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Original Article

Effect of ankle-foot orthosis with a built-in spring on muscle activity during the sit-to-stand movement in healthy individuals

Masafumi Itokazu, RPT, PhD[1)]

[1)] *Department of Physical Therapy, School of Health Science at Narita, International University of Health and Welfare: 4-3 Kouzunomori, Narita City, Chiba 286-8686, Japan*

Abstract. [Purpose] This study aimed to evaluate the influence of a newly developed ankle-foot orthosis with a built-in spring on the activity of lower limb muscles during the sit-to-stand movement. [Participants and Methods] This cross-sectional study recruited 20 male volunteers. The sit-to-stand movement (rising from a chair) was performed under three conditions: no ankle-foot orthosis (NA), ankle-foot orthosis with no spring (NS), and ankle-foot orthosis with a built-in spring (SP). Muscle activity during the sit-to-stand movement was measured using surface electrodes placed on the vastus medialis, tibialis anterior, medial gastrocnemius, and soleus muscles. Root mean square and integral value were calculated from the raw data, and statistical analysis was performed using SPSS version 24.0. [Results] The electromyography data of the vastus medialis, medial gastrocnemius, and soleus muscles showed a significant decrease in muscle activity in the SP condition, whereas the activity of the tibialis anterior muscle increased significantly in the SP condition compared to that in the NA and NS conditions. [Conclusion] Our data showed that the use of an ankle-foot orthosis with a built-in spring affected not only the muscle activity at the ankle joint but also the activity of the knee joint extensor muscle. It is possible that the control of the ankle joint motion affects movement above the knee joint; this finding may help development new physical therapy techniques. Further research is warranted in this regard.

Key words: Sit-to-stand movement, Ankle-foot orthosis, Electromyography

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INTRODUCTION

One of the objectives of physical therapy is the recovery of activities of daily living, and approaches to improving basic movement ability have been undertaken in clinical practice[1)]. Particularly, sit-to-stand (STS) movements are performed frequently during daily life[2, 3)], and the success or failure of the STS movement causes a large difference in the range of activities a patient can perform[4)]. Extensive research on the STS movement has been performed, and Schenkman et al.[5)] and Millington et al.[6)] have clarified the kinematic characteristics of the STS movement.

Techniques for assisting the STS movement have practiced, but supporting the STS movement is a great physical burden for caregivers[7)]. Introduction of patient lifts and wearable robots has been recommended to reduce the care burden of assisting with the STS movement[8)]; but, although such measures can reduce the physical burden on caregivers, promoting active behavior among the subjects remains difficult.

In clinical practice, a leg orthosis is used for fixing and supporting joints, especially the ankle-foot orthosis (AFO), which is often worn for a long time during daily activities because it is easy to wear. In recent years, Yamamoto et al.[9)] reported a new design of AFO that improved the rocker function during gait by means of resistive force provided by joints with oil

Corresponding author. Masafumi Itokazu (E-mail: itokazu@iuhw.ac.jp)

dampers. Based on the AFO designed by Yamamoto, we have developed a new AFO aimed at assisting the ankle dorsiflexor and plantar flexor muscles and have reported that it improved the gait of patients with cerebral palsy and spina bifida[10]. Although the oil damper used in the AFO by Yamamoto et al.[9] shows an action similar to the eccentric contraction of the muscles by absorbing the impact, it does not have the same effect of concentric contraction as does the ankle plantar flexor muscle.

Hence, we developed a new AFO using a coil spring at the ankle joint as a power source for assisting the eccentric and concentric contraction of the ankle plantar flexor muscle. Bregman et al.[11] examined the energy efficiency of walking using an AFO with a function similar to spring. However, the STS movement on AFO with a built-in spring has been little investigated. We hypothesized that the new AFO with a built-in spring would change lower limb muscle activity during the STS movement, because the spring in the AFO would assist joint movement. For this reason, the purpose of this study was to evaluate the influence of the new AFO with a built-in spring on the STS movement in healthy participants using analysis of the results of surface electromyography (EMG) of the lower limb muscles.

PARTICIPANTS AND METHODS

Twenty healthy men (age: 20.7 ± 0.9 years, height: 171.5 ± 6.2 cm, body weight: 66.4 ± 4.5 kg, body mass index: 22.6 ± 1.4) who had no bone or joint problems were enrolled in this study. This study adheres to all relevant ethical standards and was approved by the Ethics Committee of International University of Health and Welfare (Approval No. 2017-Ig-7). Participants were given an information sheet, and they all provided written informed consent for participation. A cross-sectional design was used to study differences among three conditions.

