©Journal of Sports Science and Medicine (2019) **18,** 248-252
http://www.jssm.org

Research article

Muscle Activity Pattern with A Shifted Center of Pressure during the Squat Exercise

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Abstract

The squat exercise is a fundamental movement in athletic training and rehabilitation. In this study, we measured muscle activities in a normal squat posture (NSP) and a squat posture with the center of foot pressure (COP) intentionally shifted forward as far as possible (FSP). Ten healthy men performed double-limb squats, adopting the NSP and FSP, with three knee flexion angles (30, 60, and 90 degrees). The muscle activities of the vastus medialis (VM), semitendinosus (ST), tibialis anterior (TA), and gastrocnemius muscle lateral head (GL) were measured using surface electromyography, and activity patterns were analyzed. Compared to that for the NSP, the COP was significantly shifted forward in the FSP by at least 30% of the foot length for all knee flexion angles ($p < 0.05$). At all knee flexion angles, VM muscle activity significantly decreased, while GL muscle activity increased, in the FSP compared to that for the NSP ($p < 0.05$). In addition, ST muscle activity increased significantly in the FSP compared to that for the NSP at knee flexion angles of 30 and 60 degrees ($p < 0.05$). TA muscle activity significantly decreased in the FSP compared to that for the NSP at only 90 degrees of knee flexion ($p < 0.05$). These results demonstrate that muscle activity patterns vary significantly according to squat posture. Thus, the active control of the COP position during the squat can be a new training approach in targeting specific muscle groups.

Key words: Body weight squats, surface electromyogram, stabilometer, forward-shifted posture, rehabilitation.

Introduction

The benefits of squat exercises have been reported in studies of athletic training (Grooms et al., 2013), rehabilitation (Escamilla et al., 2001), and locomotive syndrome in elderly people (Nakamura, 2011). The squat is a wide entity, comprising the partial squat (Escamilla et al., 2001), half squat (Hartmann et al., 2013), parallel squat (Caterisano et al., 2002; Contreras et al., 2016; Hartmann et al., 2013), full squat (Caterisano et al., 2002; Contreras et al., 2016), and deep squat (Hartmann et al., 2013). Furthermore, there are front (Aspe and Swinton 2014; Clark et al., 2012; Contreras et al., 2016), back (Aspe and Swinton 2014; Clark et al., 2012; Gullett et al., 2009) and overhead squats (Gullett et al., 2009) with various bar positioning, which have been previously analyzed. In the squat exercise, several factors or conditions can influence the muscle activity, including the knee angle (Gryzlo et al., 1994), foot width (Escamilla et al., 2001; McCaw and Melrose, 1999), rotation of the lower limbs Escamilla et al., 2001; Ninos et al., 1997; Signorile et al., 1995), or whether the knees going over the toes or not (Fry et al., 2003; Isear et al., 1997). In addition, the position of the center of gravity (COG) has been reported as a critical factor for electromyographic activity of lower extremity muscles (Kvist and Gillquist, 2001; Nishiwaki et al., 2006), although active control of the posture was not examined in these reports.

In patients with anterior cruciate ligament (ACL) reconstruction, exercise for activities of the hamstrings and gastrocnemius are especially important in the closed kinetic chain (CKC), and squat exercise is widely used in the rehabilitation program. (Palmitier et al., 1991). However, compared to that of other muscles, the activations of these muscles are relatively low in squat exercises, even with the addition of the barbell (Aspe and Swinton, 2014; Contreras et al., 2016; Gullett et al., 2009). Thus, a new strategy that better focuses on the target muscles is clearly required for effective squat training. We hypothesized that the active control of the COP position could be used to increase the training efficacy of the squat in targeting specific muscles. Herein, we measured the electromyographic muscle activity of the lower limbs during isometric squat hold with two alternative positions of the COP (normal squat posture and front shifted posture), and three angles of the knee joint (30, 60, and 90 degrees). The muscle activity patterns were analyzed and the possible target muscles in each squat variation were assessed.

