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Continuously Estimate and Control Prosthetic Grip Force by an Optical Waveguide Sensor

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***Abstract*—The emergence of intelligent prostheses has facilitated the life and work of disabled patients. The interaction aspect of prostheses has become a highlight research topic in the field of rehabilitation robotics. However, most of the existing prosthetic interaction methods focus on the use of myoelectricity to classify finite gestures, rather than continuous (infinite) force detection, which greatly limits the use of prosthetic scenarios. In this study, a novel optical waveguide sensor was used to collect muscle deformation information from the human arm for continuous control of the prosthetic grip force. The optical waveguide sensor was embedded with carbon fiber to limit the stretching of the waveguide, which led to the optical waveguide sensor being sensitive to bending deformation. Compared with EMGs, the accuracy of continuous grip force control based on the optical waveguide sensor is higher. The R-Square for prosthetic grip force and hand grip force were 0.867 and 0.9724 in the periodic and sustaining grip force experiments, respectively. The results suggested that the proposed method could provide a new approach to the interaction of prostheses.**

***Index Terms*—Prosthetic interaction, grip force, muscle deformation information, optiacl waveguide**

I. INTRODUCTION

As the global population of people with upper extremity disabilities increases[1], the demand for prostheses is also increasing with the development of society. The appearance of intelligent prostheses has facilitated the life and work of patients with disabilities[2], and the interaction of prostheses has become a research hotspot in the field of rehabilitation robotics. With the development of computer-assisted medical technology, human-computer interaction technology[3–5] has been widely used in the field of rehabilitation medicine, especially in the field of functional assistance for disabled people[6–8].

Many scholars have proposed the use of surface electromyography (sEMG) for the recognition of hand movement patterns, and various surface electromyography-based prosthetic strategies have been proposed, and this precise classification of hand movement patterns has been very successful. Li C et al. designed nine gestures and extracted raw EMG signals from the surface of human forearm muscles, then after pre-processing the signals, gesture recognition was achieved by SVM with a recognition rate of 98.64%[9]. Similarly, most of the EMG-based gesture studies[10, 11] basically employ the use of neural network algorithms to classify the EMG signals, resulting in a recognition rate of more than 90%. In addition , another approach is to monitor muscle deformation. Force-sensitive resistors[12], displacement mechanomyographic signal (MMG)[13], air pressure sensors[14], and optical sensors[15] can be used to monitor muscle deformation and thus analyze the gestures of the wearer. In general, the research on prosthetic gestures is relatively mature, but the research on prosthetic grip control is relatively little and the technology is not mature. Therefore, it is meaningful to study the continuous control of prosthetic grip force, which can greatly expand the scenarios of prosthetic use.

In the process of grip force estimation, the more used method is to detect the strength of muscle contraction from EMG signals and motion signals and then map the measured strength to grip force[16–18]. However, the non-smoothness, susceptibility to interference, and weakness of the EMG signal[19], as well as the fact that it can be disturbed by hair and sweat in daily use, can have an impact on the recognition accuracy. So it is difficult to continuously control the prosthetic grip force based on EMG signals. On the other hand, it has been demonstrated[12–15] that the deformation of the skin surface of the residual limb can be used as a new biological signal to control the prosthetic movement. Therefore, it should be feasible to predict the grip force by collecting muscle deformation through sensors. Recent studies have found that optical waveguide sensors have unique advantages in giving prostheses the sense of touch[20] and sensing deformation[21, 22]. Therefore, this study attempts to investigate a new method to establish the relationship between muscle deformation and grip strength using optical waveguide sensors.

