공학석사학위논문

앞발 착지 주법 달리기의 근력 보조와 부상 방지를 위한 신발형 보조 장치

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Abstract

Shoe-based Assistive Device for Muscular assistance and Injury prevention of Forefoot strike running

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Over the last decades, numerous wearable robots have been developed to assist human locomotion. In the evolutionary process, elastic components, that make human locomotion efficient, were formed in human body. These provide clues for the development of locomotion assist devices. A typical example of a biomimetic approach is a body–powered ankle assist mechanism that mimics the function of the Achilles tendon. The body–powered assist mechanism, also called as passive assist mechanism, assists its user by circulating dissipated energies during human locomotion in the form of elastic energy. This mechanism has the strength of being simple and lightweight system. However, it has a limit in its assistance capability due to the limited energy source. To overcome this limitation, the lever arm of the system can be increased to amplify the assistance force. But this also causes big protrusion from the user's body and weakens the strength of the body–powered assist mechanism. In this paper, the elastic function of the foot arch is integrated with the Achilles tendon-mimicking mechanism to overcome the limited assistance capability of the passive mechanism. The arch of the foot stores and releases about 17% of energy during locomotion, which is about half of the capability of the Achilles tendon. Inspired from this, we attempted to extend the energy source of the passive mechanism by additionally involving the elastic function of the foot arch into the system along with the Achilles tendon. With this approach, the system can utilize elastic energies generated by both motions of the foot arch and the ankle. For this, we designed a mechanism, in which the assistance spring is located at the plantar side of the foot and backside of the ankle, so that the motions of the Achilles tendon and the foot arch can be synchronized with the assistance spring. To realize the mechanism, we developed a shoe-based anchoring platform, that has a separation between forefoot and hindfoot, and integrated it with the assistance spring. Unlike previous ankle assist wearable robots and conventional shoes, the system interacts with the foot arch by the assistance spring, which is synchronized with the foot arch motion. This interaction allows the contraction force of the spring to prevent excessive collapse of the foot arch, thereby reducing the load on plantar fascia, an elastic component in human body that sustains the arch of the foot. In addition, among various strategies of human locomotion, we aimed to assist forefoot strike running that requires high-intensity muscular efforts of plantarflexors. Considering muscle activities of the plantarflexors during the forefoot strike running, we took an assistance strategy, assisting landing posture and reducing muscular efforts by applying posture-assisting force using a pre-tensioned assistance spring. We propose *Digitigrader*, which has a shoe-based anchoring platform integrated with the body-powered assist mechanism. It has a low-profile form factor with maximum protrusion of 20 mm that makes it to be a practical running assistant for daily living. For a running on treadmill at a speed of 2.5m/s, compared to Assist-off condition, the device improved running economy by 4.08%. Gastrocnemius medialis and lateralis, which are related to the forefoot strike running, showed 27.22% and 23.95%

reduced muscle activities, respectively. The ankle was 13.46% more plantarflexed at landing instances and strike index also increased slightly, showing the effects of posture assistance. Collapse of the foot arch decreased by 51.72%, confirming the interaction between the arch of the foot and the device. Based on these experimental results, we propose a novel forefoot strike running assistant for augmenting both of running performance and injury safety.

Keyword : Running assistance, Ankle assist device, Metabolic cost, Muscular Assistance, Injury prevention
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Chapter 1. Introduction

1.1. Study Background

Running is a locomotion strategy that enables rapid movements of humans. To execute the locomotion strategy, each part of the body needs to move quickly, so it increases metabolic energy consumption and requires strong muscular strength. In the evolutionary processes, against highly-loaded biomechanical characteristics of running, humans have adjusted themselves into cursorial way to efficiently utilize limited metabolic energy [1]. The soft tissues of human body formed during the evolutionary process function as springs and recycle dissipated energies. This leads to utilize more positive works for propulsion of the body under the same energy consumption. Representative examples related to locomotion are foot arch and Achilles tendon. These two elastic elements store and release energy each step and contribute greatly to increasing the overall efficiency of locomotion [2,3].

The arch of the foot stores about 17% of energy during stance phase and returns by recoiling during push-off [2,4]. During weightbearing, the weight transmitted in the downward direction from tibia and the ground reaction force (GRF) transmitted in the upward direction from the ground compress the foot and cause the arch to collapse. In this process, the soft tissues supporting the arch are stretched and store elastic energy. As the foot pushes against the ground to propel the body, the stored elastic energy is released. The arch is restored to its original shape due to contraction of each soft tissue and assists propulsion of the body. *Stearne et al.* measured the change in energy efficiency of locomotion when the elastic mechanism of the arch is limited [5]. They confirmed increases in metabolic rate of +6.0% at 2.7m/s running regardless of strike patterns. Soft tissues that support the arch of the foot include plantar fascia, plantar ligaments, and calcaneonavicular ligament, among which the key structure is the plantar fascia [6,7]. On the plantar side, the plantar fascia connecting the calcaneus and the base of the toes (phalanges) forms a truss structure of the foot arch and acts as a spring. The plantar fascia sustains the truss of the arch, prevents excessive collapse of the arch, and releases the stored elastic energy after collapse and recoils to restore the truss to its original shape. In addition to that, the plantar fascia works as a force transmission structure. Due to the anatomical configuration, inserting into the bottom of toes, the extension motion of the toes, occurring during the push−off, winds the plantar fascia and makes the plantar fascia to pull the calcaneus. This modulates stiffness of the foot arch and forms a rigid lever arm for transmitting the force generated by the calf muscles to the ground [8]. In brief, the plantar fascia, acting as a spring, improves the efficiency of locomotion through two functions: energy recycle and lever arm modulation.

The Achilles tendon stores and releases energy during the stance phase, just like the arch of the foot. It stores about 35% of energy for each step, which is about twice the capability of the arch of the foot [2]. Achilles tendon originates from gastrocnemius and soleus, the plantar flexors of the ankle, and is inserted into the calcaneus. Plantarflexors remain isometric for dorsiflexion of the ankle during stance phase. At the same time, the Achilles tendon, acting like a spring, stretches and stores elastic energy. The stored elastic energy is released for the push−off, and the Achilles tendon contracts rapidly and propels the body. This mechanism is called as catapult mechanism and makes human locomotion efficient [9].

Although the plantar fascia and the Achilles tendon are distinct soft tissues, they share a common attachment point, called as calcaneus and form a kinetic chain. Due to this connection, the tension applied in the plantar fascia can be predicted as a linear relationship (Eq. 1) with the exerted tension on the Achilles tendon [10]. Muscular efforts generated by the calf muscles are transmitted through the Achilles tendon and plantar fascia to the forefoot, and act as a force to propel the body against the ground until the end of the push−off motion. The biological kinetic chain formed between the Achilles tendon and the plantar fascia is not only beneficial for force transmission, but also acts as an energy recycle chain and forms a core biomechanical structure that increases efficiency of locomotion.

Various ankle-assistive wearable robots have been developed [11], aiming to assist human locomotion, that work in conjunction with the motion of the calf muscles or the Achilles tendon. Active systems that work together with the calf muscles, they share the muscular efforts of calf muscles required to make the target ankle motions. Through this, the muscular effort for locomotion can be reduced and assisted. Passive (i.e., body-powered) systems generally works with the catapult mechanism of the Achilles tendon. it assists the motion of the ankle through a spring-clutch mechanism that mimics the catapult mechanism of the Achilles tendon. The assistance spring of the system stretches along with the Achilles tendon during early-to-mid stance phase, storing elastic energy. Then it releases the elastic energy for the push-off, and contracts to assist plantarflexion of the ankle. In this process, the clutch is clutched during stance phase, so that the spring is stretched with dorsiflexion of the ankle, and recoils for push-off, assisting plantarflexion of the ankle. It is declutched for swing phase, so that dorsiflexion motion of the ankle that occurs in the air is not affected by the system [12,13]. Unlike the active systems, which provides positive works required for the motion of the ankle using external actuators, such as a motor, those Achilles tendon-inspired passive robots get assistance energy from a spring that stretches and contracts together in synchronization with the motion of the ankle. These systems are categorized as passive systems since they depend on the motion of the ankle. The passive systems are advantageous to be simple and lightweight compared to the active systems. However, since the energy source that can be utilized is confined to the displacements generated by the ankle, their assistive abilities are limited. To overcome this, lever arm can be increased, resulting in amplified displacements of the spring, but this causes big protrusion of the system from the body of its user and decline of usability and practicality.

