Ankle-foot orthosis powered by artificial pneumatic muscles

Atefe Khadem

The material in this tutorial is based in part on Wearable Robots: Biomechatronic Exoskeletons (1st Ed., 2008) by JL Pons and my own research. For more information, please write to atefekhadem@email.kntu.ac.ir
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Ankle-foot orthosis, or AFO, is a support intended to control the position and motion of the ankle, compensate for weakness, or correct deformities. AFOs can be used to support weak limbs, or to position a limb with contracted muscles into a more normal position. In addition, AFOs are used to control foot drop caused by a variety of neurologic and musculoskeletal disorders. Due to the common use for addressing foot drop, AFO has become synonymous with the term “foot-drop brace.

This tutorial has been developed to help you understand what ankle foot orthoses (AFOs) is, why it is important, and how to present computational modeling for it. First, we introduce ankle-foot orthosis and then we introduce pneumatic muscle. Finally, Components of AFOs are then described including their Actuator, Sensor, and controller.

What is AFO?

Lower-limb orthotics: A lower-limb orthotic is an external device applied (or attached) to a lower-body segment to improve function by controlling motion, providing support through stabilizing gait, reducing pain through transferring load to another area, correcting flexible deformities, and preventing progression of fixed deformities.

The Ankle-Foot Orthosis is a boot to which an ankle joint is fixed through the stirrup. There are metal uprights (medial and lateral bars) ascending up to the calf.
region. The components are: Proximal calf band with leather straps. Medial and lateral bars articulating with medial and lateral ankle joints help in control of plantar and dorsiflexion. Stirrups anchor the uprights to the shoe.

There are 5 types of artificial ankle joints fit to the AFO, prescribed according to the power of the muscles controlling the ankle. They are:
1. Free ankle
2. Limited ankle joint (10 degree of plantar and dorsiflexion)
3. 90 degree foot drop stop
4. Reverse 90 degree ankle joint
5. Fixed ankle joint

Ankle-Foot orthosis is prescribed for:
1. Muscle weakness affecting the ankle and sub talar joint.
2. Prevention or correction of deformities of foot and ankle.
3. Reduction in appropriate weight bearing forces.
   a) Dorsiflexor muscle paralysis
   b) Ankle foot paralysis
   c) Spasticity
   d) Limited weight bearing

**Treating Foot drop with Ankle - Foot Orthoses?**

To understand how AFOs work, we must first understand two standard motion that occur at the ankle joint – “dorsiflexion” and “plantarflexion”.

![Dorsiflexion and Plantar flexion][30]

We use several different types of AFOs to treat drop foot in patients. Some of them are custom and require a mold of the foot, ankle and leg. Others are prefabricated. The goal is to provide patients with a comfortable AFO that will give them the most normal gait possible.

**6 types of passive AFO:**
1) Posterior Leaf Spring (Often useful for some patients who have instability of the knee along with their foot drop).
2) Solid AFO (This stops plantar flexion and also stops or limits dorsiflexion. These are used for drop foot patients with a nearly complete loss of dorsiflexion strength and who also have an unstable knee. It is a bit bulky, but gives a tremendous amount of control).
3) Short Leg AFO (Short Leg AFO with Fixed Hinge (doesn’t flex at ankle joint) Good
choice for patients who have drop foot and also have a very flat foot. This AFO keeps the foot at 90 degrees to the leg. It can also help control unwanted inward rotation of the foot, which can commonly accompany drop foot in stroke patients).

4) Dorsiflexion Assist AFO (This is one of the best AFOs for patients with mild to moderate drop foot and a flat or unstable foot).

5) Plantarflexion stop AFO (A plantar flexion stop AFO acts to stop plantar flexion by not letting the foot point downward. This type of AFO has a hinge that allows for normal dorsiflexion. Effective, for patients with more severe drop foot).

6) Energy Return AFO.

Ankle joint motion is controlled by pins or springs inserted into channels. The pins are adjusted with a screw driver to set the desired amount of plantar flexion dorsiflexion. The spring is also adjusted with a screw driver to provide the proper amount of tension necessary to aid motion at the ankle joint. A solid stirrup is a U shaped metal piece permanently attached to the shoe. Its two ends are bent upward to articulate with the medial and lateral ankle joints. The proximal stirrup attachment sites are shaped to enforce the desired movements at the ankle joint. The sole plate can be extended beyond the metatarsal head area for conditions requiring a longer lever arm for better control of plantar flexion such as in plantar flexor spasticity.

