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Original Article

Effect of thigh muscle fatigue on the biomechanical factors of the lower limbs when walking in a squatted position

Wan-Ki Hong, PE, PhD[1)], Chul-Gab Lee, MD, PhD[2)], Dae-Sik Ko, PT, PhD[3)*]

[1)] *Department of Physical Education, College of Physical Education, Chosun University, Republic of Korea*
[2)] *Department of Occupational and Environmental Medicine, School of Medicine, Chosun University, Republic of Korea*
[3)] *Department of Emergency Medical Service, College of Health Science, Honam University: 417 Eodeung-daero, Gwangsan-gu, Gwangju 506-714, Republic of Korea*

Abstract. [Purpose] The purpose of this study was to compare and analyze the effects of thigh muscle fatigue caused by walking in a squatted position on biomechanical factors, to evaluate the risk of a job performed sitting in a squatted position for a long period of time. [Subjects and Methods] Eighteen right foot dominant women without any injuries in their joints and body in the last 6 months were selected. They walked in a squatted position, and then muscle fatigue was induced by using an isokinetic muscular function measuring device (CSMI, USA). After the CSMI measurement, the participants performed walking in a squatted position again. [Results] After inducing thigh muscle fatigue, the knee joint maximum adduction moment significantly increased and the required duration was reduced. The muscle fatigue index was positively correlated with adduction moment and negatively with the duration. It influenced the changes of maximum adduction moment; 55.0% of the adduction moment change was explained by the degree of fatigue. [Conclusion] A quantitative analysis of working in a squatted position was performed. The thigh muscle fatigue index negatively the knee joint during walking in a squatted position. Therefore, this experiment can be used as an ergonomic analysis tool of general farm work.

Key words: Biomechanical factors, Muscle fatigue, Squatted position

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INTRODUCTION

Farm works activities, requires sitting in a squatted position, or severely bending and twisting at the waist, therefore; a high incidence of musculoskeletal disorders occurs in farm workers because of inappropriate working positions[1)]. Moreover, it has been reported that 80–90% of the workers sit in a squatted position or sit on the ground on their knees and vigorously bend and twist their waist, to > 60°, when cultivating vegetables[2, 3)].

For Korean female farmers, many of their field activities involve moving forward or side-to-side in a squatted position or kneeling down on the ground. When such work is done for a long period, the pressure on the patellofemoral joint increases, which results in deformation of the knee cartilage and induction of knee osteoarthritis due to increased muscle fatigue in the lower limbs[1)]. According to Kim and Jang, working in a squatted position for ≥2 h applies 2.77 times higher work-load on the knee joints compared with working at such a position for ≤2 h[4)]. Furthermore, working in a squatted position increases the work-load on the knee joints by increasing the muscle fatigue around the knee joints compared with working in a standing position[5)].

Muscle fatigue influences biomechanical factors such as the reaction time to the external environment, joint position

*Corresponding author. Dae-Sik Ko (E-mail: kds4941@naver.com)

sense, and coordination and control of motion[6]. Therefore, understanding the biomechanical mechanisms associated with muscle fatigue will help prevent musculoskeletal disorders.

However, there are no studies on the biomechanical mechanisms associated with muscle fatigue, Moreover, it is inappropriate to apply the known biomechanical risks of the squatted position, which is evaluated in a specific static working position, to the dynamic position, which is evaluated by gradually increasing the work load[7, 8].

In this study, we evaluated the impact of increased muscle fatigue on the load on the knee joints while working in a squatted position.

SUBJECTS AND METHODS

In this study, form among 48 adults whit ages of 20–23 years without any injuries in lower-limb joints and the body in the last 6 months, 18 women were selected who performed the motion in which the body center do not depart from the lateral direction of the supporting shaft, similar to an actual farm-work movement. Their general characteristics are shown in Table 1.

The purpose and methods of this study were explained to the participants, who signed an informed consent form that outlined all details of the study protocol, which was approved by the ethics committee of Chosun University (no. 2013-12-006).

To analyze the biomechanical factors of thigh muscle fatigue during walking in a squatted position, a ground reaction force-measuring device (AMTI ORG-6, USA) was used at a sampling rate of 1,000 Hz/s, and the data were collected by using Kwon 3D XP (Visol, Korea) with six infrared cameras (MotionMAster 200, Visol).

To synchronize the image and the ground reaction force-measuring device, LED was synchronized with the ground reaction sync channel by using a sync system box (VSAD-101USAB, Visol). Muscle fatigue was measured with an isokinetic muscular function–measuring device (CMIS, USA). As shown in Fig. 1, a total of 11 reflective markers with the diameter of 2 cm were attached to the center of the body joints and lower-limb joints, respectively.

As shown in Fig. 2, the experiment was conducted after a participant walked in a squatted position. Muscle fatigue was induced by using an isokinetic muscular function-measuring device (CSMI), and then the participant walked in a squatted position again.

The isokinetic muscular function-measuring device was used to induce thigh muscle fatigue. The range of motion of the knee joint was extension angle 0° to a flexion angle of 90° during the measurement, and the angular velocity was set to 90°/s[9]. This was repeated 50 times.

