EFFECTS OF CALF ANCHORING COMPRESSION LEVELS ON ANKLE KINEMATICS, MOTOR UNIT BEHAVIOR, ENERGY COST, AND DISCOMFORT DURING WALKING

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We propose a method for quantifying the anchoring compression of wearable devices using limb occlusion pressure (LOP). Under 0%, 20%, 40%, and 60% of LOP, five healthy male participants performed an isometric ankle plantarflexion task before and after walking on an inclined treadmill. Significant differences were shown in calf discomfort ($p < 0.001$), and ankle plantarflexion angle ($p = 0.013$) during walking. Although no significant difference was found for oxygen consumption and motor unit behavior of the gastrocnemius medialis, the maintenance of ankle plantarflexion angle was related to an increase in peak motor unit action potential amplitude and average firing rate at 60% of LOP. The results suggest that subjective assessment is more sensitive than the physiological indices, and calf anchoring force should not exceed 60% LOP to avoid any possible negative effect on the muscle.

KEYWORDS: anchor, wearable device, limb occlusion pressure

INTRODUCTION: Walking assistive wearable devices have been developed to help wearers walk safely with less fatigue for long periods of time (Carpino et al., 2018; Malcolm et al., 2013). For wearable devices, an anchor, a connection part between the body and the robot, is essential to effectively transmit the assistance force from the actuator to the human body. Considering that walking assistive wearable devices are mostly anchored on the upper calf to support the ankle, the anchors inevitably apply compression to the calves, and the level of anchor compression should increase as the required assistance force increases.

Excessive pressure on the calves may produce negative effects on the wearer's body. According to previous studies, excessive pressure can increase energy consumption (Abe et al., 2006; Loenneke et al., 2012; Mendonca et al., 2014; Pfeiffer et al., 2019; Silva et al., 2021), calf discomfort (Pfeiffer et al., 2019; Silva et al., 2021), peak motor unit action potential (MUAP) amplitude and average firing rate of gastrocnemius medialis (GM) involved in ankle plantarflexion (Fatela et al., 2019).

Despite the predicted negative effects due to excessive compression, there is no guideline on choosing the appropriate levels of anchor compression. In this study, our goal was to propose a method that would trigger faster and more accurate anchor development by quantitatively establishing the setting of the anchoring force. We considered limb occlusion pressure (LOP), the minimum pressure to stop arterial blood flow in the arm or leg as the baseline of the criterion for the anchor compression. LOP is known to be robust against changes of cuff types and compression positions (McEwen et al., 2019). Thus, we controlled the compression level as % of LOP and investigated the effects of compression on energy consumption, calf discomfort, kinematic pattern, and motor unit behavior.

METHODS: Five healthy young male adults (age: 26.2 ± 1.3 years; height: 1.75 ± 0.03 m, weight: 70.9 ± 6.2 kg) without any record of neuromuscular, cardiovascular, or orthopedic disorders participated in the study. This study was approved by Institutional Review Board, and consented by the participants.

Participants performed incline walking on an instrumented treadmill (Bertec, USA). 9 infrared cameras and a motion analysis software (Arqus A5, Qualisys, Sweden) collected the kinematic data during the incline walking at a sampling rate of 100 Hz. Twenty reflective markers were attached to the lower extremities according to the plug-in-gait model marker set. An indirect calorimetry device (K5, COSMED, Italy) was used to measure the whole-body oxygen consumption rate during the incline walking. A cable driven variable resistance machine (CrossMAST, MASTS Inc.) combined with a customized ankle module was used to measure the maximum voluntary contraction (MVC) of the gastrocnemius medialis (GM) and the force during an isometric contraction task. A single non-invasive surface dEMG sensor (Galileo sensor, Delsys, USA) was attached to GM to collect EMG data.

