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Pneumatic Assist Suit to Facilitate Lower-Body Twisting for the Training of Forehand in Table Tennis

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***Abstract*—Engineering support for sports has the potential to improve training performance. Most research on sports training support has focused on support in areas that directly affect the point of force action. On the other hand, even if sports with hand-held tools, the importance of lower body motor function has been indicated. This suggests that supporting areas away from the point of force action can improve the performance of novice players. Therefore, in this study, we developed an assist suit that facilitates lower body twisting for table tennis beginners during forehand swing. Using this assistive suit, experiments were conducted for the experimental group under the following four conditions (1) "No wear (before)," (2) "Without assist," (3) "With assist," and (4) "No wear (after)" to clarify the effect of wearing, assist, and training. In addition, a control group in which participants hit the ball without the assist suit was set up to examine the training effect of repetition. The results showed that both the amount of waist rotation and racket velocity increased significantly in the experimental group compared to the control group, which indicates the effect of the assist suit on training.**

***Keywords*—pneumatic actuator, wearable suit, sports training support**

I. Introduction

A. Background

Exercise in sports is important for physical and mental health. However, it takes much practice time to learn effective body motion in each sport. Therefore, it is important to provide support for beginners in sports [1]. There are two ways to practice sports: to improve through repetitive motion, such as swing practice or footwork training by oneself, and to practice with others to get feedback and improve. This means that sports training can be broadly classified into two types: self-learning and guidance from others. However, in the case of self-study, beginners may learn a form that puts a burden on only specific body parts or a form that does not exert sufficient power. In the case of guidance from others, an experienced instructor is necessary. Therefore, a device that enables beginners to acquire the appropriate movement form for each sport by themselves could be useful. In this study, we focus on table tennis, a sport that has a large population [2][3] because it is familiar to men and women of all ages.

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B. Previous Research

In order to provide effective assistance in sports training, it is necessary to understand which parts of the body have a significant impact on exercise performance. Previous studies in golf, tennis, volleyball, and other sports have shown that twisting movements of the waist are important [4][5][6]. In addition, training of the trunk has been shown to have a significant impact on performance and injury potential [7]. As for table tennis, while some studies have focused on upper body kinematics [8][9], others have evaluated differences in the lower body and trunk kinematics. Wang *et al.* stated that advanced table tennis players have larger motion ranges of the lower body and can use their muscles more efficiently compared to beginners [10]. Qian *et al.* also investigated the differences in lower body movements by comparing advanced and intermediate table tennis players [11]. The results showed that intermediate players had less waist and trunk rotation and less lower body motor skills than advanced players. In addition, He *et al.* showed that advanced table tennis players have a greater amount of joint angle change in the lower body during swinging and a greater range of joint motion than intermediate players [12]. These studies indicate that table tennis beginners and experienced players differ greatly in lower body motor skills which are important in the sport.

There are studies on support for sports exercise, such as feedback of body movements by visual information [13], timing guidance by sound [14], and training using VR [15]. These studies do not provide support by an external force, such as directly applying force to the person or providing feedback through force. On the other hand, there are studies that provide ideal movements through the support of external forces. In an experiment by Griffiths *et al.*, participants were trained to improve their driving skills by operating a steering wheel while watching a screen [16]. During the training, the steering wheel automatically moved in response to changes in the road displayed on the screen, providing feedback to the participants on correct maneuvering. The results showed that the participants' control skills were improved compared to the training method without feedback using the steering wheel. Furthermore, Marchal-Crespo *et al.* showed that training using contacting guidance such as the method proposed by Griffiths *et al.* is more effective for people with low initial skills [17]. In studies of sports assistance using contacting guidance, there are studies that teach swing form by controlling the movement of a tennis racket or golf club [18][19]. As devices that assist body movement using contacting guidance, there are studies proposing an assist suit on the lower body when walking [20][21] and an assist suit that supports the arm strength of wheelchair passengers when they operate the wheelchair by themselves [22]. There is also an assistive suit that supports the rehabilitation of upper limbs of stroke patients [23], and an assistive suit that provides training assistance for tennis backhands [24]. These studies have guided or assisted the areas that directly affect the point of force action, such as the thighs and lower legs involved in manipulating the feet that contact the ground during running, and the shoulders and arms that manipulate the racket to hit the ball. However, as mentioned above, the motion of the lower body, which is located far from the point of force action, is important in some sports. Therefore, it is hypothesized that the performance of exercise could be improved by providing assistance to the position away from the point of force action using a method similar to that in the above study.

