A Strain Gauge Based Calibration Method for Ankle Joint Angle Measurement in Powered Transtibial Prosthesis

Yanggang Feng, Jinying Zhu, and Qining Wang

***Abstract*—Powered transtibial prostheses that can overcome deficiencies of passive ones are gaining increasing interests in the research field. Accurate ankle joint angle measurement is important for active prosthetic control. In this paper, we proposed a calibration method based on a strain gauge to obtain accurate ankle joint angle measurement. Experiments are carried out on the powered transtibial prosthesis developed by our previous study. Preliminary results showed the ankle joint angle was well calibrated.**

I. Introduction

Robotic transtibial prostheses are getting more and more attentions [1–7]. Ankle joint angle measurement is significant for robotic transtibial prosthesis control [2–7]. The foot plates used in most existing robotic transtibial prostheses are modeled as rigid bars. Consequently, ankle joint angle is directly calculated by the ankle joint angle sensor (encoder or potentiometer) at the joint [2, 3, 6, 7].

To reduce the weight and improve walking dynamics, recent robotic transtibial prostheses implemented carbon-fiber foot plates. However, deformation happens to carbon-fiber foot plates while walking, which causes ankle joint angle change. To measure ankle joint angle, the angle sensors are typically placed on a rotating shaft, which do not reflect the effect of the deformation of the carbon-fiber foot plates on the ankle joint angle. No analysis has been done on eliminating the impact of carbon-fiber foot plate deformation on the measurement of ankle joint angle.

A strain gauge is widely used to measure deformation on an object. The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. As the object is deformed, the foil is deformed, causing its electrical resistance to change. As the electrical resistance changes, the voltage of amplifier circuit changes. In the field of prosthetic research, Sup *et al.* designed a sensorized foot, which incorporated strain gauges to measure the ground reaction forces on the ball of the foot and on the heel [8].

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To obtain accurate measurement of ankle joint ankle for a powered transtibial prosthesis having carbon-fiber foot, in this paper, we propose a method that uses the strain gauge to measure the deformation of the carbon-fiber foot plates, thereby calibrating the ankle joint angle.

II. Prototype and Control Strategy

A. Powered Prosthesis Prototype

The powered transtibial prosthesis (PKU-RoboTPro-II) used in this study is shown in Fig. 1. Compared with PKU-RoboTPro-I [6], the PKU-RoboTPro-II which we developed recently [9] employed a more powerful Direct Current (DC) motor (Maxon, RE-40) to actuate the ankle joint. The rated power of the DC motor (150 W) was three times higher than that of the motor (50 W) used in the previous prosthesis. In order to reduce the total weight, most parts were made ofa luminum alloy. Then the total weight of PKU-RoboTPro-II (excluding the rechargeable Li-ion battery) was 1.75 kg, which was 0.45 kg heavier than the previous one. A belt transmission was used to replace the gearbox in the previous prosthesis. Both prosthesis versions had the same ankle joint angle range: from 25^o dorsiflexion to 25^o plantar flexion.

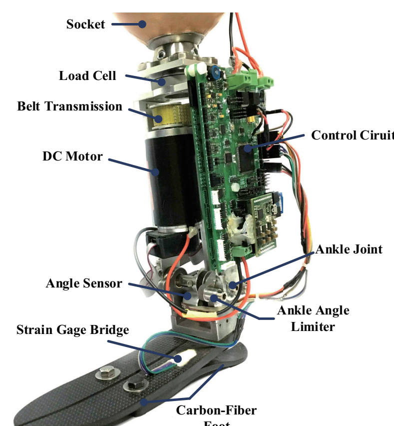

Fig. 1. The prototype of the proposed prosthesis PKU-RoboTPro-II.