The participants were asked to stand from a chair of standard height (40 cm) three times with their arms folded. The speed of the movement was standardized by means of a metronome (60 beats/min). Total movement time was set at three beats by instructing the subjects to start the movement at the first beat and to stand fully upright at the third beat. The newly developed AFO with a built-in spring is shown in Fig. 1. The AFO incorporates a spring inside the ankle joint and was designed to give support power to ankle plantarflexion by the spring, which was compressed during ankle dorsiflexion movement. The power to compress the spring was about 70N. The reason was to assume that the average weight of participates was 70 kg and to aim to obtain assistance power to about 10% of them. The STS movements were performed under three conditions; no AFO (NA), AFO with no spring (NS), AFO with a built-in spring (SP).

We measured the muscle activity during the STS movement using a surface EMG system (TELEmyo DTS, NORAXON U.S.A. Inc., Arizona, USA). The activity of the vastus medialis (VM), tibialis anterior (TA), medial gastrocnemius (MG), and soleus (SO) muscles on the participants' right side was recorded (Fig. 2). The raw EMG signal was passed through an analog to digital converter through a sampling frequency of 1,500 Hz. The raw signal was filtered using bandpass filters between 20 and 500 Hz. The filtered EMG signal was full-wave rectified and normalized relative to the values at maximal amplitude in the barefoot condition before calculating the root mean square (RMS).

The filtered signal was normalized relative to the values at maximal amplitude in the barefoot condition before calculating the root mean square and value of integrated electromyogram[12] (iEMG) during the STS movement.

For each variable, the Friedman test was performed using SPSS version 24.0 to determine statistically significant differences among the three conditions. Bonferroni adjustments accounted for multiple comparisons within all conditions. The level of significance was set at $p<0.05$.

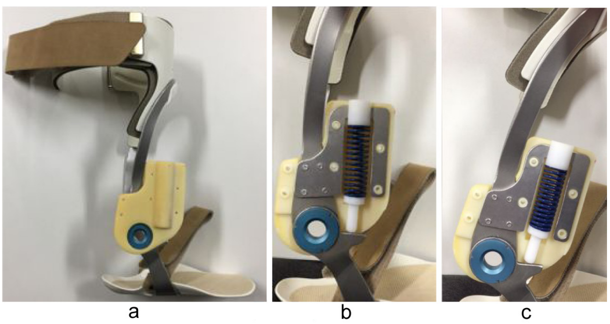

Fig. 1. Ankle-foot orthosis with a built-in spring (right side).
(a) Appearance of AFO, (b) A spring is located outside the ankle joint, (c) The spring is compressed by the ankle dorsiflexion movement.

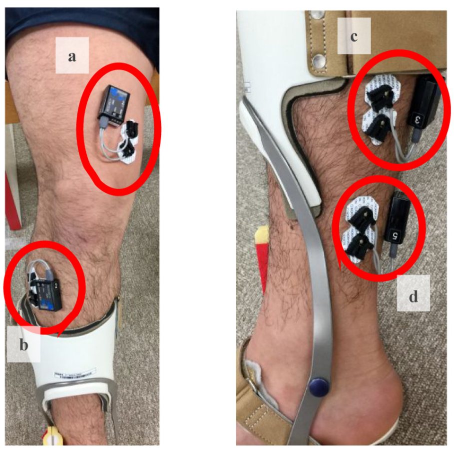

Fig. 2. Surface electrode positions for each muscle.
(a) Vastus medialis: VM, (b) Tibialis anterior: TA, (c) Medial gastrocnemius: MG, (d) Soleus: SO.

Table 1. Comparison of %RMS during no AFO (NA), AFO with no spring (NS), and AFO with a built-in spring (SP)

%RMS, median (25%, 75%)	NA	NS	SP	Significant main effect
VM	48.3 (42.2, 55.4)*	49.2 (40.0, 61.3)*	35.6 (29.8, 45.1)	NA > SP, NS > SP
TA	42.1 (33.7, 52.2)	36.3 (30.2, 50.1)*	41.9 (28.4, 61.8)	SP > NS
MG	48.4 (40.4, 60.9)*	41.5 (28.7, 52.7)	38.1 (27.4, 56.0)	NA > SP
SO	55.4 (44.5, 64.5)*	54.4 (44.2, 67.7)	43.2 (31.8, 55.5)	NA > SP

RMS: root mean square; VM: vastus medialis; TA: tibialis anterior; MG: medial gastrocnemius; SO: soleus.
*$p<0.05$.