A split stirrup can be used instead of a split stirrup. It has a sole plate with two flat channels for insertion of the uprights. The uprights are now called calipers as they can

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Metal AFO

The metal AFO consists of a proximal calf band, two uprights, ankle joints and an attachment to two uprights, ankle joints and an attachment to the shoe to anchor the AFO. The posterior metal portion of the calf band should be 1.5 to 3 inches wide in order to evenly distribute pressure. The calf band should be 1 inch below the fibular neck to prevent a compressive common peroneal nerve palsy.

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open and close distally to allow donning and
doffing of the AFO.

![Metal AFO](image)

**Figure 2**: Metal AFO

**Motion of the foot and ankle**

The key movement of the ankle joint
complex are plantar- and dorsiflexion,
occurring in the sagittal plane[1]; ab-
adduction occurring in the transverse plane
and inversion-eversion, occurring in the
frontal plane. Combinations of these
motions across both the subtalar and
tibiotalar joints create three-dimensional motions called
supination and pronation[2]. Both terms
define the position of the plantar surface of
the foot (sole). During supination, a
combination of plantarflexion, inversion and
adduction causes the sole to face medially.

![Diagram illustrating relative motions of the ankle joint complex.](image)

In pronation, dorsiflexion, eversion and
abduction act to position the sole facing
laterally.

**Figure 3**: Diagram illustrating relative
motions of the ankle joint complex.[3]
Range of motion

The ankle range of motion (ROM) has been shown to vary significantly between individuals due to geographical and cultural differences based on their activities of daily living[4], in addition to the method used for assessing ROM. Motion of the ankle occurs primarily in the sagittal plane, with plantar- and dorsiflexion occurring predominantly at the tibiotalar joint. Several studies have indicated an overall ROM in the sagittal plane of between 65 and 75°, moving from 10 to 20° of dorsiflexion through to 40–55° of plantarflexion[4][5]. The total range of motion in the frontal plane is approximately 35° (23° inversion – 12° eversion)[5]. However, in everyday activities, the ROM required in the sagittal plane is much reduced, with a maximum of 30° for walking, and 37° and 56° for ascending and descending stairs, respectively[2]. Historically there has been a convention where dorsi- and plantarflexion motion was solely attributed to the tibiotalar joint motion, and inversion–eversion was considered to occur only at the subtalar joint[6]. More recently, the complete separation of the motions to each joint has been dismissed; most plantar/dorsiflexion is still considered to occur at the tibiotalar joint but with a few degrees accounted for at the subtalar joint. The distribution of inversion and/or eversion and rotation across the two joints has been an area of greater contention, with some studies indicating eversion to occur at the subtalar joint and rotation/inversion to occur at the tibiotalar, whereas others have shown version to be distributed across both joints[7]. Whilst gait analysis can be used as an objective tool for quantifying motion of lower limb joints and forces that act upon these joints, gait analysis cannot separate the talocalcaneal (subtalar), tibiotalar (talocrural) and transverse-tarsal (talocalcaneonaviculcar) joint due to the major limitation of accurately measuring talus motion using skin-mounted markers. However, despite this limitation, gait analysis is still a commonly used tool for the quantification of ankle joint complex kinematics and kinetics.

Figure 4: ROM in the frontal plane
Figure 5: Conventional ROM measurement method of the ankle joint[8].

Analysis data of the ankle joint complex kinematics

During a normal gait cycle, the stance phase can be split into three sub-phases based on the sagittal motion of the ankle;

i) the heel rocker;

ii) the ankle rocker

iii) the forefoot rocker.

The heel rocker phase begins at heel strike, where the ankle is in a slight plantarflexed position pivoting around the calcaneus (the continuation of plantarflexion) until the end of the heel rocker phase when the foot is flat on the ground. During this sub-phase the dorsiflexors are eccentrically contracting to lower the foot to the ground.

The ankle rocker phase is where the ankle moves from plantarflexion to dorsiflexion during which the shank (tibia and fibula) rotate forward around the ankle allowing forward progression of the body.

During the forefoot rocker phase, the foot rotates around the forefoot phase, starting when the calcaneus lifts off the ground evident by the ankle beginning to plantarflex and continuing until maximum plantarflexion (approximately 14°) being achieved at toe-off, where power generation is achieved for the leg to begin the swing phase.