The PKU-RoboTPro-II control system included an angle sensor to measure the ankle joint angle, a six-axis force torque sensor (M3553E, Sunrise Instruments) to measure the interaction force between the amputee and the prosthesis, and a control circuit (using the controller chip STM32F103). An integrated strain gauge bridge including four strain gages was placed onto the upper surface of the carbon fiber foot to measure deformation. The original signals of strain gauge were amplified 100 times and processed by a low-pass digital filter with a 10 Hz cutoff frequency.

B. Control Strategy

The finite-state machine control strategy [10] has been used in several prosthetic/orthotic applications [11–14]. A gait cycle begins with the heel strike of one foot and ends with the next heel strike of the same foot [2]. A gait cycle is generally divided into stance phase and the swing phase. Stance phase includes controlled flexion and powered plantar flexion.

- *Controlled flexion (CF)*. Controlled flexion includes controlled plantar flexion (CP) and controlled dorsiflexion (CD). Controlled plantar flexion starts at heel strike (the ankle joint starts to plantarflex) and ends at foot-flat (the ankle joint starts to dorsiflex). Controlled dorsiflexion starts at foot-flat and ends when the ankle reaches the maximum dorsiflexion angle [2].
- *Powered plantar flexion(PP)*. Powered plantar flexion begins after CD and ends at toe off.
- *Swing phase*. Swing phase begins at toe off and ends at heel strike.

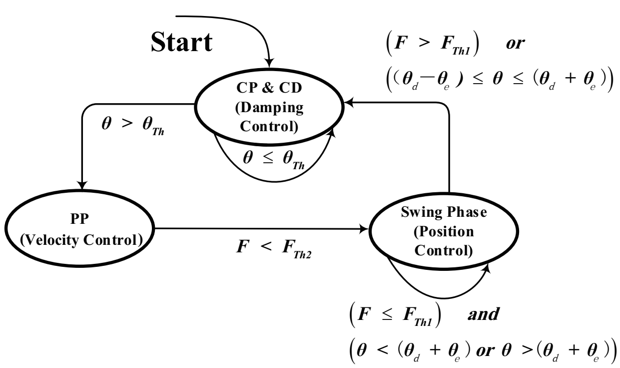

Fig. 2. Finite-state machine control diagram. $F_{Threshold1}$ represents the gravitational pressure threshold at the instant of heel strike. $F_{Threshold2}$ represents the gravitational pressure threshold while toe-off. $\theta_{Threshold}$ represents a minimum angle to detect the beginning of push-off. θ_e represents the allowable angle of error. θ represents the ankle joint angle.

In this paper, we divide the stance phase into controlled flexion and powered plantar flexion, as shown in Fig. 2. During the controlled flexion phase, we propose the damping control strategy. During the powered plantar flexion phase, we develop the velocity control strategy. $F_{Threshold1}$ represents the gravitational pressure threshold at heel strike. $F_{Threshold2}$ represents the gravitational pressure threshold at toe off. $\theta_{Threshold}$ represents a minimum angle to detect the beginning of push-off. θ_e represents the allowable angle of error. θ represents the ankle joint angle. Detailed control strategies were shown in [9].

III. EXPERIMENTAL METHODS

A. Matching Joint Angle with Strain Gauge

The first step of the proposed study is to find the relationship between the measured value of the strain gauge and the ankle joint angle. The experiment was carried out at room temperature of 18°C shown in Fig. 3. The simulation of rearfoot strike and forefoot strike was shown in Fig. 3 (a) and (b), respectively. The electro-mechanical universal testing machine (UTM5105, SUST Inc., China) slowly exerted a force of $0N$ to $1000N$ along the vertical direction, and then, relaxed from $1000N$ to $0N$. The same trial repeated 10 times and the interval trial time was $10s$. Meanwhile, a motion capture system (Raptor-E, Motion Analysis Inc., USA) was used to collect the deformation information of the carbon-fiber foot and the strain gauge circuit was used to collect the relevant data. The baseline value was subtracted from the original values of ankle joint angle, and then the average calculation was carried out. The average value was finally the reference ankle joint angle.