Varying the properties of soles, shoes have been developed to assist human locomotion. As a leading-edge approach, carbon fiber plates are being adapted for the soles. This approach increases the longitudinal bending stiffness of the soles and results in increased foot gear ratio. Through this, the energy dissipation of the foot is reduced, and the force-generating capacity of the muscles increases by slowing down contraction speed of the plantarflexors. This approach increased energy efficiency by 7.1% for fast walking and 4% for running [14-16]. However, although this approach is effective in reducing the energy dissipation at the metatarsophalangeal joint (MTP joint) and modulating the contraction speed of the calf muscles, direct interaction with the collapse-recoil mechanism of the foot arch in terms of efficiency and related injuries is limited. Shoes have wiggle room to maintain comfort even if the length of the foot changes in the anterior-posterior direction due to the motion of the foot arch within the shoes. This allows the relative motion between the shoe and the foot, but also meaning that the shoe cannot make a direct interaction with the motion of the arch of the foot. When the elastic mechanism of the foot arch works, the plantar fascia has a high risk of injuries such as plantar fasciitis and rupture. While walking and running, the plantar fascia undergoes repeated stretching. If this stretching becomes excessive, the plantar fascia cumulates micro-tears and it is risky to worsen to inflammation and physical degradation, resulting in severe injuries [17,18]. In particular, for the forefoot strike, the plantar fascia is exposed to heavy loads [19]. Considering that both of the forefoot strike and carbon plate-embedded shoes are typically used for the high performance running, it is required to improve both of the performance-enhancing capability and injury prevention functionalities. The most common way to deal with the injury prevention function is to insert a wedge that can prevent excessive collapse of the arch in the shoe [20], but this limits the elastic function of the arch and declines athletic abilities [5].

Figure 1. Prototype of *Digitigrader* for assisting forefoot strike running

1.2. Purpose of Research

In this paper, we propose *Digitigrader* (Fig. 1), a shoe-based ankle assist device for forefoot strike running. The proposed device has a typical shoe-like form factor, and it is integrated with passive assist mechanism.

It has practicality with a low-profile form factor, usability with easy wearing, and comfort with soft materials. The low-profile form factor has maximum protrusion of 20mm, allowing it to be a practical running assistant in activities of daily living. The shoe-based form factor also has the same simple donning process with typical shoes, 1) put the foot in and 2) lace up. In addition, 3D printed parts are inserted only for essential parts to improve anchoring stability, efficiency of force transmission and spring fixation. The other parts are composed of leather, fabrics, and EVA, so it can be worn comfortably like conventional shoes.

For the assist strategies, we take a different approach rather than the previous clutch-based methodologies [12,13] that minimizing negative works generated when the system and the user's motions are out-of-phase. This study aims to assist the running technique called forefoot strike, in which the user lands on the ground with plantarflexed ankle. It requires strong strength of the calf muscles compared to heelstrike. Plantarflexors get activated 15% earlier before landing, when the foot is in the air. Considering those characteristics of the target gait, the landing posture is supported by inducing the plantarflexed posture of the ankle using a pre-tensioned spring. The spring also enhances running economy by mimicking the elastic mechanism in the human body, similar to the previous passive ankle assist robots. Following the existing approaches, it mimics the catapult mechanism of the Achilles tendon. One end of the spring is placed at the backside of ankle so that the displacement of the ankle stretches the spring. Furthermore, rather than increasing the lever arm to increase the assistance capability of the passive mechanism, the elastic function of the foot arch is additionally mimicked to increase the energy cycling capacity of the mechanism. To realize it, the other end of the spring is placed underneath foot so that the collapse of the arch stretches the spring. In order to synchronize the motion of the foot arch and the displacements of the spring, the connection between forefoot and hindfoot of the shoe-based anchoring platform is separated. The spring, interacting with the foot arch, augments the stiffness of the plantar fascia by having the parallel placement to the plantar fascia, and it applies torque to the calcaneus in the anterior direction to prevent excessive collapse of the arch and results in decreased risk of injuries.

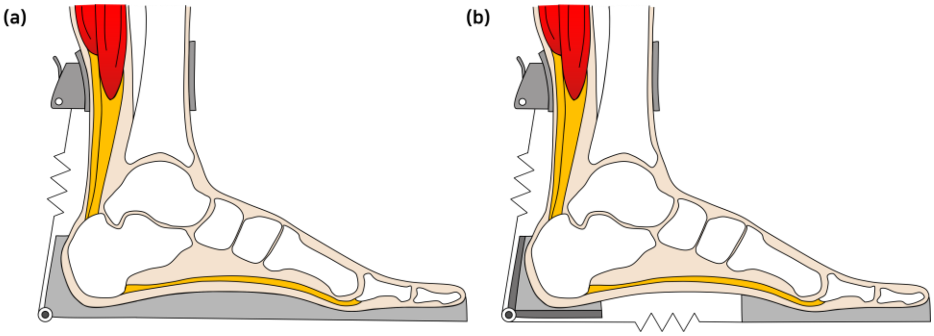

Figure 2. Biomimetic passive assist mechanism; (a) Achilles tendon–only mimicking mechanism (b) Achilles tendon and arch of the foot mimicking mechanism

Chapter 2. Methodology

2.1. Biomimetic Passive Assistance

Passive assistance has been adopted for numerous wearable robots [11–13,21]. When humans move their body, soft tissues deform. These deformations dissipate energy or store and then return the energy to the body, resulting in deteriorated or improved energy economy of the motion [22]. Passive assistance uses the same principle with this to augment energy efficiency of the human motion. *Collins et al.* followed the working principle of the Achilles tendon, so called the catapult mechanism, to improve walking economy [12]. Their passive assist mechanism recycled the dissipated energy of human motion using elastic energy function of spring. Because the elastic energy of a spring is proportional to the square of its displacement, it means that the assistance capability of the system is proportional to the amount of the stroke that the spring can have. It is also possible to increase lever arm to amplify the stroke but, it leads to increased protrusion and lowers the usability of the wearable robot in daily livings.

To enhance the assistance capability of the passive assistance mechanism, we tried to find out another energy source. Human foot arch holds 17% of the mechanical energy gained and lost each step,

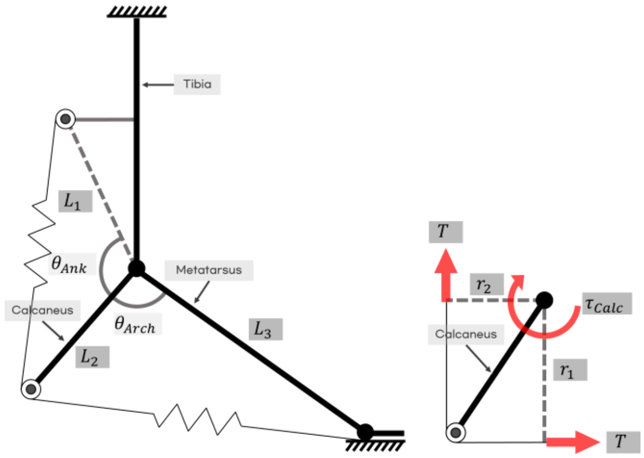

Figure 3. Torque applied on the arch of the foot during stance phase; $\boldsymbol{T}$ denotes tension on the assistance spring and $\boldsymbol{\tau_{Calc}}$ denotes torque exerted on the calcaneus by bodyweight, the plantarflexors and ground reaction force

which is about half of the 35% energy storage of Achilles tendon [2,3]. It was also found that, for running, restricting the foot arch function increases metabolic cost by 6.0% [5]. The foot arch is sustained by the plantar fascia, a soft tissue connecting the hindfoot and the forefoot and acting like a spring [23]. The plantar fascia and the Achilles tendon have the same attachment point, calcaneus, and this forms linear kinetic relationship between the two elastic components (Eq. 1) [10,24].

$$F_{PA} = 0.474F_{AT} + 0.414\ [\mathrm{BW}] \tag{1}$$

Inspired by the elastic function of foot arch and connectivity between the plantar fascia and the Achilles tendon, a foot arch integrated passive ankle assist mechanism is developed (Fig. 2(b)). Unlike the previous approaches, the proposed mechanism involves both of foot arch and ankle motion into a single spring. This allows the assistance spring to have bigger strokes and assistance capabilities compared to the previous Achilles tendon-only mimicking designs (Fig. 2(a)). Assuming the spring stiffness is the same and non-friction conditions, the difference of assistance capabilities between the two approaches is as follows (Eq. 2-4) (Fig.