When performing complex exercises, it is shown to be effective in reducing the number of tasks and practicing with guidance [16]. For training using an assistive device, substituting a task with the device would be effective. Previously, we developed an assistive suit to facilitate lower body twisting movements of table tennis beginners [25]. In that study, although some participants increased their waist rotation by training using the device, others did not. It might be caused by the device setting that the assistive motion was started by pushing the button with the participant's left hand. Namely, the additional pushing task might distract from the focus on lower body twisting, and as a result, inhibit the training effect. Therefore, in this study, we develop an assistive suit that automatically starts operating, and conduct training using this suit.

C. Research Purpose

The final goal of this research is to develop an assist suit that allows table tennis beginners to train effectively by themselves without an instructor. To achieve it, we first develop an assist suit that facilitates a twisting motion of the lower body during table tennis forehand. Then, experiments are conducted to verify whether the performance of beginners can be improved by training with the developed assist suit.

II. Developed Assist Suit

A. Actuator

The assist suit in this research is used during sports training. Therefore, the actuator must be lightweight, not inhibit movement, and be able to safely control the force exerted by the actuator. Based on the above, the McKibben-type pneumatic artificial muscle was used as an actuator. Pneumatic muscles are lightweight and have a large exerted force relative to their weight. In addition, because it is made of flexible material, it does not inhibit the wearer's movement even when it is located around the human body. Furthermore, as the length of pneumatic artificial muscles decreases, the exerted force decreases. Thanks to this feature, the artificial muscles do not shrink excessively. Thus, the safety of the wearer is ensured.

B. Placement of Assist Suit

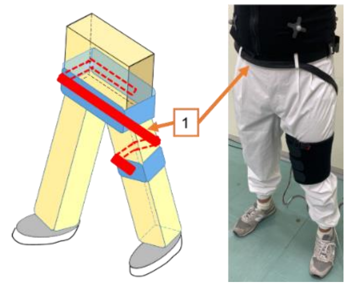

Fig. 1. The position of a pneumatic muscle.

The artificial muscle shown in Fig.1 plays a role in generating a twisting of the waist. The artificial muscle is fixed from the thigh supporter (Matsuyoshi Medical Instruments, compression sirup) to the waist belt (Kajimake, Men GI Belt RB roller buckle, 40 mm) fixed to the pants (Aitos, white coat slacks, double weave, crossed, size L) over the thigh. The artificial muscle is made to reach the back of the waist by circling the thigh so that the length of the artificial muscles can be extended to ensure the exerted force for twisting the waist. The fixing section is a buckle (Esco, 20 mm buckle) to unify the conditions of attachment and prevent losing the power of the artificial muscle. The total weight of the lower body of the assist suit is 0.69 kg.

C. Control Mechanism

Fig. 2. The appearance of the upper body.

The appearance of the upper body of the assist suit is shown in Fig.2. The bag on the back (Fukutoku, waist bag) contains the control devices shown in Fig.2. On top of a 16.8 cm long and 24.0 cm wide acrylic plate (Kuraray, acrylic plate (Como Glass), 3 mm thick), a DA converter (Analog devices, AD5308), a microcontroller (Arduino, Arduino Uno R3), a pressure control valve (Hoerbiger, tecno basic) are fixed. To protect the wiring on the microcontroller, an acrylic cover is attached.

The flow of control and operation of the device is described below. Fig.3 shows the relationship between devices. The sound sensor (A: Dfrobot, Analog Sound Sensor Module, DFR0034) picks up the sound of the ball bouncing and sends a signal to open the pressure control valve after 0.2 s so that the ball can be hit at the apex of the bound. The microcontroller (B) then sends a signal to control the pressure control valve (D) at the specified pressure. The signal is converted to a voltage by the DA converter (C) to control the pressure control valve (D) at the specified pressure.

