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Table Tennis Prosthetic Hand Controlled Based on Distance Measurement Using a ToF Sensor

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Abstract— **Table tennis is a popular sport for forearm amputees. However, forearm amputees with limited pronation and supination movements cannot switch the racket angle properly for forehand and backhand drives. This paper reports a table tennis prosthetic hand controlled based on distance measurement using a ToF Sensor. The developed hand can switch the racket angle between forehand drive and backhand drive based on the distance between the wrist and the trunk or upper arm measured by the ToF sensor attached to an electric wrist. The participant with forearm amputation could play table tennis with the developed hand in the test play. The racket angle was switched to the appropriate angle for the forehand drive and the backhand drive, and the participant could return a ball 6.3 times in 10 seconds. The satisfaction of the participant with the prosthetic hand was good.**

I. INTRODUCTION

Sports are important for persons with disabilities [1]–[3]. Physical exercise is beneficial for rehabilitation, health maintenance, and stress reduction. Sports can also be an opportunity to participate in a new community and interact with other people. This paper focuses on the sports of forearm amputees.

In addition to prosthetic hands to assist forearm amputees' daily living, prosthetic hands for sports have been developed. TRS sells prosthetic hands for various sports such as baseball, tennis, volleyball, boat, and floor exercise [4]. Prosthetists also make original prosthetic hands for forearm amputees to play sports [5]–[10].

Table tennis is a popular sport for forearm amputees [11]. They usually attach a racket directly to their stump by a band or hold it by a fixture at the end of their prosthetic socket when they have to use it by the affected upper limb.

In table tennis, the racket angle needs to be switched between forehand drive and backhand drive. Since forearm amputees with limited pronation and supination movements, they cannot switch between backhand drive and forehand drive appropriately and use trick motion to compensate for limited movement. Switching between forehand drive and backhand drive is necessary for natural play.

This paper report a table tennis prosthetic hand controlled based on distance measurement using a ToF (Time of Flight) Sensor. The developed hand can switch the racket angle between forehand drive and backhand drive based on the distance between the wrist and the trunk or upper arm measured by the ToF sensor attached to an electric wrist. The effectiveness of the prosthetic hand was verified by playing table tennis by a forearm amputee and a satisfaction questionnaire.

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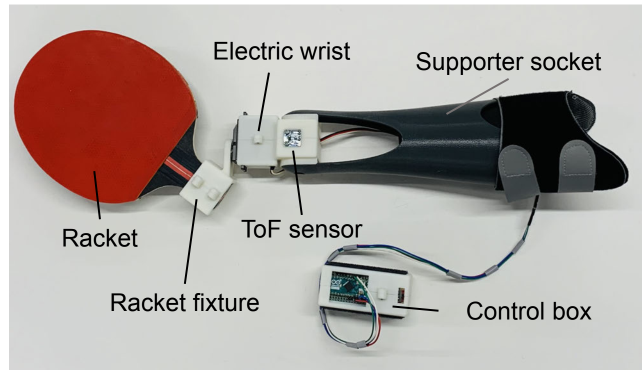


Fig. 1. Component of the table tennis prosthetic hand for a right forearm amputee.

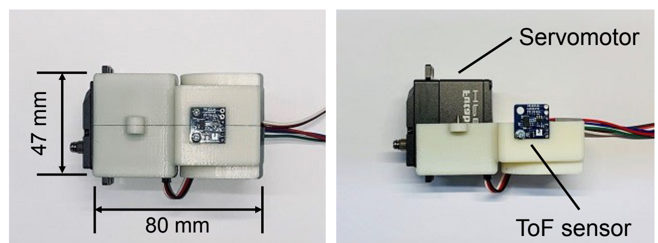


Fig. 2. Electric wrist.

II. DESIGN

The developed table tennis prosthetic hand consists of a racket fixture, electric wrist, control box, and supporter socket, as shown in Fig. 1. The racket fixture holds the racket. A servomotor is built into the electric wrist, and a ToF sensor is attached to the outside. The control box contains a microcontroller and a battery to control the servomotor. The supporter socket developed by Yoshikawa et al. [12] was used to insert a user's stump. The ToF sensor measures distance from the wrist to the trunk or upper arm, and the electric wrist is controlled based on the measured distance to switch to the corresponding angle for the forehand drive and backhand drive. In the following subsection, we describe the details of each component.