3).

$$E_{AT} = \frac{1}{2}k(\sqrt{{L_1}^2 + {L_2}^2 - 2L_1L_2\cos\theta_{Ank}})^2 \tag{2}$$

$$E_{AT+PF} = \frac{1}{2}k(\sqrt{{L_1}^2 + {L_2}^2 - 2L_1L_2\cos\theta_{Ank}} + \sqrt{{L_2}^2 + {L_3}^2 - 2L_2L_3\cos\theta_{Arch}})^2 \tag{3}$$

$$\Delta E = E_{AT+PF} - E_{AT} \tag{4}$$

During the stance phase, according to the moment arm ratio between the plantar side(r_1) and the backside(r_2), the torque exerted on the foot arch can be differed (Fig. 3). If the r_1 is bigger than r_2, the torque on the calcaneus exerts in the anterior direction (Eq. 5). It prevents over−collapse of the arch of the foot, cancelling out the load on the plantar fascia.

$$\tau_{Arch} = T \cdot (r_1 - r_2) - \tau_{Calc} \tag{5}$$

2.2. Assistance Strategy

The proposed device aims to assist forefoot strike running, which requires significantly higher muscular efforts of plantarflexors compared to heel strike [25−27]. For the forefoot strike, the plantarflexors activate 15% earlier before foot landing. This muscle activation makes hindfoot not to touch the ground, reduces contact time of the foot and results in better running performance.

Previous passive ankle assist wearable robots used mechanical clutches to minimize negative works caused by the systems [12,13]. The clutch mechanism required physical triggering to shift its state from declutched state to clutched state. For the forefoot strike, because plantarflexors activate before the foot landing and the foot is in the air at the instance, the working principle of those mechanism would not be suitable to be applied.

To effectively assist the forefoot strike running, before the beginning of running, pre−determined tension applied on the

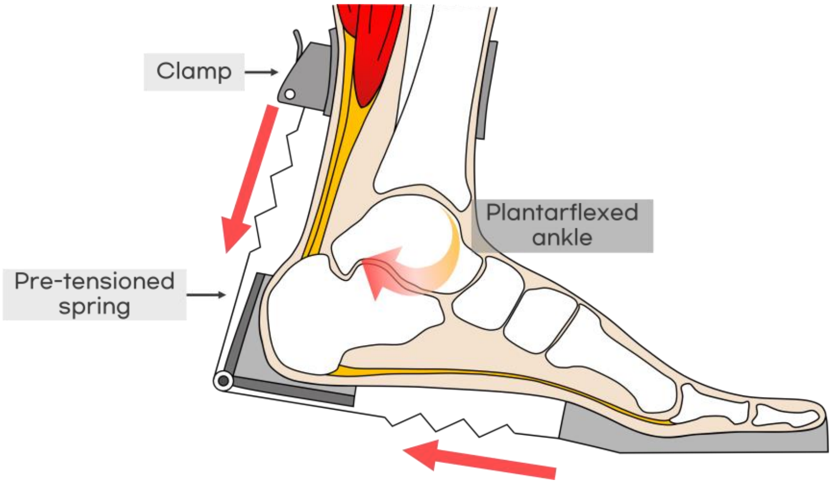

Figure 4. Posture assistance strategy; Contraction force of the pre−tensioned spring induces the ankle to be plantarflexed and assists running posture to be forefoot strike running

assistance spring through stretching and fixing it using a clamp (Fig. 4). The pre−tension, inducing the landing posture of the ankle to be plantarflexed, works as posture−assisting force and shares the muscular efforts of the plantarflexors required to keep the running posture.

When the elastic energy, stored in the assistance spring during the early−to−mid stance phase, is released, the recoiling force assists the push−off motion of ankle and applies compression to the foot arch. This not only assists the muscular efforts of the plantarflexors but also prevents the over−collapse of the foot arch. Since repeated over−collapse of the foot arch is risky for injuries of the plantar fascia [19,28,29], this assistance strategy simultaneously achieves muscular assistance and injury safety of the plantar fascia.

2.3. Anchoring Design and Prototype

To allow the plantar fascia and the Achilles tendon−inspired spring to move together with the motions of the foot arch and the ankle, typical shoe structures, midsole and outsole connecting the forefoot and the hindfoot, were needed to be modified. In order to make the motions of the foot arch and the ankle to be synchronized

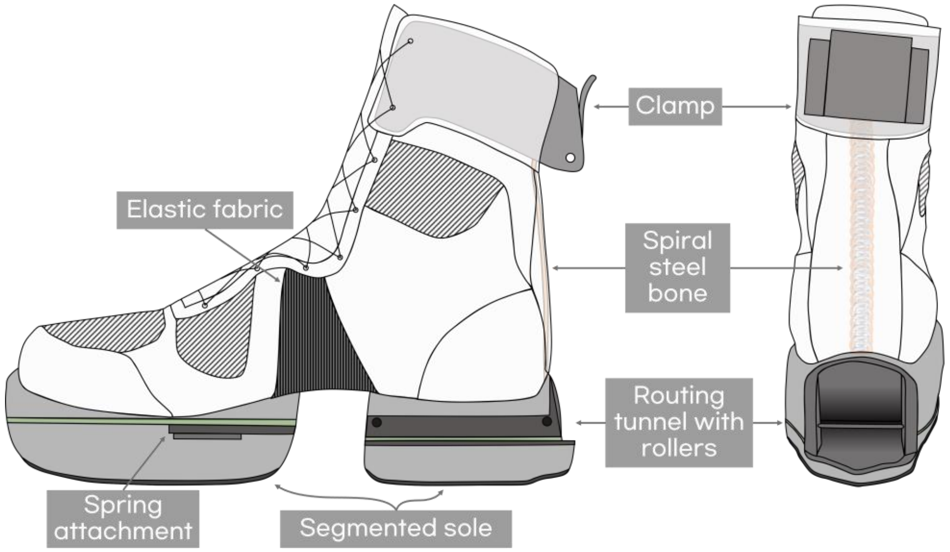

Figure 5. Design of the shoe−based anchoring platform

with the movement of the entire anchoring platform, the middle connection of the sole is broken and segmented into forefoot and hindfoot parts (Fig. 5). Furthermore, different deformation patterns of the medial longitudinal arch (MLA) and lateral longitudinal arch (LLA) were taken into account for building the upper. MLA shows a larger translational motion in the anterior−posterior direction than LLA during landing [30]. Considering the motion difference, the MLA part of the upper is composed of elastic fabric and the LLA part is composed of inelastic leather. This allows the upper to stretch with the arch motion.

The assistance force pulls the clamp downward. This may cause buckling of the upper at the back side of the ankle and failures of the anchoring. If this happens, it results in loss of the assistance force and causes discomforts to its user. To prevent this failure, a spiral steel bone, typically used for corsets, is inserted inside the upper and it supports the clamp. Since the bone resists to compression while allowing ankle dorsiflexion−plantarflexion and inversion−eversion to be free, this design does not interfere with natural ankle motions and makes the anchoring stable.

The segmented soles and the assistance spring are attached below the plantar side of upper using hook−and−loop fasteners.

After detaching the soles, the assistance spring can be replaced. The spring goes through the plantar and the back side of the hindfoot. When the foot and ankle move, the assistance spring stretches and recoils through this routing. To make this smooth and prevent the spring from being squashed by the user’ s bodyweight, a roller-embedded routing tunnel is implanted on the hindfoot sole.