During swing phase the ankle dorsiflexes enabling the foot to clear the ground and avoiding stumbling/tripping, before returning to slight plantarflexion at heel strike. This flexion motion is complemented by motion at the sub-talar joint, with approximately 15° of eversion/inversion. For the majority of individuals, inversion occurs at heel-strike, and progresses to eversion during mid-stance phase, allowing the heel to rise and push off into swing [2]

In the two next figure to show Details of previous content:
Figure 6: Diagram illustrating typical outputs from gait analysis of five walking trials. a) representing ankle complex rotation in sagittal, frontal and transverse planes (left to right, respectively); b) sagittal plane ankle moments and c) sagittal plane ankle power. The shaded area on all graphs represents ±1 standard deviation [3].

The ankle undergoes one cycle of the gait

The 3 rockers of gait:

(A) During the first rocker, the heel strikes the ground, the foot rotates around this, and the ankle joint axis to come to rest in the flat foot position. Contraction of the anterior compartment muscles* controls this motion.

(B) During the second rocker of gait, the tibia is brought "up and over" the talus, rotating around the ankle joint. The intrinsic muscles of the foot and tibialis posterior fire, to maintain a medial longitudinal arch.

(C) The terminal portion of the second rocker signals the powerful triceps surae to fire.

(D) During the third rocker, the ankle plantar flexes over a fixed forefoot (about the metatarsophalangeal joints) ending in toe-off, initiating the swing phase of gait.

Figure 5: The ankle undergoes four arcs of motion in one cycle of the gait: Controlled plantar and dorsi flexion, powered plantar-flexion and swing dorsi-flexion.[9]

Figure 7: The 3 rockers of gait[9].
To date, three kinds of AFOs have been developed, including the passive AFOs, semi-active AFOs, and active AFOs. The passive AFOs do not include any electrical elements or power sources, except for some mechanical elements such as springs and dampers. Generally, they are designed with articulated or non-articulated joints. During the past decade, robotic technologies have been employed in the research and development of medical devices such as exoskeletons[13][14] for robot-assisted rehabilitation. Semi-active AFOs do not include any actuator to a power supply. They have the ability to modulate the ankle joint compliance or damping. For active AFOs, they are more complex and are normally composed of actuators, power source, sensors, and controllers. According to the applications and users, AFOs can be classified into two groups: one is for rehabilitation for individuals with muscle weakness at the ankle, and the other is for reducing the metabolic cost of walking for healthy people.

Ankle-foot orthoses can be roughly categorised as passive or active orthoses. Passive foot orthoses generally use various spring mechanisms made of different materials for supporting the patient’s gait. Unlike conventional passive orthoses, active orthoses contain powered mechanisms that achieve the required force to lift the foot into a position that is necessary for normal gait[11][12].

In the other hand An ankle-foot orthosis (AFO) is a device that assists a person’s ankle by constraining and limiting the range of motion or assisting the muscles of the ankle though dorsi and plantar flexion of the ankle [15]. While the detailed motion of the human ankle joint is complex and is actuated by multiple muscles, most AFOs have a single-degree-of-freedom and operate within the range of normal motion, which is ankle plantar flexion is between and between 10° to 30° of dorsiflexion and 40° to 65° of plantar flexion [16]. AFOs can be separated into two categories, passive and powered. A passive AFO is used to constrain the motion of the ankle, but can also store the energy generated by the movement of the body in linear or rotary spring elements. The energy generated by the movement of the body in linear or rotary spring elements. The energy
can be released to assist weak muscles in moving the ankle [15]. A powered AFO uses an actuator and energy from an external power source to assist the muscles in dorsi and plantar flexion of the ankle. Current clinical AFOs are passive and used in physical therapy, rehabilitation and as assistive devices for people with chronic or temporary motor impairments that affect the ankle [15].

**Ankle-foot orthoses classification**

A repeated measures study design was used to compare biomechanical, metabolic, and performance-based metrics in the four conditions described below and in Fig. 10a). **Blue Rocker** (BR condition, Allard, USA): The BR is commercially available carbon fiber AFO with cuff below the knee, lateral strut, and flexible foot plate.

**Intrepid Dynamic Exoskeletal Orthosis (IDEO):** The IDEO is a custom carbon fiber AFO with cuff below the knee, lateral strut and rigid foot plate that has been described previously.