The formula for the degree of muscle fatigue calculation is as follows:

Fatigability % = (min peak torque − max peak torque) / max peak torque × 100

The formula for the loading rate calculation is as follows:

$$\text{Loading rate (loading rate \%) (N/s)} = (P1 - F20+) / (T1 - T20+)$$

Where

· P1: the maximum value of the vertical ground reaction force generated when landing (N)
· F20+: the first vertical ground reaction force (N) value exceeding 20 N before P1
· T1: P1 duration (sec)
· T20+: F20+ duration (sec)

Table 1. Characteristics of the subjects

Subjects	N=18
Leg length (m)	0.8±0.1
Weight (kg)	56.8±3.0
Skeletal muscle mass (kg)	21.0±3.4
BMI (kg/m^2)	21.5±3.0
Fat mass (kg)	17.8±5.7

BMI: body mass index

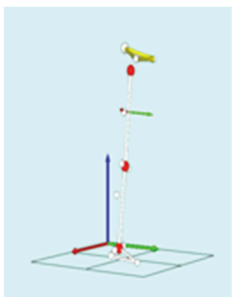

Fig. 1. Marker set

Fig. 2. Experimental design

For the image analysis, three-dimensional coordinates were calculated by using the direct linear transformation method of Abdel-Aziz and Karara[10)], by synchronizing with the coordination of control points and the center of the body joints. A low-pass filter was used when smoothing with the frequency of 6 Hz. For the human joints, four segments including the ankle joint, joint and foot of knee joint, shank, thigh, and pelvis were remodeled as rigid bodies by using the anatomical makers attached to the subjects, and the body segment parameters of Plagenhoef et al.[11)] were used. The center of the joints was set with Tylkowsky's[12)] method for the hip and the mid-point (secondary point) method for the knee and ankle by using the images taken to locate the center of each joint.

A paired t-test was performed to test the differences of biomechanical factors (the changes of knee angle, maximum flexion, maximum adduction moment, and thigh rotation angle, duration, and work-load) before and after the performance of walking in a squatted position after inducing thigh muscle fatigue. Spearman nonparametric correlation analysis was conducted to test the relevance of biomechanical factors according to the degree of muscle fatigue, and a simple regression analysis was performed targeting the factors showing a correlation. SPSS 20.0 statistical program was used for all statistical analyses, and the level of the significance was set at $p < 0.05$.

RESULTS

Table 2 illustrates the differences in the biomechanical factors of the lower limbs after inducing muscle fatigue. The knee angle was 50.1 ± 8.1° before thigh muscle fatigue induction and 49.6 ± 8.3° after the induction, showing insignificant differences. Moreover, the differences of the maximum knee flexion/extension moment before and after the induction of thigh muscle fatigue were not significant, which were 0.26 ± 0.06 and 0.25 ± 0.06 Nm/kg/m, respectively. The variation of the thigh rotation angle while walking in a squatted position was reduced after the induction, showing a change from 14.7 ± 6.8° to 13.9 ± 9.8°; however, the difference was not statistically significant. Furthermore, although the loading rate increased from 507.7 ± 88.2% to 520.3 ± 127.8% after the induction, the difference was not statistically significant ($p>0.05$). However, the maximum adduction moment of the knee joint showed a change from 0.01 ± 0.01 to 0.04 ± 0.01 Nm/kg/m after the induction, which was a 0.03 Nm/kg/m increase and the difference was statistically significant ($p<0.001$). The duration also significantly decreased from 1.27 ± 0.08 s to 1.16 ± 0.07 s ($p<0.05$).

Table 3 shows the correlation of biomechanical factors between the degree of muscle fatigue and the lower limbs, and the biomechanical variables were analyzed according to changes before and after the muscle fatigue induction.

As shown in Table 3, the variation of the degree of muscle fatigue and the maximum adduction moment showed a positive correlation ($r = 0.694$), and the degree of muscle fatigue showed a negative correlation with the duration ($r = −0.539$). However, the knee angle change ($r = 0.224$), maximum bending moment change ($r = 0.429$), thigh rotation angle change ($r = −0.047$), and loading rate ($r = −0.060$) were not significantly correlated ($p > 0.05$).

To statistically test the impact and contribution of the duration and the degree of muscle fatigue, which showed a correlation, statistical regression analysis was conducted. The result of regression analysis is shown in Table 4.

After analyzing the effects of two independent variables on the maximum adduction moment by regression analysis, the duration was exempted due to its insignificant effect, but the effect of the degree of fatigue was significant ($F = 9.174$, $p < 0.01$). As a result, 55% of the variation of the maximum adduction moment was explained by the degree of fatigue, and it was defined as an effective variation.