A. Electric Wrist and Racket Fixture

The electric wrist connects the racket fixture to the supporter socket. It contains a servomotor (HPS-A700, Futaba

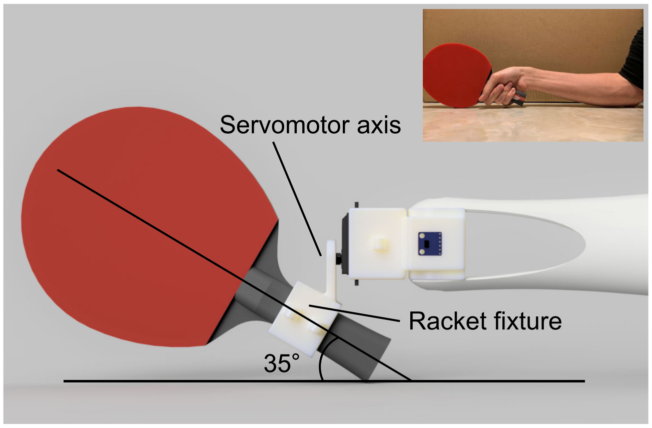


Fig. 3. Racket fixture.

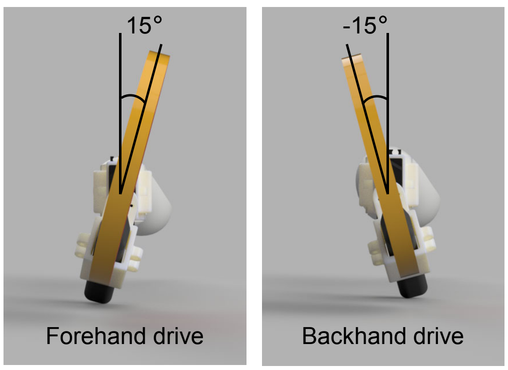


Fig. 4. Racket angles of the forehand drive and the backhand drive.

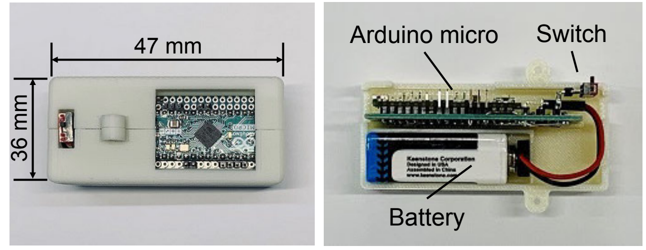
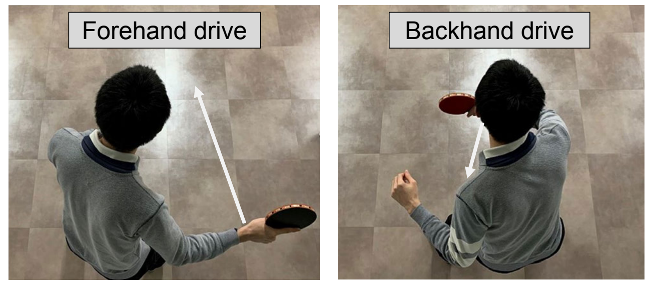
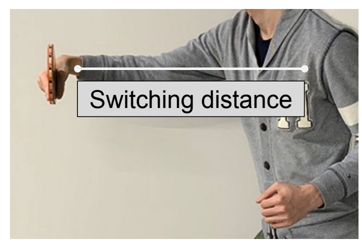


Fig. 5. Control box.



(a) Posture of the forehand drive and the backhand drive



(b) Switching distance

Fig. 6. (a) Posture of the forehand drive and the backhand drive. (b) Switching distance

Electronics) to switch the racket angles and a ToF sensor (VL53L0X, STMicroelectronics) to measure the distance, as shown in Fig. 2. The speed and the torque of the servomotor are 0.5 deg/ms and 7.26 Nm, respectively. The distance sensor can measure distances from 0.03 m to 2 m to the object in front.

The racket fixture holds the grip of the shake-handed racket (HY-MS, Boliprince) at a 35-degree angle to the table, as shown in Fig. 3. The angle was determined based on the angle at which five males (20s) held the racket. The position where the racket is held is offset downward from the axis of the servomotor. Rubber sheets are attached to the inside of the racket fixture on all sides to prevent slippage. The grip of the racket was cut off by 40 mm to reduce weight. Thus, the total weight of the racket, the racket fixture, and the electric wrist is 310 g.

The racket angle is switched between forehand drive and backhand drive by the servomotor as shown in Fig. 4. In this figure, the angles of the forehand drive racket and the backhand drive racket are 15 degrees and -15 degrees, respectively. The angles can be adjusted from 70 degrees to -70 degrees according to the user's preference.

A fixed joint connects the electric wrist and the supporter socket. The user inserts the stump into the supporter socket and tightens the belt to wear the prosthetic hand. The inner side is lined with high frictional fabric (Daiya Industry Co., Ltd.) to prevent the supporter socket from slipping from the user's stump. The weight is 123 g.

All plastic parts were made of ABS resin by a 3D printer (uPrint SE, Stratasys Ltd.). The layer thickness of the 3D printer was 0.254 mm.