Table 2. Comparison of %iEMG during no AFO (NA), AFO with no spring (NS), AFO with a built-in spring (SP) conditions

%iEMG, median (25%, 75%)	NA	NS	SP	Significant main effect
VM	141.0 (124.0, 181.8)*	152.0 (124.3, 191.3)*	117.5 (89.1, 144.0)	NA > SP, NS > SP
TA	128.0 (106.0, 156.8)*	119.0 (94.4, 160.0)*	136.5 (96.8, 183.5)	SP > NA, SP > NS
MG	141.5 (84.4, 193.3)*	124.0 (84.4, 179.3)	123.0 (82.3, 184.8)	NA > SP
SO	165.6 (134.5, 199.8)*	174.0 (132.8, 220.0)*	140.0 (101.8, 188.8)	NA > SP, NP > SP

iEMG: integrated electromyogram; VM: vastus medialis; TA: tibialis anterior; MG: medial gastrocnemius; SO: soleus.
*$p<0.05$.

RESULTS

Tables 1 and 2 show the change of normalized average amplitude (%RMS) and muscle activity[12] (%iEMG) during STS movement. Except for TA, EMG activation was markedly and significantly lower between NA and SP, NP and SP. SP resulted in significantly greater TA activation compared to NA. No significant difference was observed between the NA and NS conditions for each muscle.

DISCUSSION

In this study, the effect of assistance by an AFO with a built-in spring during the STS movement was investigated using surface EMG of the lower limb muscles. The assistance to the ankle joint by the AFO during the STS movement has been shown to significantly reduce the activity of the knee extensor muscle and ankle plantar flexion muscle, as well as to significantly increased the activity of the ankle dorsiflexion muscle.

It is reported that the STS movement can be divided into three phases (flexion phase, transition phase, and extension phase) and that the activity of the lower limb muscle group generated in each phase also differs[5, 6]. The knee extension muscle is regarded as an especially important muscle for performing the STS movement, but cooperative activities of other joint muscles are also required. Roebroeck et al.[13] and Roldán-Jiménez et al.[14] explain that the knee and hip joint extensor muscles are required to cooperate in order to smoothly shift from the transition phase to the extension phase. In contrast, the activity of the ankle muscles during the STS movement has not been studied extensively. However, it can be presumed from the fact that the sole of the foot is in contact with the floor that the ankle joint muscles also play important roles in the STS movement[15].

A significant reduction in the muscle activity of the MG and SO was observed in the SP condition than in the NA and NS conditions, suggesting that the compressive or repulsive force of the spring acted to assist the ankle plantarflexion muscles. The AFO used in this study was designed such that the spring is compressed by the ankle dorsiflexion movement, and the force generated by the repulsion rotates the lower leg backward. It suggests that as the spring is compressed, ankle dorsiflexion movement is braked, which assists the eccentric contraction of the ankle plantarflexion muscles; then the repulsive force of the spring acts to assist in the concentric contraction of the ankle plantarflexion muscle. In addition, it is interesting to note that the activity of the knee extensor muscle has been shown to be significantly reduced in the SP condition. It can be presumed that the repulsive force of the spring rotates the lower leg around the ankle joint and its force is converted into a force that extends the knee joint, thus working as a supplement to the knee joint extensor muscle.

Other muscle activity decreased in the SP condition, but only the activity of the TA increased significantly. The spring built into the AFO assumed the role of preventing ankle dorsiflexion movement. We hypothesized that the participants would need to select either of two strategies to perform the STS movement in the SP condition. The first is to dorsiflex the ankle joint by concentric contraction of the TA muscle. And other is to increase the anterior flexion angle of the trunk to use the mass of the segment above the knee joint. From our results, we found that the ankle dorsiflexion muscle plays a role in resisting the force of the spring. However, since a kinematic analysis was not performed in this study, it is not possible to clarify the relationship between TA muscle activity and trunk angle.

Furthermore, the conditions of NA and NS were set to investigate the psychological effect by wearing AFO. The range of motion of ankle plantar and dorsiflexion was the same between the NS and NA conditions. As a result, no significant change in muscle activity was observed between the NA and NS conditions. There was no effect of muscle activity due to wearing the AFO, it was suggested that the force of the built-in spring in the AFO changes the activity of the lower limb muscle. Thus, it was found that the psychological impact of wearing the AFO did not influence the activity of the lower limb muscles.

This study is the first to indicate the activity of lower limb muscles during the STS movement when wearing an AFO with a built-in spring. It should be noted that support to the ankle by the AFO influenced the muscle activity of the ankle joint muscles but also of the knee extensor muscle. One limitation of this research is that the number of participants is not large enough to eliminate the influence of individual differences in the STS movement. In addition, a further study on the association between kinematic data and EMG data on the STS movement should be conducted.

In conclusion, it is possible that control of ankle joint motion affects the movement of the segment above the knee joint. This result may be evidence that physical therapy techniques to control the patient's lower leg angle could aid the STS movement. In the future, the data collected in this study will be useful for the development of assistive equipment for the STS movement.

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Conflict of interest

There are no other conflicts to declare.

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