Methods

Experimental approach to the problem

This is a prospective observational study. To evaluate the effect of changing the COP in the squat posture on muscle activity patterns, we compared target muscle activities in the normal squat posture (NSP) to those in a squat posture designed to move the COP forward as far as possible (forward-shifted posture: FSP) at three flexion angles of the knee joint (30, 60, and 90 degrees). Subjects held a squat position and flexion angles of the knee joint were controlled by a goniometer. We set acceptable range of plus/minus 5 degrees.

Participants

Ten healthy men with no history of knee injury, knee pain, or surgery participated in this study (Table 1). All

Received: 08 October 2018 / Accepted: 06 March 2019 / Published (online): 01 June 2019

had squat experience. The content of the experiment was sufficiently explained to the subjects, and only those who voluntarily agreed to participate in the experiment were enrolled. All subjects provided informed consent for the study procedures. Participation was voluntary and in agreement. This study was approved by the ethics committee of Nara Medical University (No. 1969). No subjects had difficulty to hold the squat position for 5 seconds.

Table 1. Characteristics of subjects. Values are means (±standard deviation).

Variables	Subject (n=10)
Age (yrs)	26.9 (2.2)
Height (m)	1.70 (.05)
Body mass (kg)	70.2 (11.1)
Foot length (cm)	24.6 (0.7)
Maximal angle of ankle dorsi flexion (degree)	47.9 (9.8)

Procedures

The location of the COP was measured using a stabilometer (Twin Gravicorder G-6100; Anima Corp., Tokyo, Japan) at a sampling frequency of 100 Hz. The participants could visually check the COP during the squats. In the NSP condition, the shoulder joint was abducted as an external rotation and the middle finger was placed on the temple, and the squat posture was adopted with the COP located just between feet (Figure 1). In the FSP condition, the squat posture was adopted with palms faced downward and the COP shifted forward as far as possible (Figure 1). The foot width in the squat posture was 45 cm, between the left and right fifth metatarsal bone bottoms. The participants were told that the long axis of the femur was on the long axis of the third metatarsal bone of the foot. In addition, the participants were directed to look frontward.

Measurement of the COP

The measurement of the COP was performed barefoot, using a stabilometer. The ratio of the distance from the heel to the COP and the foot length were then calculated. The center of the subject's foot length was adjusted to the center of the stabilometer plate (Figure 1). Waveforms of the COP in the longitudinal direction were extracted from the total COP and a stable average value of the COP per second was calculated.

Muscle activity assessment

According to Perotto's method (Perotto, 1994), the muscle activities of the right vastus medialis (VM), semitendinosus (ST), lateral head of the gastrocnemius (GL), and tibialis anterior (TA) were measured electromyographically, using the MWATCH-101 (Wada Aircraft Technology CO. Ltd. Aichi, Japan). The areas chosen for electrode placement were prepared by shaving and cleansing with alcohol to reduce the surface impedance. The electrodes (Ag/AgCl, solid gel, 19×38 mm, Air rode type SMP-300, METS INC. Tokyo, Japan) were placed over each muscle with a 2-cm center-to-center distance.

Electromyography (EMG) signals were sampled at 1000 Hz with lower and upper cut-off frequencies of 5 Hz and 1500 Hz, respectively, with a 60 Hz band-stop filter. For the calculation of the integrated electromyography (IEMG), the obtained EMG waveform was full-wave rectified and integrated. The EMG signals were measured for 5 seconds in a stable posture. The first and last two seconds of data were discarded, and the one second in the middle were used in the analyses.

To normalize the muscle activity, EMG at the maximum voluntary isometric contraction (MVIC) was measured for each muscle according to the manual exercise testing method of Daniels and Worthingham's Muscle Testing (Hislop and Montgomery, 2007). The signal was integrated for one second as well. Only the GL was measured in prone position. The IEMG at MVIC was measured after sufficient preparatory exercise and muscle activity was normalized using the IEMG at MVIC of each muscle as 100%.