In this study, a optical waveguide sensor attached to the arm was used to monitor the muscle deformation generated when the subject grasped an object. We mapped the signal from the optical waveguide sensor to the grip force signal and explored the relationship between the two to establish the relationship between muscle deformation and grip force, and then investigated the feasibility of controlling the grip force of the prosthesis by monitoring muscle deformation. Fig. 1 shows the overview of this study. When a human hand

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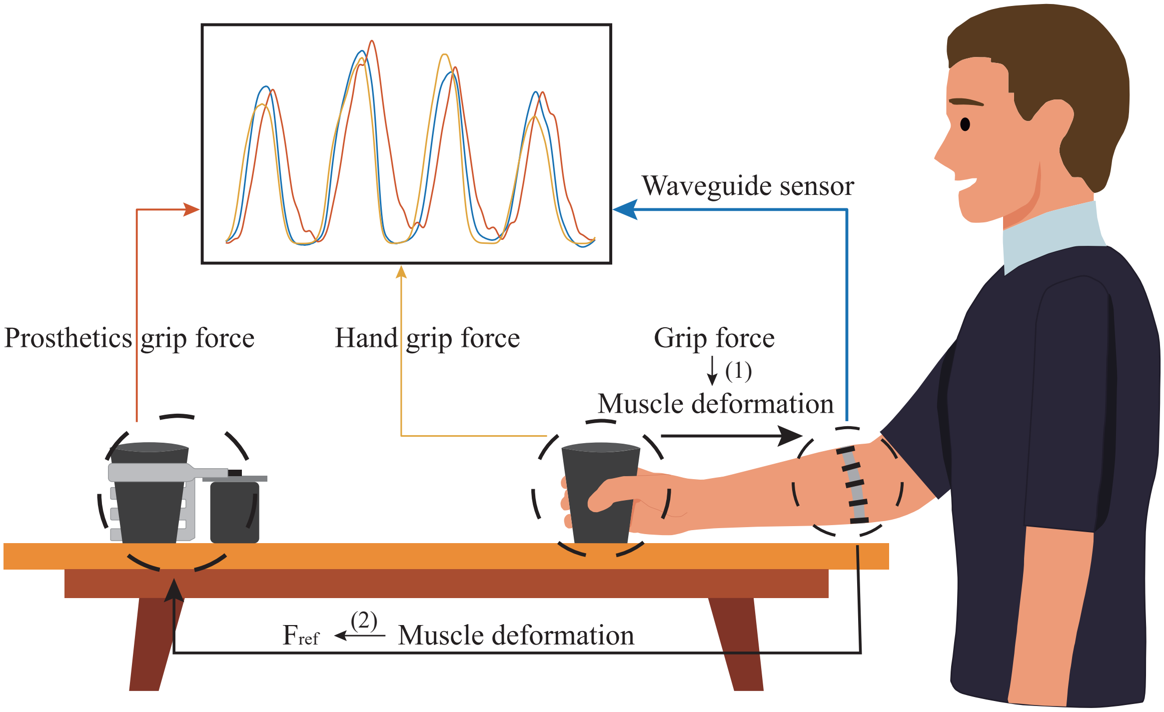

Fig. 1. Overview of this study.

grips a cup, the muscles that control grip force are deformed, and this deformation was captured by an optical waveguide sensor and then mapped to grip force. This grip force was sent to the prosthesis as a reference grip force, and then the prosthesis produced a grip force to clamp the cup in front of it. The hand grip force, the optical waveguide sensor signal, and the prosthetic grip force were recorded for comparison.

II. SENSOR CHARACTERISTICS

In this section, we introduce the components of our waveguide sensor and the response of the sensor to deformation.

A. *Composition of the Waveguide Sensor*

As shown in Fig. 2(a), LED & photodiode, 3D printed resin sleeves, and an optical waveguide make up our waveguide sensor. The light from the LED (TSHA4400, Vishay Semconductors; peak wavelength: 875nm) at one end of the sensor passes through the optical waveguide and is then sensed by the photodiode (SFH229, OSRAM Licht AG; spectral range: 380nm to 1100nm) at the other end. And the optical waveguide has two parts: the core (Clear Flex 30, $n_{core} = 1.47$, Smooth-on Inc.) and the cladding (Dragon Skin 20, $n_{cladding} = 1.41$, Smooth-on Inc.). Fig. 2(b) shows a photo and cross-section of the optical waveguide; the black line in the photo is carbon fiber. It serves to limit the stretching deformation of the optical waveguide and reduce the effect of stretching deformation when the optical waveguide is bent.