**None:** The None condition refers to walking with shoes only and without an AFO.

**PowerFoot Orthosis** (PFO, BionX Medical Technologies, Inc., USA).

![Figure 9: An ankle-foot orthosis powered by artificial pneumatic muscles](image)

![Figure 10: a Study devices worn by each individual.](image)
passive conventional AFO, IDEO – passive dynamic advanced AFO, PFO – powered advanced AFO. The PFO is a computer-controlled ankle-foot orthosis in which joint position, impedance, and torque are varied in response to walking phase and step-to-step gait variations. The PFO is comprised of a series-elastic actuator, motor controller, a state controller, and a scaffold structure (Fig. 10 b). [25]

Overview of pneumatic artificial muscles

A pneumatic muscle is a contractile and flexible pulling actuator operated by gas pressure. Since being first conceived (in the early 1930s) a considerable number of concepts of fluidic muscle actuators have been developed and some examples are given in Figure 11.

There exist various types of fluidic muscles that are based on the use of rubber or some similar elastic materials which have been studied in scientific literature, such as the McKibben artificial muscle [17][18], the rubbertuator made by the Bridgestone company [19][20], the air muscle made by the Shadow Robot Company, fluidic muscle made by the Festo company.

In most cases the structure of fluidic muscle is composed of an airtight inner polymer tube placed within a flexible piece of hollow braided construction and appropriate metal end-fitting pieces for external attachment and pressurisation. When the internal membrane is inflated with compressed air, the pressurised gas pushes against its external shell, tending to increase its volume. The muscle radius increases and together with radial expansion the muscle contracts axially and exerts a pulling force. The force of PAM can be described as the function of pressure and length (or contraction ratio) and in most

Pneumatic artificial muscles (PAMs) are contractile or extensional devices operated by pressurized air filling a pneumatic bladder. In an approximation of human muscles, PAMs are usually grouped in pairs: one agonist and one antagonist.
cases the constant-pressure characteristic of fluidic muscle is used. [21]

$$\begin{aligned}
F &= p \left[a (1 - \varepsilon)^2 - b\right] \\
a &= \frac{3 \pi D_0^2}{4 \tan^2(\beta_0)} , \quad b = \frac{\pi D_0^2}{4 \sin^2(\beta_0)}
\end{aligned}$$

**Box 1: Equation**

- $D_0$ is the nominal diameter of the PAM when it does not contract
- $\beta_0$ is the initial angle between the thread and the muscle long axis
- $F$ is the relationship amongst actuator contraction (pulling) force
- $P$ is applied air pressure (internal muscle pressure)
- $\varepsilon$ is and contraction rate $\varepsilon$ can be expressed in the following form

PAM operates by means of overpressure and contract when pressuried, generating a loadcarrying capacity at its ends during this contraction. Powered by compressed gas, the artificial muscle actuator contracts lengthwise when radially expanded and converts the radial expansive force into axial contractile force. As can be seen in Figure 12, the force and motion generated by this type of actuator are linear and unidirectional. Typically, maximum contraction of muscle actuators is about 25 % over the nominal length.

![Figure 12: Operating principle of PAM[22]](image)

**PAFOs classification**

Numerous PAFOs have been developed recently to assist healthy and impaired users while walking. With respect to their main goal, they can be divided into four distinctive groups as follows [23]:

- **Basic Science PAFOs**: PAFOs that have been developed to study human physiology and biomechanics by analyzing the user’s response to external ankle actuation;
- **Augmentation PAFOs**: PAFOs whose goal is to increase the walking endurance of healthy users, by reducing their metabolic cost and/or muscle effort;
- **Assistive PAFOs**: PAFOs that aim to assist users with impaired ankle capabilities to bring their performance closer to that of healthy individuals;
• **Rehabilitation PAFOs**: PAFOs whose goal is to rehabilitate subjects who suffered an injury or illness and to re-train their walking capabilities to pre-injury ones.[24]

**Active ankle-foot orthotic device actuated by PAM (Design a particular model)**

Pneumatic muscles are widely used during the processes of musculoskeletal rehabilitations of elderly or injured people as actuators for actively powered orthoses. Ankle-foot orthoses can be roughly categorised as passive or active orthoses. Passive foot orthoses generally use various spring mechanisms made of different materials for supporting the patient’s gait. Unlike conventional passive orthoses, active orthoses contain powered mechanisms that achieve the required force to lift the foot into a position that is necessary for normal gait [11][12]. The second test system presents an active, pneumatically powered ankle-foot orthosis as a technical device that could help people who have difficulty lifting their feet independently when they walk (so-called ‘foot drop’). This device can prevent foot drop and provide the necessary force to return the patient’s foot to its neutral position to maintain a better walking ability. Our attempt to create an efficient and light-weight foot orthosis powered by an air muscle is shown in Figure 13. The orthosis as a powered mechanism uses an air muscle (Festo DMSP-20-150N-AM-CM) driven by a solenoid valve.