B. Control Box

The control box contains a microcontroller (Arduino micro, Adafruit) and a battery (9V lithium-ion battery, Keenstone), as shown in Fig. 5. The control box receives input from the ToF sensor and controls the servomotor. The weight is 83 g. It is worn on the upper arm with a band to reduce the load on the forearm.

C. Switching Algorithm

The racket angle is switched between forehand drive and backhand drive based on the distance between the wrist and the trunk or upper arm measured by the ToF sensor attached to the wrist. As shown in Fig. 6 (a), there is nothing in front of the wrist in the forehand drive. In the backhand drive, the trunk or upper arm is in front of the wrist. Considering this

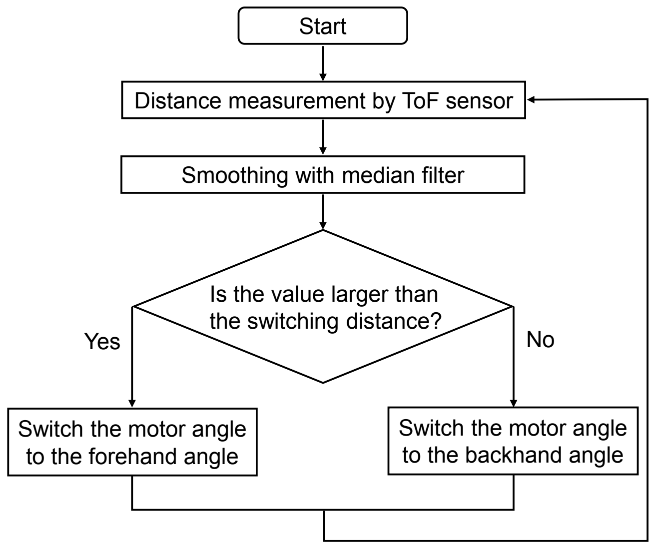


Fig. 7. Flowchart of the switching algorithm.

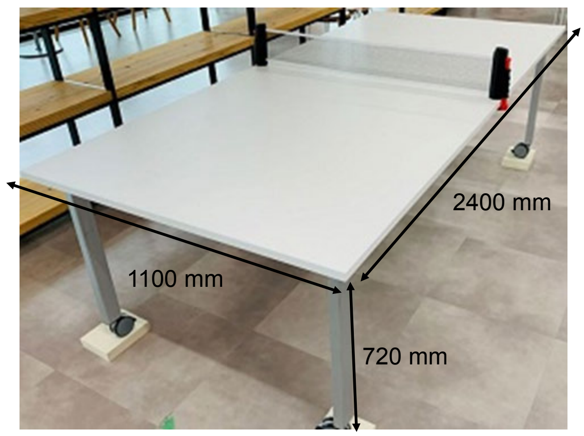


Fig. 8. Table used in the test play.

relationship, we use the algorithm that the racket angle is switched based on the distance measured by the ToF sensor when the arm is extended to the maximum in a backhand drive, as shown in Fig. 6 (b).

The flowchart of the switching algorithm of the racket angle is shown in Fig. 7. The value of the ToF sensor is sampled at 40 Hz. The sampled values were smoothed by a five-point median filter. If the distance between the sensor and the trunk or the upper arm is less than the switching distance, the racket is switched to the backhand angle. If the distance is larger than the switching distance, the racket is switched to the forehand angle. If the distance changes before the racket angle is completely switched, a command to switch the angle is sent to the servo motor.

III. Evaluation

A. Method

In order to verify the effectiveness of the developed prosthetic hand, a test play was conducted by an amputee. A

TABLE I

Number of times that the participant returned the ball.

	1st	2nd	3rd	Average
Forehand rallies	6	8	6	6.7
Backhand rallies	7	7	6	6.7
Freestyle rallies	7 (3)	7 (3)	6 (2)	6.3 (2.7)

The number in parentheses is the number of times of backhand drive.

TABLE II

Participant's satisfaction

Question	Score
Weight	4
Usability	4
Enjoyment	5

right forearm amputee (50s, right-handed, stump length: 210 mm) participated in the test play. He had some experience in table tennis before amputation. The switching distance was set to 0.5 m based on the reach of his backhand drive. The angles of the forehand drive racket and the backhand drive racket were 15 degrees and -15 degrees, respectively. This angle was determined according to the user's preference. It took 100 ms to switch from the forehand drive angle to the backhand drive angle. A simple table, smaller than the regular table, was used. (Fig. 8).