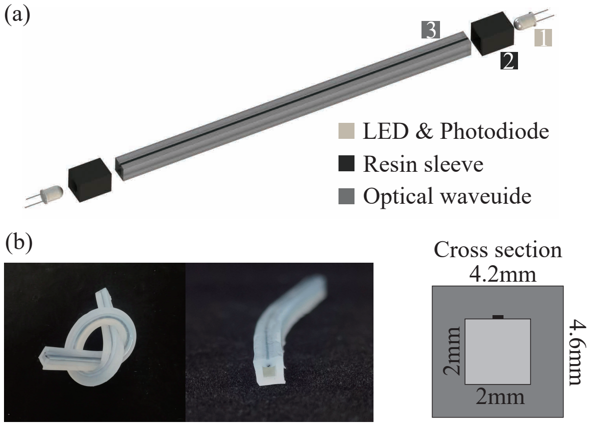

Fig. 2. Composition of the waveguide sensor. (a) Exploded view of the optical waveguide sensor. (b) Photo and cross-sectional view of the waveguide.

B. *Response to Deformation*

Light is emitted from the LED, passes through the waveguide, and is then sensed by the photodiode. If the waveguide is deformed, such as bending and pressing, some of the light will escape from the waveguide. And the greater the deformation of the waveguide, the more light will escape. To measure the deformation of the optical waveguide, We designed a signal modulation circuit to monitor the voltage of the photodiode, the lower the light intensity (the higher the light loss) the higher the voltage of the signal modulation circuit. So, let the voltage of the signal modulation circuit when the optical waveguide sensor has no deformation be V_0 and let the voltage of the signal modulation circuit when the optical waveguide sensor has deformation be V. Therefore, the light intensity loss ratio is defined as

$$r = 10 \log_{10} \frac{V}{V_0} \tag{1}$$

When the optical waveguide is not deformed, V is equal to V_0, and the light intensity loss ratio $r = 0$. When the optical waveguide is deformed, V increases and $r > 0$.

Because our optical waveguide is limited in stretching by being embedded with carbon fiber, we only tested the optical waveguide sensor's response to bending deformation and pressing. Fig. 3 shows the response of the optical waveguide sensor under bending or pressing deformation. Clearly, the optical waveguide sensor has excellent sensitivity to both bending and pressing deformations.

