Design and Development of a Flexible Active Ankle Joint Orthosis for Locomotion Assistance

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Abstract

Active ankle joint orthosis is an artificial wearable device that is closely fitted to the human ankle and combines human intelligence and intentions with the powered robot joints. However, most of the existing designs have only focused on one degree of freedom (DOF) of the ankle joint: namely plantarflexion-dorsiflexion. Alternatively, a modular power-assist flexible active ankle orthosis is proposed, addressing anthropomorphic architecture of design, and supporting multiple DOFs of ankle for locomotion assistance of the physically weak individuals. The proposed ankle joint orthosis was designed with the aid of CAD tools followed by fabrication of a working model. Electrically powered systems with gear transmissions were adapted to support the principal motions during normal Gait. In parallel, the design of the control algorithm was carried out based on the EMG signals. The future advancements have been focused on developing a novel control method that provides sufficient flexibility to assist a wide variety of lower-limb motions.

Keywords: Active ankle orthoses, power-assist robots, anthropomorphic design, joint axes mapping, rehabilitation

1. Introduction

Every human being would prefer to spend their entire lifetime as an independent individual without becoming dependent on others for locomotion. According to statistics around the globe, the elderly population exceeds 10% of the total population and conversely, the number of people suffering from neurological or muscular disorders is on the rise. As such, the medical industry has shown a growing interest in using exoskeleton robots for restoring patients' mobility and to alleviate health care issues arising from locomotion difficulties.

With the continuous development in biomedical engineering field over the past few decades, the robotic orthosis devices have been used for many different applications. The active orthosis/ robotic exoskeleton is an artificial wearable device that is powered by the means of electric motors, pneumatics, hydraulics, or linear actuation methods. In the current market, active orthoses are classified as upper extremity systems, lower-extremity systems, and full-body systems. The lower extremity exoskeletons (LEE) are designed to support anatomical functions of different joints of the lower extremity. In general, hip, knee and ankle joints have seven degrees of freedom (DOF) per limb. The LEEs are primarily developed for three main types of applications such as gait rehabilitation (i.e. helping patients with mobility disorders in the rehabilitation of musculoskeletal strength, motor control, and gait), human locomotion assistance (i.e. targeted at paralyzed patients who have lost motor and sensor function in their lower limbs) and human power augmentation (i.e. enhance human strength and endurance during locomotion and enable individuals to perform tasks that they cannot easily perform by themselves).

The ankle joint complex is concerned, encompassing the lower leg and foot, serves as the crucial link facilitating interaction between the lower limb and the ground. Especially the essential aspect for activities like walking and daily tasks. Despite experiencing significant compressive and shear forces during walking, the ankle's robust structure provides a high level of stability. The key ankle joint complex movements include sagittal plane, plantarflexion-dorsiflexion, transverse plane, abduction-adduction, and frontal plane, inversion-eversion [1].

While commonly referred to as the 'ankle joint,' the foot's movement is facilitated by several articulations. The ankle joint complex comprises the subtalar joint (talocalcaneal), tibiotalar joint (talocrural), and transverse-tarsal joint (talocalcaneonavicular) [1]. The subtalar joint's geometry permits ankle inversion and eversion, with a primary role in these movements. Although other motions are possible, the bulk of foot inversion and eversion occurs here. The talocrural joint acts as a hinge, mainly contributing to plantar- and dorsiflexion. The transverse tarsal joint is considered part of the functional unit with the subtalar joint, sharing a common axis, and contributing to foot inversion-eversion. The combining motions at the subtalar and talocrural joints results in three-dimensional supination and pronation [2], [3].

While some suggest the talocrural joint is multi-axial due to internal rotation during dorsiflexion and external rotation during plantarflexion, evidence indicates it may be uniaxial. The observed simultaneous motions are attributed to its oblique axis. Similar to the talocrural joint, the subtalar joint has an oblique axis, contributing to multiple motions during plantar- and dorsiflexion, leading to pronation and supination [4].

In the past, there was a traditional belief that dorsiflexion and plantarflexion were exclusively associated with the motion of the talocrural joint, while inversion and eversion were thought to occur solely at the subtalar joint. However, recent perspectives have rejected the idea of completely segregating these motions to each joint. Although the majority of plantar and dorsiflexion is still attributed to the talocrural joint, there is now acknowledgment that a few degrees of these motions also involve the subtalar joint [5].

Despite some of the research efforts aimed at creating active ankle orthoses to aid human movements, challenges persist in effectively supporting natural human motions. These challenges revolve around the goal of enabling limbs to move freely and comfortably, particularly in relation to the corresponding oblique axes.