The prototype weighs 520g for each foot. The maximum protrusion is 20mm and locates at the clamp. The anchoring platform is fabricated with handmade shoemaking method (Fig. 6). The upper is composed with leather, elastic fabric, and air-mesh fabric. The sole is made with EVA and rubber pad is attached at the bottom to prevent slippage. Latex bands *(SSen band, GC MS, South Korea)* are used to fabricate the assistance spring. The number of stacked layers of the latex bands are differentiated to make different spring stiffnesses. The springs are made by stacking 35mm x 200mm rectangular latex bands in 4, 7, and 10 layers, and each of them corresponds to k_{Low}, k_{Med}, and k_{High}, respectively.

Figure 6. Fabrication process of the anchoring platform

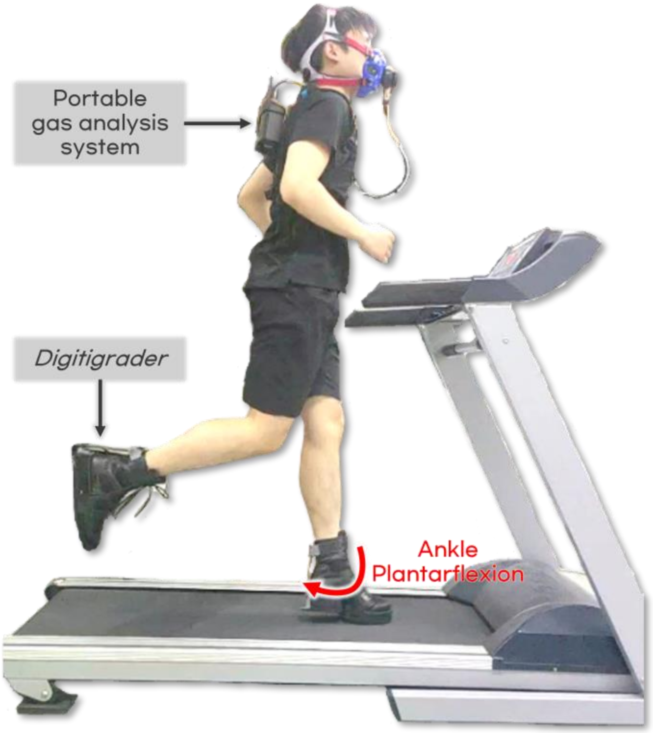

Figure 7. Metabolic cost experiment setup

Chapter 3. Experiment

3.1. Efficiency Augmentation

3.1.1 Experiment setup and protocol

One male subject ran on a treadmill at a speed of 2.5m/s. The experiment was conducted for two days, with a one–week rest period between each day to prevent fatigue effects.

On the first and second day, the effect of efficiency augmentation was tested. A portable metabolic cost system (*K5, COSMES, Italy)*, was used to measure energy expenditure while running (Fig. 7). To find out the optimum reduction of metabolic costs, combinations of two levels of pre–tension and three spring stiffness were tested. For comparisons, Assist–off condition, in which the assistance spring

Figure 8. Metabolic cost experiment protocol

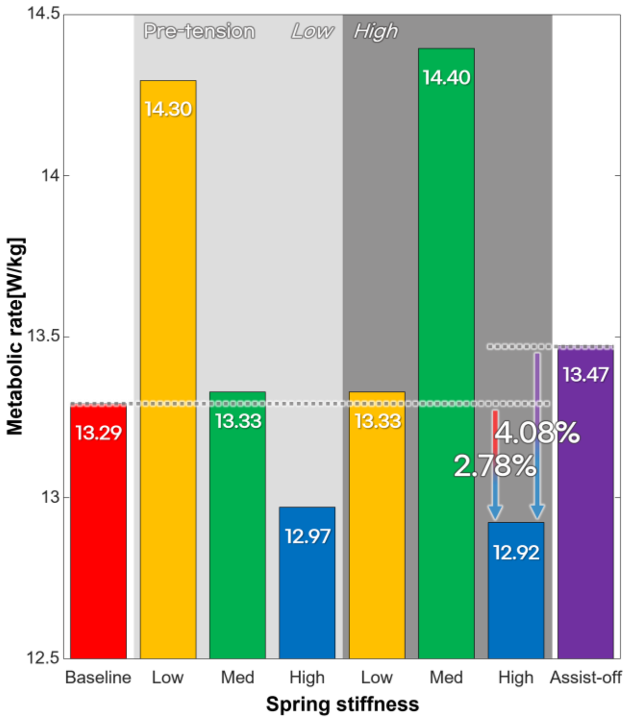

Figure 9. Change in metabolic cost; The light grey−shaded area denotes Low pre−tension and the dark grey−shaded area denotes High pre−tension

was set to be slack, and Baseline condition, in which the participant runs in commercial barefoot shoes (*Free Run Flyknit 3.0 2020, Nike, United States)*, were also tested. On the first day, each stiffness was tested with the Low(40N) pre−tension, and the second day the same process was conducted for High(60N) pre−tension.

During the experiments, the participant was instructed to maintain forefoot strike running for all the conditions [31]. Right before each testing trial, the participant ran 3−min training trial for each condition. Then, the participant took a rest, and 5-min testing trial was conducted. Between each trial, 5-min rest was given. This procedure repeated for all the conditions [32]. Detailed protocol is described in Fig. 8.

The metabolic cost was calculated using measured data of the last 2-min of each trial [31], using the software provided by *COSMED* [33,34]. The calculated results converted into watts and normalized by the body weight of the participant. The Baseline, and the Assist-off conditions were calculated as averages of the two-day results.

3.1.2 Experiment result

Digitigrader improved running economy up to 4.08% compared to the Assist-off condition and 2.78% compared to the Baseline condition (Fig. 9). Combination of High pre-tension and High spring stiffness showed the maximum improvement. Considering that the shoe used as the Baseline condition weighs 150g, which is about 70% lighter than *Digitigrader*, and the effect of carrying weight is critical for running economy [35], 2.78% improvement of metabolic rate is not negligible.

3.2. Posture Assistance

3.2.1 Experiment setup and protocol

One week after the efficiency experiment, effects of posture assistance were further evaluated. To verify the effects, muscle activities, strike index, and motion change were measured for Assist-off and Assist-on conditions. The same male subject ran on a treadmill for 1-min at a speed of 2.5m/s. For all the trials, the subject was instructed to maintain a forefoot strike pattern. The measured data of the last 10-sec were used for all the metrics. For the muscle activities and foot plantar pressure, pre-tension was set

Figure 10. Electromyography signal and strike index experiment setup

Figure 11. Optical motion capture experiment setup

to High and High stiffness spring was used. For the kinematics, pre-tension was set to Low and High stiffness spring was used. Each metric was analyzed as follows.

Muscle activities

Muscle activities of Tibialis anterior (TA), Soleus (SOL), Gastrocnemius medialis (GAS.M), and Gastrocnemius lateralis (GAS.L) were measured using the electromyography (EMG) signal detecting device (*Trigno, Delsys, United States*) (Fig. 10).

The raw EMG signals were band-pass filtered using 4th order

Butterworth filter with cut-off frequency of 20~450 Hz and then, low-pass filtered using 4th order Butterworth filter with cut-off frequency of 6 Hz [37]. The EMG linear envelopes were normalized using the peak values of each muscle measured on the assist-off condition. The normalized EMG linear envelope of each muscle divided into steps and averaged to compare between conditions.

Strike index

Foot-pressure monitoring system (*PEDAR, novel, Germany*) was used to check the center of pressure (C.O.P) at the foot landing instances and strike index (SI), which is generally used to identify running posture (Fig. 10) [36].

The locations of the C.O.P at the landing instances were normalized by the length of the foot. The SI is defined as Eq. 6.

$$SI = \frac{C.O.P}{Foot\ length} \times 100\ [\%] \tag{6}$$

The SI of each step was averaged to compare between conditions.

Motion change

The motion of ankle, and foot arch were tracked using optical motion capture system (*Bonita B10, Vicon, United States*). The marker attachments are described in Fig. 11. All the markers were attached on the upper of the left foot. The motion of the ankle, arch of the foot, and hallux were tracked.

The recorded motion data were labeled using the software provided by *Vicon*, and then post-processed to obtain trajectories time-normalized to the gait cycle and divided into steps using landing events. The landing instances were detected using the vertical displacements of the hallux marker. Before each recoding, the participant stood still on the treadmill for 10-sec and the height of the hallux from the belt of the treadmill were averaged. During the experiments, when the hallux reached 1.1 times the averaged value it was classified as the foot landed on the ground. Considering the

Figure 12. Assistance force experiment setup

oscillation of the treadmill, it was multiplied by 1.1. The cycle-normalized motions of each joint were averaged to compare between conditions.