During the process of making the proposed orthosis made a 3D prototype using SolidWorks design software and then print it in PLA plastic using a 3D printer. In order to reduce the weight of the orthosis, the plastic parts are made with hollow interiors. The connecting pieces are made of aluminum or steel materials. The device is designed to be worn fixed to the patient’s lower leg and tied with strap belts. The controller is implemented by using a TmegA 328 microcontroller. On the bottom side of the orthosis two switches are built-in, in the areas under the heel and toes. The microcontroller receives a signal from the first micro-switch located on the heel, then activates the timer and waits for a signal from the second micro-switch. After receiving the second signal, the microcontroller stops the timer and activates the valve over the same period of time that has elapsed between the two signals. This principle allows the patient to control the walking speed, which helps to keep his/her stability and faster adaptation to the device. For activation of the solenoid
a signal voltage of 24 V is required. Therefore, a voltage regulator was developed which uses the ULN2803A Darlington driver. By controlling the pressure within the muscle, the contraction force of the muscle is also controlled and thereby the foot is lifted into position for a new movement of the leg.[22]

Methods:

Design Analysis of Articulated Ankle Foot Orthoses

a new design of passive AFO with pneumatic passive element, which is made of thin laminated sheets of polystyrene in an airtight chamber. This element was modified with a rotational axis and placed at the axis of rotation of ankle to control motion. The vacuum pressure inside the chamber influences the frictional force between the laminated sheets. An air buffer functioning similar to a pump is attached under the sole, controls the air flow to the passive element chamber, and alters the vacuum pressure to change the constraint force on the elements. During loading response, the strong constraint torque of the joint prevents foot-slap. During midstance to toe-off, the buffer is compressed due to body weight and air flows to the passive element causing the sheets of the element to rotate freely around the axis and allowing the ankle joint to move without any restriction. During swing, air comes out from the element causing the thin sheets to stick together to prevent drop-foot (Figure 14). By adjusting the constraint force of the pneumatic element, this AFO can imitate the functional characteristics of other AFOs. This AFO is favorable for patients because of its light weight and compactness. A novel design of
AFO, which can harvest energy during middle to late stance and ensure toe-clearance by means of locking the ankle in neutral position during swing, was developed by Chin et al. [26]. The design is comprised of two sections, tibial upright and foot, fabricated from carbon fiber composite material. These two sections are attached with each other with a conventional hinge joint. The control system of the articulated joint integrates a cam lock mechanism, a linear actuator, and a pneumatic circuit. A stationary cam is added to the lateral side of the tibial upright and the linear actuator is attached to the foot section (Figure 15(a)).

**Actuator Mechanism:**

The mechanism is comprised of a linear cylinder with spring return, a follower with small rollers, and a guide rail housing for the follower. The minimum pressure needed to move the cylinder rod is 120 KPa. A pneumatic circuit is located in the plantar surface of the foot section. The circuit is comprised of a bellow pump with 4.5 cm outside diameter, valves, and tubing. The size, shape, and design of the bellow are determined in such a way that it can achieve pressure above 150 KPa and generate around 10 KW power per gait cycle [27]. The bellow pump is placed under 2nd and 3rd metatarsal heads. This placement provides best possible pressure generation and optimal timing for release valve and actuator activation. The release valve discharges compressed air of the actuator cylinder into the atmosphere. During heel strike this valve is activated and the spring in the cylinder pulls back the actuator rod and unlocks the cam lock to allow free movement of the ankle. During midstance to late stance the release valve is closed, the weight of the body compresses the below pump, and the harvested fluid power extends the cylinder rod and follower. The design of the cam allows the follower to roll over the cam surface to permit ankle dorsiflexion. During late stance, due to plantarflexion of the ankle the follower rolls into the locking position and locks the ankle in neutral position to prevent foot drop in swing phase (Figure 15(b)). The outsole prototype of the AFO is compact but cosmetically not attractive and clinical assessment is not done.