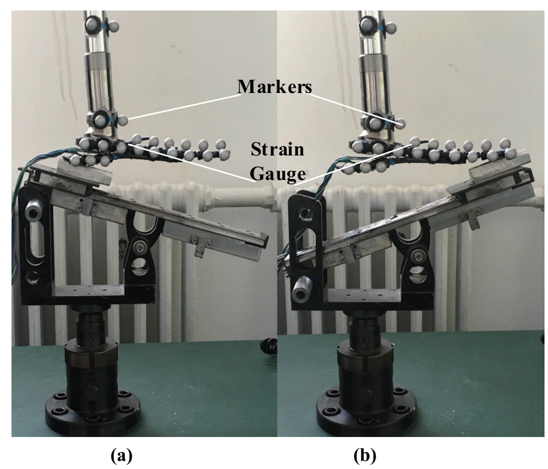

Fig. 3. The experiment on the relation between joint angle and strain gauge.

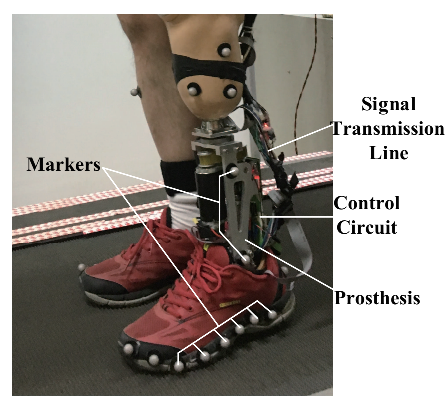

Fig. 4. Walking test experiment.

B. Walking Test

The purpose of the walking experiment is to verify the relationship obtained by the first experiment. The markers of the motion capture system were used as the reference of the ankle joint angle. A male unilateral transtibial amputee subject (age: 50 years; height: 170 cm; mass: 70 kg) volunteered to participate in the study and provided written consent prior to testing. The amputee subject has been amputated (left leg) for fifteen years. The subject with PKU-RoboTPro-II walked on the treadmill at 0.9 m/s. The position information of markers was measured by the motion capture system to calculate the reference ankle joint angle and the data from prosthetic sensors were transferred to a computer to make a comparison with the reference ankle joint angle shown in Fig. 4.

IV. Experimental Results

The function between reference ankle joint angle and the amplitude of strain gauge obtained by the first experiment would be applied to calibrate the ankle joint angle in the walking experiment.

A. Relation between Joint Angle and Strain Gauge

TABLE I
DETAILED STATISTICAL EVALUATION PARAMETERS

Methods	SSE	R-square	RMSE
polynomial	1173	0.9988	0.09733
exponential	1585	0.9984	0.1131
Fourier	1172	0.9988	0.09728

Curve fitting is the process of constructing a curve or mathematical function, that has the best fit to a series of data points, possibly subject to constraints [15]. In this paper, polynomial, exponential and fourier functions were selected to achieve the curve fitting. To evaluate the goodness of fit, three statistical evaluation parameters are given as follows:

1) Sum of Squares Due to Error (SSE): This statistic measures the total deviation of the response values from the fit to the response values. It is also called the summed square of residuals and is usually labeled as SSE. A value closer to 0 indicates a better fit.

2) R-square: This statistic measures how successful the fit is in explaining the variation of the data. Put another way, R-square is the square of the correlation between the response values and the predicted response values. It is also called the square of the multiple correlation coefficient and the coefficient of multiple determination. A value closer to 1 indicates a better fit.

3) Root Mean Squared Error (RMSE): This statistic is also known as the fit standard error and the standard error of the regression. It is an estimate of the standard deviation of the random component in the data. A value closer to 0 indicates a better fit.

