Walking Metabolic Cost of Transtibial Amputee at Slow Speed Using Robotic Prosthesis with Damping Behaviors

Yanggang Feng, Baojun Chen, Tianshuo Huang, and Qining Wang*
The Robotics Research Group, College of Engineering, Peking University, Beijing 100871, China.
*E-mail: qiningwang@pku.edu.cn

1 Introduction

The weight of most existing robotic transtibial prostheses are more than $2kg$ due to their power motors and complex mechanical structures[1, 2, 3, 4]. A heavy prosthesis tends to increase the knee extension load and cause larger interaction force between the adaptor and the residual limb. Therefore, we have developed a robotic prosthesis named as PKU-RoboTPro (short for ROBOtic Transtibial PROsthesis, Peking University), which has light weight and can adapt to different terrains [4].

In our previous studies,we have evaluated the performance of the PKU-RoboTPro prosthesis on gait symmetry and walking stability. Wang *et al.* proposed a damping control strategy, which improved the amputees' performance on gait symmetry and walking stability [4]. However, the performance of the proposed prosthesis on walking metabolic cost has not been investigated. In this paper, we further evaluate the performance of the amputee with the robotic prosthesis on walking metabolic cost under different slopes.

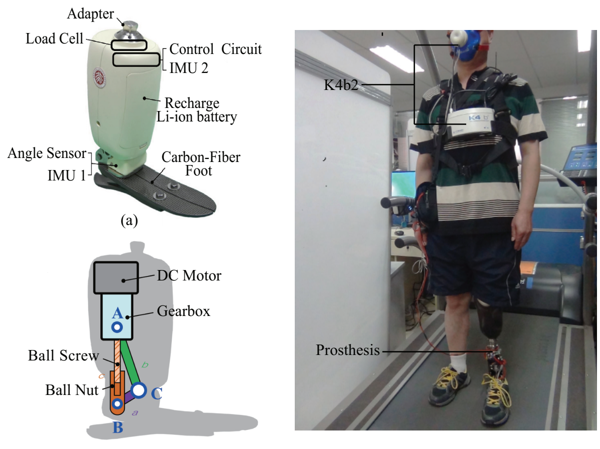

Figure 1: (a) The prototype of the proposed prosthesis (PKU-RoboTPro), including an active ankle joint and a carbon-fiber foot. All the modules, including mechanical structure, control circuits, sensors and battery, have been integrated in the prosthesis. The installed sensors includes one angle sensor, one load cell, and two IMUs (IMU 1, placed on the foot, and IMU 2, placed on the shank.). The total weight of the prosthesis is $1.3kg$ (excluding the rechargeable Li-ion battery), which is comparable to the able-bodied limb. (b) Ankle model, simplified as a three-bar mechanism which comprises three bars a, b, and c, and three hinges, A, B, and C. a can be seen as the foot, b as the shank, and C as the ankle joint. (c) Experimental setup.

2 Transtibial Prosthesis and Experimental Methods

2.1 Transtibial Prosthesis: PKU-RoboTPro

The prototype of PKU-RoboTPro is shown in Fig. 1(a). Current prosthesis is an integrated one that takes all the modules in the transtibial prosthesis including mechanical structure, control circuits, sensors and battery. As shown in Fig. 1(b), the model of the ankle joint can be simplified as a three-bar mechanism which comprises three bars a, b, and c, and three hinges, A, B, and C. To visualize the model, a can be seen as the foot, b as the shank, and C as the ankle joint. c is a customized bar, which is made up of a motor-driven ball screw transmission. The screw pitch is $2mm$. The motor system uses a $50W$ DC brushless motor from Maxon (EC $45-50W$), equipped with a $5.8:1$ reduction gearbox. The angle range of the ankle joint is from 25^o dorsiflexion to 25^o plantar flexion. The total weight of the proposed prosthesis (excluding the rechargeable Li-ion battery) is $1.3kg$.

Three kinds of sensors are installed on the prosthesis including one load cell, one angle sensor and two inertial measurement units (IMUs), as shown in Fig. 1(a). The single-axis load cell (Interface LBS) has a measurement range of $0-250lbf$ and is used to detect the interaction force between the residual limb of the amputee and the prosthesis. The absolute angle sensor (Angtron-RE-25) is used to measure the ankle angle with a 0-360^o range and 12-bit resolution. Two IMUs are used to measure the inclination angle and other inertial information such as the acceleration and the rotation rates. One IMU is installed on the upper surface of the foot, and the other is installed on the shank of the prosthesis. Each IMU has an embedded tri-axis gyroscope and a tri-axis accelerometer. The gyroscope has a full-scale range of $2000^o/s$ and a resolution of $0.06^o/s$ while the accelerometer has a full-scale range of $157m/s^2$ and a resolution of $0.005m/s^2$.