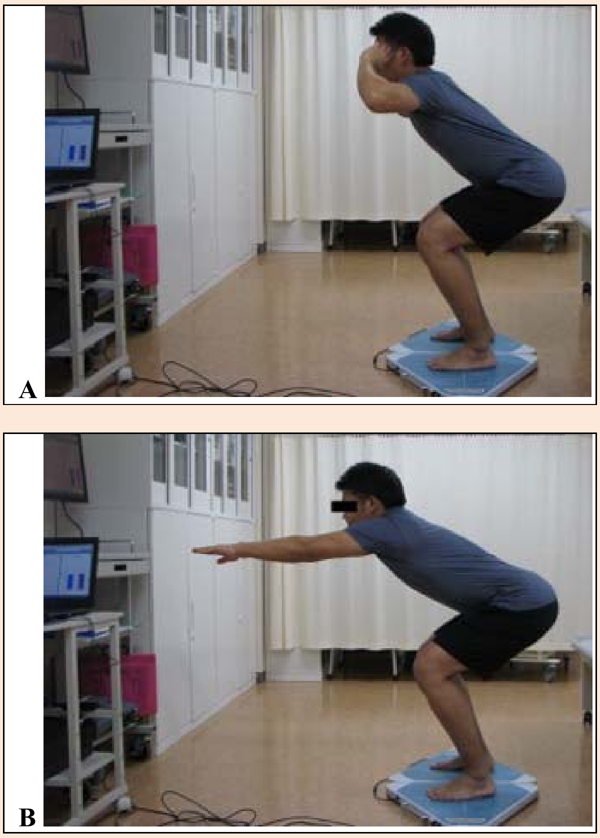

Figure 1. A) The normal squat posture (NSP): The shoulder joint was abducted as an external rotation and the middle finger was placed on the temple. The center of the foot pressure (COP) was between the left and right feet, but the subjects did not focus on the sagittal plane. B) The forward-shifted posture (FSP): Subjects looked at the front monitor, lifted their upper limbs and shifted the COP forward.

Statistical analyses

Statistical analyses were performed using Statcel 4 (Yanai, 2015), and GPower software 3.1(University of

Dusseldorf). A *p* value <0.05 was considered statistically significant. The paired t-test was used to confirm that the COP was shifted forward in the FSP compared to that in the NSP, after confirming the equal variance and normality of the data. The Wilcoxon signed-rank sum test was used to evaluate differences in the EMG data between the NSP and FSP at each of the evaluated knee joint angles, because the EMG data were non parametric. Sample size determination was performed using GPower software prior to the data collection (power=0.8). After the data collection, we confirmed the power for all variables in table 2 with group parameters (mean, SD, and correlation). We performed a post-hoc analysis using Wilcoxon signed-rank tests. We calculated determined effect size from the group parameters.

Results

Changing the posture from NSP to FSP successfully shifted the COP location

Figure 2 shows the differences in the COP location (expressed as the percentage of the distance from the heel (%COP)) between the NSP and FSP at the three evaluated knee flexion angles. At a knee flexion angle of 30 degrees (Figure 2A), the %COP was 41.8 ± 6.0% (mean ± SD) in the NSP, but was increased to 75.5 ± 8.2% when participants switched to the FSP, which confirms that the COP location was shifted forward significantly. Likewise, when the participants switched from the NSP to the FSP at knee flexion angles of 60 and 90 degrees, the %COP increased from 46.0 ± 8.3% to 79.9 ± 4.6% (Figure 2B) and from 44.8 ± 12.1% to 76.4 ± 7.5%, respectively (Figure 2C). Thus, changing the posture from the NSP to the FSP successfully shifted the COP in every participant at all knee flexion angles.