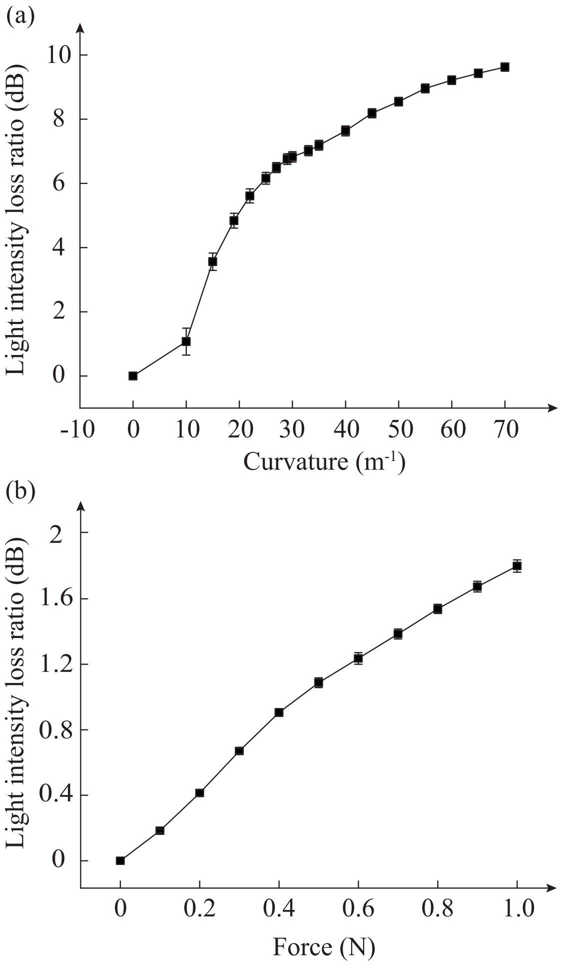

Fig. 3. Characterization of the optical waveguide sensor in different deformation modes. Characterization for (a) bent and (b) pressed. (Error bars indicate SDs from 10 cyclic tests of one waveguide sample).

III. Experimental Setup

In this section, we will introduce the placement of the optical waveguide sensor, the placement of the force sensor used to monitor hand grip force and prosthetic grip force, the prosthetic design, and the experimental process.

A. Sensor Position

As shown in Fig. 4(a), the optical waveguide sensor is attached to the arm close to the elbow because this is where the extensor digitorum and flexor digitorum are located, and they are the main muscles that control a person's grip strength. When a person grasps an object, these two muscle groups produce the greatest deformation and the signal changes measured by the optical waveguide sensor are more obvious. In order to ensure that the optical waveguide sensor has tightly adhered to the skin so that it does not miss any small deformation of the muscle, the glue used for wearing the prosthesis was applied to the side of the waveguide in contact with the skin. This glue held the waveguide tightly to the skin and did not cause problems in removing the light waveguide from the skin. In addition, we also reinforced the adhesion of the light waveguide sensor to the skin with adhesive tape.

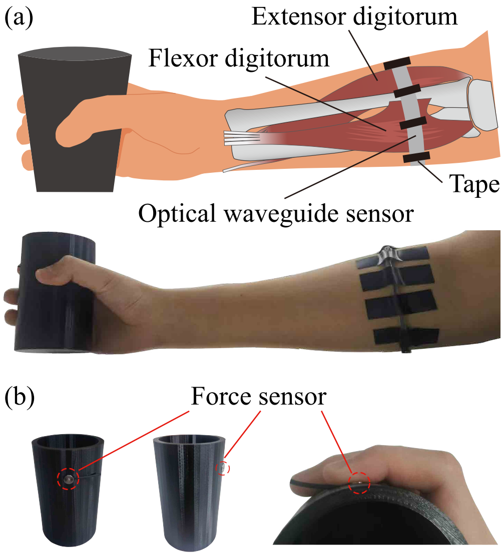

Fig. 4. Position of the optical waveguide sensor and force sensor. (a) The optical waveguide sensor is placed close to the elbow. (b) The force sensor is embedded in the cup wall.

Fig. 4(b) shows the location of the force sensor, a miniature force sensor (AT8101, Autoda Ltd.) is embedded in the wall of the cup, which monitors the grip force when the cup is grasped. This force sensor has a range of 100N and can sense a change in force of 0.01N, which ensures accurate measurements.

B. Prosthetics Design

We used a single-degree-of-freedom gripper to grip objects to simulate prosthetic grasping (shown in Fig. 5). The gripper is driven by a brushless servo motor (QDD-NE30-36, Mintasca Ltd.), and the power is transmitted through gears.

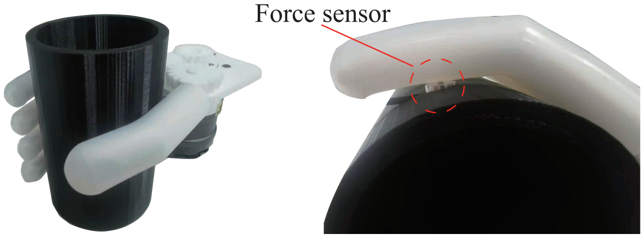

Fig. 5. Photo of the single-degree-of-freedom gripper and the detail of the finger in touch with the force sensor.