Assistance force

The assistance force was measured for both of Low and High pre-tension with High stiffness spring. A custom-built sensing module was used to track the spring tension and gait phases at the same time (Fig. 12). The module consisted of a loadcell (*333FDX-50kg, Ktoyo, South Korea*) and a force sensitive resistor (FSR; *Flexiforce A201-25, Tekscan, United States*). The loadcell attached at back side of the ankle and provided mount to attach the clamp. The FSR attached between the upper and the sole underneath the forefoot using hook-and-loop fasteners.

The measured spring tension were normalized to the gait cycle and divided into steps using landing events. The landing instances were detected using the FSR values. Before each recoding, the participant stood still on the treadmill for 10-sec and the measured value of the FSR were averaged. During the experiment, when the FSR value reached the averaged value, it was classified as the foot landed on the ground. The cycle-normalized assistance forces were averaged to compare between conditions.

3.2.2 Experiment result

Muscle activities

All the muscles showed decreased peak muscle activities (Fig. 13,14). Forefoot strike exerts greater demands on GAS, but when assisted its activities were reduced by 27.22% for the medialis and 23.95% for the lateralis. TA showed double peaks, one for stance phase and the other for swing phase, and both were reduced by 27.46% and 3.56%, respectively.

Strike index

The SI classifies gait patterns based on the C.O.P location relative to foot length at the landing instance (Fig. 15) [36]. If the C.O.P locates at 0~33%, it classifies as rearfoot strike (RFS). If the C.O.P locates at 33~67%, it classifies as midfoot strike (MFS). If the C.O.P locates at 67~100%, it classifies as forefoot strike (FFS). The subject showed FFS for both of the Assist-off and the Assist-on conditions. For the Assist-on condition, the result showed 0.44% increased SI value, meaning that *Digitigrader* assisted the running to be FFS (Fig. 15).

Motion change

When assisted, ankle motion at the landing instances showed 1.09° more plantarflexed angle compared to the Assist-off condition, corresponding to 18.66% more plantarflexion. At the toe-off instance, the ankle was 3.28° more plantarflexed, corresponding to 27.63% more plantarflexion. The range of motion of the ankle was increased by 3.36°, from −15.15° ~ +13.18° to −11.87° ~ +13.10°, corresponding to 13.46% increased ankle motion (Fig. 16).

The hallux motion showed 0.41° more flexion at the landing and 2.50° less extension at the toe-off (Fig. 17). However, the measured data of hallux were noisy, so it requires further verifications.

Assistance force

For the High pre−tension, the maximum assistance force reached 81.21N, corresponding to 12.49%BW, at the peak dorsiflexion instance of stance phase (Fig. 18). The assistance force was 56.51N and 54.94N at the landing and the toe−off instances, respectively.

For the Low pre−tension, the maximum assistance force reached 62.59N at the peak dorsiflexion instance of stance phase. The assistance force was 44.05N and 42.92N at the landing and the toe−off instances, respectively.

3.3. Injury Prevention

In the motion capture experiment (Fig. 11), the motion of the arch was also tracked to evaluate the collapse of the foot arch. When assisted, the peak collapse decreased by 3.36° , corresponding to 51.72% reduced collapse (Fig. 19). The overall range of motion decreased by 2.15° , corresponding to 9.11% reduced range of motion, from −16.63° ~ +6.96° to −18.08° ~ +3.36° . The peak collapsing velocity reduced by 20.75% (Fig. 20). Causes of injuries of the plantar fascia are regarded as repeated over−collapse of the foot arch. These reductions of collapse are expected to lower the risk of plantar fascia−related injuries.

