Wearability improvement of untethered pneumatic ankle foot orthosis

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Abstract

Pneumatic active ankle foot orthosis (AFO) for drop foot correction has the advantages of inherent compliance and remote force control. However, pneumatic AFOs that use heavy stationary air compressors as the energy source have limitations for outdoor use. Although a portable air-compressor-powered pneumatic AFO has been developed recently, it is difficult to operate in practical applications owing to the bulky design of the AFO and excessive power sources with overheating issues. In this study, the AFO system was optimized to improve wearability. The weight of the AFO was decreased from 720 to 600 g. A Bluetooth module was installed instead of a 1.2-m cable between the master and slave boards. The efficiency of the portable pneumatic actuator increased 12.4%, whereas its volume decreased 11%. The internal temperature was reduced from 100°C to 40°C using two cooling fans. Throughout the optimization process, the wearability of the AFO system was improved for real-life use.

Wearability improvement of untethered pneumatic ankle foot orthosis

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Abstract: Pneumatic active ankle foot orthosis (AFO) for drop foot correction has the advantages of inherent compliance and remote force control. However, pneumatic AFOs that use heavy stationary air compressors as the energy source have limitations for outdoor use. Although a portable air-compressor-powered pneumatic AFO has been developed recently, it is difficult to operate in practical applications owing to the bulky design of the AFO and excessive power sources with overheating issues. In this study, the AFO system was optimized to improve wearability. The weight of the AFO was decreased from 720 to 600 g. A Bluetooth module was installed instead of a 1.2-m cable between the master and slave boards. The efficiency of the portable pneumatic actuator increased 12.4%, whereas its volume decreased 11%. The internal temperature was reduced from 100°C to 40°C using two cooling fans. Throughout the optimization process, the wearability of the AFO system was improved for real-life use.

Introduction: Drop foot is a gait abnormality caused by neurological disorders, such as stroke and multiple sclerosis [1–4]. Drop foot causes disruption of the motor control pathway between the spinal cord and lower limb, and it causes the absence of ankle dorsiflexion [3, 4]. The swing phase is impeded by front foot drops, resulting in falling or compensatory hip movements [5, 6]. Although ankle foot orthosis (AFO) has emerged to correct abnormal gait patterns, most commercial AFOs have limitations of restrictive adaptiveness [2] from the passive structure [7]. To overcome these limitations, active AFO has been developed [8–16]. The most frequently used types of actuator for AFO are cable driven and pneumatic driven [8]. Although cable-driven actuators have been widely used for remote force transmission [10] because of their lightness and compact size, they cannot overcome the limitations of uncomfortable wearability owing to the tension problem of the cable [11]. Pneumatic-powered actuators can be an alternative to solve the limitations of cable actuators, but they have the limitation of tethered heavy external energy sources [11] or small-volume air tanks [12]. To reduce the volume of the actuator, Kim et al. developed an AFO with a double-crank untethered pneumatic actuator [13]. The developed portable air compressor can power the pneumatic AFO, satisfying the required flow rate and pressure level. However, an unstructured power source with a pneumatic component embedded jacket has thermal issues and high noise levels, which make the user uncomfortable.

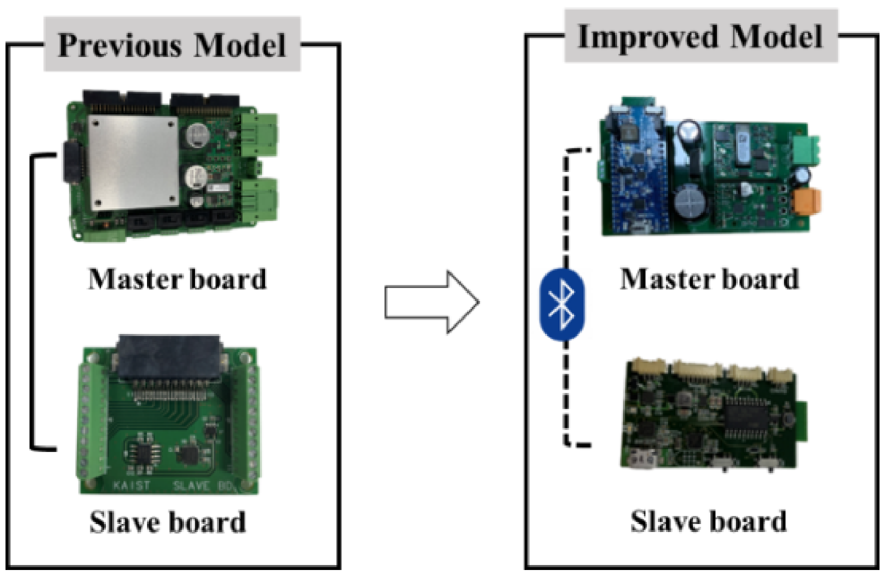
In this study, the AFO system was optimized by minimizing the number of electronic parts, including the printed circuit board (PCB), pump design, and additional cooling fans. To improve the wearability of the AFO, a bulky plastic foot cast was replaced with a carbon insole, and a BOA Fit System was loaded instead of a Velcro strap. The wearability of the system was also increased in three ways: untethering the actuator from the AFO, reducing the size of the motor and gear box of the actuator, and adding cooling fans to reduce the internal temperature.

