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COMPUTER-AIDED ANALYSIS OF MUSCULAR MOVEMENT OF LOWER LIMBS AND GAIT CHANGE WHEN WALKING WITH UNSTABLE SHOES

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ABSTRACT

Several healthcare products have been developed and marketed in recent times as a result of people's growing interest in personal health. Unstable shoes have been introduced to revitalize the muscles of the lower limbs and to modify the gait posture while walking. However, healthcare products for people should first be proved functional and safe, as some of those can sometimes result in severe injuries and side effects. Certification is, therefore, necessary in the case of unstable shoes. In this study, the functionality of unstable shoes was analyzed; it was proved that difference in pressure distribution resulting from the shape of the unstable shoes helps strengthen the muscles of the lower limbs. These analyses focused on the activation of the muscles by employing EMG (Electromyography). However, the approach involving EMG cannot carry out measurements on hidden muscles, and the noise involved is a source of potential error; therefore, this study utilizes the simulation software SIMM (Software for Interactive Musculoskeletal Modeling) for this purpose. We performed a biomechanical study using a full-body musculoskeletal model. Using the captured 3D motion data and ground reaction forces data, kinetic data was calculated in order to determine its influence on the adjacent segments. We captured the movements of six volunteers, all males in their twenties. The volunteers wore both unstable and normal shoes during each trial. This study focuses on the activation of muscles of the lower limbs when wearing unstable shoes. We inspected the muscles and analyzed the disparities between unstable and normal shoes. We observed from experimental results that most muscles of the lower limbs were revitalized. Further, we observed an improvement in the gait posture after unstable shoes were used for a period of 12 weeks. This analysis of inner muscles that cannot be examined by direct methods can help consumers make informed choices regarding healthcare products. Such analysis is made possible by simulation programs such as SIMM.

INTRODUCTION

While the recent economic growth has brought about an increased focus among people on personal health, the hectic pace of their modern lifestyles prohibits them from devoting considerable time to it [12]. This has led to the invention of healthcare devices that could be used during daily routines; along these lines, unstable shoes such as MBT, which revitalize the muscles of lower limbs, were invented [1,2].

Unlike normal shoes, unstable shoes contain an added rounded soft cushion beneath the sole of the shoe. Users of these shoes reported that their experience was similar to that of walking on a rolling wheel. Since unstable shoes provide an unstable support base, they revitalize the leg muscles [2].

From the viewpoint of consumers, such healthcare equipment should be investigated for its safety and functionality. With this objective, several verification trials have been conducted; however, most certification processes relied on direct experiments alone. For instance, the unstable shoes were examined with a direct experiment that measured the change in muscle electric current using electromyography (EMG) or video analysis [1,5,8].

The results show that unstable shoes are effective in the strengthening and rehabilitation of the muscles of lower limbs due to the differences in pressure distribution on their soles. These early studies employed EMG to analyze muscle activation [1, 12, 13].

One study attempted to explain how gastrocnemius and rectus femoris were activated when subjects used unstable shoes by using image analysis with a video camera in combination with the EMG method [12]. In [13], the pressure distribution on the sole was investigated, and it was discovered that the gait on wearing MBT shoes was similar to that of the barefoot sole rather than that of normal flat-sole shoes.

Most of the above studies analyzed data with a video camera and EMG. However, image analysis performed using a video camera is qualitative and not quantitative in nature. EMG also has other demerits, as its results can vary from person to person, depending on their skin condition and the depth of their fat layer [15]. Therefore, we suggest computer simulations with motion capture in order to examine the reliability of unstable shoes. Firstly, gait simulation is performed with a computer-developed model with the motion capture data and inverse dynamic calculation is carried out in order to obtain the activation of muscles. The results will demonstrate whether the MBT shoes provide appropriate functionality.

For this purpose, we used SIMM (Software for Interactive Musculoskeletal Modeling), a computer program that can develop and analyze a model of the human body. The accuracy of SIMM has been acknowledged in several papers and journals [3]. It can provide effective results for unstable shoes, as it can analyze muscles that the EMG approach cannot.

