Analysis of Changes in Muscle Length of Lower Limbs during High-heeled Walking Based on the Musculoskeletal Model

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Abstract
In this paper, we analyzed changes in muscle length of lower limbs during high-heeled walking based on the musculoskeletal model. Twenty young healthy women participated in this study. For each subject, the 3D motion analysis was performed for four different cases; walking with flat shoe, 3cm high-heel, 6cm high-heel, and 9cm high-heel. Then the musculoskeletal model, with modified Hill-type muscles, was made from subjects' anthropometric data and 3D motion capture data. Results showed that heel height did not show significant difference in hip joint motion. However, for 6cm and 9cm high-heels, knee flexion increased during loading response due to the insufficient extension of biceps femoris short head. Changes in muscle length of soleus and tibialis anterior significantly decreased and the muscle force of soleus decreased. Our results showed that the ankle joint played most important role to adapt high-heel lower than 6cm, but the contribution of other lower extremity joints, especially knee joint, would be required for the higher heel. Changes in muscle length provided more valuable information to determine gait characteristics in various clinical conditions.

1. Introduction
In these days, the role of shoes is changing from the functional aspect for protecting foot to the cosmetic one for decorating oneself. Women, especially, tend to pursue the cosmetic importance so that they usually wear high-heels, even though high-heeled walking could bring musculoskeletal problems in foot or lower limbs. There are some previous studies about some side-effects of high-heeled walking. Gollinick et al. reported the knee flexion during stance phase increased in high-heeled walking [1]. De Lateur et al. studied compensatory strategies for different heel height adjustment of the body and reported that the stride length decreased in high-heeled walking [2]. Most of these researches comprised of kinematic analysis, and few studies were performed to analyze joint moments and muscle forces in high-heeled walking. Recently, the musculoskeletal modeling technique has been developed by many researchers [3], which makes possible to calculate individual muscle length and its force by using the analytical equation to describe the length-tension characteristics given by various experiments [4]. Hwang et al. evaluated joint moments in various high-heeled walking using the inverse dynamic method [5]. However, they could not describe individual muscle length and muscle force. Therefore, the present study was performed to determine the effect of heel height and individual muscle length and muscle force for various high-heeled walking using the inverse dynamic simulation of the lower limbs musculoskeletal model with 3D motion capture data.

2. Methods
2.1. Subjects and Materials
Twenty young healthy women (age: 23.2±1.3yrs, height: 159.1±3.1cm, weight: 51.9±5.4kg) who experienced neither musculoskeletal diseases nor
discomfort during high-heeled walking were chosen as subject for this study.

Four different shoes of 235mm in size were used. As seen in Figure 1, one has no heel, and the other three shoes have the same design but differ only in heel heights as 3, 6, and 9cm respectively. Subjects were required to walk in the gait laboratory until they felt comfortable with each shoe. Experiments were performed at the subject's comfortable walking speed.

![Figure 1. Four shoes with different heel heights](image)

### 2.2. Motion Analysis

Gait analysis was performed for high-heeled walking using the 3D motion analysis system (VICON Motion Systems Ltd., England) with six infrared cameras, coupled with two force plates (AMTI, U.S.A.). Reflective markers on lower limbs were placed, based on Helen-Hayes marker set [6]. Each subject walked, first wearing shoes with no heel, and then similar experiments wearing shoes with heel heights of 3, 6 and 9cm respectively were repeated. All subjects were required to walk three times for each heel height.

### 2.3. Musculoskeletal Modeling

In order to simulate an inverse dynamics, all gait analysis data were imported to a musculoskeletal modeling software, SIMM (Musculographics Inc., U.S.A.), and inverse dynamic analysis was performed with a lower extremity musculoskeletal model of six major muscles in each limb. Gluteus maximus and psoas, controlling hip joint in sagittal plane, rectus femoris and biceps femoris short head, controlling knee joint in sagittal plane, and soleus and tibialis anterior, controlling ankle joint in sagittal plane, were chosen.

Muscle model to calculate the individual muscle force was based on modified Hill-type model [7] and those muscle parameters, for example origin, insertion and maximum force etc., were referenced with the Delp's work [3]. Changes in muscle length were plotted as percent rates compared with the length in the anatomically neutral position.

![Figure 2. Musculoskeletal model with 6 muscles in lower body](image)

### 3. Results and Discussions

Figure 3 shows hip joint angle, hip joint moment, the length and force of hip flexor/extensor during high-heeled walking. The gluteus maximus, a major hip extensor, produced the large force to support the body weight by generating extension moment in early stance and by controlling hip flexion speed in terminal swing. The psoas, an important hip flexor, produced the force to move the leg forward during terminal swing. There are no significant differences in angle, moment, muscle length and muscle force. These results imply that different heel heights do not affect the hip joint motion.

![Figure 3. Hip joint angle, joint moment, muscle length and muscle force in gait cycle (100%)](image)
Figure 4 shows knee joint angle, knee joint moment, the length and force of knee flexor/extensor acting on the knee joint during high-heeled walking. The rectus femoris, an important knee extensor, produced the force in early swing controlling the knee flexion speed by eccentric contraction. In 9cm high-heel, the biceps femoris short head, a major knee flexor, was more tightened during loading response, which is comparable Gollinick’s work [1]. This tells us that only an ankle joint adjustment does not provide enough shock absorption during this period especially for higher heel. Because the ankle joint was already plantarflexed in high-heeled walking, the stronger contraction of the knee flexor seems to contribute to shock absorption. These results showed that 9cm heel height changes joint movements, muscle length and muscle force and it seemed compensatory strategies at knee joint to maintain the balance of a body.

Figure 4. Knee joint angle, joint moment, muscle length and muscle force in gait cycle (100%)

Figure 5 shows ankle joint angle, ankle joint moment, the length and force of plantarflexor/dorsiflexor acting during high-heeled walking. As heel heights increased, ankle joint movements decreased. The ankle extension moment decreased during pre-swing, because a major plantarflexor, soleus force is reduced. In 9cm high-heel the eccentric contraction of tibialis anterior, a major dorsiflexor in loading response, did not play an important role in shock absorption, compared with the flat shoe. In addition, in 9cm high-heel a weakened push-off was noted during pre-swing, because changes in soleus muscle length decreased. These results showed that the ankle joint was well adapted for the dynamic balance in high-heels lower than 6cm heel height. On the other hand, the compensation of the other joints, especially the knee joint, might be necessary for walking with the higher heels.

Figure 5. Ankle joint angle, joint moment, muscle length and muscle force in gait cycle (100%)

4. Conclusion

In this paper, we analyzed joint movements, muscle length and muscle force during high-heeled walking by the 3D motion analysis and the musculoskeletal modeling. In hip joint, different heel heights have little effects on hip joint and compensation at knee joint was occurred by biceps femoris short head and rectus femoris. The tibialis anterior in 9cm high-heel did not play an important role during loading response and range of length change in the soleus was decreased and ankle extension moment decreased during pre-swing...
because of reduction of the soleus force. In this study, we tried to analyze the muscle length and force. Changes in muscle length are useful to understand gait characteristics, but we couldn't have information about concentric or eccentric contraction through muscle force. It seems to be hard to explain motion by just muscle force data, so we would better study with EMG data to be easy and clear analysis. These results showed that changes in muscle length provided more valuable information to determine gait characteristics in various clinical conditions.

5. Acknowledgments

This work has been partially supported by Research and Development of Sport Industry of the Ministry of Culture and Tourism, and Regional Innovation Center Program which was conducted by the Ministry of Commerce Industry and Energy of the Korean Government.

6. References