AFO improvements: The prototype of the AFO [15, 16] was fabricated using thermosetting plastic parts, as shown in Fig. 1(a). The plastic structure can be worn like a foot and calf cast. The frame of the AFO consisted of several aluminum parts. Two pressure sensors (I2A Systems, Daejeon, Korea) were attached under the cast to measure the ground reaction force. However, as mentioned above, the AFO could not be hidden in the shoe because of the large volume of the cast. The AFO was improved in the form of an insole to reduce the prototype volume, as shown in Fig. 1(b). The insole is thin and compact; therefore, it can be inserted into the shoe easily. The total thickness of the insole was similar to that of commercial insoles. The number of frame parts was reduced and consisted of titanium instead of aluminum. Braces are a necessary part of the AFO to ensure stable fixation on the leg of the wearer.

The prototype AFO has only one strap-type brace on the calf, which causes unstable and uncomfortable wearability during walking, and more brace was added above the

(a) (b)

Fig. 1 *AFO improvement. The prototype AFO with bulky volume (a). Improved AFO with BOA fit system, additional brace and thin carbon insole (b).*



(a) (b)

Fig. 2 *Electronics refinement. The previous model of master and slave boards with tethered line (a), and the refined model of master and slave without tethering (b).*

Table 1 Specification of the master board .

	Previous	Improved
Weight	234 g	81 g

	Previous	Improved
Size	150 mm × 102 mm × 25 mm	93 mm × 59 mm × 18 mm

ankle. In addition, the strap was changed to a BOA Fit System-based brace to make it easier to wear. The total weight of the AFO was 600 g, which was 120 g lighter than that of the prototype AFO.

Electronics refinement: For the electronics of the AFO system, the size and weight of the master board were reduced to 1/4 and 1/3, respectively (Table 1). In addition, a Bluetooth module was loaded for communicating instead of a 1.2-m cable in the previous system (Fig. 2).

Compressor refinement: Based on a previous study [14], the customized dual-piston crank compressor was improved by reducing the gear ratio and increasing the nominal torque of the DC motor to reduce the noise level. The rotational motion generated by an electric motor combined with a gearbox was transformed into a reciprocating linear motion with a piston crankshaft mechanism. The reciprocating linear motion of the piston is shown in Equation (1)

$$x(\theta) = R\,(1 - \cos\theta) + L + x_L - \sqrt{L^2 - R^2\,\theta} \quad (1)$$

where R is the length of the crank, L is the connecting rod, θ is the angle of the crank measured from the top position (TP)

Fig. 4 *Distribution of the actuator system. High temperature from each component can be cooled by two cooling fans.*

The specifications of the motor with a gearbox were selected by analyzing the required piston head force with the simulated forces from the output torque. The gear ratio was changed from 66:1 in a previous study by 26:1 (planetary gearhead GP 42 C, Maxon Motor, Switzerland) to reduce the noise level, which is dominant in the noise level of the compressor operation. Following the gear change, the specification of the DC motor was also changed to a 60% higher level of nominal torque (0.177 Nm) and the comparable nominal speed (6940 rpm). The revised combination of the DC motor with the gearbox shows an output torque of 4.6 Nm and a velocity of 260 rpm, which satisfies the required performance of the compressor as the energy source of the pneumatic AFO. In addition, the energy efficiency of the new motor with gearbox increased from 60.9% to 73.3%. However, the weight of the motor with the gear increased from 534 to 840 g, which was compensated for by reducing the thickness of the compressor case to sustain the total weight of the system. The volume of the refined compressor was decreased by 11% compared with the previous one [13].

