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3D PRINTED PASSIVE COMPLIANT & ARTICULATING PROSTHETIC ANKLE FOOT

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ABSTRACT

The human ankle is crucial to mobility as it counteracts the forces and moments created during walking. Around 85% of the 1.7 million people in the United States living with limb loss are transtibial (below knee) and transfemoral (above knee) amputees who are missing their ankle and require a prosthetic. This paper presents the Compliant and Articulating Prosthetic Ankle (CAPA) foot, a solution that uses torsional springs to store and release energy at three different locations on the mechanism, assisting in forward motion. The CAPA foot utilizes 3D printing and allows for the full ankle range of motion in the sagittal plane. Testing was performed with the CAPA foot on the Computer Assisted Rehabilitation Environment on an able-bodied person wearing a prosthetic simulator. Compared to the conventional non-articulating Solid Ankle Cushioned Heel foot, the CAPA foot is shown to better mimic the ground reaction forces and ankle angles of a healthy gait.

BACKGROUND

The human ankle allows for rotational movement that resembles a ball and socket joint and provides the support for ground reaction forces up to ten times an individual's body weight [1]. Winter [1] found that the contraction of the plantar flexors act to create a moment about the ankle joint that is both twice an individual's body weight and twice the moment created about either the knee or hip. Kepple et al. [2] extended upon Winter's work to conclude that the forward motion that occurs during gait is generated primarily by the plantarflexor muscles about the ankle joint. Thus, it is essential for an ankle foot prosthetic to mimic the propulsion forces created by the ankle to produce a natural gait.

The simplest type of ankle foot prosthetic is the conventional non-articulating SACH (Solid Ankle Cushioned Heel) foot. The SACH foot is able to closely resemble the shape of an actual foot and provides the user with some cushioning during movement. However, it is unable to provide the range of motion and energy return of a healthy ankle [3]. Regardless, many less active amputees prefer the SACH foot because of the greater control it gives the amputee [4].

Dynamic response ankle foot prosthetics provide a passive solution by storing energy during the beginning of the gait cycle and using the stored energy to propel the foot forward [5]. Also called ESR for Energy Storing and Returning, the energy storage mechanism of dynamic response ankle foot prosthetics are similar to the role of the Achilles tendon. During gait, the Achilles tendon is stretched and stores potential energy that is released during push off [6]. The process of storing energy in the dynamic response ankle provides some resistance to movement similar to that of a healthy ankle [6].

Because the energy produced by the ankle joint during average walking speeds is almost completely self-sustaining with no net external energy loss, there is the potential for a purely mechanical mechanism such as the dynamic response ankle to generate the forward motion necessary for a healthy gait [7]. However, this potential has yet to be fully realized as the most efficient designs claim no more than a 90% energy return and it has yet to be proven that a dynamic response ankle foot prosthetic

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can significantly decrease metabolic cost [5, 8]. Stiffer designs provide greater propulsion forces which decrease metabolic cost but also requires more stabilization effort by the amputee which increases metabolic cost [9].

Active ankle foot prosthetics use microprocessors to provide another option for amputees. For speeds faster than normal walking, passive systems are not capable of fully emulating a healthy ankle because a positive net external energy is produced by the ankle [7, 10]. The use of active ankle foot prosthetics for faster speeds may be necessary in the future but current design limitations make this application less than ideal. Active ankle foot prosthetics can be over twice as heavy as conventional ankle foot prosthetics, are expensive, and experience hardware and control issues adjusting to different speeds [11, 12]. Fundamentally, active ankle foot prosthetics operate using preplanned kinematic trajectories as opposed to the impedance control mechanism of a human ankle [13]. Finally, while still operating as an ESR system, active ankle foot prosthetics are difficult to customize or match biomimetically in size and weight [14].

Missing in almost all available ankle foot prosthetics, the ankle joint has a ROM (range of motion) from about 50° plantar flexion to 20° dorsiflexion in a ankle [1]. Many ankle foot prosthetics only design for the ROM experienced during walking on an even surface, around 10-15% plantar flexion and 10% dorsiflexion [15]. While this may seem sufficient as the ROM of the ankle remains consistent with changes in speed, a study looking at individuals with limited ankle ROM due to a sprain showed that ankle ROM does impact gait symmetry in regards to step length and step time [16, 17]. Additionally, ankle ROM is important for walking on sloped surfaces as it helps accommodate for movement about different equilibrium positions [18–20].