C. Control System

Fig. 6 shows the control system for the experiment. We used an STM32F429VET6 as the master control. When the subject grasps the object, the deformation of the arm muscle is captured by the optical waveguide sensor, which then sends the muscle deformation to the STM32 in the form of light intensity loss ratio(r). At the same time, the force sensor between the subject's hand and the object sends the real grip force (F_H) to the STM32. After this, the STM32 receives the light intensity loss ratio from the optical waveguide and performs a regression analysis of the signal to obtain a reference grip (F_{ref}) which will be sent to the prosthesis. Finally, the prosthesis generates a grip based on F_{ref}. And the grip force will be returned to the STM32 via the force sensor between the prosthesis and the object. By connecting the STM32 to the computer through the serial port, the hand grip force, the prosthesis grip force and the signal of the optical waveguide sensor can be acquired.

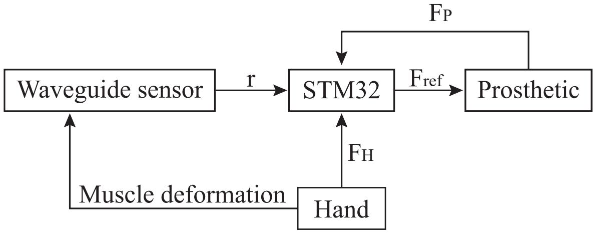

Fig. 6. Block diagram of the control system.

D. Experimental Process

The whole experiment process is divided into the following steps.

(1) Attach the optical waveguide sensor to the subject's arm. It is important to ensure that the optical waveguide sensor is tightly adhered to the subject's skin and does not move relative to it, which affects the accuracy of collecting muscle deformation.

(2) Place the subject's arm flat on the table and then have the subject grasp the cup periodically for 3 minutes, during which time the grip strength changes periodically. The hand grip force, the prosthesis grip force, and the signal of the optical waveguide sensor were also collected.

(3) Place the subject's arm flat on the table and then have the subject grasp the cup periodically for 3 minutes, during which time try to maintain a grip force for some time before adjusting the grip. The hand grip force, the prosthesis grip force, and the signal of the optical waveguide sensor were also collected.

(4) Analyze the collected data, and the preliminary results are presented in Section IV.

We recruited one 23-year-old healthy male volunteer to conduct the experiment. The experiment was approved by the Local Ethics Committee of Beihang University. The subject read and signed informed consent forms before the experiment.

IV. PRELIMINARY RESULTS

To investigate the potential of the optical waveguide sensor in controlling prosthetic grip force, we attached the sensor to the arm to monitor the deformation of the muscles that control grip force by mapping the muscle deformation to the real grip force of the human hand. Fig. 7 shows the preliminary results obtained from the experiment. The dashed lines were the raw signals of the optical waveguide sensor and the prosthetic grip force. In order to more intuitively observe the relationship between hand grip force, prosthetic grip force, and optical waveguide sensor signal, we used a quadratic polynomial transformation on the raw signals of the optical waveguide sensor and prosthetic grip force to obtain the corresponding solid lines.

A. Periodic Grip Force

Fig. 7(a) shows the partial result of the periodic grip force experiment. The R-Square of prosthetics grip force and hand grip force was 0.867, and the R-Square of optical waveguide sensor signal and hand grip force was 0.9343. It can be seen that hand grip force, prosthetic grip force, and optical waveguide sensor signal had a good correlation. In each cycle, when the hand grip force changed, the prosthetic grip force also changed, which indicates that the optical waveguide sensor had a good ability to continuously control the prosthetic hand to grasp objects of different weights. There was no significant phase difference between the hand grip force curve and the optical waveguide sensor signal curve, which indicates that there is no delay in monitoring muscle deformation by the optical waveguide sensor. In contrast, there was a delay of approximately 100 ms between the hand grip force curve and the prosthetic grip force curve, and this delay mainly originated from the PID controller. But the existing literature[23] shows that acceptable delays for prosthetic systems are in the range of 50-400 ms. Therefore, the delay of 100 ms will not affect the normal life of the prosthetic user.