METHODS

1. Subjects

Six healthy males, none of whom had worn unstable shoes prior to this experiment, volunteered to participate as subjects in this study. The relevant characteristics of the subjects are listed in Table 1 [6]. In order to analyze the long-term effects, the subjects wore the shoes everyday for 12 weeks. Prior to the study, they were educated by an expert on the proper usage of the unstable shoes. Every graph means

	Mean	S.D	Range
Age (years)	23.3	1.751	21-26
Weight (kg)	71.5	8.458	60-84
Height (m)	1.783	0.056	1.7-1.86
Foot size (mm)	275	3.162	270-280
Gait speed (m/s)	0.845	0.094	0.72-0.96
Normalized gait speed (s^{-1})	1.045	0.0764	0.9-1.12
Step length (m)	0.7667	0.053	0.68-0.82

Table.1. Subject characteristics (N = 6)

2. Study protocol

The study protocol comprised modification of gait posture and muscle activation in the lower limbs when using unstable shoes. The experiment was performed four times during the course of the study, with a four-week interval between each trial in order to verify the gradual changes occurring with the use of unstable shoes.

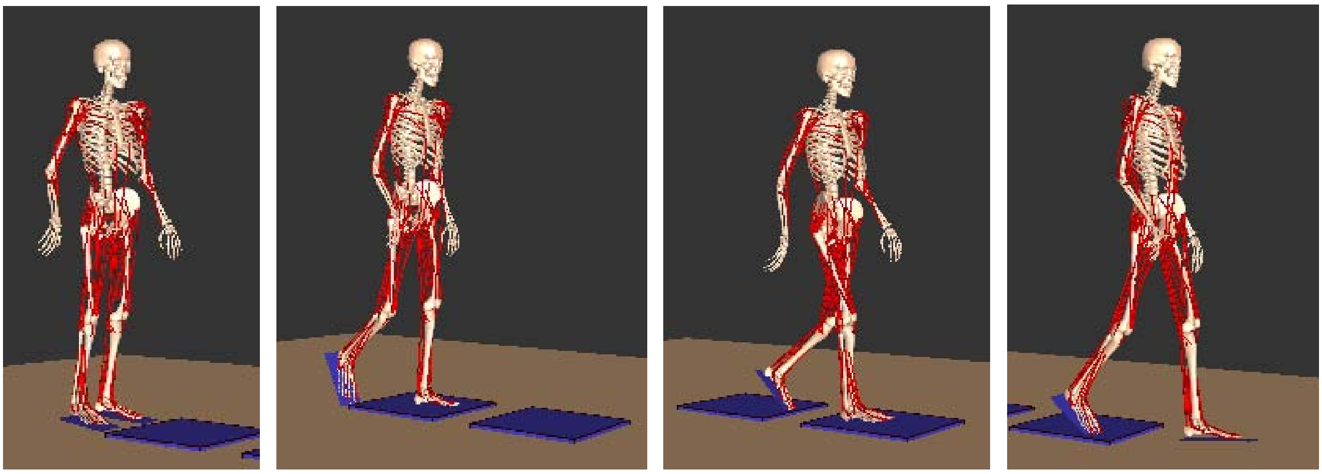
Fig. 1 Unstable shoes produced by MBT

3. Measurement equipment

The 3D position data was captured using Qualysis Motion Capture System (Qualysis, Gothenburg, Sweden). The movement corresponding to the displacement of the attached marker was recorded using 11 Qualysis cameras at a uniform rate of 100 Hz.

Ground Reaction Forces (GRF) were extracted using two AMTI force platforms (Model OR6-7, Advanced Mechanical Technology Inc., Watertown, MA, USA). The GRF data was digitally filtered through a low-pass filter at 25 Hz.

