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# Design of an Underactuated Powered Ankle and Toe Prosthesis

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*Abstract*— **Powered ankle/foot prostheses aim to replicate the biomechanical function of the missing biological limb. Biomechanical analysis shows that while the ankle injects positive energy into the gait cycle, the toe joint dissipates energy. Yet virtually all powered ankle/foot prostheses use custom ankle actuators in combination with carbon fiber foot springs to imitate the function of the missing ankle/foot complex. Here we introduce a powered ankle and toe prosthesis with an underactuated mechanism. The underactuated mechanism connects the toe and ankle joints, providing biomechanically accurate torque and enabling mechanical energy recovery during gait. The proposed powered ankle/toe prothesis is the first device to match the weight, size, and build height of microprocessor-controlled prostheses.**

*Clinical Relevance*—**A lightweight, efficient prosthesis with powered ankle and toe joints has the potential to improve ambulation in individuals below-knee amputations.**

## I. INTRODUCTION

Lower-limb amputation is becoming more prevalent in the United States [1], with below-knee amputations being the most common [2]. Below-knee amputations create significant barriers for mobility, for instance, making it more difficult to walk [3], climb stairs and ramps, and transition from sitting to standing [4]. Mobility is the only significant independent factor in quality of life decreases among some studied amputee populations [5], and improving the mobility of individuals with below-knee amputations can have a significant impact on a large and growing number of people. Thus, there is a need for new prosthetic technologies with the ability to improve mobility in below-knee amputees.

Most ankle/foot prostheses for individuals with below-knee amputation are energetically passive devices with a combined ankle/foot structure which do not have an articulated ankle joint [6]. More recently, ankle/foot prostheses with articulated ankle joints have been introduced in the market which use passive springs and dampers to provide resistance at the articulated ankle joint. In the most advanced devices, microcontrollers are used to actively regulate the resistance at the ankle joint during gait. Microprocessor-controlled prostheses have shown to improve ambulation compared to simpler passive prostheses [7] and several similar research devices are currently under development [8]–[12]. However, none of these ankle/foot prostheses can contribute net-positive energy to the gait cycle, which is a key characteristic of the biological ankle. Thus, there is a need for ankle/foot prostheses capable of injecting net-positive energy into the gait cycle.

Powered prostheses aim to replicate the biomechanical function of the missing biological ankle/foot complex with embedded electromechanical actuators [13] Virtually all powered ankle-foot prostheses are designed with a custom ankle actuator connected to a carbon fiber foot plate [14]. Typically, the custom ankle actuator has one degree of freedom in the sagittal plane, and is designed to replicate the ankle torque and speed observed in nonamputee subjects during ambulation [15]–[20]. However, biomechanical studies show that the biological foot has an important function during gait that the carbon fiber plates commonly used in powered ankle/foot prostheses cannot replicate. Thus, we need novel powered ankle/foot prostheses to better imitate the function of the biological foot.

Biomechanical studies of nonamputee gait suggest that the metatarsal joint (i.e., toe joint) plays an important function during gait [21], [22]. Individuals with metatarsophalangeal arthrodesis, which is fusion of the toe joint, have decreased step length and reduced plantarflexor moment in the affected side [23]. Studies with a passive prosthesis emulator show that the stiffness of the toe joint has a significant effect on ankle power, center of mass power, and push-off work during walking [24]. Moreover, a previous study has shown improvements in the metabolic cost of walking of individuals with below-knee amputations using a passive prosthesis with midfoot and metatarsophalangeal joints [25]. Because the toe joint has a considerable effect on gait biomechanics, replicating its function in powered ankle/foot prostheses may result in improved ambulation.

Only one powered prostheses with separate actuators for the ankle and the toe joint has been previously developed [26], [27]. However, this powered prosthesis is substantially heavier than powered devices prostheses without active toe joints (i.e., 2.95 kg vs 2.2 kg [13]), which has a negative impact on metabolic effort and socket stability [28]. To address this limitation, in this paper, we present the design of a lightweight underactuated powered ankle and toe prosthesis. Instead of dissipating mechanical energy at the toe joint, the proposed design transfers energy from the toe to the ankle joint during walking. Simulations show that this mechanical energy recovery system has the potential to improve electrical efficiency. The proposed powered ankle/toe prothesis is the first self-contained device to match the weight, size, and build height of microprocessor-controlled ankle/foot prostheses. A prosthesis with these characteristics has the potential to improve ambulation in individuals with below-knee amputations.