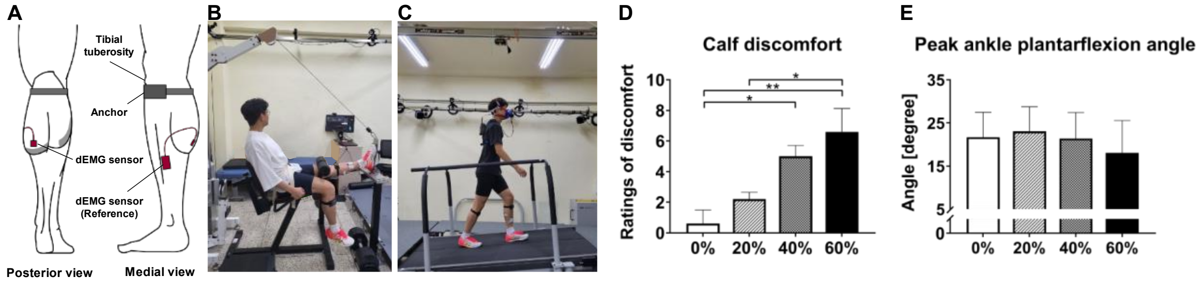

Figure 1: Positions of anchor and dEMG sensor (A), isometric contraction (B), 15% incline walking (C), calf discomfort (D) and peak ankle plantarflexion angle (E) * : p < 0.05, ** : p < 0.01.

To investigate the effects of compression with four different levels (0, 20, 40 and 60% of LOP), participants visited the laboratory on two different days and completed experiment under two conditions per visit with a minimum gap of 24 hours between each visit. On the first visit, LOP was measured by increasing the compression level in increments of 5 N until there was no pulse for four beats of the resting heart rate, following the method described in Younger et al. (2004). The pulse was monitored by attaching a pulse oximeter (MD300C316, Beijing Choice Electronic Technology, China) to the third toe. The order of compression level conditions was randomly assigned. At each visit, we first instructed participants to walk at their preferred walking speed for 5 min on the instrumented treadmill with 15% incline. After this 5 min warm up, we measured MVC. Then, the participant performed an isometric contraction task. We applied pressure to the participants' calves using anchors attached right below the tibial tuberosity with a built-in load cell at the predefined compression level. Participants were then instructed to perform an isometric contraction task with visual feedback, in which they were asked to reproduce a force profile that reached 60% of the MVC at a speed of 10% MVC/s and maintained the 60% MVC for 20 s (Muddle et al., 2018). This isometric contraction task was repeated three times with 30 s interval between each repetition. After the isometric contraction task, participants walked on a 15% inclined treadmill three times for 4 min with a 1 min rest period. Both the whole-body oxygen consumption rate and walking kinematics were collected. After the walking sessions, participants repeated another set of three repetitions of the isometric contraction task with a 30 sec interval. Then, participants answered a survey about calf discomfort (Henson et al., 2006) on a scale of 1 to 10. After the survey, participants rested for 30 min. All these procedures except warm up and MVC measurement were repeated under another compression condition. The same procedures were repeated on the second visit.
Kinematic and force data were processed using Visual 3-D software (v6, C-Motion Inc., USA) and MATLAB (Mathworks, Inc., USA). The EMG data were decomposed using Neuromap software (Delsys, USA) for motor unit behavior analysis. One-way repeated measures ANOVA was used to evaluate the difference across the four conditions. The Bonferroni correction was used for post-hoc analysis. The level of statistical significance was set as $p < 0.05$.

RESULTS: Across four conditions, we found significant differences in calf discomfort ($p < 0.001$) and ankle plantarflexion angle ($p = 0.013$) (Figure 1). No significant differences were found for oxygen consumption and motor unit behavior. Participants whose peak ankle plantar angle were maintained at 60% LOP had an increased peak motor unit action potential (MUAP) amplitude and an increased average firing rate of GM at 60% of LOP (Figure 2).

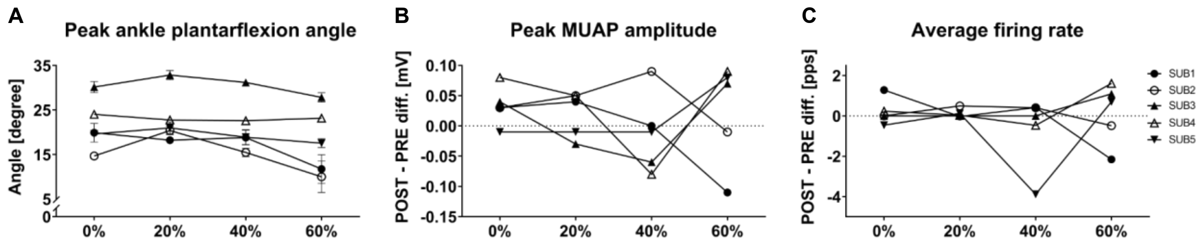

Figure 2: Peak ankle plantarflexion angle (A), peak MUAP amplitude (B), and average firing rate (C) of each participant.