The tank (E: JC Service, Inc., ECO JET E) is attached to the back bag. This tank is used as a buffer by storing the high-pressure air sent from the pneumatic compressor (F: JUN-AIR, Inc., 6-4) to reduce the time delay. The air is sent through the tube (PISCO, Inc., UC640) to the artificial muscle (G). In addition, an LED lights up when the sound sensor responds, so that the user can visually confirm when air is supplied to the artificial muscle. The total weight of the upper body of the assist suit is 1.27 kg.

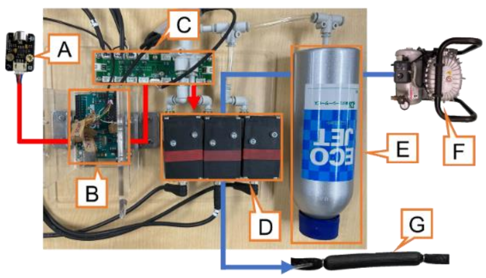

Fig. 3. The devices in the assist suit.

III. VERIFICATION EXPERIMENT OF SUIT EFFECT

A. Experiment Purpose

The purpose of the experiment is to verify whether the assist suit is effective in facilitating lower body twisting movement and the benefit of training with an assist suit that provides automatic support.

B. Experiment Method

The experimental protocol is approved by the Research Ethics Committee of the Faculty of Engineering at Kyushu University (approved number: 2021-04). The following four conditions were set for participants A-C, the experimental group.

(1) Not wear the assist suit.

(2) Wear the assist suit without assist.

(3) Wear the assist suit with assist.

(4) Not wear the assist suit

From here, each condition will be described as (1) "No wear (before)", (2) "Without assist", (3) "With assist", and (4) "No wear (after)".

The effect of wearing the assist suit on the swing is verified by comparing the results of 1 and 2, the effect of the assistance when wearing the assist suit is verified by comparing 1 and 3, and the effect of training with the assist suit is verified by comparing 1 and 4, respectively. Under each condition, participants hit a ball (Nittaku NB-1150) 20 times. The participants were asked to hit the ball according to the instruction to emphasize accuracy rather than ball speed.

The balls were supplied by a ball launcher (Nittaku NT-3015). Since the research participants were novice table tennis players, the bounce position was set to 495 mm from the center of the net in the X-axis direction and -365 mm in the Y-axis direction. The rotation speed was set to 26.7 r/s in the upper rotation, and the pitch was set to 1.83 s intervals to facilitate hitting for novice players. All experiments were conducted under the same conditions. In order to have the participants get familiar with the support by the suit, a few practice balls were hit before the (3) "With assist". The target pressure in the artificial muscle was set to 0.6 MPa, and the air was allowed to begin to be exhausted 0.3 s after the start of the air supply to the artificial muscle.

Participants D-F were as a control group for the experiment to examine the training effect of hitting the ball repeatedly. The experimental condition consisted of four repetitions of 20-ball hitting practice without the use of an assist suit. An interval of 10 min between conditions 1 and 2, 20 min between conditions 2 and 3, and 5 min between conditions 3 and 4 were set so that the experimental time was brought closer to that of the experimental group. Participants were selected on the condition that they had never practiced table tennis for a long period of time. Table I shows the participant information.

TABLE I. THE DATA OF PARTICIPANTS

Participant	***Age***	***Sex***	***Height (cm)***	***Body mass (kg)***	***Dominated had***
A	24	Male	170	57	Right
B	22	Male	165	65	Right
C	25	Male	178	80	Right
D	24	Male	178	78	Right
E	24	Male	171	72	Left
F	24	Male	168	65	Right

C. Measurement and Analysis Method

The amount of waist rotation was measured to consider the influence of the assist suit on the twisting movement of the lower body and racket speed were measured to evaluate the improvement of swinging ability. A motion capture camera (NaturalPoint, Prime 13W) was used as the measurement device. As shown in Fig. 4, eight motion capture cameras were installed in the room. The sampling rate during measurement was 120 Hz. The participant's upper body was measured as a skeleton body (OptiTrack, Skeleton, Upper Body (25)). The racket was defined as a rigid body with eight reflective markers attached around it.