2.2 Experimental Methods

As the ankle joint has different kinematic and kinetic properties in stance phase and swing phase, these two phases have different control strategies, and readings of the integrated load cell are used to detect phase changes. During the stance phase, we proposed a damping control strategy. The principle of damping control strategy is that if we switch on/off the motor-winding-short with a pulse width modulation (PWM) signal, the braking torque during the switch-on period will be very large and the ankle joint can only rotate at a very low speed, while the braking torque during the switch-off period will be very small and the joint can rotate quickly. The damping output acting on the ankle joint consists of two parts: ankle-position-related damping and GRF-related damping. During the swing phase, we developed a Proportional-Derivative(PD) position control strategy. The prosthetic ankle joint is adjusted to an appropriate position, so as to prevent the foot from dragging along the ground and better absorb impacts from the ground to maintain balance[5].

A male unilateral transtibial amputee subject (age: 29 years; height: $170cm$; mass: $68kg$) was recruited in the research, and provided written and informed consent. The amputee subject has been amputated (left leg) for 7 years.The weight of the passive prosthesis with a carbon-fiber foot is $680g$.

Oxygen consumption (V_{O_2}) and carbon dioxide production (V_{CO_2}) were measured by a computer interfaced portable metabolic unit (K4b2, Cosmed, Rome, Italy), as shown in Fig. 1(c). It was warmed up for one-hour and was calibrated for turbine flow, gas concentration, and delay before test. Control parameters were tuned according to the amputee's feedback.

Before testing, the subject walked on the treadmill at $0.5m/s$ for acclimatization with the passive prosthesis and robotic prosthesis, respectively, for at least 30 minutes. During testing, the subject walked at each of three slope conditions ($-5°$, $0°$ and $5°$) at $0.5m/s$ with the passive prosthesis and robotic prosthesis, respectively. The subject took a rest for 5 minutes, and then walked on the treadmill for 10 minutes while metabolic data was recorded in each trial. The time interval between two trials is 15 minutes. The net values of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ were determined by subtracting the resting $\dot{V}_{O_2}$ (ml/s) and $\dot{V}_{CO_2}$ (ml/s) values from the walking trial data. Metabolic energy consumption ($\dot{E}_m$, J/s) was calculated from these net values using the formula form[6].

$$\dot{E}_m = 16.48(J.ml^{-1})\dot{V}_{O_2} + 4.48(J.ml^{-1})\dot{V}_{CO_2}. \quad (1)$$

To derive metabolic energy expenditure (EE, $J/(kg.s)$), $\dot{E}_m$ was divided by body mass (Kg). EE reflects the metabolic power per *kilogram*.

3 Experimental Results

Table 1 presents the amputee's walking metabolic cost at $0.5m/s$ under different slopes. P refers to the passive prosthesis,while R refers to the robotic prosthesis.

Mean EE value of the amputee with the passive prosthesis and the robotic prosthesis, increases as slope increases ($-5°$, $0°$ and $5°$) at $0.5m/s$. Results reveal that mean EE value of the amputee with the robotic prosthesis is smaller than that with the passive prosthesis for three slope conditions at $0.5m/s$, which implies that the robotic prosthesis can improve walking metabolic economy at low walking speed. Compared with the passive prosthesis, the improvement with the robotic prosthesis in walking metabolic economy for slope ascent and descent is higher than that for level-ground walking, which indicates has a better adaptability to slope walking than the passive one. It is probably because the robotic prosthesis can intelligently adjust ankle angle for different ground slopes.

Table 1: Walking metabolic cost at $0.5m/s$ under different slopes

Slope (°)	P(EE) ($J/(kg.min)$)	R(EE) ($J/(kg.min)$)	1 - R(EE)/ P(EE) (%)
-5	73.7	68.8	6.65
0	107.06	104.99	1.93
5	188.86	173.12	8.33

4 Conclusion and Future Works

We evaluate the performance of the amputee with the robotic prosthesis on walking metabolic cost at slow speed under different slopes. Experimental results indicate that the improvement with the robotic prosthesis in walking metabolic economy for slope ascent and descent is higher than that for level-ground walking compared with the passive prosthesis at slow walking speed. In this study, the amputee was unable to walk on the treadmill at highe speed, mainly because he was not yet familiar with walking on treadmill. Therefore, the amputee was only required to walk with the robotic prosthesis and the passive prosthesis at low speed. In the future, we will carry out experiments on more subjects at different speeds to obtain more convincing results.

References

[1] R. Versluys et al., Int. J. Modell. Identif. Control, 2008.

[2] S. Au et al., IEEE Trans. Robot, 2009.

[3] P. Cherelle et al., IEEE Trans. Neural. Syst. Rehabil. Eng., 2014.

[4] Q. Wang et al., IEEE Robot. Autom. Mag., 2015. (accepted)

[5] B. Chen et al., IEEE/ASME Trans. Mechatronics, 2014.

[6] J. Brockway et al., Hum.Nutr.:Clin.Nutr., 1987.

[7] M. Hsu et al., Arch Phys Med Rehabil., 2006.