Table 2. Results of kinetic variables

Variable	Pre	Post
Variation of knee angle (°)	50.1±8.1	49.6±8.3
Peak knee flexion/extension moment (Nm/kg/m)	0.3±0.1	0.3±0.1
Peak knee valgus/varus moment (Nm/kg/m)	0.01±0.01	0.04±0.01***
Time (s)	1.3±0.1	1.2±0.1*
Variation of thigh rotation (°)	14.7±6.8	13.9±9.8
Loading rate (%)	507.7±88.2	520.3±127.8

*$p < 0.05$, ***$p < 0.001$

Table 3. Results of kinetic variables

Variable	Variation of knee angle (°)	Peak knee flexion/ extention moment (Nm/kg/m)	Peak knee valgus/ varus moment (Nm/kg/m)	Time	Variation of thigh rotation (°)	Loading rate (%)
Fatigability	0.2	0.4	0.7**	−0.5*	−0.1	−0.1

*$p < 0.05$, **$p < 0.01$

DISCUSSION

Many studies constantly assessed the risk of a knee joint in accordance with the work operation form, but most researches used surveys or questionnaires responding about the pain itself and the risks of standardized work form targeting a single person[13–15]. Moreover quantitative studies of dynamic postures are very limited[3, 16]. In this study, we investigated the effects of walking in a squatted position on the biomechanical factors of the lower limbs on the basis of the hypothesis that working in a squatted position for a long time increases the work load on the knee joints.

While bending the knee, the force on the patellofemoral joint causes the external torque of the knees to induce a strong contraction of the thigh quadriceps muscle. Therefore, fatigue of the thigh quadriceps muscle leads to difficulty of normal joint movement during walking in a squatted position. This study showed that there were no differences in thigh rotation and bending moment; however, after muscle fatigue, high adduction moment variation was observed. Moreover, although thigh muscle fatigue did not affect the winding and the amount of rotation, it induced an increase in the adduction moment.

When walking in a squatted position, the variation of the adduction moment without any knee joint movement can be explained by an internal moment arm variation because the knee joint, which is a supporting structure, failed to control body movements because of thigh muscle fatigue. Epidemiological studies on knee arthritis have shown that twisting the knees while sitting in a squatted position is related to knee osteoarthritis[17].

However, this study showed that the adduction moment is increased by changes of the body center without knee twisting, and the increase of the adduction moment change can be seen as causing an increase in the pressing force of the inner contact surfaces of the tibia and femur. In general, knee joint arthritis results from local aggravating factors such as those affecting the anatomical structures and the muscular strength of joints; however the higher abrasion of implanted materials in farmers who underwent total knee arthroplasty for knee osteoarthritis compared with non-farmers can be predicted on the basis of the above mentioned reasons[18].

The load rate is determined by using the maximum vertical ground reaction force and the supporting time. The increase of the load rate means a rapid increase of the vertical ground reaction force within a relatively short time while moving in a squatted position. In this study, the load rate did not show a significant difference; however, the duration was significantly different. The reason is that because after sitting in a squatted position, the duration time was short after muscle fatigue, but the maximum vertical ground reaction force appeared at a relatively later time. Like a drop and landing motion requiring eccentric contraction of the quadriceps muscle in a short time, the fatigue of quadriceps muscle clearly acted as a regulatory factor of the knee joint[19]. However, thigh muscle fatigue did not affect the loading rate when the knee joints were fully bent.

When moving, the knee joint moment shows predictable variation according to the loading rate transmitted to the knee[20]. In this study, linear regression analysis was conducted for the duration and the degree of fatigue as independent variables, which showed positive correlations with the degree of muscle fatigue and the biomechanical variables of the lower limbs. As a result, the duration was disregarded because its effect was not significant. As a result of determining the contribution of the independent variables on the knee joint adduction moment, the degree of fatigue was found to have explanation power of $R^2 = 0.550$ (55.0%). R^2 is an important statistical value describing the strength of the association between two variables[21]. It can be interpreted to indicate that the degree of muscle fatigue is highly related to the maximum adduction moment; therefore, a high fatigue degree means an increase in the maximum adduction moment of the knee joint. Therefore, thigh muscle fatigue resulting from the working posture of farmers sitting in a squatted position for a long period can be considered as a factor increasing osteoarthritis of the knee joint. Given that the average time of engagement in agricultural work of the studied subjects was 33.3 years, musculoskeletal disorders of the knee joints in these workers can be highly associated with their occupation. On the basis of these results, health care programs should be provided for farmers whose work requires sitting in a squatted position for a long period. Furthemore, on the basis of previous studies stating that strengthening of the lower limb muscles can reduce the burden on the knee joints, lower limb strengthening exercise are essential.

Thigh muscle fatigue when walking in a squatted position is strongly suggested as a knee injury risk factor. In addition, this study enabled a quantitative analysis of working in a squatted position by means of biomechanical evaluation of agricultural workers, and showed the possible use of biomechanical evaluation as an ergonomic analysis tool for general agricultural workers.

Table 4. Regression analysis

Dependent variable	Unstandardized coefficients		Standardized coefficients	t
	B	Std. Error		
Fatigability	0.002	0.001	0.862	−4.191
$R^2 = 0.550$, $F = 9.174^{**}$				

**p < 0.01

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