RGB cameras (Fig.4, A: GoPro, HERO8 Black; B: Panasonic, Lumix DMC-FZ300) were placed on the ceiling above the table tennis table and diagonally behind the participant's right side to capture the participant's swing. The resolution of the GoPro camera was set to 1920px (horizontal), 1080px (vertical), and 240 fps, and that of the LUMIX camera to 1920px (horizontal), 1080px (vertical), and 60 fps.

The amount of waist rotation was calculated using the measured Euler angle values around the rigid body's Z-axis, with the start of the swing defined as the timing when the angle around the Z-axis reached a minimum value and the end of the swing defined as the timing when the angle around the Z-axis reached a maximum value. The angle difference between the start and end of the swing was evaluated as the amount of waist rotation.

Racket speed was calculated from the time difference of the measured rigid body movement. Since there was noise in the calculated racket speed data, an FFT filter was used to remove high-frequency noise. The cutoff frequency of the filter was set at 20 Hz. The timing at which the racket's Y-coordinate reached a minimum value was defined as the start of swinging, and the timing at which the racket's X-coordinate reached a minimum value was defined as the end of swinging. The maximum racket speed between each swing was then evaluated.

First, six data were derived for each condition by finding the average of the data from each participant's 20 balls in each condition to examine the overall tendency of the participants for the four conditions. Second, the data of the 20 balls between the four conditions for each participant were compared. After checking the normality and equal variances of the 20 balls, we performed a one-way ANOVA for normality and equal variances. In the absence of normality and equal variances, Welch tests were conducted to check for significant differences between conditions. The Dunnett test was conducted for conditions 1 and 2, 1 and 3, and 1 and 4, with condition 1 as the control group, for multiple comparison tests. For all tests, a value of *p*<0.05 was considered statistically significant.

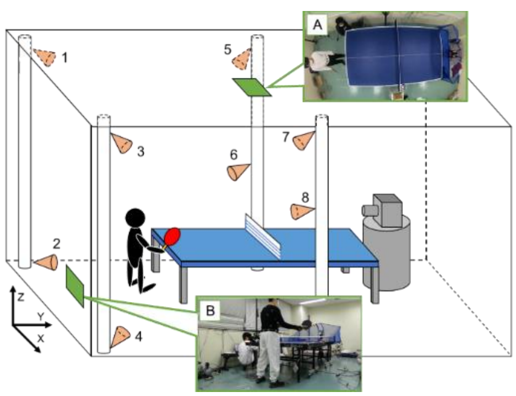

Fig. 4. The layout of cameras.

IV. Experimental Result

A. Overall Participant Trend

Fig.5.A shows the overall trend in the amount of waist rotation, and Fig.5.B shows the overall trend in racket speed for all participants.

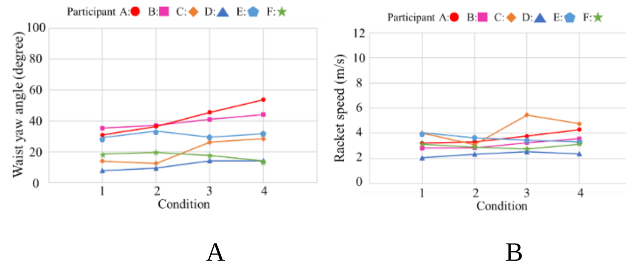

Fig. 5. The average waist yaw angle (A) and racket speed (B).

B. Waist Yaw Angle

The results of the amount of waist rotation are shown in Fig.6.