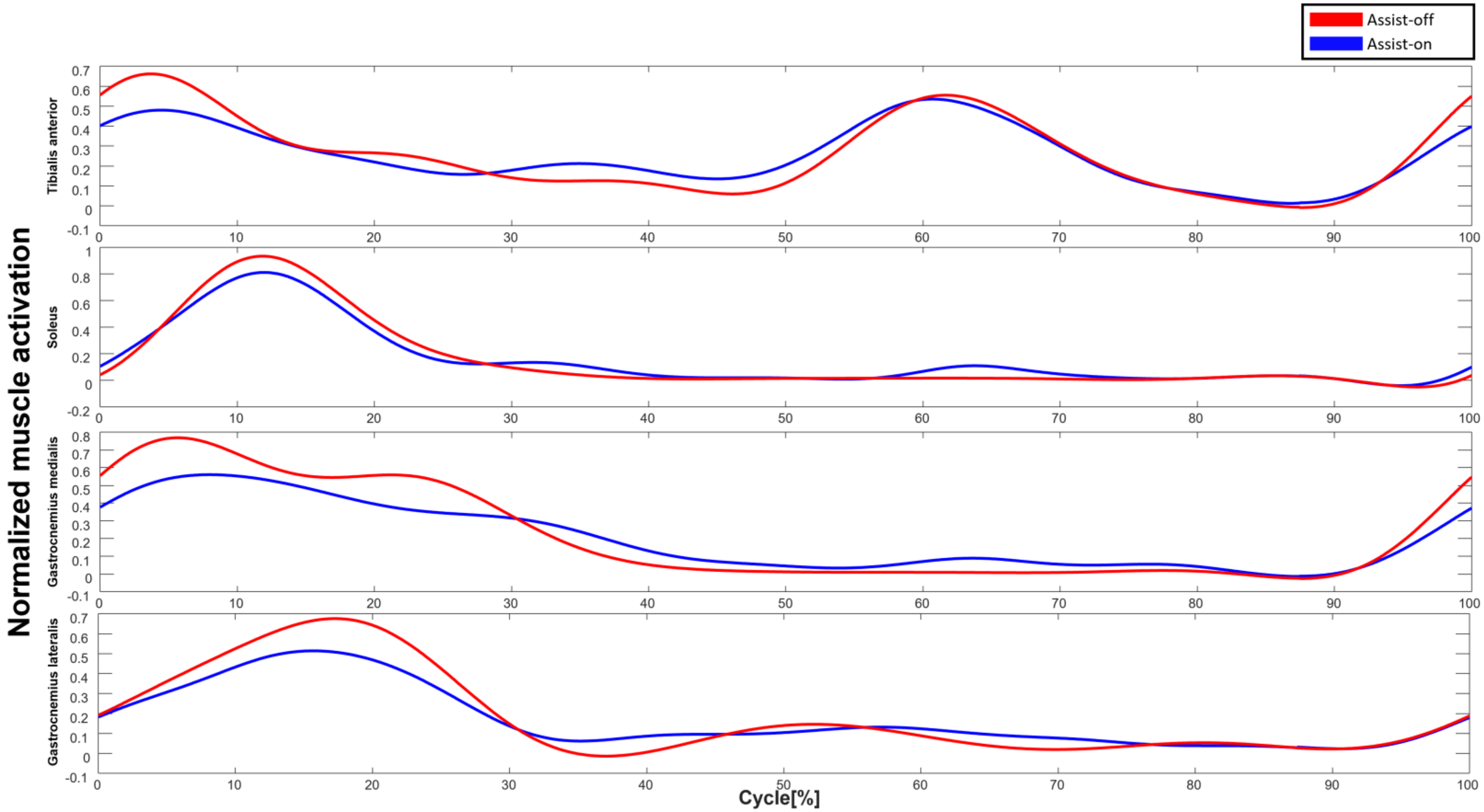

Figure 13. EMG linear envelope of each muscle

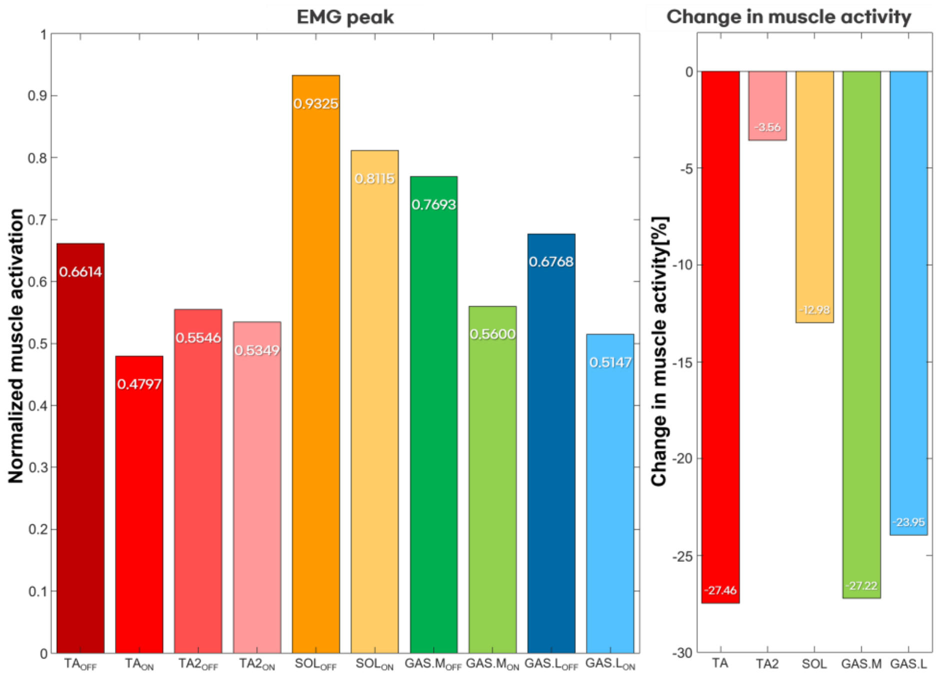

Figure 14. Change in peak muscle activities

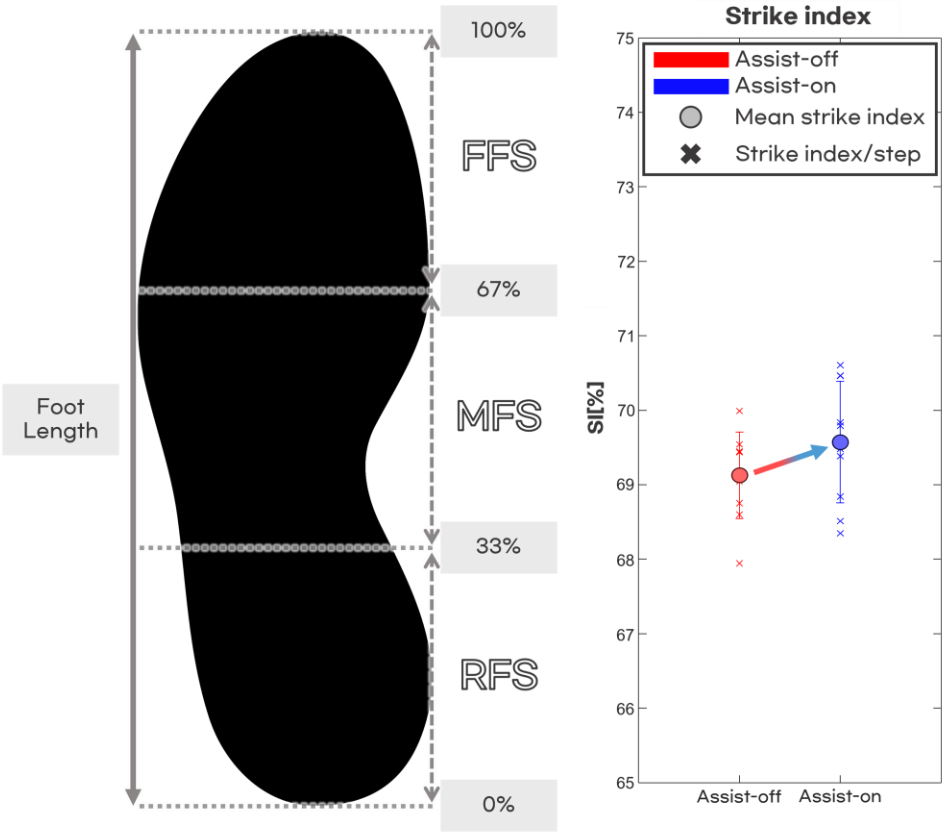

Figure 15. Change in strike index

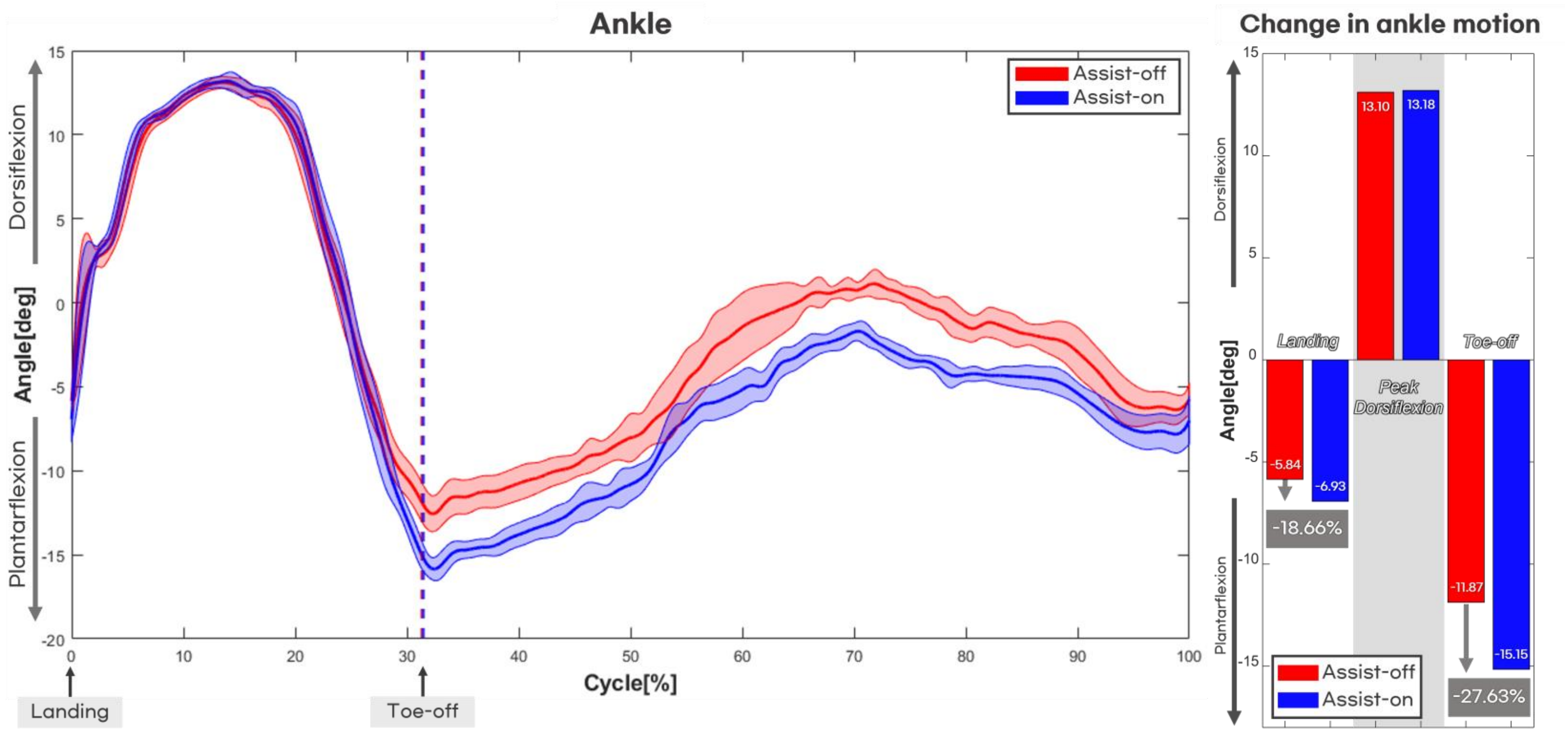

Figure 16. Change in ankle motion; The solid lines are mean and shaded areas are ±1 standard deviations; The dashed lines are the toe−off instances

