Training with a Pneumatic Assist Suit to Generate Lower-Body Twisting during the Forehand Swing in Table Tennis

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Abstract: Movement form is important in sports. However, self-learning of the form has a possibility that people will acquire a form which puts a burden on one part of the body or a form which cannot exert sufficient power. Although there is also a way to have an instructor, people do not always receive the instruction of the form. Therefore, it is useful for sports training to develop a device which allows participants to acquire a form suited for each sport. Existing research about support in sports with a racket does not pay much attention to the lower body. In this research, we developed an assist suit that assists the lower body in executing a forehand swing in table tennis with lower-body twisting. Using this suit for beginners of table tennis, we conducted experiments under four conditions:(1) "No wear (before)", (2) "Without assist", (3) "With assist", and (4) "No wear (after)". As a result of Tukey analysis within each participant, the range of movement of the lower body is statistically increased by the assist suit and there are individual differences in whether to acquire a swing with twisting the lower body.

1 INTRODUCTION

1.1 Background

Exercising in sports is one of the effective ways of maintaining physical health and reducing stress. However, a lot of learning and practice time is required for beginners to master how to move their bodies in each sport (Wulf & Shea, 2002).

As a training method for sports at present, two typical examples are considered: self-learning like using some services such as a pitching machine and guidance by an experienced person. In the case of self-learning, however, there is a possibility that a beginner will acquire such as a form that puts a burden on only one part of his/her body or a form that is difficult to transmit force. Also, in the case of guidance by an experienced person, an experienced instructor is necessary. From the above, it is considered that it is necessary to make a device that can help a beginner acquire an ideal form. In this research, we focused on table tennis, which is popular with a wide range of ages, to investigate the supporting method for the training of forehand swing.

1.2 Previous Research

To provide efficient sports support, it is necessary to understand the parts of the body that greatly affect sports movements. In previous studies of golf (Evans & Tuttle, 2015) and tennis (Gordon & Dapena, 2006), it is shown that waist twisting exercise is important. Qian *et al*. investigated differences between advanced and intermediate table tennis players in lower limb movements during the forehand swing of table tennis. In their research, it was found that intermediate players rotated the hip joint and trunk lesser than advanced players and the exercise skills of the lower limbs were lower than advanced players (Qian *et al.*, 2016). Also, Zhang's study states that advanced players have a greater range of motion during swings and trunk twisting is important in table tennis (Zhang, 2017).

About sports support methods, it has been found that tactile guidance is efficient to learn movement more quickly (David & James,2009; Huang *et al.*, 2007). As a sport-aided device using tactile guidance, there are robots that teach swing by controlling the movement of tennis rackets and golf clubs (Kümmel

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et al., 2014; Hirata *et al.*, 2017). In addition, there are studies that use wearable robots to assist in running and swing movements (Miyazaki *et al.*, 2021; Zhou *et al.*, 2021; Klein *et al.*, 2012; Sakoda *et al.*, 2018). These studies supported a body part that directly affects the action point of force. However, as mentioned in the first paragraph of this subsection, it is stated that the exercise of the part far from the point of action is also an important factor in playing sports. Therefore, it is expected that the performance will be improved by supporting the training of the part far from the point of action.

1.3 Purpose of Research

This study aims to achieve effective training by developing an assist suit to help the wearer master the form by inducing the twisting motion of the lower body during the forehand swing of table tennis.

2 ASSIST SUIT DESIGN

Figure 1 shows the appearance of the developed assist suit.

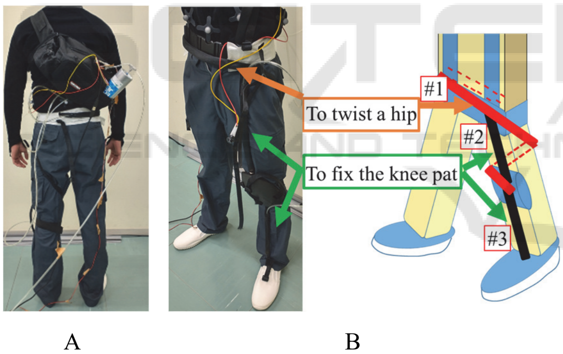

Figure 1: A) The back of the assist suit. B) Position of pneumatic muscles.