The parameters of each method were selected as the most optimal curve fitting, when that R-square can take maximum value. The detailed parameters of each method are shown in the following table I. The parameters of Fourier function led to the best fitting curve in three methods. Thus, the Fourier function was selected as the final function to calibrate the ankle joint angle in the formal experiment. Get the specific formula as follows,

$$\theta(\chi) = 1.615 - 2.867\cos(0.4671\chi) - 3.58\sin(0.4671\chi) + 0.8076\cos(0.9342\chi) + 0.0492 sin(0.9342\chi) \tag{1}$$

where $\theta(\chi)$ refers to the calibrated ankle joint angle (°), and χ refers to the voltage (V) of measurement circuit about strain gauge. Based on Fourier function, the fitted curve was shown in Fig. 5. The blue points refer to the original data. The red line refers to the curve fitting based on Fourier function.

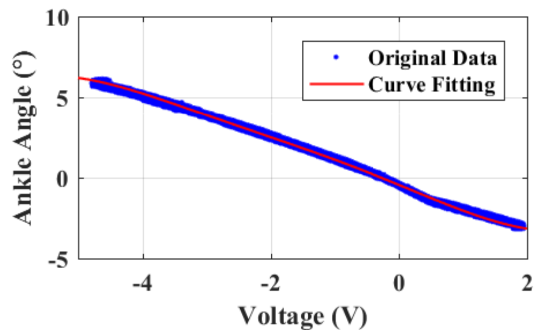

Fig. 5. Curve Fitting. The blue points refer to the original data. The red line refers to the curve fitting based on Fourier function. 0° indicates that the plane where the shank lies is perpendicular to the plane of the carbon-fiber foot plate.The positive angle represents the dorsiflexion and the negative angle represents the plantar flexion.

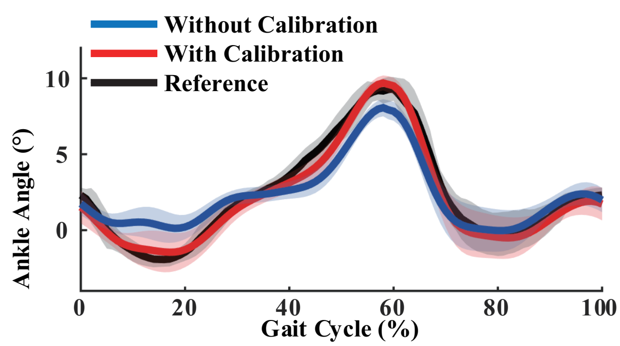

Fig. 6. Experimental results of walking test. The solid blue lines refers to the average trajectories of ankle joint angle without calibration. The solid red lines refers to the average trajectories of ankle joint angle with calibration. The solid black line refers to the reference average trajectories of ankle joint angle calculated by the motion capture system. The shade areas indicate standard deviation. 0° indicates that the shank is perpendicular to the carbon-fiber foot plate. The positive angle represents the dorsiflexion and the negative angle represents the plantar flexion.

B. On-board Results

The results of walking experiments are shown in Fig. 6. The abscissa represents the gait cycle started from heel strike. The ordinate represents the ankle joint angle. 0° indicates that the shank is perpendicular to the carbon-fiber foot plate. The positive angle represents the dorsiflexion and the negative angle represents the plantar flexion. The stance phase approximately lasts from 0 % to 70 % and the swing phase approximately lasts from 70 % to 100 %. In the stance phase, ankle joint angle is calibrated by the function obtained by the pre-experiment. The main difference after the calibration is reflected in the rearfoot strike and forefoot strike. In the swing phase, the calibration does not lead to significant difference. The results of these experiments were consistent with our expectations, the pre-experimental formula had been well verified.

V. Conclusion and Future Work

In this paper, we proposed a calibration method based on a strain gauge for ankle joint angle measurement. The calibration function was obtained by off-line experiments with electro-mechanical testing machine and motion capture system. Then the obtained relation was applied to the powered prosthesis (PKU-RoboTPro-II) in on-board walking experiments. Preliminary results indicated that the ankle joint angle was well calibrated based on a strain gauge. In the future, more experiments on more subjects need to be performed to obtain detailed results.

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