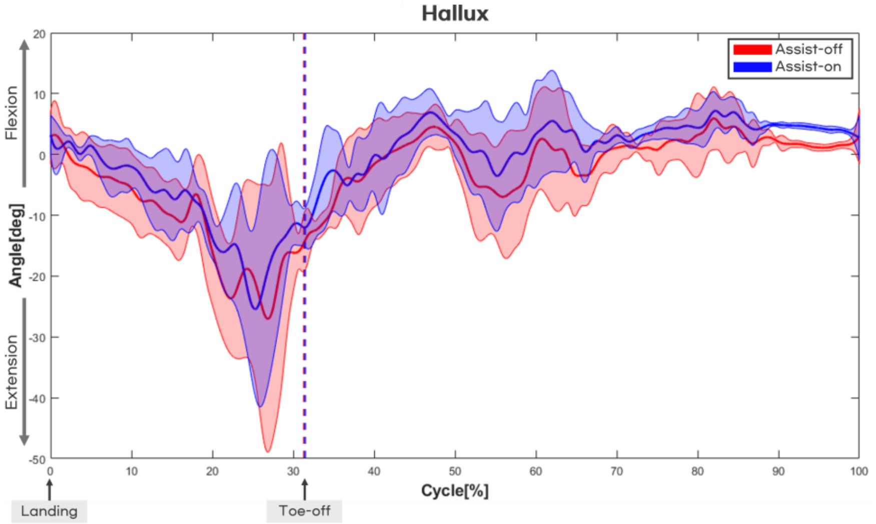

Figure 17. Change in hallux motion; The solid lines are mean and shaded areas are ±1 standard deviations; The dashed lines are the toe−off instances

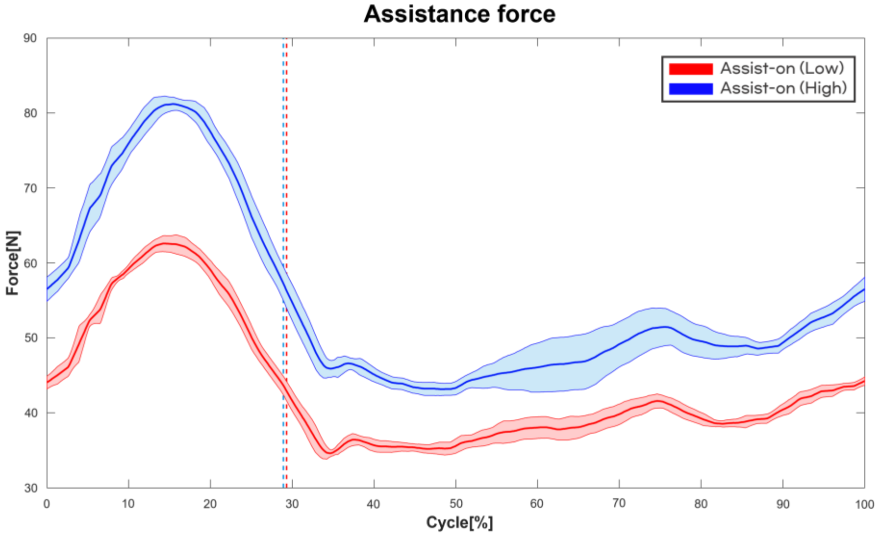

Figure 18. Assistance force profile; The solid lines are mean and shaded areas are ±1 standard deviations; The dashed lines are the toe−off instances

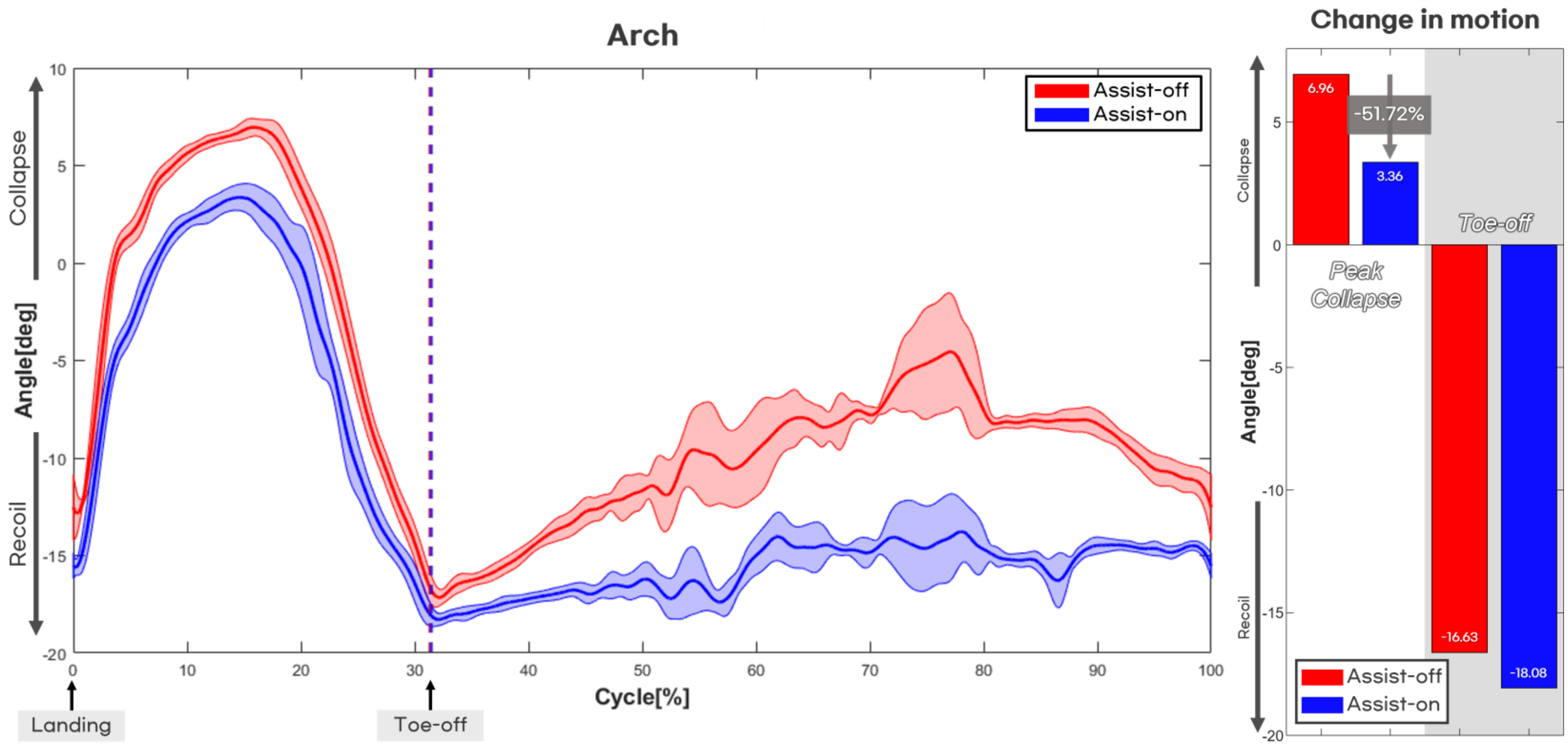

Figure 19. Change in foot arch motion; The solid lines are mean and shaded areas are ±1 standard deviations; The dashed lines are the toe−off instances

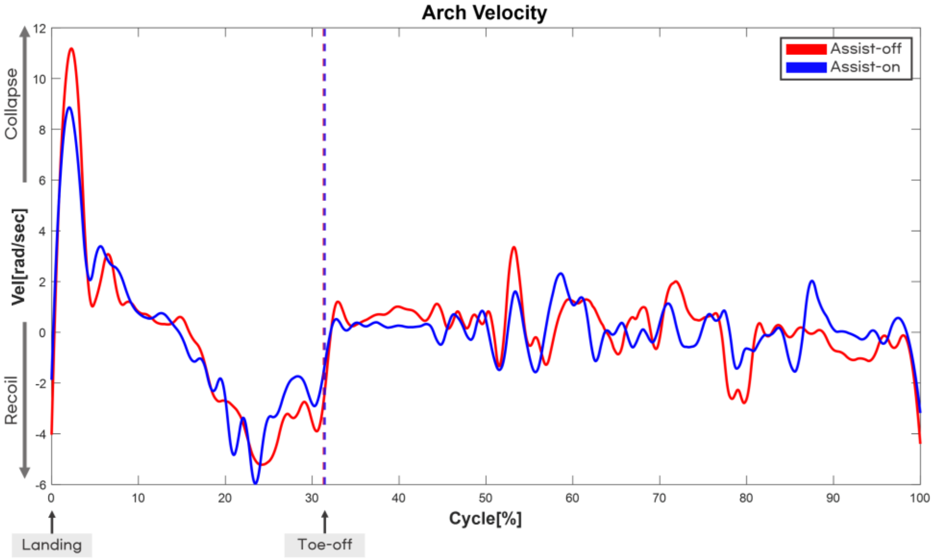

Figure 20. Foot arch collapse velocity profile; The solid lines are mean; The dashed lines are the toe−off instances

Chapter 4. Conclusion

Wearable robots have made remarkable progress in functionalities in terms of performance augmentation. However, despite such technological advances, wearable robots still have difficulty in disseminating the technologies. We guess the causes would be too many protruding attachments and unfamiliar appearances, which are not suitable to be "Wearable".

