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Toward a Low-Cost Modular Powered Transtibial Prosthesis: Initial Prototype Design and Testing

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1 Background

In human walking, the ankle plays an important role of supplying power needed for the forward motion [1]. However, traditional transtibial (TT, a.k.a. below-knee, BK) prostheses are passive, lacking the ability of generating power output in the prosthetic ankle. Consequently, amputees fitted with such prostheses suffer from multiple issues (asymmetric gait, greater metabolic energy expenditure, etc.).

To address such issues, researchers have explored various technical approaches to develop powered TT prostheses. Hydraulics and pneumatics have been attempted, leveraging the high power density with these actuators (e.g. [2]). Electromagnetic actuators were used more extensively with its technological maturity and convenience in packaging. Typical examples include the multiple prototypes developed by the MIT Biomechatronics Group (e.g., [3]), the SPARKy project, and the Vanderbilt Transtibial Prosthesis.

The TT prostheses mentioned above all include powered ankle joints to provide power for the users' locomotion. However, cost and complexity are often given lower priority than performance in the development of such devices. Powered TT prosthesis is a typical low-volume product from a commercial perspective, and the resulting high cost is a major hurdle for the large-scale adoption among amputee users. General robotic components (motors, gearsets, etc.), in contrary, are produced in large quantities with relatively low prices. Such contrast is the major inspiration for this work: the goal is to develop a modular powered TT prosthesis based on low-cost commercial robotic components while minimizing the complexity in manufacturing and assembly.

2 Methods

The powered TT prosthesis developed in this work is **APPL-A-E1**, representing the first electric version of the *Alabama Powered Prosthetic Limb – Ankle* (Fig. 1). Two commercial products were selected as the foundation of the entire design: a brushless permanent-magnet motor with 70 W power rating (EC 45 flat, Maxon Motor, Sachseln, Switzerland), and a harmonic drive gear set with 160:1 ratio (SHD-20-160-2SH, Harmonic Drive, Peabody, MA). The former provides a peak torque of 200 mNm and a maximum permissible speed of 10,000 rpm at a very light weight of 141 g. The latter provides a large gear ratio in a very compact package (90 mm outer diameter and 19 mm thickness). Furthermore, a cross-roller bearing is included to take both radial/axial loads and bending moments, simplifying the

design for the supporting structure. These components were selected to ensure the compactness and light weight of the prosthesis while providing acceptable performance.

To form a complete power train, a timing belt drive with 1.25:1 ratio is placed between the motor and the harmonic drive. This configuration provides multiple advantages, including reducing device width, providing adjustability for the total gear ratio, and reducing the manufacturing accuracy requirement with the flexibility of a belt drive. Combining the two stages, the total ratio reaches 200:1, generating a peak output torque of 40 Nm when transmission loss is neglected.

To reduce the complexity in fabrication and assembly, most components are combined into modules before being integrated into the prosthesis. The motor is combined with the input pulley of the belt drive to form the motor-input pulley module. The output pulley forms the basis of the output pulley module, which also includes the intermediate shaft and its support structure. Both modules were then mounted to a central structural piece, namely Support Plate. Support Plate also bears the axial and bending loads in walking. As shown in Fig. 1a, Support Plate has an opening to allow the motor-input pulley module to be mounted with vertical adjustability. As such, the belt tension can be adjusted without using a tensioner. Support Plate also features a flat top surface to mount the standard prosthetic connector, as well as ribs on both vertical edges to improve strength and rigidity. Additionally, the lower half of the Support Plate provides the mounting surfaces for the output pulley module and the harmonic drive assembly on each side. The fully-supported intermediate shaft in the output pulley module extends through the Support Plate and drives the wave generator of the harmonic drive. In the harmonic drive, the flexspline is mounted to the Support Plate, and the circular spline serves as the output. Finally, a foot adapter is used to mount the entire assembly to a carbon fiber foot plate to form a complete TT prosthesis (Fig. 1b).

A special feature of the TT prosthesis worth mentioning is a unidirectional leaf spring with the function of providing extra push-off torque and improving the energy efficiency in walking. In the stance phase, after the foot lies completely flat on the ground, the ankle starts dorsiflexion until reaching the maximum joint angle, and in the process the plantarflexional ankle torque also increases to the maximum. This energetic behavior is similar to loading a torsional spring and storing energy for the subsequent push-off. To simulate such behavior, a carbon fiber leaf spring is integrated into the foot plate, which provides resistive force to the ankle motion only when the joint angle exceeds $\sim 4^\circ$ (i.e., the ankle is in dorsiflexion). With the spring stiffness at 4 Nm/deg, the peak torque for powered push-off can be increased by approximately 24 Nm, reducing the torque requirement for the actuation system significantly.

3 Results

A prototype of the modular powered TT prosthesis has been fabricated and tested. As shown in Fig. 2, 3D-printed non-load-bearing plastic covers were added on both sides to protect the internal components. For the control purposes, the prosthesis is instrumented with sensors and other electronic components. The ankle angle is measured with a magnetic encoder (AS5145, AMS, Premstaetten, Austria), which provides non-contact joint position

measurement to improve the reliability in use. The power output of the DC motor is regulated with a PWM servo drive (AZBDC20A8, Advanced Motion Controls, Camarillo, CA), which controls the motor current according to the PWM duty cycle. Onboard control calculation is conducted with a micro-controller (Microstick II, Microchip Technology Inc., Chandler, AZ), which implements a finite-state impedance controller for walking.

Four phases are included in the state machine of the controller, including three stance phases (early stance, middle stance, and late stance) and a swing phase. In each phase, the controller simulates the dynamic behavior of a linear spring combined with a viscous damper, and thus guarantees the passivity of the system. From the global perspective, the shift in equilibrium point of the artificial spring generates the desired energy input at the phase transitions, and thus the system still remains energetically active to support the user's locomotion. The details of the controller can be found in [2].

For the initial testing of the proposed TT prosthesis, a healthy subject was fitted with the prosthesis through an able-body adapter. The adapter is constructed based on a pair of skate boots, which lock the user's biological ankles and allow the prosthesis to be attached underneath through the standard pyramid connector. With this setup, the authors were able to test the prosthesis in treadmill walking without involving an amputee subject. A set of typical results are shown in Fig. 3, including the ankle position and torque trajectories within a gait cycle, both of which are very similar to the corresponding trajectories plotted from biomechanical data [1].

4 Interpretation

Presented in this paper is a new powered TT prosthesis, for which a modular design approach was adopted to reduce the cost and complexity. Off-the-shelf commercial components were used and combined into basic modules, and the modules were mounted on a central structural piece to form the prosthesis. A leaf spring were also integrated into the foot plate to increase the push-off torque and improve the energy efficiency. A prototype has been fabricated and tested, with the results demonstrating that this new prosthesis is able to provide a natural gait in treadmill walking.

Acknowledgments

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References

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Fig. 1. Major modules and components of the powered TT prosthesis APPL-K-E1 (timing belt not modeled): (a) Disassembled state; and (b) Pyramid connector and foot plate to be attached.

Fig. 2.
The powered TT prosthesis prototype.

(a)

(b)

Fig. 3.

Ankle position trajectory (a) and torque trajectory (b) measured in the testing of the powered TT prosthesis.