2.1 Actuator

An assist suit for sports needs to be lightweight, not interfere with movement, and be able to safely control the exerted force of the suit. Therefore, in this study, we adopted pneumatic artificial muscle as an actuator. Pneumatically driven artificial muscles have a large exerting force relative to weight, flexible materials, and the characteristic that the exerting force decreases as the length of the artificial muscle decreases from the start to the end of a contraction. By the last feature, the artificial muscle does not give excess power. So, there is little risk of injury to the wearer. These features are consistent with the requirements for assist suits.

2.2 Placement of Artificial Muscles

Figure 1.B shows the placement of the artificial muscle of the assist suit. Three artificial muscles are used for the assist suit. To get sufficient power for the twist of the lower body, a longer artificial muscle is needed. Also, by increasing the length of muscle fixed parallel to the waist, the perpendicular force for the axis of the body is increased. By this structure, the force for causing the twisting motion of the lower body is enough. Considering the above, the artificial muscle #1 shown in Figure 1.B is fixed in a way that makes one circumference of the thigh from the knee to the waist. To fix the knee supporter as fixing the position of the artificial muscles, the muscles #2 and #3 are used. Artificial muscle is fabricated using the braided tube (DENKA ELECTRON Co., NFL-19), and the initial diameter is 12 mm. Table 1 shows the initial length of each artificial muscle and the length after contraction when the internal pressure is 0.6 MPa at no load.

Table 1: Length of each pneumatic muscle (mm).

	1	2	3
Normal (0MPa)	820	315	165
Maximum contraction (0.6MPa)	600	220	115

2.3 Control Mechanisms

When the push-button (ELPA (Asahi Electric) Co., HK-PSS04H) is pressed, a signal to open the valve is output from the microcontroller (Arduino Co., Arduino Uno R3). The signal is converted to a voltage with a DA converter (ANALOG DEVICES Co., AD5308), and the valve (HOERBIGER Co., tecno basic) changes the pressure in artificial muscles to a specific value according to the voltage. These parts are fixed to an acrylic plate (Kuraray Co., COMOGLAS). Then, this control unit is put in a bag. The total weight of the bag is 1.52 kg. The total weight of the assist suit is 2.12 kg. Since this suit is for right-handers, so as not to interfere with the swing of the right hand, it was placed over the left shoulder. In addition, air from the compressor (JUN-AIR Co., 6-4) is stored in a tank (JC Service Co., ECO JET E) and this tank is carried on the back. By doing this, the time of supplying air to the artificial muscles gets shorter. In this experiment, the participants pressed a button with their left hand to control the internal pressure of the artificial muscle to rise from 0 MPa to 0.6 MPa. After 0.3 s, the air let out automatically.

3 VERIFICATION EXPERIMENT OF SUIT EFFECT

3.1 Purpose of the Experiment

The purpose of the experiment is evaluating the effect of the suit on beginners in table tennis by conducting experiments with the developed suit.

3.2 Experimental Method

Table 2 shows each participant information. All participants are right-handed. In order to evaluate the improvement of swing ability by the suit, we used two parameters: the amount of rotation of the waist around the vertical axis during a swing and the maximum racket speed.

The following four experimental conditions were set: condition (1) to examine the participant's swing before training, condition (2) to examine the effect of wearing this suit, condition (3) to examine the support effect, and condition (4) to examine the training effect.

(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)".

In each experiment, a table tennis ball launcher (Nittaku Co., NB-1150) provided a ball 20 times. In addition, data on the participant's swing to strike the ball were recorded. The trajectory of balls provided by the table tennis ball launcher was set to bounce at a position of 495 mm in the Z-axis direction (in Figure 2) and -365 mm in the X-axis direction (in Figure 2) on the participant side court from the center of the table. The ball speed was set to 3.64 m/s, the rotation speed was set to 26.7 round/s in the upward rotation, and the ball launch interval was set to 1.83 s. The experiment was conducted with the approval of the Experimental Ethics Committee of the Faculty of Engineering, Graduate School of Kyushu University (approval number 2021-04).

Table 2: Each participant data.