DESIGN

The CAPA foot was designed in an attempt to address some of the flaws in previous ankle prosthetic systems and better mimic a healthy ankle. The application of 3D printing to the design allows for the CAPA foot to be easily and cheaply customized to better fit individuals of different sizes, natural gait patterns, and personal preferences. While the current model of the CAPA foot was made from Acrylonitrile Butadiene Styrene (ABS) with 100% infill, the design utilizes a rapidly advancing field and models can be later made from different materials that are lighter, more durable, and stronger [21]. The visual appeal of the CAPA foot can be optimized with 3D printing to avoid the uncanny valley and develop a prosthetic that has both a large degree of human likeness and familiarity [22].

The CAPA foot is assembled from four articulated components as shown in Figure 1 for the Phalanges (1), Metatarsal bones (2), Ankle (3), and Calcaneus (4). The relative motion

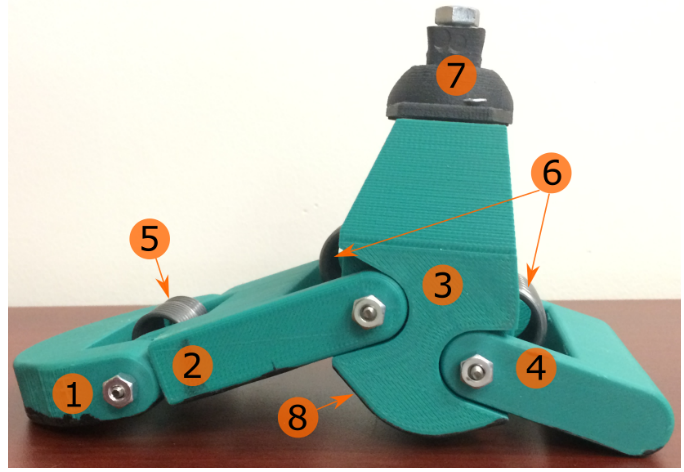

FIGURE 1. **1**-*Toe/Phalanges* **2**-*Foot/Metatarsals* **3**-*Ankle* **4**-*Heel/Calcaneus* **5**-*Two 1.18 N-m 180° steel torsion springs* **6**-*One 5.01N-m 120° steel torsion spring* **7**-*Carbon-fiber and nylon composite pyramid* **8**-*Rubber coating*

of these components allows for the CAPA foot to experience the full ROM of the ankle joint. Platforms prevent excess flexion for greater stability. The CAPA foot would be classified as a type of dynamic response foot as it stores potential energy at the joints and releases that energy to assist in forward movement. Unlike the majority of current ankle systems that only mimic the ESR that occurs in the Achilles tendon for plantar flexion, the CAPA foot stores energy at each joint to mimic toe flexion at location 5 in Figure 1 and both plantar flexion and dorsiflexion at location 6.

The energy is stored using torsion springs at locations 5 and 6 in Figure 1. The arms of the torsion springs are slid into holes designed into the 3D printed toe, foot, ankle, and heel components at locations 1-4 in Figure 1. During the unloading phase of a healthy ankle, there is a linear increase in the moment exerted by the ankle [7]. This can be emulated by a torsion spring because the force exerted by a spring also follows a linear profile and the angular velocity of an ankle is constant about a point [23]. The springs can be easily replaced, allowing the same ankle foot prosthetic to accommodate different applications or speeds. Each individual can adjust the stiffness to what would best reduce their metabolic cost of walking. Optimizing the stiffness is important to provide a balance between the greater propulsive forces provided by stiffer designs and the stabilization stiffer designs require [9].

The final design was assembled using 3.175 mm stainless steel shafts at each joint that extended through the springs and for the entire width of the CAPA. Choices in shaft size and direction of 3D printing were made with tearout failure in mind. A carbon-fiber and nylon composite pyramid head was bolted on so the design could be attached to other prosthetic pieces at location 7 in Figure 1. Rubber was painted onto the bottom of the CAPA for traction shown by location 8 in Figure 1. The CAPA is 20 cm in length, 10 cm in width, and 9 cm in height. With a weight of 662.9 g, it is heavier than the SACH foot that weighs 415.1 g. However, 3D printing the CAPA foot using different materials such as a carbon-fiber nylon composite can reduce the weight in future models.