Developed a prototype of a portable pneumatic power harvesting ankle foot orthosis that can raise the dorsiflexion angle by 20° in swing phase by providing dorsiflexion assisting moment (Figure 16(a)). The design includes a commercially available AFO (dream brace), a wire type pneumatic
actuator cylinder, and a pneumatic circuit in the plantar surface of the foot (Figure 16(b)). The pneumatic actuator is affixed to the articulated joint of AFO with a moment arm. It acts as a driving actuator with high power/weight ratio and it can be used in a narrow space as it is driven by a wire instead of piston rod. A balloon is inserted into the cylinder which acts as a seal and the wire is connected to the piston inside the cylinder.

**Sensor Mechanism**

The pneumatic circuit is comprised of a bellow pump placed under the heel, a mechanical sensor located under the toe, a five-port pilot valve at the middle of the shoe bottom to switch the flow direction, and an air buffer.

The mechanical sensor is connected to the pilot valve, which changes the flow direction by lowering pilot pressure. During stance period, the bellow pump is compressed and at a certain pressure (about 60 KPa) the pilot valve is actuated and compressed air starts to accumulate in the air buffer. At the late stance the toe steps on the mechanical switch and then in swing phase at atmospheric pressure the pilot valve switches the accumulated air flow from the air buffer to the actuator cylinder.

As the cylinder pressure rises, the piston pulls the moment arm to generate dorsiflexion ankle moment. The AFO can produce small dorsiflexion assisting moment around the ankle. Moreover, the bulky nature of the AFO is not suitable for daily use.

![Figure 14](image1.png) Free and constraint mode of passive pneumatic element.[28]

![Figure 15](image2.png) Posterior and lateral views of the power-harvesting AFO See Figure 15 for reference to symbols (A, R, C1, C2).[26]
Figure 15b: pneumatic circuit diagram and shoe sole. Pneumatic circuit diagram (a) and actual foam sole (b) with bellow pump mounted at the metatarsal. (C1) check valve is open to atmosphere for intake, (C2) check valve ensures one-way flow direction from bellow to actuator, (A) actuator for locking mechanism, and (R) pressure release valve for exhaust. Valve (R) opens to atmosphere upon contact with the floor (c).[26]

![Figure 15b: pneumatic circuit diagram](image)

**Figure 15b:** Pneumatic circuit diagram and shoe sole. Pneumatic circuit diagram (a) and actual foam sole (b) with bellow pump mounted at the metatarsal. (C1) check valve is open to atmosphere for intake, (C2) check valve ensures one-way flow direction from bellow to actuator, (A) actuator for locking mechanism, and (R) pressure release valve for exhaust. Valve (R) opens to atmosphere upon contact with the floor (c).[26]

Figure 16: (a) Different components[29]

![Figure 16: (a) Different components](image)

**Figure 16:** (a) Different components[29]
**Control system:**

The control system scheme is shown in Figure 15a, the pressure in PAM is controlled through the force resistive sensor (FRS). As the force is applied to the FRS sensor, the air from the opening space is being pushed and the conductive material make a contact with the active area parts. As this sensor changes its resistance with force, as the active area touches the conductive area activity increases, the lower its resistance thus low resistance to electric current. The sensor send signals to a micro controller (Arduino) to connect to the motor driver. These control signals are directed to solenoid valve that supply air to activate the PAM. Ankle angle, plantarflexion angle and artificial muscle force are recorded every minute during 5 full strides by using an encoder.

A limitation of conventional mechanical ankle joints is that their control mechanisms cannot be timed to the gait cycle to switch function. Thus, a control mechanism that blocks motion often is sustained throughout the gait cycle, thereby sacrificing normal functional movement elsewhere. Such limitation can cause deviations from normal ankle-foot dynamics and could lead to reduced gait stability and efficiency. The proposed PhAFO overcomes this limitation. The design advances demonstrated with the PhAFO are the ability to restrict plantarflexion during swing while permitting free ankle motion during stance, and the capacity to harvest pneumatic power to control these functions. Through use of a mini-actuator to drive a novel cam-lock mechanism, motion control at different times in the gait cycle is possible. The most notable of these advances is the capability for self-power using a pneumatic bellow since this feature allows untethered operation and control of the orthosis. The high forces generated through walking are ideally suited for harvesting fluid power. Multiple channel pneumatic circuits and additional actuators could provide further orthotic control options and features.
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