Muscle activity patterns

Table 2 shows the EMG muscle activity in the lower extremities for the NSP and FSP. VM muscle activity was significantly decreased in the FSP compared to that in the NSP at knee flexion angles of 30, 60, and 90 degrees. The greatest reduction in VM activity was found at a knee flexion angle of 60 degrees, decreasing from 43.19 ± 11.01% to 23.14 ± 11.48% when the participants switched from the NSP to the FSP. In contrast, ST muscle activity was significantly increased in the FSP compared to that in the NSP at knee flexion angles of 30 and 60 degrees. The greatest increment in ST activity was found at a knee flexion angle of 30 degrees, increasing from 7.35 ± 4.62% to 32.62 ± 15.20% when the participants switched from the NSP to the FSP. Uniquely, TA activity was significantly decreased in the FSP compared to that in the NSP at only a knee flexion angle of 90 degrees, decreasing from 45.41 ± 22.65% to 15.23 ± 16.19% when the participants switched from the NSP to the FSP. GL activity was increased significantly in the FSP compared to that in the NSP at 30, 60, and 90 degrees of knee flexion. The greatest increment in GL activity was observed at a knee flexion angle of 30 degrees, increasing from 5.20 ± 2.60% to 24.01 ± 15.97% when the participants switched from the NSP to the FSP.

In general, shifting to the FSP resulted in increased activity in the ST and GL, which are “posterior muscles”, and decreased activity in the VM.

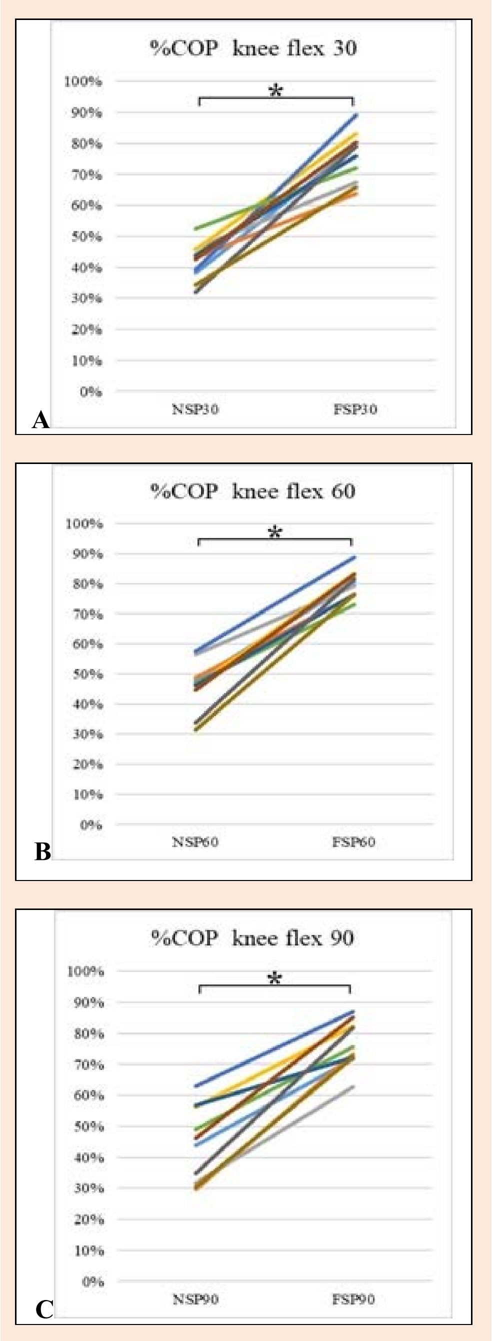

Figure 2. The differences in the COP location between the NSP and FSP are shown for the three knee flexion angles. **A)** The mean %COP shifted from 41.8 ± 6.0% to 75.5 ± 8.2% (NSP vs FSP). **B)** The mean %COP shifted from 46.0 ± 8.3% to 79.9 ± 4.6% (NSP vs FSP). **C)** The mean %COP shifted from 44.8 ± 12.1% to 76.4 ± 7.5% (NSP vs FSP). * Significant difference ($p < 0.05$). COP, center of the foot pressure; NSP, normal squat posture; FSP, forward-shifted posture.