METHODS

Data was collected using the CAREN (Computer Assisted Rehabilitation ENvironment) shown in Figure 2 that is equipped with 10 motion capture cameras, a split-belt treadmill with force plates, 180° of projection screens, and a six degree of freedom motion base. The CAPA foot was compared to the conventional SACH foot using a prosthetic simulator on able-bodied individual's right leg. The prosthetic simulator in Figure 3 was assembled from a portion of an iWalk© and a polycentric prosthetic knee. The subject who weighed 58 kg walked at a speed of 0.7 m/s for 1 min first using the simulator with the CAPA foot, then using the simulator with the SACH foot, then walking normally. Data from the position coordinates from 18 markers and the magnitude and direction of forces exerted on the treadmill was collected for analysis. Ten steps on the right leg with times within +/- 0.3% of the mode step time were chosen and the forces and angles during gait cycle compared.

FIGURE 2. CAREN: *Computer Assisted Rehabilitation ENvironment*

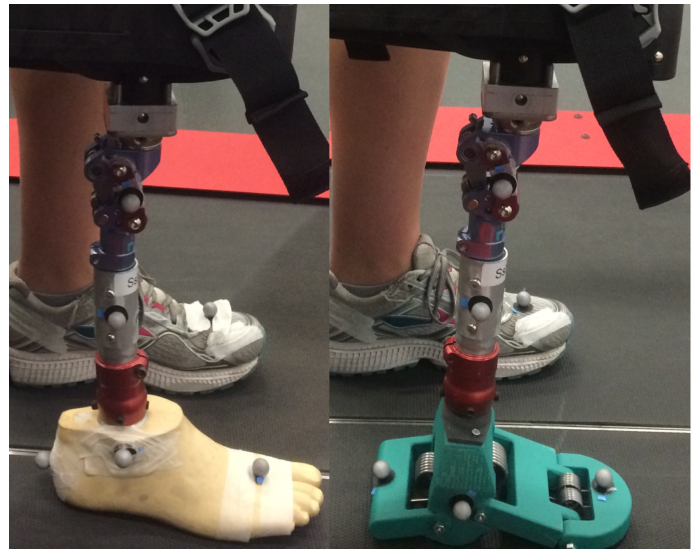

FIGURE 3. *Prosthetic simulator with position markers on CAREN using the SACH foot (left) and the CAPA foot (right)*

RESULTS

The braking and push off forces can be analyzed by looking at GRF (ground reaction forces) exerted horizontally in the front to back direction (z-axis on CAREN). Figure 4 plots ground reaction forces with respect to gait cycle increasing from heel strike to toe off and starting when the heel marker is at its frontmost position to when it is at its backmost position. At the beginning of the gait cycle, heel strike is experienced and negative GRF are generated. The step proceeds with push off that produces positive GRF and assists in the forward motion of gait. The gait cycle ends in swing phase with close to zero GRF. It can be observed from Figure 4 that the GRF of the CAPA foot during gait cycle follows more closely to normal gait than the SACH. The average push off force during testing was greater for the CAPA foot (97.7 N) compared to the SACH foot (95.9 N). It also can be noted from Figure 4 that the magnitude of the braking force of the CAPA foot and the SACH foot was less than that experienced during normal walking.

The ankle angles were computed from the positions of the toe, ankle, and knee markers. Figure 5 shows that the CAPA exhibits a similar ROM during gait that an able-bodied individual experiences, from around 15° plantar flexion to 10° dorsiflexion. The results of normal walking were removed from Figure 5 because the subject exhibited less dorsiflexion and excessive pronation during gait that caused the ankle angles to substantially differ from the well understood ankle angles of an able-bodied individual. Instead, raw ankle angle data collected by Winter was plotted to demonstrate typical ankle angles [24]. Gait begins with an initial increase in ankle angle for plantar flexion during heel strike and the angle decreases as the step proceeds reaching minimum dorsiflexion just before push off during which plantar flexion occurs. The CAPA foot was shown to emulate the ankle angles of a healthy gait much better than that of the SACH foot whose ankle angles remained relatively constant throughout the gait cycle.