Fig. 2 Measurement equipment (motion capture camera and force plate)



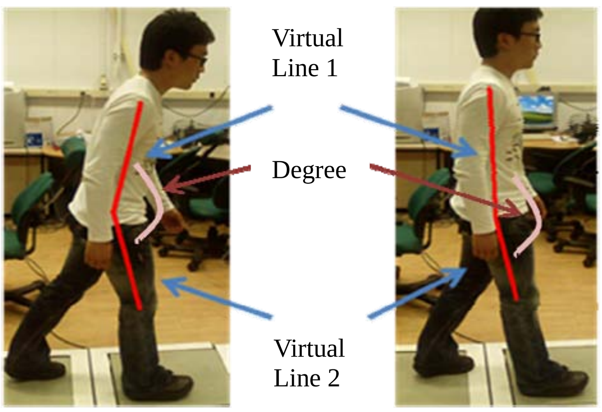
(a) 0% (gait cycle) (b) 39% (gait cycle) (c) 77% (gait cycle) (d) 100% (gait cycle)

Fig.3 Gait postures during a subject's walk. (a) Pose before walking (b) Pose when left foot touches ground (c) Pose when right foot touches ground (d) Pose when left foot touches ground

4. Data collection

Coordinate point data was collected using an infrared camera system that can capture the motion of a body. The camera recorded the gait of the subjects by tracking the retro-reflective markers attached to the joints of the subjects' bodies. To examine the improvement in the gait posture, we placed markers on the right shoulder, waist, knees, and ankles.

The virtual angle shown in Fig. 4 was set based on the above data. In order to analyze muscle activation, markers were placed based on the Helen marker set [16] shown in Fig. 5. Additionally, reaction force data for each foot was measured by two force plates placed along the walking path. Each plate measures the amount and direction of the forces instantaneously when subjects step on it. Gait motions are shown in Fig. 3. With these points and reaction data as input, changes in gait and muscle activity were simulated by SIMM.



(a) Improper gait (b) Desirable gait

Fig. 4 The virtual waist angle while walking

In order to perform the analysis using SIMM, we used a musculoskeletal model of each individual by scaling a generic full-body model (MusculoGraphics, Inc., Chicago, IL, USA). Based on the marker data tracked in a static pose, the current posture of an articulated body was detected by matching the projections of a kinetic model with the detected set of marker points. This model contained 328 body segments, 37 joints, 55 degrees of freedom, and 94 muscles [16].

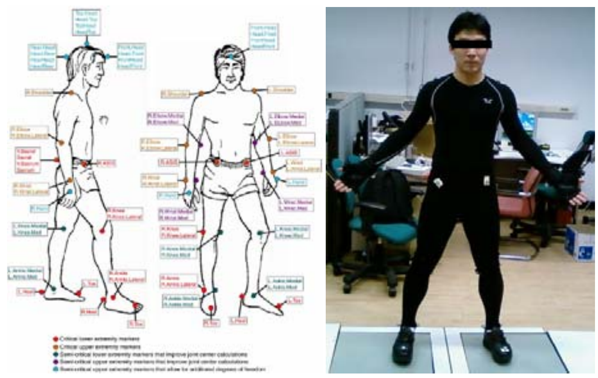


Fig. 5 Placement of the Helen-Hayes marker set

5. Computer simulation

SIMM was used to analyze the changes in gait and lower muscular activity by utilizing motion and force data. Joint torque was calculated based on the captured motion data and ground reaction force, GRF. This process is illustrated in Fig. 6 [16, 17].

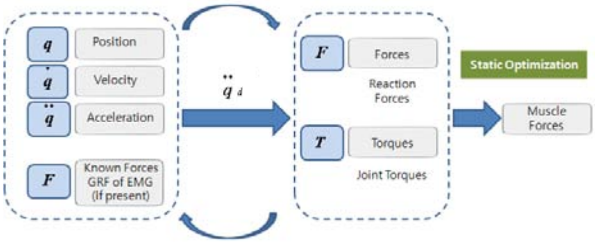


Fig. 6 Schematic of the computer simulation algorithm

Inverse dynamics is the main process involved in computer simulation [17]. We calculated joint torques using the input motion as follows. Firstly, a set of desired accelerations were computed based on a set of experimental kinematics data and the current kinematic state of the model (Eq. (1)). Secondly, if the desired accelerations, as given by Eq. (1), were achieved, the velocity and position errors would be driven to 0 and would display the behavior described by a set of decoupled second-order ordinary differential equations (Eq. (2)) [16,17]. Finally, by eliminating the errors, the joint torques, or alternately, the output from the inverse dynamics analysis, were calculated.