The participant performed three rallies with a healthy experimenter for 10 seconds three times: forehand rallies, backhand rallies, and freestyle rallies. In the forehand rallies, only forehand drive was used. In the backhand rallies, only backhand drive was used. According to the user's preference, the freestyle rallies were free to use the forehand drive and the backhand drive. Starting from the service of the healthy experimenter, the number of times that the participant returned the ball was counted in the rallies. The participant practiced for 20 minutes before the test play. The same freestyle rallies were performed with five healthy participants (male, 20s) to acquire reference data. After the test play, the participant was asked to evaluate the weight, usability, and enjoyment on a five-point scale from strongly dissatisfied (= 1) to strongly satisfied (= 5).

The research ethics boards approved the experimental protocol of this study of the Osaka Institute of Technology. Informed consent was obtained from the participant before the test play.

B. Result

The number of times the participant returned the ball in each rally is shown in Table I. The average number of forehand, backhand, and freestyle rallies was 6.7, 6.7, and

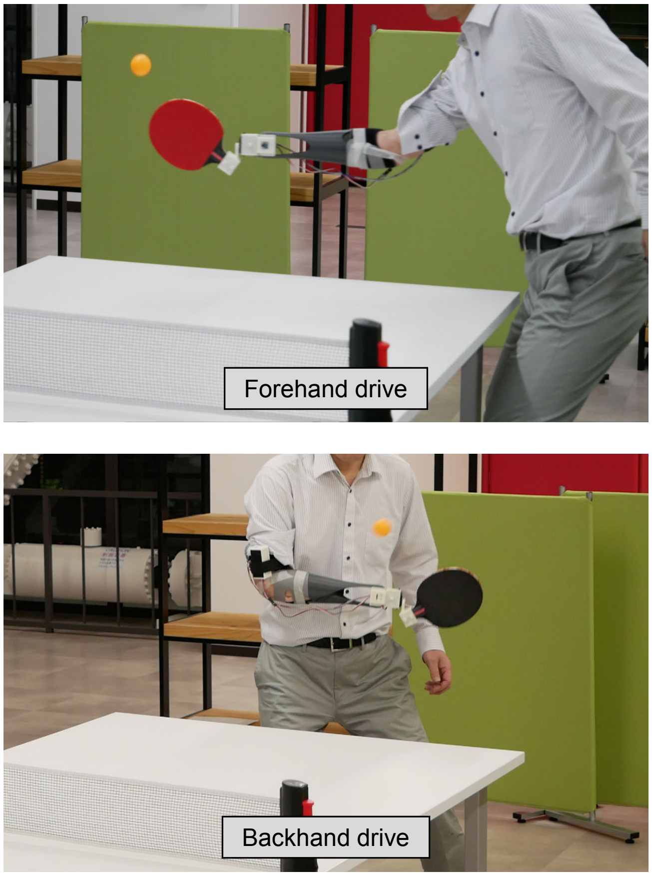


Fig. 9. Forehand drive and backhand drive performed by the participant in the test play.

6.3, respectively. The average number of times five healthy participants return the ball was 7.8 in the freestyle rallies.

After the test play, we investigated the participant's satisfaction for weight, usability, and enjoyment using a five-point scale. The result is shown in Table II. For all questions, the satisfaction of 4 or higher was obtained. A participant commented that he wanted the weight of the prosthetic hand could be reduced because he felt that it seemed to fell out during the play. In addition, he commented that it would be even better if he could intentionally control the racket angle for more advanced play. Although he was a unilateral forearm amputee, he enjoyed playing table tennis with his dominant hand for the first time since his amputation.

IV. Discussion

In the backhand rallies, the participant returned the ball as many times as in the forehand rallies. The backhand drive should be difficult to hit the ball if the racket is at the same angle as the forehand drive. In the freestyle rallies, the participant uses the backhand drive in about half of the returns, and the racket angle was switched appropriately. Fig. 9 shows the forehand drive and the backhand drive performed by the participant in the test play.

Although it is difficult to make a simple comparison with healthy participants, it is shown that the amputee could play table tennis without difficulty. However, a comparison with the performance when the racket angle was fixed needed to be conducted.

The racket angle could be automatically switched according to the forehand drive and the back drive. However, when the hitting point is low in the forehand drive, the ToF sensor detected the table and resulted in the backhand racket angle. A function that allows the racket angle to be arbitrarily adjusted by the user's intention will be necessary for advanced play. In addition, the rotation speed of the racket may also need to be faster. In order to prevent the prosthetic hand from falling out, it is necessary to develop an orthosis to suspend the prosthetic hand on the upper arm.

V. Conclusion

This paper reported a table tennis prosthetic hand controlled based on distance measurement using a ToF Sensor. The participant with forearm amputation could play table tennis with this hand in the test play. The racket angle was switched to the appropriate angle for the forehand drive and the backhand drive, and the participant could return the ball 6.3 times in 10 seconds. The satisfaction of the participant with the prosthetic hand was good.

Acknowledgment

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