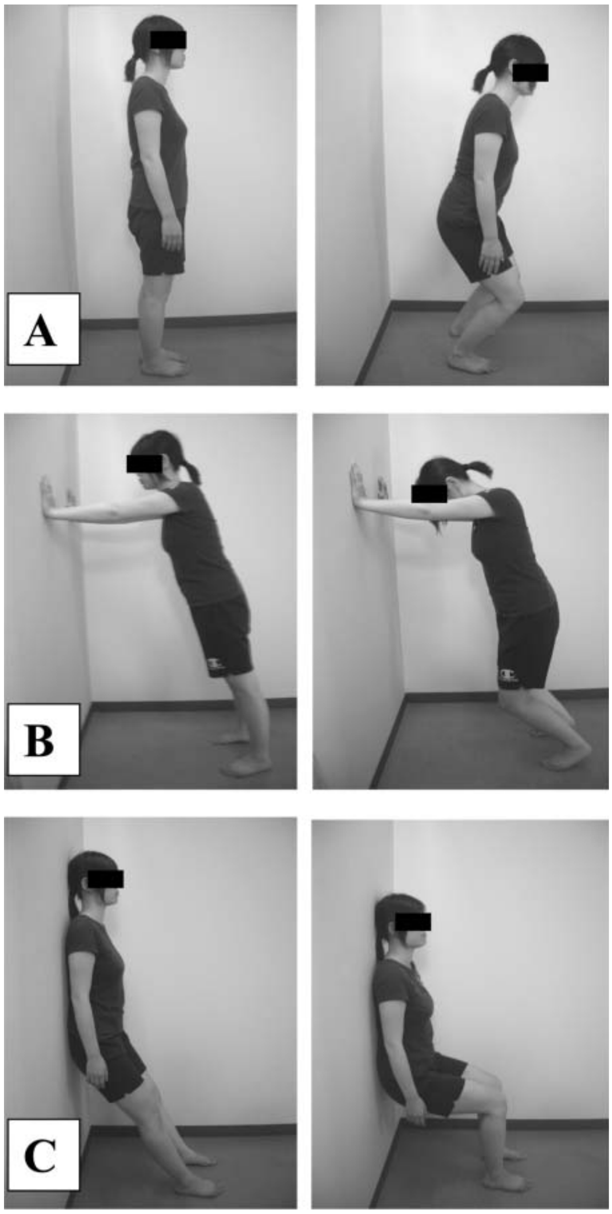

Fig. 1. The three exercises, stating position and 90° of knee flexion. A, squat where the projection of the center of gravity was approximately over the feet (CGO). B, squat where the projection of the center of gravity was approximately in front the feet (CGF). C, squat where the projection of the center of gravity was approximately behind the feet (CGB).

Subjects squatted from 0 to 90 degrees of knee flexion measured with an electric goniometer (NK System, Nippon Med. & Chem. Inst. Co., Japan); knee flexion speed was 45 degrees per seconds until 90 degrees following the rhythm of the metronome (60 beats per minute). Each measuring sequence was randomized. The data from the EMG was divided in three equal phases 30° each. Three trials method was adopted for all experiments in this study. This study protocol was approved by Hiroshima University Review Board.

Data collection

Muscle activity data was collected using bipolar superficial EMG electrodes on Vastus Medialis (VM), Semitendinosus (ST), long head of Biceps Femoris (BF) and SO muscles. Surface electrodes (Blue sensors, Medicotest A/S, Denmark) were placed on the skin surface in the dominant leg or kicking leg (all measurements were performed on the right leg), according to Perotto's method for the four muscles reported before[12]. The skin was shaved and cleaned with (70%) alcohol and Neprep (NEC Medical Systems, US) to reduce the skin resistance. In advance all signals were sampled at 1000 Hz by an EMG amplifier (Bio-amp ML 132, AD Instruments, US). The high pass filter was set at 10 Hz and the low pass filter at 500 Hz; this device was connected to a personal computer for data collection.

Data analysis

The EMG raw data was analyzed with a Chart v 3.6.5 (AD Instruments, US), and changed to the root mean square (RMS) value with a constant time of 20 ms. The RMS data was calculated separately in three phases of 30 degrees each from the starting position (zero degrees of knee flexion) up to 90 degrees. The maximum isometric voluntary contraction to the rectified EMG signals was integrated and was used to normalize the dynamic contraction recorded during the three squat tasks. The procedure to collect this data was according to Daniels and Worthingham's literature[13] for two seconds. Each EMG value was calculated with the rate of maximum voluntary contraction (%MVC).

Statistical analysis

The EMG data was analyzed at a range of motion between 0 and 90 degrees of knee flexion. Analysis of variance for repeated measures was analized for differences ($p<0.05$) in EMG values between each squat task. Statistical analysis was performed using commercially available software Stat View 5.0J (SAS Institute Inc., US). A two way ANOVA was used to compare the results. Scheffe post-hoc analysis was used to examine for specific differences.