Discussion

The influence of COP position-shifting on muscle activity in a body weight squat has not been previously reported. Nishiwaki et al. (2006) and Kvist et al. (2001) reported the influence of shifting the COP in wall-leaning tasks. However, in these tasks, we could not examine

Table 2. Muscle activity was compared between the NSP and the FSP at knee flexion angle of 30,60 and 90degrees. Muscle activity was normalized using the integrated EMG at maximum voluntary isometric contraction. Values are means（±SD).

	Knee Flexion 30°		Knee Flexion 60°		Knee Flexion 90°	
	NSP	**FSP**	**NSP**	**FSP**	**NSP**	**FSP**
VM (%)	16.65(6.79)†	10.09(5.59)	43.19(11.01)†	23.14(11.48)	83.78(19.23)†	52.22(14.06)
ST (%)	7.35(4.62)†	32.62(15.20)	7.64(4.81)†	27.69(17.75)	14.76(10.17)	17.81(11.62)
TA (%)	3.79(5.61)	8.88(5.16)	22.78(22.65)	11.73(12.73)	45.41(22.65)†	15.23(16.19)
GL (%)	5.20(2.60)†	24.01(15.97)	5.00(2.29)†	15.74(5.51)	7.49(4.05)†	13.29(5.48)

NSP: Normal Squat Posture, FSP: Forward-Shifted Posture, VM: Vastus Medialis, ST: Semitendinosus, TA: Tibialis Anterior, GL: Gastrocnemius Lateral head, †: Significant differences from FSP condition ($p < 0.05$).

the effect of active shifting of the COP on the muscle activity pattern, because of the weights distribution. The present study is the first to report the impact of shifting the COP location on the muscle activity pattern of the lower limbs in a body weight squat posture. We found that the COP moved forward approximately 30% of the foot length when participants shifted from NSP to the FSP. Furthermore, we clearly showed that the muscle activities of the ST and the GL were increased, while those of the GM and the TA were decreased, by shifting the COP forward.

Palmitier et al. (1991) reported that the hamstrings stabilize the knee joint by counter-acting the anterior shear forces imparted by the quadriceps during an unloaded squat. However, it is also known that hamstrings activity is relatively low, compared to that for other lower limb muscles, in the NSP (Aspe and Swinton, 2014; Contreras et al., 2016; Gullett et al., 2009). For athletes and patients who require strengthening of the hamstrings and gastrocnemius (for example, for patients in the return to activity phase after anterior cruciate ligament reconstruction, Wright et al., 2008), we speculate that the FSP with 30 degrees of knee flexion is desirable.

This task is also appropriate for patients with knee anterior pain because of the protection afforded to the knee extensors (quadriceps). On the other hand, to strengthen the tibialis anterior muscle (for example, after the tendon rupture surgery, Harkin et al., 2017), the NSP with 90 degrees of knee flexion is preferable in the return to activity phase.

In the biomechanics of the squat, the COP location may affect muscle activity (Lynn and Noffal, 2012). Because the muscle activity increased significantly, the ST and the GL can be trained more effectively in the FSP, while the VM and TA can be trained more effectively in the NSP. The knee flexion angle is also critical. The FSP with 30 degrees of knee flexion is desirable for athletes or patients who need to stabilize an anterior cruciate ligament-deficient knee. For athletic training and rehabilitation using squat exercises, the active control of the COP location should be considered, with the optimal location depending on the type of deficiency.

Conclusion

The present study demonstrated that the muscle activities of the lower limbs vary according to the COP location and knee flexion angle. The forward shift COP resulted in higher loads for “posterior muscles”. In this study, we focused on the muscle activity pattern in the CKC exercise. In various clinical situations where the CKC exercise should be used, the active control of the squat posture in terms of the COP position can be a new and effective approach for targeting specific muscle groups in athletic training and rehabilitation.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers JP24592241 and JP15K01381, and by World Health Organization (PO201931642). The author declare that they have no conflict of interest. The experiments comply with the current laws of the country.

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Key points

- We measured muscle activities in a NSP and a squat posture with the COP intentionally shifted forward as far as possible.
- Muscle activity patterns vary significantly according to squat posture.
- The active control of the COP position during the squat can be a new training approach in targeting specific muscle groups.

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