## II. KINEMATIC MODEL

We designed an underactuated mechanism to power both the ankle and toe the joint with a single actuator. The kinematics of the proposed underactuated system comprise

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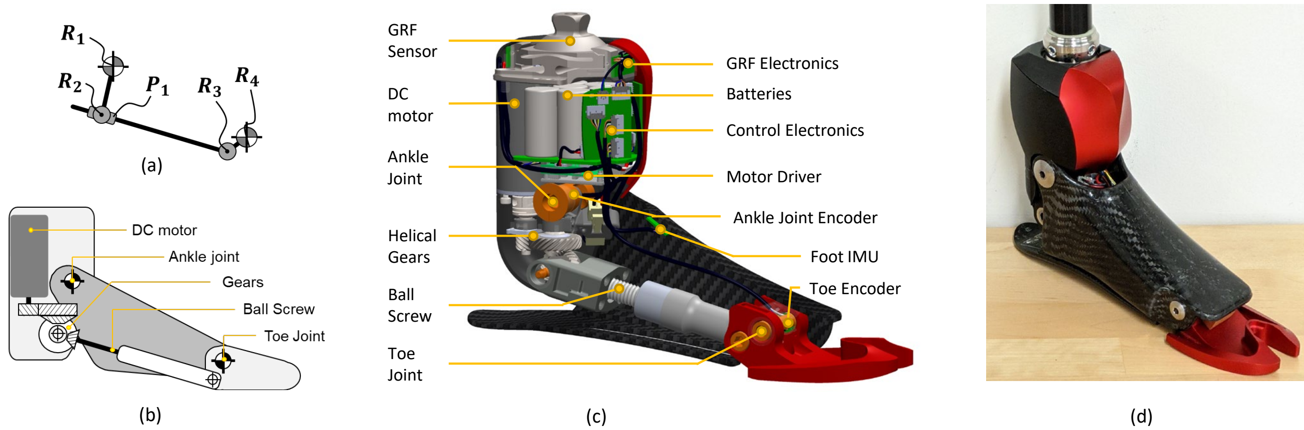


**Figure 1. (a) Closed-loop kinematics of the propsed ankle/toe prosthesis where $R_1$ is the ankle joint, $R_4$ is the toe joint, and $P_1$ is the input joint. (b) Simplified diagram of the underactuated mechanism with callouts for major components. (c) Sectioned view of the CAD model showing the mechanical and electrical components. (d) Photo of the proposed underactuted powered ankle/toe prosthesis.**

five joints in closed configuration ($R_1R_2P_1R_3R_4$) creating a five-bar mechanism with two degrees of freedom (Figure 1). Because the system is underactuated, both the torque at the ankle joint ($R_1$) and at the toe joint ($R_4$) depend on the force applied by the input joint ($P_1$), which is a linear actuator. Moreover, given a certain force at the input joint ($P_1$), the torque at the ankle joint and the torque at the toe joint depend on the angular position of both the ankle ($R_1$) and the toe joint ($R_4$) due to the non-linearity of the proposed kinematics (Figure 2(a)). Thus, the torques at the ankle and toe joints are not independent and the ratio between ankle and toe torque changes with the ankle and toe joint position (Figure 2(b)).

Due to the presence of a mechanical end-stop, the position of the toe joint has a considerable effect on the behavior of the proposed underactuated mechanism. When the toe joint is at the end of its range of motion (i.e., the toe joint is resting on the mechanical end-stop), one degree of freedom is removed from the closed kinematic chain and the system is no longer underactuated. This function is important because the toe joint stays in a neutral position, against the mechanical end stop, for a significant portion of the gait cycle, mostly moving during late stance when the ankle generates power and the toe absorbs power (Figure 1). The toe stays in this neutral position because a spring and damper gently force the toe against the mechanical end-stop when no force is applied at the input joint. Thus, the under actuation is limited to the late stance portion of the gait cycle.

## III. Mechatronic Design

The kinematic model of the proposed underactuated mechanism was used in combination with a simulation framework similar to the one used for our previous powered prostheses to guide the design of the proposed powered ankle/toe prosthesis [19], [29], [30]. As can be seen in Figure 1, the proposed powered ankle and toe prosthesis comprises an underactuated mechanism integrated with a structural carbon-fiber foot shell, a shank frame, and a toe frame. Both the toe and shank frames are machined out of 7075-T6 aluminum. The carbon-fiber foot shell is adapted from a commercially available microprocessor-controlled ankle/foot prosthesis (Ottobock Meridium). A linear actuator powers both the ankle and toe joint using a brushless DC motor (Maxon EC-30 4-Pole, 200 Watts), a ballscrew and nut (Ewellix 12x2R SD) assembly with a double-row ball bearing (Schaeffler ZKLN0619-2RS-XL), and a custom gearbox based on helical and bevel gears. The ball screw is located inside the foot shell, whereas the brushless DC motor is located inside the shank frame.