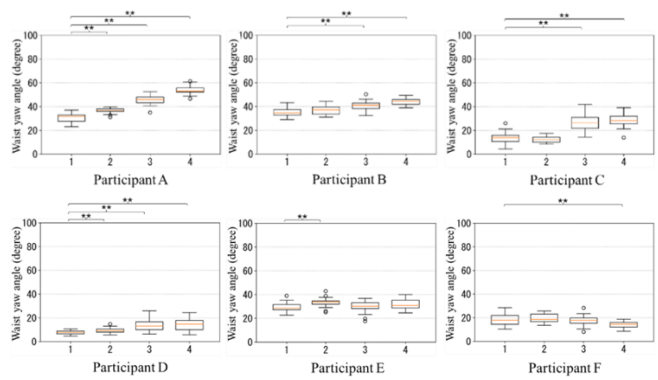

Fig. 6. Waist yaw angle of each participant (*: *p*<0.05 **: *p*<0.01).

C. Racket Speed

The results of the racket speed are shown in Fig.7.

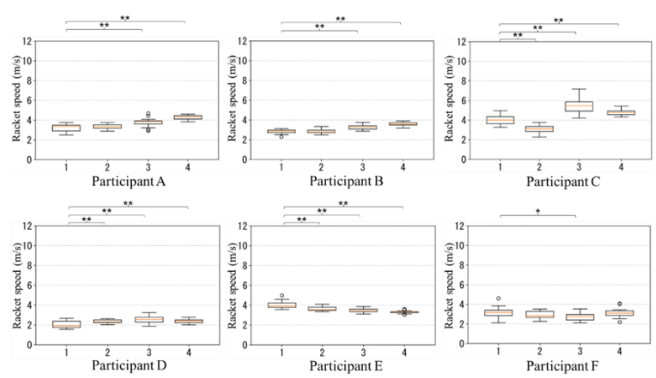

Fig. 7. Racket speed of each participant (*: *p*<0.05 **: *p*<0.01).

V. Discussions

A. Repetitive Effect of Hitting a Ball

In this subsection, the results of a control group are discussed to evaluate the repetitive effect of training on the motion. Participant D showed a significant increase in both the amount of waist rotation and racket speed between all conditions (conditions 1 and 2, 1 and 3, and 1 and 4). This suggests that Participant D improved his performance through repetitive hitting of a ball. Participant E showed a significant increase in waist rotation between conditions 1 and 2 but a significant decrease in racket speed between all conditions. The box-and-whisker diagram of Participant E's racket speed showed a smaller range from conditions 1 to 4. This suggests that Participant E converged to a racket speed at which he could hit the ball stably by repeating the ball-hitting action. Participant F showed a significant decrease in waist rotation between conditions 1 and 4, and a significant decrease in racket speed between conditions 1 and 3. The box-and-whisker diagram of Participant F's waist angle has decreased in width, suggesting that he can acquire the amount of swing that allows him to hit the ball stably as in Participant E. To summarize the above, no consistent trend in waist rotation and racket speed was identified by the repetitive hitting of a ball.

B. Effect of Wearing the Assist Suit on the Swing

In this subsection, the discussed theme is the effects of wearing the assist suit on the participants based on the results for conditions 1 and 2. Participants A and B showed no significant decrease in the amount of waist rotation and racket speed, suggesting that wearing the assist suit had little effect on their swings. On the other hand, participant C showed a significant decrease in racket speed, suggesting that the wearing of the assist suit may have restricted his swing. From Fig.6 and Fig.7, participant C had a smaller amount of waist rotation in Condition 1, but a larger racket speed than Participants A and B. This suggests that Participant C mainly used his upper body to hit the ball. Large upper body motion might be affected by the bag in Participant C. From the above, it is possible that the wearing of the assist suit has an effect on participants who swing mainly using their upper body, but not on those who swing using their upper and lower bodies.

C. Assistive Effect of the Assist Suit

In this subsection, discussed theme is the assistive effects of the assist suit from the test results for conditions 1 and 3. The amount of waist rotation and racket speed increased significantly for all participants A-C. This suggests that the support by the assist suit has the effect of increasing the amount of waist rotation and racket velocity.

For Participants A-C, the increase in values from 1 to 3 can become due to the effect of repeated practice. Therefore, the experimental and control groups are compared to discuss the effect of repetition on the training effect. Fig.8 shows the difference in the mean values of the amount of waist rotation and racket speed for each participant in conditions 1 and 3. For both waist rotation and racket velocity, the difference between the mean values for conditions 1 and 3 is greater in the positive direction for the experimental group than for the control group. This indicates that the improved performance was caused by the assistive effect rather than the training effect of repetition.