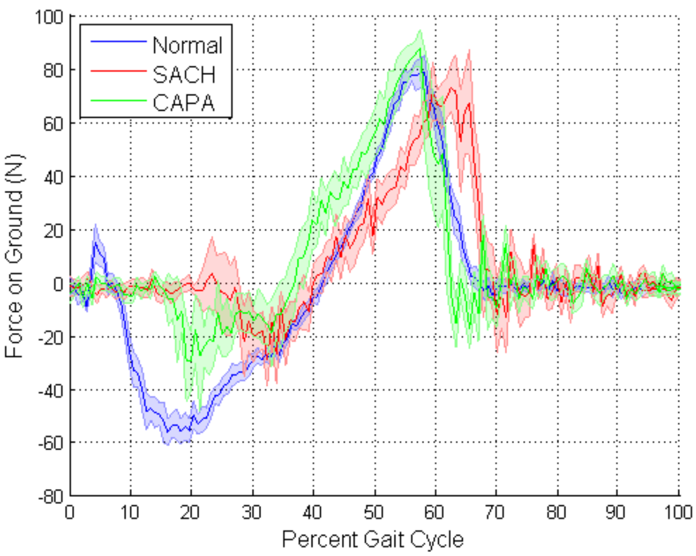

FIGURE 4. *Ground Reaction Forces During Gait Cycle: The shaded areas represent half the standard deviation between steps.*

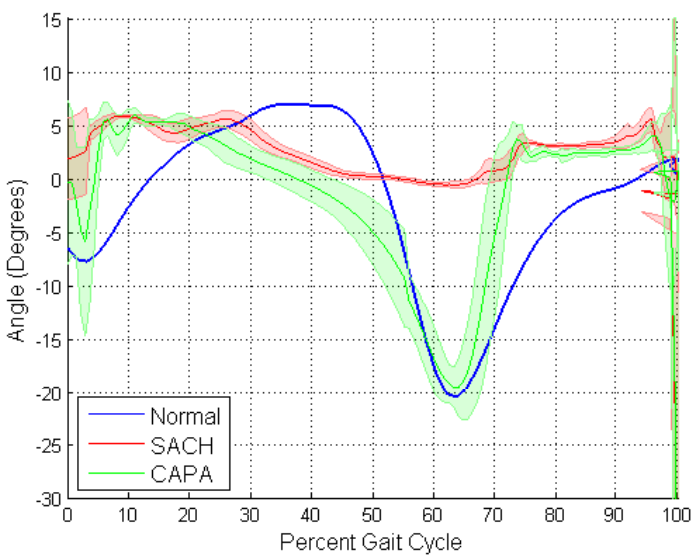

FIGURE 5. *Ankle Angles During Gait Cycle: The shaded areas represent half the standard deviation between steps.*

DISCUSSION

The GRF experienced while wearing the CAPA foot came closer to emulating normal walking than the SACH foot. However, the push off force was only slightly greater for the CAPA foot despite the ESR mechanisms of the springs. Stiffer springs could help achieve a larger push off force.

Both the CAPA foot and the SACH foot fell short of replicating the braking forces during the beginning of the gait cycle. However, because the braking force acts against forward motion, high braking forces may inhibit an amputee from producing the necessary forward propulsion from their prosthetic limb. Also, high GRF could cause greater socket forces and lead to discomfort.

With regards to the movement in the sagittal and tranverse planes that a healthy human ankle experiences, the design of the CAPA foot falls short. Incorporating sagittal and transverse plane movement into the design improves stability and walking on uneven terrain [8]. This has been accomplished by multi-axial prosthetic ankle foot designs that offer a good alternative to the SACH foot for more active amputees [25]. Future models can integrate some of the beneficial aspects of multi-axial designs such as a split foot mechanism to better emulate movement of a healthy human ankle. Also, shock absorption mechanisms can be implemented to improve future models.

CONCLUSION

This experiment demonstrates the potential of the CAPA foot to be used by lower limb amputees. When compared to the conventional SACH foot, the ground reaction forces and ankle angles better mimicked that of a healthy human gait. However, testing was only done on one individual. More subjects would help the researchers better understand the differences between the CAPA foot and existing prosthetic ankle feet. Testing on transfemoral and transtibial amputees might prove more effective for comparison than the use of a prosthetic simulator on an able-bodied individual.

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