	Age	Sex	Height [cm]	Body mass [kg]
Participant1	22	Male	175	60
Participant2	23	Male	166	51
Participant3	23	Male	170	50
Participant4	21	Male	173	61
Participant5	21	Male	173	58
Participant6	22	Male	167	67

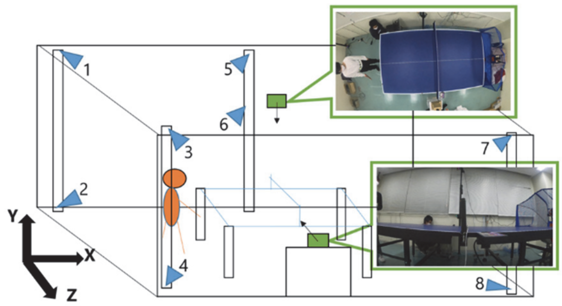

Figure 2: The Arrangement of measuring equipment. This is a side view of the experiment room. The blue triangles (1-8) are motion capture cameras. The green rectangles are normal cameras.

Figure 3: The Appearance of the experiment.

3.3 Measuring Instruments and Analysis Methods

For measurement of two parameters, we use eight motion capture cameras (NaturalPoint Inc., Prime 13W) installed at positions 1-8 as shown in Figure 2. Also, Figure 3 shows the experiment appearance. For participants 1-6, the three-dimensional position coordinates of the center of the racket defined as rigid bodies were measured. Also, for participants 1-3, the three-dimensional position coordinates of the center of the waist defined as rigid bodies were measured. For participants 4-6, the three-dimensional position coordinates of upper body skeleton were measured. The sampling rate was 100 Hz.

The amount of rotation around the vertical axis of the waist was calculated based on the measured value of the Euler angle in the Y-axis direction of the rigid body. In addition, the racket speed was calculated by dividing the moving distance of the racket between frames by the time between frames. Regarding the amount of rotation of the waist, the minimum value of the angle around the Y axis was defined as the start of the waist rotation and the maximum value of the angle around the Y axis was defined as the end of the waist rotation. Also, the angle difference between the start and end of the waist rotation was calculated as the rotation amount of the waist. About the racket swing, the minimum value of the X coordinate was defined as the start of the swing and the minimum value of the Z coordinate was defined as the end of the swing. Also, the maximum racket speed was examined in the swing.

To investigate the effect of the suit, the amount of waist rotation and the racket speed between the conditions were compared. First, using the mean of 20 trials with each condition in each participant, four conditions were statistically compared by paired t-test with the Bonferroni correction. Second, the Tukey method was used to statistically compare four conditions within each participant for detailed analysis. The significance level was set to $p < 0.05$.

4 EXPERIMENTAL RESULTS

4.1 Analysis across Participants

Figure 4 shows the waist yaw angle of all participants. Figure 5 shows the racket speed of all participants. In the comparison of waist yaw angle between "With assist" and "No wear (after)", there was a significant decrease.

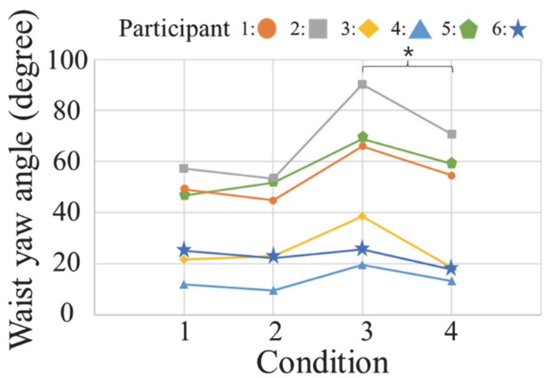

Figure 4: Waist yaw angle of each condition (Bonferroni method *: p<0.05 **: p<0.01). Each plot shows the mean of 20 trials with each condition in each participant.

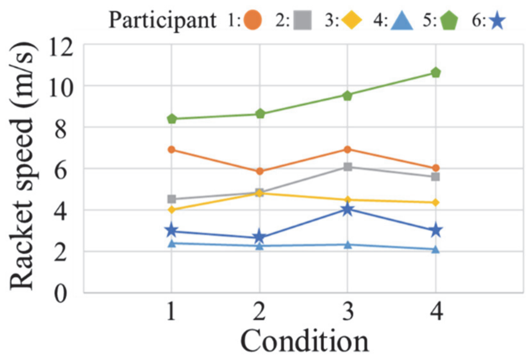

Figure 5: Racket speed of each condition (Bonferroni method *: p<0.05 **: p<0.01). Each plot shows the mean of 20 trials with each condition in each participant.