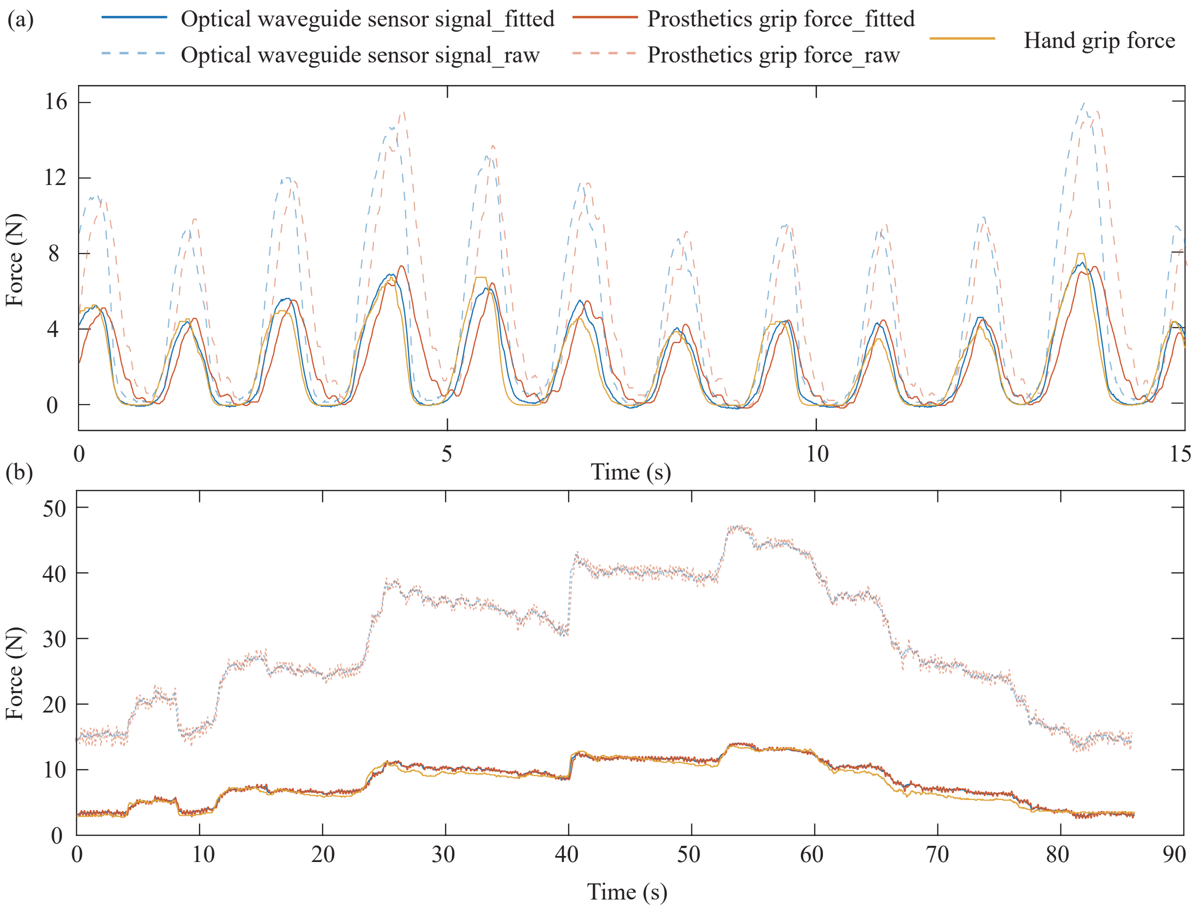

Fig. 7. Subsets of cyclic test results for controlling grip force. (a) Hand grip force, prosthetic grip force, and optical waveguide sensor signal in the periodic grip force experiment. (b) Hand grip force, prosthetic grip force, and optical waveguide sensor signal in the sustaining grip force experiment.