Results

When comparing the different position of squats in each muscle, %MVC of BF was the only one showing significant difference as the knee flexion angle was increased during the three tasks ($p<0.01$). The rate of %MVC of BF at the range of 0 to 30° of knee flexion was 12.4 ± 2.2 %, at the range of 30 to 60° of knee flexion was 15.3 ± 2.3% and 16.3 ± 2.8% at the range of 60 to 90° during CGO. At CGF the range was 11.5 ± 1.2%, 13.9 ± 1.9% and 14.6 ± 1.8, and during CGB the range was 10.3 ± 2.5%, 13.2 ± 2.4 and 15.4 ± 2.8% respectively (Table 1).

For the VM muscle, the activation level during CGO at the range of 0~30° was 47.6 ± 1.9%, at 30 to 60° was 62.5 ± 2.1% and in the last degrees of flexion was 70.2 ± 1.8%. This was greater than in CGF that were 44.3 ± 1.5%, 54.7 ± 1.8% and 61.2 ± 1.6% MVC. And much more than CGB that shows 37.7 ± 2.1% at 0 to 30°, 47.6 ± 1.6% at 30 to 60° and 52.0 ± 2.4% at 60 to 90° (Table 1). In both squat positions there wasn't significant different, and VM values was considerably higher than the Hamstring and soleus activity levels. In SO muscle case, the activity levels were in CGO, 12.8 ± 1.4%, 14.1 ± 1.7%, and 13.5 ± 1.2% from 0 to 90°. During CGF the values were 11.9 ± 1.6%, 11.1 ± 1.8% and 11.4 ± 1.2% and finally in CGB the activity levels were 8.1 ± 1.5%, 8.5 ± 1.3% and 8.8 ± 1.4% in the three segments that the squat was divided (Table 1). ST muscle %MCV levels were in CGO at 0 to 30° was 9.9 ± 1.5%, at 30 to 60° was 11.1 ± 1.1% and in the last degrees of flexion was 11.8 ± 1.8%. Approximately very similar values were in CGF that were 9.4 ± 1.6%, 11.4 ± 1.8% and 11.8 ± 1.3% MVC as well as CGB that shows 9.2 ± 1.1% at 0~30°, 11.5 ± 1.5% at 30~60° and 11.9 ± 1.8% at 60~90° (Table 1). There was no significant difference between one squat from another and among the phases (0–30°, 30–60° or 60–90°) of knee flexion. The H:Q ratio (Table 2) of ST/VM presents no significant difference, as well as BF/VM ratio case (Table 2) There not even close to the values presented in previous study[7] between 0.6 and 0.8 for uninjured lower limb.

Discussion

We suggested that placing the center of gravity behind the feet increase the activities of the hamstrings and the SO muscles. Although these results were not as expected, there was no significant difference of muscle activity changing the projection of the center of gravity, except for the BF. The finding that neither the hamstrings nor the SO muscle increased their activity contradicts our suggestion. However, the EMG activity of BF show a significant difference between the first phase (0~30°) and the third phase (60~90° as the knee was flexed in all the squats. These results support Ohkoshi *et al.*[14] previous study, where muscles gradual increase their activation contraction of the hamstring as the knee angle increase and consequently a posterior drawer force will be provided. There was also significant difference of BF in CGF between the second phase and the third phase (60~90°) ($p<0.01$). This difference could be supported from Kvist *et al.*[11] study, where in normal knees the squat with the center of gravity in front the feet caused the most translation, we infer that the activity of BF in CGF increase significantly as a increase recruitment for the restraining mechanism due to the increase in translation.

Table 1. %MVC values for BF (Biceps Femoris), VM (Vastus Medialis), SO (Soleus) and ST (Semitendinosus) during the three squat positions (mean ± SD)

%MVC

	CGO		CGF		CGB	
BF						
0°–30°	12.4 ± 2.2	*	11.5 ± 1.2	*	10.3 ± 2.5	*
30°–60°	15.3 ± 2.3		13.9 ± 1.9	*	13.2 ± 2.4	
60°–90°	16.3 ± 2.8		14.6 ± 1.8		15.4 ± 2.8	
VM						
0°–30°	47.6 ± 1.9	N.S	44.3 ± 1.5	N.S	37.7 ± 2.1	N.S
30°–60°	62.5 ± 2.1		54.7 ± 1.8		47.6 ± 1.6	
60°–90°	70.2 ± 1.8		61.2 ± 1.6		52.0 ± 2.4	
SO						
0°–30°	12.8 ± 1.4	N.S	11.9 ± 1.6	N.S	8.1 ± 1.5	N.S
30°–60°	14.1 ± 1.7		11.1 ± 1.8		8.5 ± 1.3	
60°–90°	13.5 ± 1.2		11.4 ± 1.2		8.8 ± 1.4	
ST						
0°–30°	9.9 ± 1.4	N.S	9.4 ± 1.6	N.S	9.2 ± 1.1	N.S
30°–60°	11.1 ± 1.1		11.4 ± 1.8		11.5 ± 1.5	
60°–90°	11.8 ± 1.8		11.8 ± 1.3		11.9 ± 1.8	

* Significantly different (p<0.01).
N.S: not significant.
CGO: Squat where the projection of the center of gravity was approximately over the feet, CGF: Squat where the projection of the center of gravity was approximately in front the feet, CGB: Squat where the projection of the center of gravity was approximately behind the feet.