2. Design Considerations

Designing a device that will effectively interact with the human dynamic conditions is a difficult task to accomplish, especially at the distal end of limbs. Gait analysis can be used as an objective tool for quantifying motion of lower limb joints and forces that act upon these joints. However, gait analysis cannot separate it joint wise due to the major limitation of accurately measuring talus motion using skin-mounted markers. Fig. 1 depicts example gait analysis data of the ankle joint complex kinematics [6]. During a normal gait cycle, the stance phase begins at heel strike, where the dorsiflexors are eccentrically contracting to lower the foot to the ground based on the sagittal motion of the ankle. Then the ankle moves from plantarflexion to dorsiflexion during which the shank rotates forward around the ankle and after that the foot rotates around the forefoot phase continuing until maximum plantarflexion (approximately 14°) being achieved at toe-off. In the swing phase of walking, the ankle undergoes dorsiflexion, allowing the foot to lift off the ground and then transitioning to a slight plantarflexion upon heel strike. Simultaneously, there is motion at the subtalar joint, involving around 15° of inversion and eversion to complement this flexion movement [7].

As illustrated in Fig. 2, the anatomical axes of talocrural and subtalar joints are placed in an oblique sense that cause foot to move across all three planes allowing pronation and supination to occur during walking [6], [8]. Hence, constraining motions to a single plane can lead to abnormal joint movements, poor muscle recruitment and increasing overall energetic cost. Therefore, it is essential to facilitate multiple DOF to improve exoskeleton performance by active or passive means.

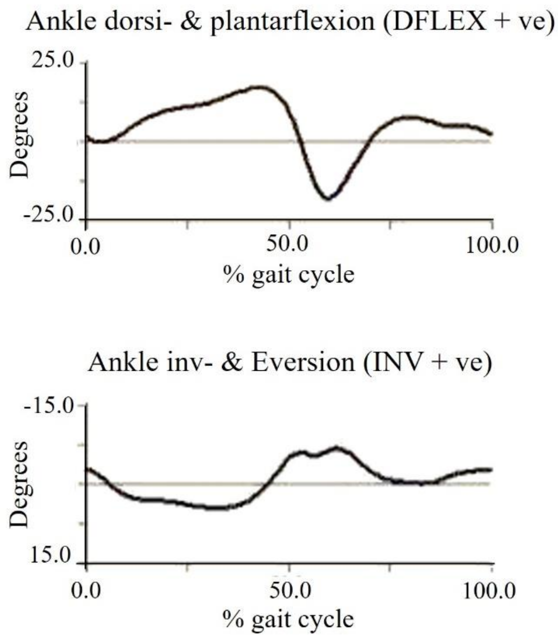


Fig. 1. The outputs from gait analysis representing ankle complex rotation in sagittal and frontal planes [6].

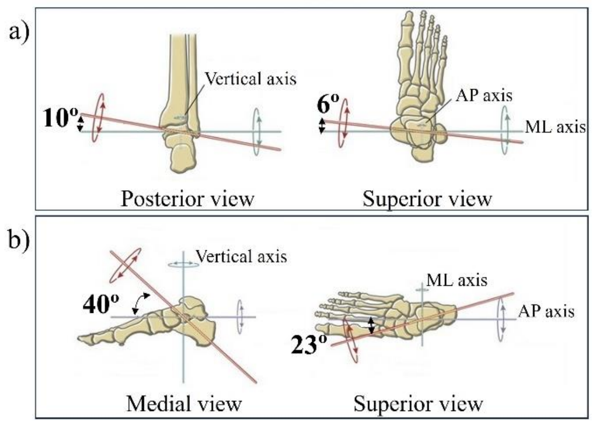
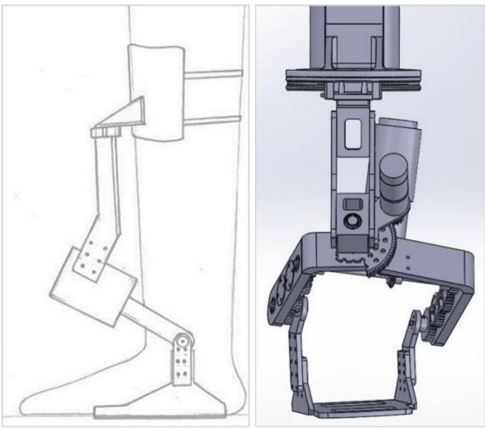
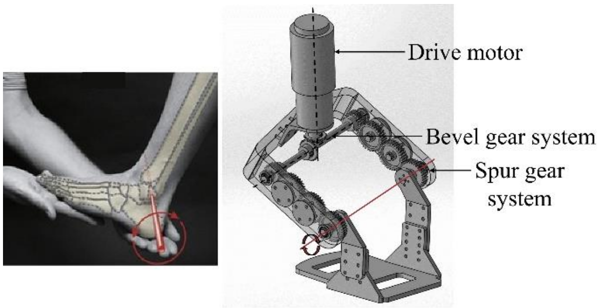


Fig. 2. The axis of rotation at the talocrural joint and subtalar joint - oblique axes of rotation (red) are shown in different views; a) talocrural joint; b) subtalar joint.