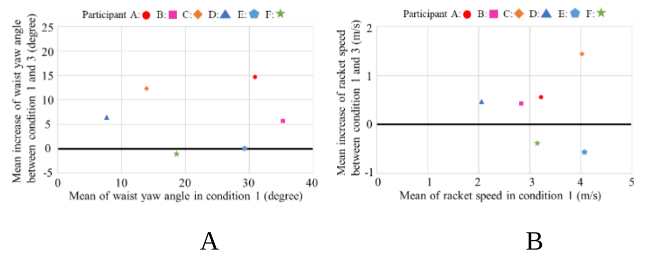

Fig. 8. The mean increase of waist yaw angle (A) and racket speed (B) between conditions 1 and 3.

D. Training Effect of the Assist Suit

In this subsection, the discussed theme is the assistive effects of the assist suit from the test results for conditions 1 and 4. The amount of waist rotation and racket velocity increased significantly for all participants A-C. This suggests that training with the assist suit is effective in increasing the amount of waist rotation and racket velocity.

For Participants A-C, the increase in values from 1 to 4 can be due to the effect of repeated practice. Therefore, the experimental and control groups are compared to discuss the effect of repetition on the training effect. Figs.9 shows the difference in the mean values of the amount of waist rotation and racket speed for each participant in conditions 1 and 4. For both waist rotation and racket velocity, the difference between the mean values for conditions 1 and 4 was greater in the positive direction for the experimental group than for the control group. This indicates that the improved performance was caused by the training effect of the assist suit rather than the training effect of repetition.

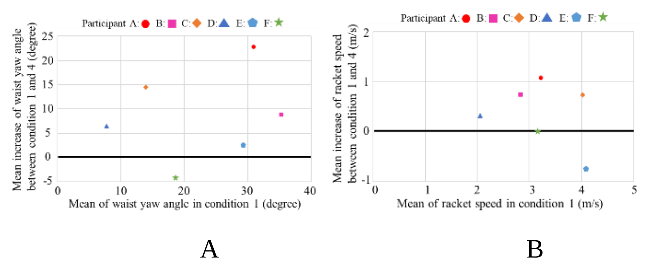

Fig. 9. The mean increase of waist yaw angle (A) and racket speed (B) between conditions 1 and 4.

E. Limitation

The developed assist suit facilitated lower body twisting and, as a result, increased racket speed. However, the mechanical relationship between lower body twisting and racket speed is not clarified. By quantitatively evaluating energy transfer and kinetic characteristics from the lower body to the upper body, it will be possible to analyze and evaluate performance in more detail. This would not only allow for improving the lower-body assist suit, but also combining it with an upper-body assist suit because the swing motion is the coordinated motion of the lower and upper body.

In this study, waist rotation and racket speed were used as evaluation parameters. Although they are characteristics of expert players [10][11][12] and a high-speed swing is necessary to give large rotation speed to a ball, it is also important how well the ball is manipulated in table tennis. In the future, the evaluation of ball speed and rotation and the accuracy of placing a ball on the court is necessary to deepen the discussion of the training effect.

The control of the assist suit also could be improved. Because the purpose of this suit is to facilitate waist rotation, the accurate tracking of the specific trajectory was not aimed. However, how to decide the timing and strength of actuation, which were decided heuristically in this study, should be clarified to design a better assist suit. As for the timing of actuation, the sound of a bouncing ball was used in this study. Thus, the support did not reflect the wearer's intention. Reflecting the intention could be one option for future development. To achieve this, a mechanism that provides support in response to changes in myoelectricity, joint torque, or other biological parameters will be necessary.

VI. Conclusion

In this study, the assist suit was developed and tested to make training more effective for table tennis beginners by facilitating the amount of waist rotation. Training with the assistive suit showed a training effect in all participants in the experimental group. The comparison with the control group confirmed that the training effect was not due to repetitive practice.

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