$$\ddot{\vec{q}}_{\mathrm{d}} = \ddot{\vec{q}}_{\mathrm{exp}} + k_{\mathrm{v}} \underbrace{\left(\dot{\vec{q}}_{\mathrm{exp}} - \dot{\vec{q}}\right)}_{\dot{\vec{e}}_q} + k_p \underbrace{\left(\vec{q}_{\mathrm{exp}} - \vec{q}\right)}_{\vec{e}_q} \qquad (1)$$

$\ddot{\vec{q}}_{\mathrm{d}}$: Desired acceleration

$\ddot{\vec{q}}_{\mathrm{exp}}, \dot{\vec{q}}_{\mathrm{exp}}, \vec{q}_{\mathrm{exp}}$:

Experimental data (acceleration, velocity, position)

$\dot{\vec{q}}, \vec{q}$: Generalized data (velocity, position)

$$\ddot{\vec{e}} + k_v \dot{\vec{e}} + k_p \vec{e} = 0 \qquad (2)$$

$\ddot{\vec{e}}$: the acceleration error $\left(\ddot{\vec{q}}_{\mathrm{exp}} - \ddot{\vec{q}}_{\mathrm{d}}\right)$

$\dot{\vec{e}}$: the velocity error $\left(\dot{\vec{q}}_{\mathrm{exp}} - \dot{\vec{q}}_{\mathrm{d}}\right)$

$\vec{e}$: the position error $\left(\vec{e}_{\mathrm{exp}} - \vec{e}_{\mathrm{d}}\right)$

k_v, k_p : feedback gains

In order to analyze the gait, an imaginary line connecting the scapula, the hipjoint, and the patella was constructed and observed while walking. The primary data of the experiment was compared with the data measured from subjects who had worn unstable shoes for 12 weeks.

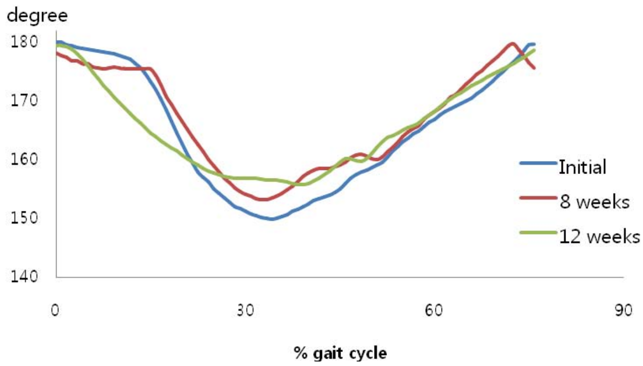
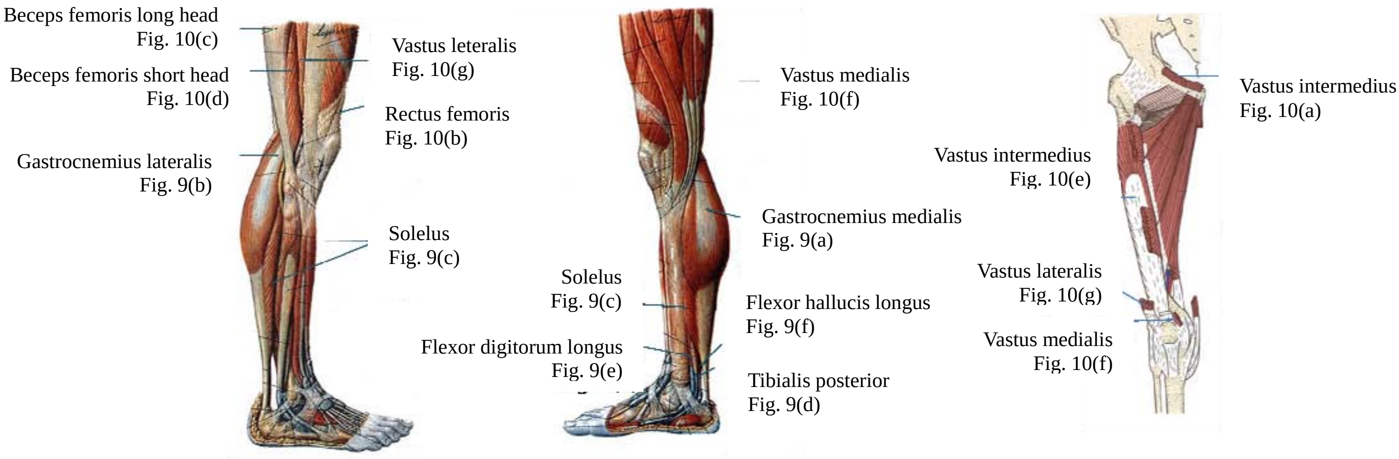