The custom gearbox enables the DC motor to remain in a fixed position with respect to the shank frame while the ankle and toe joint move and the ballscrew pivots. To achieve this movement, the motor shaft transfers power to a set of three bevel gears (Boston Gear SH302-P, SH302-G) through a helical gear pair (8:24 ratio, Boston Gear H2424R and H2408L). The first bevel gear is coaxial and directly connected to the output helical gears. The second bevel gear spins freely and is coaxial with the pivot joint ($R_1$, Figure 1). The third bevel gear is coaxial with the ball screw axis of rotation and transfers power to the ball screw.

The ball screw nut transmits forces to a shaft on the toe structure (i.e., $R_3$, Figure 1), which has an offset from the toe joint ($R_4$), and a shaft on the shank structure ($R_2$). The ball screw also has an offset from the ankle joint ($R_1$), providing a simultaneous torque to both the toe and ankle joints. The rotational joints in the toe ($R_3$), as well as the main ankle joint ($R_2$), use hardened steel shafts and dry bushings (IGUS GFM-1011-10, IGUS GFM-1516-15). The ankle has a full range-of-motion of 40 degrees (20 in dorsiflexion and 20 in plantarflexion). The toe has a full range-of-motion of 45 degrees. The shank frame connects to an instrumented

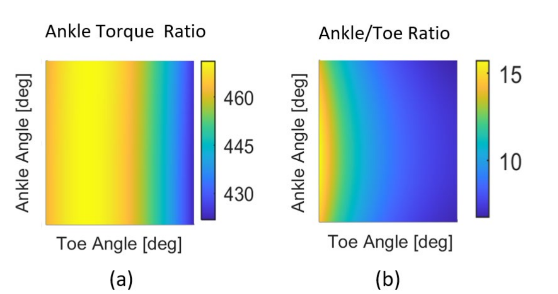


**Figure 2. (a) Ankle torque ratio as a function of ankle and toe joint position across the whole range of motion. (b) Ratio between the ankle and toe torque as a function of the of ankle and toe joint position across the whole range of motion.**

pyramid adapter which functions as a ground reaction force sensor [31].

The embedded electrical system has two processing electronic boards and one power electronic board. The first processing electronic board contains a microcontroller (PIC32MK0512MCF100) and an analogto-digital-converter (Analog Devices AD7906). This first processing electronic board runs control algorithms, sends the desired motor current commands to the power electronic board using pulse-width modulation, and communicates with the second processing electronic board using serial peripheral interface. The second processing electronic board uses a 32-bit microcontroller (PIC32MK0512MCF100) to communicate and processes data from ankle/foot sensors, including the encoders for the ankle and toe joints (AMS AS5047U), the inertial measurement units mounted on the shank and foot frames (Bosch BMX160), and the custom ground reaction force sensor (Texas Instruments ADS8887). The power electronic board features a motor driver (Elmo Gold Twitter 80/80SE) and motor chokes. The ankle contains a 6-cell 1200 mAh (KeepPower IMR18350) lithium-ion battery, as well as voltage conversion electronics for both 5 Volt and 3.3 Volt buses.

## IV. SIMULATIONS

The proposed device has the objective of providing biomechanically accurate ankle and toe functions during ambulation. As can be seen from nonamputee biomechanical analysis of a 70-kg person (Figure 3), both the ankle and toe joints provide torque primarily in one direction (i.e., plantarflexion) during walking. However, the ankle joint generates much greater peak torque than the toe joint (i.e., 1.25 Nm/kg vs 0.12 Nm/kg) [32]. In contrast, the peaks of absolute joint velocities for the two joints are comparable (i.e., 193 °/s vs. 266 °/s) and opposite in direction. This trend is particularly evident in mid and late stance (30%-60% of Stride). The toe primarily dissipates power whereas the ankle mostly generates power. Thus, the required power of the ankle and toe joints combined is smaller than the power of the ankle joint alone, a fact that motivates the proposed underactuated mechanism.

Similar to [30], Dynamic simulations were performed using Matlab to preliminarily analyze the performance of the proposed system. Starting from the previously mentioned biomechanical output joint torque and speed, the simulation program computed the required input torque, speed, power and energy from the DC motor. The geometry of the linkage and the parameters of the transmission system (e.g., gear ratio, ballscrew lead) were also inputs to the simulation. Notably, the simulation framework included the inertial effect of the transmission system and accounted for a 10% power loss in the device's mechanics. We assumed that the output ankle and toe velocity and ankle torque would perfectly match the non-amputee biomechanics reference data. Due to the underactuated nature of the system, the output toe torque might then differ from that of non-amputee biomechanics. To assess the relative performance of the proposed mechanism, an equivalent powered ankle/foot prosthesis without a powered toe joint was also analyzed in simulation.