For the cooling of the portable compressor with pneumatic components, fans (EF80251S1-1000U-G99 SUNON, China) were installed in the package comprising these components for heat emission. The temperature change was monitored in six parts: the pump cylinder, DC motor, planetary gearbox, battery, master PCB, and pneumatic fitting. Before the installation of the fan, the temperature exceeded 100°C, which could damage the user and limit the long-term operation of the compressor. Operating both fans and the compressor simultaneously enabled the temperature of each component in the compressor to be maintained at 40°C for 20 min of continuous operation. Distribution of the actuator system is shown in Fig. 4.

Wearability improvement: By optimizing the AFO system, the volume of the system can be significantly reduced. In particular, the volume of the AFO was reduced enough to be hidden in the clothes, whereas the previous model was too bulky to hide. The use of the Bluetooth module instead of the tethering wire was also helpful for concealing the AFO.

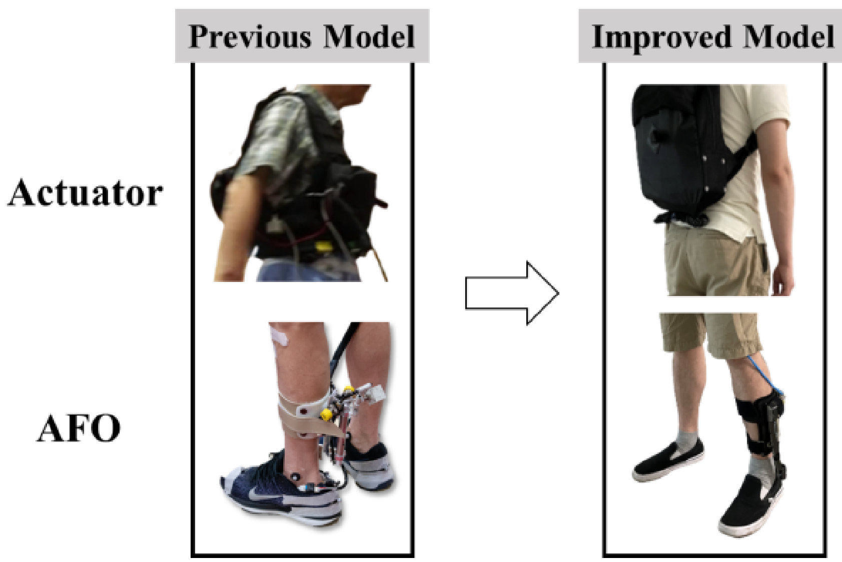


Fig. 5 *Comparison between the previous system (left) and the improved system (right).*

The volume of the vest actuator, as shown in Fig. 5, was also reduced by refining to the backpack type, and became easier to wear. The optimized AFO system is more feasible than the previous system.

Conclusion: A portable pneumatic AFO system was optimized to improve wearability. The cast of the AFO was re-formed at the insole to improve comfort. Simultaneously, the Velcro strap was revised to the BOA Fit System to enhance wearability. Thus, the volume of the AFO was significantly reduced and hidden in the pants of the wearer. In total, 120 g of weight was removed from the AFO. Based on the required piston head force and flow rate of the AFO from the kinematic model of the crankshaft mechanism, the combination of the DC motor and planetary gear was refined. When the gear ratio was reduced from 66:1 to 26:1 and a DC motor with a higher nominal torque of 0.177 Nm was used, the noise level decreased 60%, and the efficiency of the system increased 13.3%. The modified compressor satisfied the criterion for generating the required air pressure and flow rate of the AFO. Finally, optimizing the arrangement of the compressor, PCB, pneumatic fitting, and battery in the backpack and implementing both the inlet and outlet eliminated the overheating issue in the previous design by maintaining the temperature of each component at 40°C. The optimal positions of both fans for low power consumption were experimentally verified. The installation of fans in the backpack comprising the portable compressor and corresponding components made the long-term operation of the compressor possible and increased the wearability by impeding the overheating of the system. As a result of the optimization process, one can expect practical use of the AFO system not only for daily living of drop foot patients but also as a new AFO system design reference.

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