Fig. 7 Change in walking angle at different points in time



(a) Lateral view of the right leg (b) Medial view of the right leg (c) Anterior view of the right thigh

Fig. 8 Leg muscles

RESULTS

1. Improvement of gait posture

Walking with unstable shoes helped subjects improve their movement while walking. We examined the positions of the right shoulder, right waist, and right knee using infrared markers. We created two virtual lines for analyzing the gait posture; line 1 is the virtual line linking the shoulder and the side of the waist, while line 2 links the side of the waist and the knee. We can determine the angles created by lines 1 and 2 as the subjects walk; this is illustrated in detail in Fig. 4. As shown in Fig. 4 (b), for a constant step length, a larger angle implies a proper gait posture. A gait posture may be considered appropriate when the subject's back is straight and not bent while walking [19,20.21].

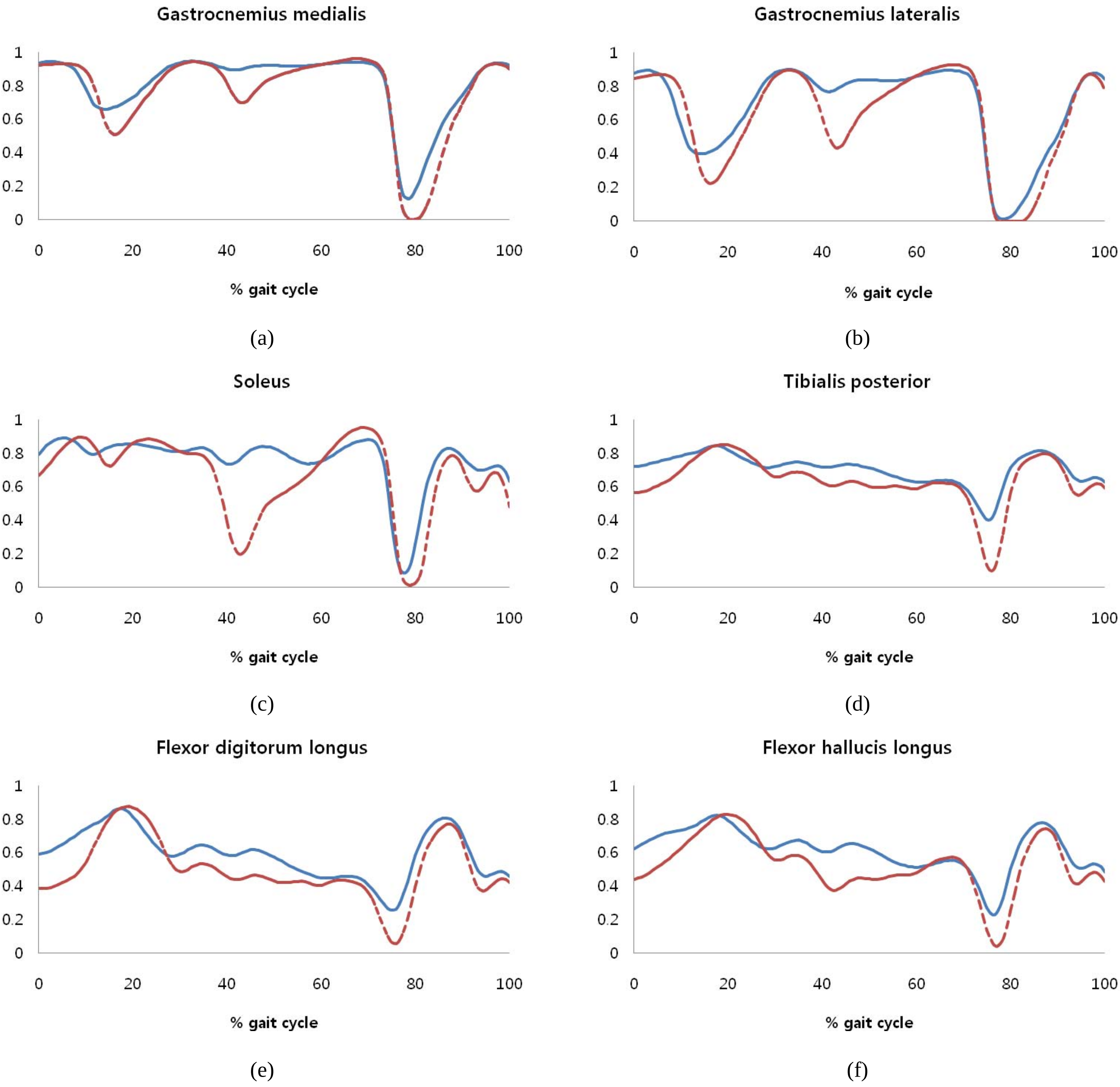
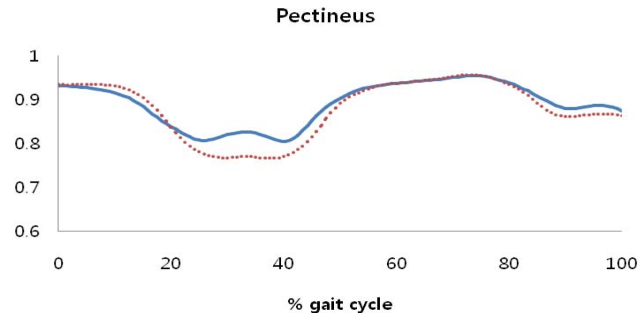
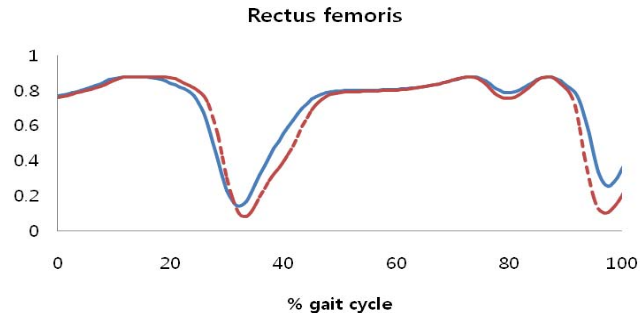


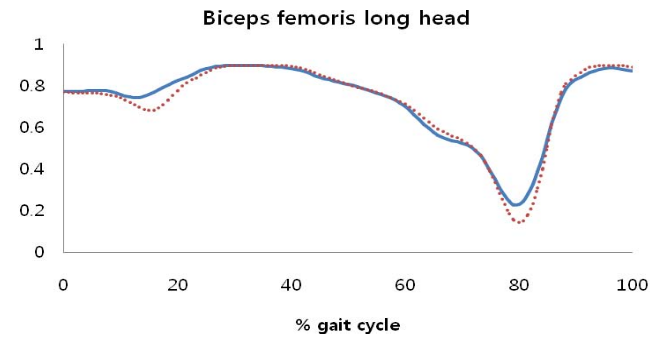
Fig. 9. Activation data for left calf muscles when walking with unstable and regular shoes. Curves represent the mean values corresponding to walking with unstable shoes (denoted by —) and regular shoes (denoted by – –) (X axis : gait cycle, Y axis : muscle activation levels)



(a)



(b)