In this paper, as a solution of the problem, we introduced *Digitigrader*, a shoe–based passive ankle assistive device, inspired by biomechanics of human body and passive wearable robots. Its familiar appearance does not separate its user from our everyday footwears and makes easy to put on and use it.

To augment running performances, it is integrated with a passive ankle assist mechanism. To further improve its assistance capability, the elastic function of the foot arch was analyzed. Inspired by the anatomical connectivity and locomotion–enhancing functions of the foot arch and the Achilles tendon, the passive assist mechanism is developed. It is similar to general passive ankle assist robot mechanism (i.e., mimicking of the catapult mechanism of the Achilles tendon), but it improves its assistance ability by bringing another energy source into the passive assistance, the arch of the foot, instead of increasing lever arm of the system.

Due to the unique arch–involving design of the system, *Digitigrader* can interact with the arch of the foot without hindering the elastic function of the foot arch. It reduces the collapse of the foot arch, causes of injuries related to the plantar fascia, and works together with the elastic function of the foot arch. With this feature, it simultaneously augments running performance and injury safety of its user.

The functionalities of the device were verified in terms of running economy, posture assistance, and injury prevention. It provided maximum 12.49%BW assistance force and improved running economy by 4.08%, reduced 27.22% and 23.95% muscle activities of GAS.M and GAS.L, respectively. The 4.08% improved running economy is comparable to state-of-the-art shoe technologies [16, 38]. The SI slightly increased, and ankle was 18.66% more plantarflexed at the landing instance. This indicates that the system assisted the user to run with FFS gait pattern and helped to maintain the running postures. The peak collapse of the arch was reduced by 51.72% and overall range of motion of the arch was also decreased by 9.11%. It is expected that these changes of arch collapse motion result in reduction of injury risk of the plantar fascia.

From the above results, the system showed basic effects of the system. However, since all the results were obtained from a single subject, statistical significances are unknown, yet. Increasing the number of the experiment participants, further experiments for all the above experiments are required. To confirm the effects of the foot arch-enhanced passive assist mechanism, comparison between the design and arch motion-limited design is needed. Since the sole parts can be detached from the upper part using hook-and-loop fasteners, an inelastic plate, connecting the forefoot and the hindfoot part, can be attached between the upper and sole using the fastener to realize the comparable condition.

We expect our low-profile and familiar form factor approach to be a key to spread out the wearable robots. So far, the device has been limited to passive assist device, inspired by passive wearable robots. If it is integrated with active actuation systems, *Digitigrader* will act as a safe anchoring platform for transmitting assistance forces to its user without risking the safety of the foot arch. Furthermore, from the fact that the design is a new approach to improve both of human running performance and safety, it has potentials to be a new way to develop safe performance shoes.

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Abstract in Korean

앞발 착지 주법 달리기의 근력 보조와 부상 방지를 위한 신발형 보조 장치

지난 수십년간 다양한 착용형 로봇들이 인간의 이동 능력을 보조하기 위해 개발되어 왔다. 진화과정간 인간의 운동을 효율적으로 만드는 생체 내 탄성 요소들이 형성되었다. 이들은 보행 보조 장비 개발을 위한 단서를 준다. 생체 모사 기반 접근의 대표적인 예시는 아킬레스건의 기능을 모사한 신체 구동형 발목 보조 메커니즘이다. 수동형 보조라고도 불리는 신체구동형 보조 메커니즘은 인간의 운동간 소산되는 에너지를 탄성 에너지 형태로 순환시켜 착용자를 보조한다. 이러한 메커니즘은 시스템의 구성이 단순하고, 가볍다는 강점이 있다. 하지만, 활용할 수 있는 에너지 원의 제약으로 인해 착용자에게 제공할 수 있는 보조에 한계가 있다. 이를 해소하기 위해 레버암을 키워 보조력을 증대하기도 하지만, 이는 동시에 신체로부터의 과도한 돌출을 유발하기에 수동형 메커니즘의 강점을 약화시킨다. 본 연구간 신체구동형 메커니즘의 제한된 보조 능력을 극복하기 위해 아킬레스건 모사 메커니즘에 발 아치의 탄성 메커니즘을 더해 통합하였다. 발 아치는 보행간 약 17%의 에너지를 저장, 방출하는데 이는 아킬레스건 기능의 약 절반에 달한다. 이에 착안해 본 연구는 아킬레스건의 기능과 함께 아치의 탄성 기능을 시스템에 포함함으로써 수동형 메커니즘의 제한된 에너지 원을 확대하고자 하였다. 이 접근을 통해, 시스템은 발목과 발 아치 동작 모두에서 야기되는 탄성에너지를 활용할 수 있다. 이를 위해 아킬레스건과 발 아치의 동작이 보조 스프링과 동기화되어 움직일 수 있도록 보조 스프링이 발 저부와 발목 후방에 위치하는 메커니즘을 고안하였다. 메커니즘의 구현을 위해 전족부

와 후족부가 분리된 신발형 앵커링 플랫폼을 개발하였고, 보조 스프링과 통합하였다. 아킬레스건의 기능만을 모사하는 기존의 발목 보조 착용형 로봇이나 일반적인 신발과 달리, 아치와 동기화 되어 함께 동작하는 스프링을 통해 발 아치와 시스템간의 상호작용이 가능하다. 이러한 상호작용은 스프링의 수축력이 발 아치의 과도한 붕괴를 방지하여 아치를 지탱하는 생체 탄성 요소인 족저근막에 가해지는 부하를 저감할 수 있게 한다. 또한, 인간의 다양한 이동 전략 중 달리기를 보조 목표로 하였으며, 달리기 주법 가운데 특히 종아리 근육의 큰 부하를 요구하는 앞발 착지 주법을 선정하였다. 앞발 착지 주법간 발목의 족저굴곡을 담당하는 종아리 후면 근육의 동작을 고려해 프리텐션 된 스프링을 통해 스프링의 수축력이 상시 작용하게 하여, 착지 자세 및 종아리 근육의 근부하를 보조하는 전략을 취했다. 본 연구에선 신발형 앵커링 플랫폼에 신체구동형 보조 메커니즘을 통합하여 완성한 *Digitigrader*를 제시한다. 신체로부터의 최대 돌출은 20mm로 일상 속 활용될 수 있는 수준의 실용성을 갖추었다. 2.5m/s 속도 달리기 실험을 통해 장비의 보조 기능 활성화시, 비활성화 대비 4.08% 효율 개선이 확인되었다. 앞발 착지 주법과 연관이 큰 종아리 근육인 내·외측 비복근은 각각 27.22%, 23.95%의 감소된 근활성을 보여주었다. 착지 순간 13.46% 더 족저굴곡 된 발목의 동작과 약간 더 증가한 스트라이크 지표(Strike index)를 통해 장비 사용시 착지 자세의 변화 및 앞발 착지 주법 보조 효과 역시 확인되었다. 아치의 붕괴는 51.72% 감소되었으며, 이를 통해 발 아치와 장비 사이의 상호작용 효과를 확인할 수 있었다. 이러한 실험 결과를 통해 본 연구는 달리기 능력 증강과 안전 보조가 가능한 새로운 앞발 착지 주법 달리기 보조 장치를 제시한다.

주요어 : 달리기 보조, 발목 보조 장치, 대사 에너지 소모량, 근력 보조, 부상 방지
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