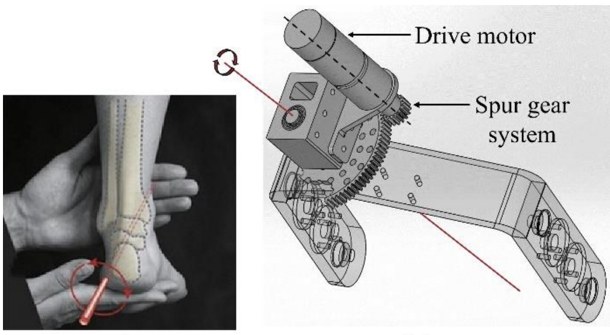
a) b)

Fig. 3. CAD model of the proposed ankle joint orthosis; a) conceptual design; b) CAD model.



a) b)

Fig. 4. The axis of rotation and osteo-kinematics at the plantar-/dorsiflexion assembly a) component axis (red) [8]; b) developed plantar-/dorsiflexion assembly.



a) b)

Fig. 5. The axis of rotation and osteo-kinematics at the inv-/ eversion assembly a) component axis(red) [8]; b) developed inv-/ eversion assembly.

3. Mechanical Design

This flexible active ankle joint orthosis is a multipurpose robotic ankle exoskeleton that can perform rehabilitation exercises as well as locomotion assistance. It is worn as a bilateral system and supports all three DOF of the ankle. The two significant DOF, namely, plantarflexion-dorsiflexion and inversion-eversion are externally powered using electrical actuators and remaining DOF, namely, internal- external rotation is passively supported. In addition, with the intention of maximizing user compatibility and performance, the mechanisms proposed in the mechanical design have compatible joint axes for each DOF. The CAD model of the flexible active ankle joint orthosis is shown in Fig. 3.

3.1. Plantarflexion/ dorsiflexion assembly

The movement of the ankle predominantly takes place in the sagittal plane, where plantarflexion and dorsiflexion are mainly observed at the talocrural joint. Various research studies have suggested a range of motion (ROM) in the sagittal plane, typically falling between 65° and 75°. This encompasses a span from 10° to 20° of dorsiflexion to 40°–55° of plantarflexion [9]. Here the plantarflexion-dorsiflexion axis of the suggested ankle joint brace is accurately aligned with the talocrural axis of the natural joint. Fig. 4 illustrates the plantar-/dorsiflexion assembly with the component axis.

3.2. Inversion/ eversion assembly

In the frontal plane, the complete range of motion is around 35°, consisting of 23° of inversion and 12° of eversion [10]. The axis of inversion-eversion in the flexible active ankle joint brace is accurately aligned with the subtalar axis of the natural joint. The assembly indicated in Fig. 5 has been mechanically formed and positioned normal to the subtalar axis of ankle.

3.3. Internal/ external rotation assembly

The internal/external rotation mechanism is crafted and adjusted to closely align with the ankle's axis of rotation. A stabilizer system is employed to maintain the assembly in its neutral position.

4. Prototype Development

The prototype incorporates tri-planar motion with oblique axes. The spacing between the two motion axes (sagittal and frontal plane motion) is adaptable to accommodate the wearer, making it one of the most human-like structures among the initial design concepts. Following multiple manufacturing processes at the production facility, the final prototype was successfully assembled. Fig. 6 illustrates the conclusive form of the active ankle orthosis device, while Table 1 provides detailed specifications outlining the design features of the developed prototype.

Fig. 6. Prototype of the proposed mechanical structure

Table 1. Design specifications of the flexible active ankle joint orthosis

Characteristic	Plantar-Dorsiflexion	Inversion-Eversion
ROM (Degree)	55/20	35/25
Actuation method	Motor driven	Motor driven
Transmission	Bevel and spur gear system	Spur gear system
Max. torque output (Nm)	22.3	2.3

5. Conclusion

The distinctive feature of the design for the flexible active ankle joint brace lies in its capability to meet the functional and ergonomic demands of the natural ankle joint. This is accomplished through precise alignment of the orthosis axes of rotation with the oblique axes of rotation found in the talocrural and subtalar joints of the ankle. The innovative mechanism, inclusive of the drive units, is situated anteriorly to the shank and foot segments. The proposed active ankle brace is easily adaptable for performing ankle rehabilitation exercises, serving as a robotic therapy module to aid paralyzed individuals in regaining or enhancing their functional mobility, or assisting those with physical weakness in their motion. Future work will involve creating an EMG-based controller for the flexible active ankle joint orthosis. This aims to enable real-time control by accurately anticipating the patient's intended motion through precise predictive capabilities.

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Authors Introduction

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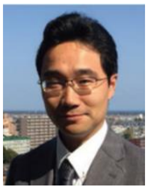

He received the B.E. and M.E. degree from Miyazaki University in 1998 and 2000, respectively. From 2000 to 2001, he was an Engineer in Asahi Kasei Corporation, Japan. In 2001, he joined Toyama University, Toyama, Japan, where he was a Technical Official in the Department of Intellectual Information Systems. In 2006, he joined Miyazaki University, Miyazaki, Japan, where he was an Assistant Professor in the Department of Electrical and Electronic Engineering. Since 2015, he is currently a Professor in the Department of Environmental Robotics. His main research interests are Neural Networks and Optimization Problems. In recent years, he has had an interest in Biomedical Signal Processing using Soft Computing.