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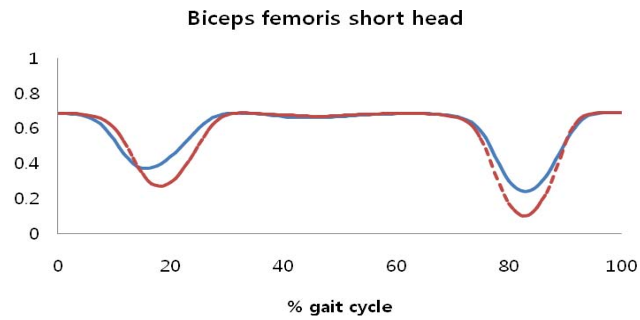
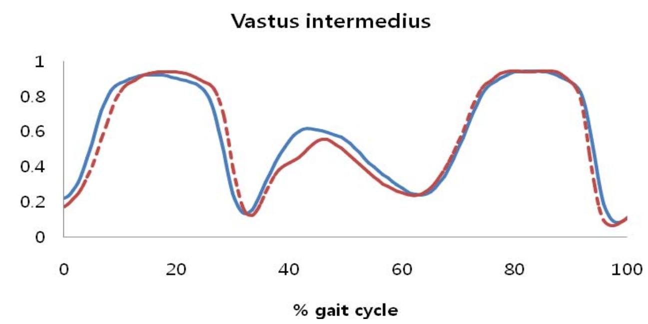
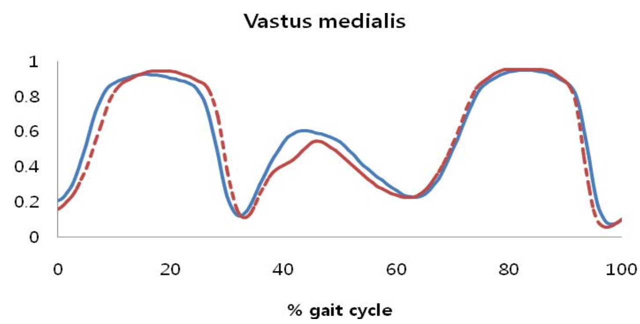


(d)



(e)



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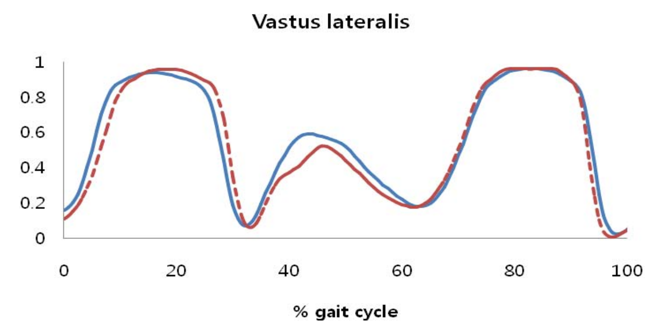

(g)

Fig. 10. Activation data for left thigh muscles when walking with unstable and regular shoes. Curves denote the mean values corresponding to walking with unstable shoes (denoted by —) and regular shoes (denoted by – –) (X axis : gait cycle, Y axis : muscle activation levels)

We compared the gait postures at different points in time by examining the postures corresponding to the first unstable shoes experiment, the second experiment, which was held four weeks later, and the final experiment at the end of 12 weeks. In order to focus on the long-term effects of unstable shoes, all three experiments were performed with subjects wearing unstable shoes.

Data concerning the walking angle is presented in Fig. 7, wherein the change in the walking angle is indicated, with the right foot being considered as the axis of walking. Training with unstable shoes was found to be effective in comparison to the walking during the first experiment. The walking angle increased at the end of 12 weeks, which implies an improvement in the gait posture.

2. Muscle activation

At the end of the twelve-week training with unstable shoes, we examined the effect of unstable shoes with regard to their role in muscle activation. It was observed that calf and thigh muscles were activated.

We examined six calf muscles and seven thigh muscles when unstable shoes were used while walking. The inspected muscles are presented in Fig. 8 [18].