Table 2. Average isokinetic torque in Nm for H/Q ratio for ST/VM and BF/VM in the three squat positions (mean ± SD)

	CGO	CGF	CGB
ST/VM			
0 – 30°	0.19 ± 1.3	0.20 ± 1.4	0.26 ± 1.8
30 – 60°	0.15 ± 1.5	0.15 ± 1.3	0.20 ± 1.7
60 – 90°	0.12 ± 1.2	0.14 ± 1.5	0.18 ± 1.2
BF/VM			
0 – 30°	0.26 ± 1.5	0.26 ± 1.6	0.27 ± 1.2
30 – 60°	0.24 ± 1.3	0.26 ± 1.5	0.28 ± 1.4
60 – 90°	0.23 ± 1.7	0.24 ± 1.4	0.30 ± 1.3

CGO: Squat where the projection of the center of gravity was approximately over the feet, CGF: Squat where the projection of the center of gravity was approximately in front the feet, CGB: Squat where the projection of the center of gravity was approximately behind the feet.

There was no significant difference between the third phase (60~90°) and the first two phases (0~30° and 30~60°). Not significantly different were muscle activation patterns of VM and ST muscles in the three squat positions.

Our results reveal that the BF and ST muscle activity was much smaller than VM muscle activity during the three phases in all the tasks. The reason is that Hamstrings are two-joint muscles or biarticular, and this means that these muscle affect motion at both joint crossed simultaneously. Therefore during jump landing or squatting, the hamstring muscles assist the gluteus maximus with an eccentric contraction or a controlled flexion at the hip making a reduction of the activity to control and stabilize the knee joint. The decrease in activity of the hamstring muscles in the most stretched position might be explained by the interaction of the muscle length and the anatomical location of the tendons. When the knee is fully extended, the hamstring tendons lie very close to the axis of the knee joint, which provides a very poor lever arm for flexion suggesting their insufficiency as knee flexors and as posterior drawer provider[3)4)]. In addition, these muscles should work at the hip and knee joints simultaneously; the interaction of these two factors might cause the lower rates of EMG activity. In this study low hamstring activity was found between 0 to 30 degrees, but this activity increase proportionally as the knee was flexed up to 90°, as well as the VM activity. This support Urabe *et al.*[15)] research were concluded that the %MVC hamstring muscle activation was lower compared to quadriceps femoris at knee flexion angles of 15° to 55°. Thus, we conclude that squatting from 60 to 90° of knee flexion could be safer for the ACL.

There was no significant difference in ST/VM and BF/VM ratio in any of the three squats. Previous researches reported values of (0.6 to 0.8) in uninjured knees[7)], our results showed lower results, indicating that this correlation is not optimum for the ACL. A possible reason for this low H/Q ratio is that Ghena *et al.*[7)] recorded their values when the muscles performed an eccentric or concentric contraction. This investigation collected the data while subjects performed a squat exercise, which means a concentric contraction of the hamstring and an eccentric contraction of the quadriceps at the knee joint was flexed.

Although there was no significant difference between the three squats, we observed a higher ratio of ST/VM and BF/VM in CGB compared with the other two task positions. These results suggest that in squats with CGB, the H/Q ratio might be favorable for the ACL, and concur with Kvist *et al.*[11)] who found that translation increased with load the uninjured and normal knees except during squats with the center of gravity behind the feet.

In the present study, The VM muscle is much stronger than the hamstring muscles; making the relation H/Q inappropriate for the tension of the ACL. It is important to strengthen the spontaneous coactivation of quadriceps and hamstring muscles, which will help to stabilize the knee joint. The activity of VM in CGB squat position, although that was not significant, it was considerably lower than in CGO and CGF, indicating a decrease of joint compressive forces. Therefore, even though the activation of the quadriceps is decrease in CGB, it was very high compared to the hamstrings and SO activity.

In this study the SO muscle activity results were irregular. The explanation for these outcomes is that, although we follow Perotto's method[12)], it is possible that due to the location of the SO muscle the superficial sensors were not able to register its activity.

Despite the facts that many important factors as gravity, forces and vectors, the present study used EMG force model as the only source for collecting the data, this can be supported by Doorenbosch *et al.*[16)] research where, with a proper calibration, co-contraction index in healthy and injured ACL subjects can be determined. Although the limited accuracy that the EMG can present, it show definitely clinical relevancies.

The limitations of our study are noted. The small sample size may have influenced the outcome. Certainly, studies with larger sample sizes are required to determine the clinical utility of the method described here.

In conclusion, the lower activity of the hamstring muscles and SO muscles compared with the quadriceps muscle activity, results in muscle imbalance even though the projection of the center of gravity was changed. This imbalance will lead to an increase of strain over the ACL and becoming a risk factor of further injuries. It is still unknown how to perform a closed kinetic chain exercise that could increase the activity of the hamstring muscles, and result in an appropriate H/Q ratio for injured and uninjured knees.

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