Results of the dynamic simulations confirmed that the proposed mechanism with the toe addition has a substantial benefit on performance. Simulations show that the instantaneous motor power was 33% lower in the proposed underactuated system compared to an equivalent system without the toe joint (Figure 3(g)). This result is due to the toe velocity being negative while the ankle velocity is positive during walking (Figure 3(b)), which results in a reduction of the instantaneous velocity of the motor (Figure 3(f)), which powers both the ankle and toe joint. Moreover, simulations show that the proposed underactuated system has the potential to decrease electrical energy consumption by 40%. This result is due to the biomechanical toe power being negative during push-off when the ankle power is positive (Figure 3). Because the toe is mechanically connected to the ankle joint, the motor power is the sum of the toe and ankle power. Thus, the negative toe power reduces the motor power, lowering the electrical energy consumption (Figure 3 (h)). Finally, it is worth noting that the resulting toe torque of the underactuated system closely follows healthy biomechanics reference, suggesting no significant deviation/disruption of normative gait (Figure 3 (a)).

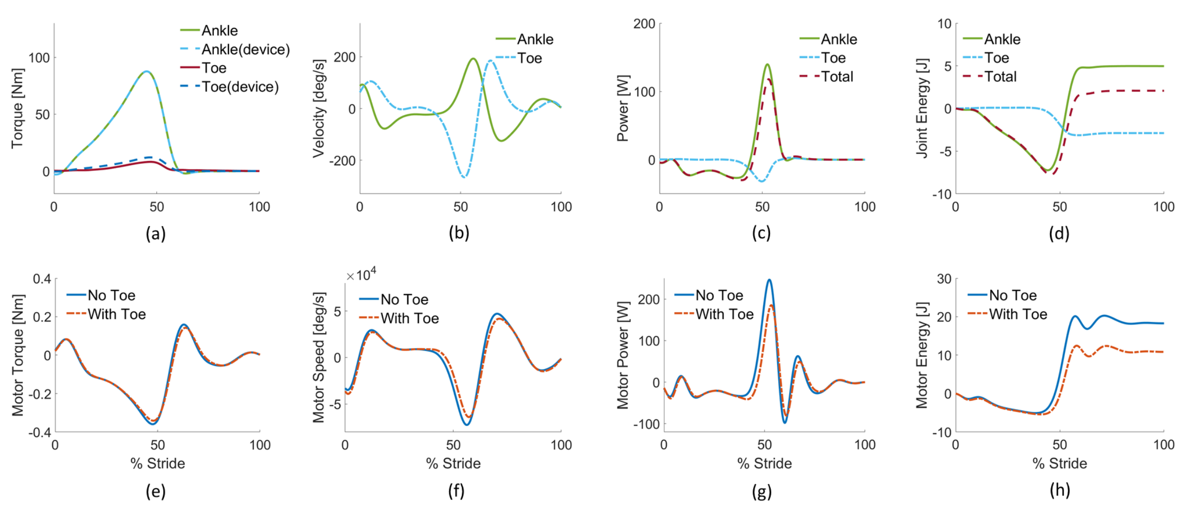


**Figure 3. TOP ROW: Biomechanical data taken from [32] of non-amputee toe and ankle joints during walking. (a) Biomechanics reference and device torque at the ankle and toe joints. (b) Speed of the ankle and toe joints. (c) Mechanical power of the ankle and toe joints. (d) Mechanical energy of the ankle and toe joints. BOTTOM ROW: Required motor performance in two scenarios (with and without underactuated toe joint), obtained from simulation (e) Motor torque. (f) Motor speed. (g) Motor electrical power, including Joule heating loss. (h) Motor electrical energy.**

## V. Conclusion

This paper presents the modeling, simulation, and design of an underactuated powered ankle/toe prosthesis. Simulations suggest that the proposed underactuated mechanism can regenerate mechanical energy between the toe and ankle joints, which is expected to substantially reduce electrical energy consumption. The proposed powered prosthetic device has a build height of 178 mm and a weight of 1497 g, which closely matches available passive microprocessor-controlled prostheses for the first time. Future work will be focused on developing a walking controller and testing the proposed device with individuals with below-knee amputations. These human studies are necessary to test whether the proposed underactuated mechanism is capable of energy regeneration and whether the articulated toe joint improves ambulation ability in individuals with below-knee amputations.

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