The activation of calf muscles is illustrated in Fig. 9. Gastrocnemius medialis, gastrocnemius laterialis, and soleus are activated with the use of unstable shoes when the left leg touches the ground. Tibialis posterior, flexor digitorum longus, and flexor hallucis longus are activated when the left leg is off the ground while walking.

In addition to calf muscles, biceps femoris is also activated (Fig. 10). Although its activation level is smaller than that of calf muscles, it is activated when the left leg is off the ground while walking. Pectineus is also activated, demonstrating that different parts of the lower limbs are affected by the use of unstable shoes. Further, rectus femoris, vastus intermedius, vastus medialis, and vastus lateralis are also activated when walking with unstable shoes.

DISCUSSION

Walking with a stretched waist is desirable, and unstable shoes were found to improve the gait motion of the subjects (Fig. 7). The angle of the waist, formed between the upper and lower limbs, is 180 degree in the standing position. Since the posture of the lower limb changes while walking, the walking angle decreases.

Apart from the lower limbs, the upper limb also causes the walking angle to change. If the body is bent while walking, the walking angle will decrease, resulting in a highly unsuitable posture that could be injurious [14]. Walking with a stretched waist is, therefore, very important. The instability of the shoes forces users to consciously attempt to maintain the balance of their body.

Other effects of using unstable shoes are illustrated in Fig. 9, Fig. 10, and Table 2. The improvement in muscle activation is indicated in Table 2. Based on this data, the increase in muscle activation can be determined; in particular, the increase in the activation of flexor digitorum longus is calculated as approximately 18%.

In their attempt to maintain the balance of the body, the lower limbs are activated when unstable shoes are worn [1]. Several studies concerning unstable shoes have been carried out; however, these studies were experiment-based. With changes in the experimental circumstances, subjects can cause errors. In particular, experiments that utilize EMG contain noise originating from the subjects' skin and hair [15].

Verified computer simulation is very powerful tool, as it can produce results with minimal error [2, 11]. SIMM has previously been verified for accuracy [2, 11]. Further, SIMM can also analyze muscles that cannot be analyzed using EMG.

The activation of gastrocnemius medialis, gastrocnemius laterialis, soleus, and rectus femoris is frequently demonstrated using EMG [1]; however, the activation of flexor digitorum longus, flexor hallucis longus, and pectineus are not demonstrated by this method.

Muscle	*US*	*NS*	*Increase (%)*
gastrocnemius medialis	0.679	0.623	9.04
gastrocnemius lateralis	0.809	0.759	6.50
soleus	0.758	0.667	13.6
tibialis posterior	0.705	0.635	11.1
flexor digitorum longus	0.592	0.501	18.4
flexor hallucis longus	0.616	0.527	16.8
pectineus	0.885	0.872	1.45
rectus femoris	0.716	0.687	4.23
biceps femoris long head	0.729	0.721	1.11
biceps femoris short head	0.588	0.565	4.16
vastus intermedius	0.589	0.570	3.33
vastus medialis	0.582	0.563	3.29
vastus laterialis	0.565	0.545	3.76
average			7.44

Table 2. Average muscle activation levels resulting from the use of unstable and normal shoes (US: unstable shoes, NS: Normal shoes)

Due to the limited number of channels and lines that interfere with the subjects' natural walking styles, EMG is not suitable for the simultaneous measurement of multiple muscles. However, using SIMM, all muscles related to walking can be examined.

Software can be used in conjunction with experiments in order to overcome the limitations of conventional studies based on real experiments such as EMG. Therefore, analysis of unstable shoes using computer simulation is a meaningful approach for the investigation of multiple muscles in a natural environment

CONCLUSION

Stable shoes, which are typically designed to provide stability to the user, may cause the muscles that normally contribute to stability to weaken over time, as their usage is minimized. In contrast, unstable shoes with rounded soles stimulate lower extremity muscles by disrupting the stability of the user's body; the degree of improvement in this regard is observed to be approximately 7.44%.

This paper marks a significant step toward understanding the effect of unstable shoes on not only muscles such as bicepsfemoris, soleus, and gastrocnemius, which have been examined in previous studies, but also those muscles that are difficult to evaluate.

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