DISCUSSION: As the force of calf anchoring increased, calf discomfort increased significantly, which is consistent with the results from previous studies (Pfeiffer et al., 2019; Silva et al., 2021). However, unlike the results of previous studies (Abe et al., 2006; Loenneke et al., 2012; Mendonca et al., 2014; Pfeiffer et al., 2019; Silva et al., 2021), there was no significant difference in oxygen consumption or motor unit behaviors of GM between the compression level conditions. Regarding oxygen consumption, it is difficult to compare the results of this study with those of previous studies because only a few studies controlled the compression level based on LOP. Even though Pfeiffer et al. (2019) and Silva et al. (2021) set the compression level based on LOP and showed an increase in oxygen consumption at 50% LOP, the pressure was applied to the thigh in these studies. The fact that more muscles and blood flow could be affected by the compression applied to the thigh might explain the difference between the results of the previous studies and the current study.

Compression level also affected the peak plantarflexion angle of the ankle. It is noteworthy that the peak plantarflexion angle of the ankle tended to decrease only under the 60% LOP condition compared to the 0% LOP, whereas the discomfort level was almost proportional to the compression level (Figure 1). One possible interpretation is that a noticeable change in walking kinematics can occur when discomfort level increases above a specific threshold.

On the other hand, we found no statistically significant difference in the motor unit behavior between the compression conditions. Previous studies showed that lower extremity compression during resistance exercise or walking increased training effects, and argued that changes in EMG signals and increase of muscle hypertrophy and muscle strength may be due to rapid muscle fatigue (Contessa et al., 2016; Kjeldsen et al., 2019; Loenneke et al., 2015; Pope et al., Ya, 2013). Another previous study compared motor unit behavior of thigh muscles during low intensity leg presses under two conditions: with and without thigh compression. They reported an increase in peak MUAP amplitude and average firing rate, a decrease in recruitment threshold, and the fatigue of muscles under the compression condition (Fatela et al., 2019). In contrast, we found that walking with calf anchoring did not cause a significant change in the behavior of motor unit in GM. Walking in fact requires about 30% of the maximum muscle strength of GM similar to general low-intensity resistant exercise (Akizuki et al., 2001). Even though our experimental task was incline walking that requires more effort than normal walking, we found no significant change in motor unit behavior. Therefore, our preliminary results suggest that the effect of lower limb compressions during low-intensity exercise on the motor unit behavior may depend on the type of exercise and target muscle even under a similar level of exercise intensity.

Considering the high variability of motor unit behavior among participants (Contessa et al., 2016), we analyzed the patterns of changes in the motor unit variables of each participant. Participants 3, 4 and 5 had relatively small changes in plantarflexion angle of ankle joint between conditions, and the peak MUAP amplitude and average firing rate of GM during post-measurement increased only for these participants under 60% LOP condition. This observation is consistent in that fatigued muscles recruit additional motor units and increase the firing rate of motor units when they are required to maintain the same force to compensate for the decreased twitch force (Adam & De Luca, 2003; Contessa & De Luca, 2013; Contessa et al., 2016). Therefore, this result suggests that the GM may be fatigued when ankle movement is maintained during incline walking while the calf is compressed at 60% LOP condition.

Another important finding is that the wearer’s subjective evaluation of the discomfort level is much more sensitive than kinematics or other physiological variables like oxygen consumption and motor unit behaviors. The discomfort level increases almost linearly according to the compression level in % LOP (Figure 1). This result suggests that wearer’s subjective evaluation (rather than other metrics) should be considered in selecting proper level of anchoring pressure.

CONCLUSION: This is the first study that proposes a method for quantifying the anchoring pressure of wearable devices using LOP. The results suggest that the anchor compression levels on the calves should be chosen considering the subjective assessment of the wearer. In addition, it is recommended to keep the compression level below 60% LOP to minimize changes in the function of GM. A clear guideline on the anchor compression levels will contribute to creating a safe and effective framework for the development of assistive wearable devices for physical activity.

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ACKNOWLEDGEMENTS: This research was supported in part by the Technology Innovation Program (No. 20008912), Industrial Technology Innovation Program (No. 20007058, Development of safe and comfortable human augmentation hybrid robot suit), and Industrial Strategic Technology (No. 20018157) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea), and National Research Foundation of Korea (NRF) Grants funded by the Korean Government (MSIT) (No. RS-2023-00208052).