B. Sustaining Grip Force

Fig. 7(b) shows the partial result of the sustaining grip force experiment. The R-Square of prosthetics grip force and hand grip force was 0.9724, and the R-Square of the optical waveguide sensor signal and hand grip force was 0.979, which indicates that the three have a good correlation. As shown in Fig. 7(b), when the hand grip force remained constant, the prosthetic grip force also remained stable, while when the hand grip force changed suddenly, the prosthetic hand grip force also immediately followed the change. This ensures that the prosthesis can quickly and steadily grasp objects.

The results of the two grip force experiments have demonstrated the feasibility of using optical waveguide sensors for continuous control of prosthetic grip force.

V. DISCUSSION

To compare the difference between the use of optical waveguide sensors and EMG signal for continuous control of prosthetic grip force, we list some literature(Table I). Since there are relatively few studies that use EMG signals directly to continuously control the prosthetic grip force, we use force estimation from EMG signals for comparison. It can be seen that the accuracy (R^2) of estimating grip force using EMG signals is around 0.9, which is not much higher than using the optical waveguide sensor to estimate grip force. And almost all of these studies used multiple EMG electrodes, even though some were intramuscular. In contrast, the optical waveguide sensor we used can achieve an accuracy comparable to the EMG signal by simply attaching one sensor to the forearm surface. And the optical waveguide has the anti-interference ability and stability that the EMG signal does not have. In addition, the optical waveguide also has good skin friendliness, flexibility, and bendability, which ensures that the wearer of the optical waveguide sensor wears it comfortably.

In the experiments, we also found some limitations of using optical waveguide sensors to continuously control the prosthetic grip force. Firstly, the optical waveguide sensor needs to be calibrated before use. To obtain a more accurate mapping of the optical waveguide sensor signal to the hand grip force, the sensor signal needs to be calibrated (adjusting the signal modulation circuit) after the optical waveguide sensor is attached to the forearm. Secondly, since the proposed optical waveguide sensor is to monitor muscle

TABLE I
LITERATURE ABOUT FORCE ESTIMATION FROM EMG SIGNALS[24]

Reference	Muscles (number and type of electrodes)[1]	Accuracy (R^2)
Bøg et al.	Forearm (1s and 1i)	>0.9
Baldacchino et al.	Forearm and upper arm (12s)	0.91
Nielsen et al.	Forearm (7s)	0.90
Kamavuako et al.	Forearm (1i)	0.89
Mirzakuchaki et al.	Forearm and upper arm (12s)	0.93
Jiang et al.	Forearm (8s)	0.90
Ameri et al.	Forearm (8s)	0.90
Kamavuako et al.	Forearm (6i and 6)	0.93

[1] Superficial (s) or intramuscular (i) electrodes.

deformation, it is vulnerable to other hand movements, after all, more than just grasping will cause muscle deformation. These problems can be solved by arranging multiple sensors and incorporating neural network algorithms to reduce the effect of non-essential muscle deformation. In the preliminary results, we compared the signal of the optical waveguide sensor and the prosthetic grip force with the hand grip force through quadratic polynomial transformation. So in the experiment, the prosthetic grip force and the hand grip force did not match. If the signal of the optical waveguide sensor can directly correspond to the hand grip force by adding a step after attaching the optical waveguide sensor to the forearm, the prosthetic grip force can be directly and accurately controlled, so that the grip force of the prosthesis corresponds to the grip force of the hand. These issues are the direction of our future work.

VI. CONCLUSION

In this study, a method to continuously control the grip force of a prosthesis by an optical waveguide sensor was proposed. The grip force was inferred by using a light waveguide sensor to monitor muscle deformation. Compared to EMG, optical waveguide sensors are more visible, stable, and anti-interference. We used a gripper instead of a prosthesis, and used the signal from the optical waveguide sensor to control the prosthetic grip force. After comparing the hand grip force, the prosthetic grip force and the signal from the optical waveguide sensor, we found a good correlation between the three. Our method provided a new idea for prosthetic interaction.

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