4.2 The Amount of Waist Rotation

Figure 6 shows the results of the amount of waist rotation within each participant. Although there was no significant difference in the comparison between "No wear (before)" and "Without assist" in all participants except participant 6, there is a significant increase in the comparison between "No wear (before)" and "With assist", in the comparison between "Without assist" and "With assist". In addition, in participants 2 and 5, there is a significant increase in the comparison between "No wear (before)" and "No wear (after)".

4.3 Racket Speed

Figure 7 shows the results of the racket speed within each participant. In the comparison between "No wear (before)" and "Without assist", there was a significant decrease in participants 1 and 6, no significant difference in participants 2, 4 and 5, and a significant increase in participant 3. In the comparison between "Without assist" and "With assist", there was a significant increase in participants 1, 2, 5 and 6. In addition, in participants 2 and 5, there was a significant increase in the comparison between "No wear (before)" and "No wear (after)".

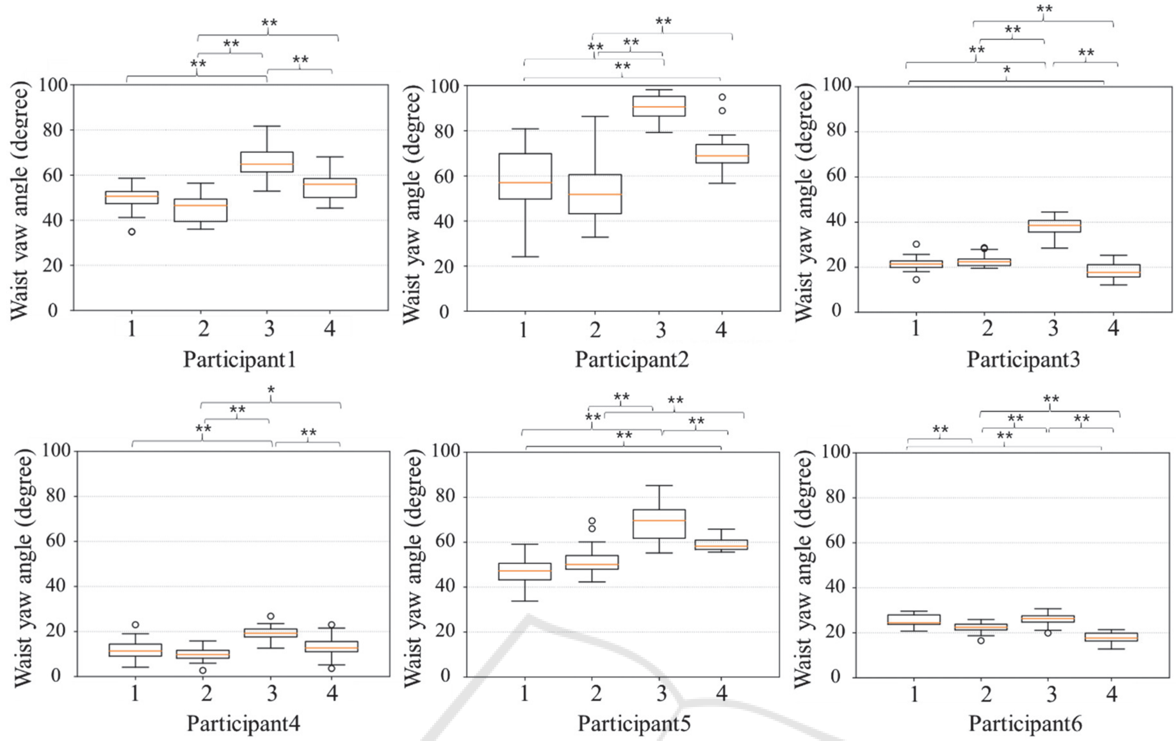

Figure 6: Waist yaw angle of each participant (Tukey method *: $p<0.05$ **: $p<0.01$).

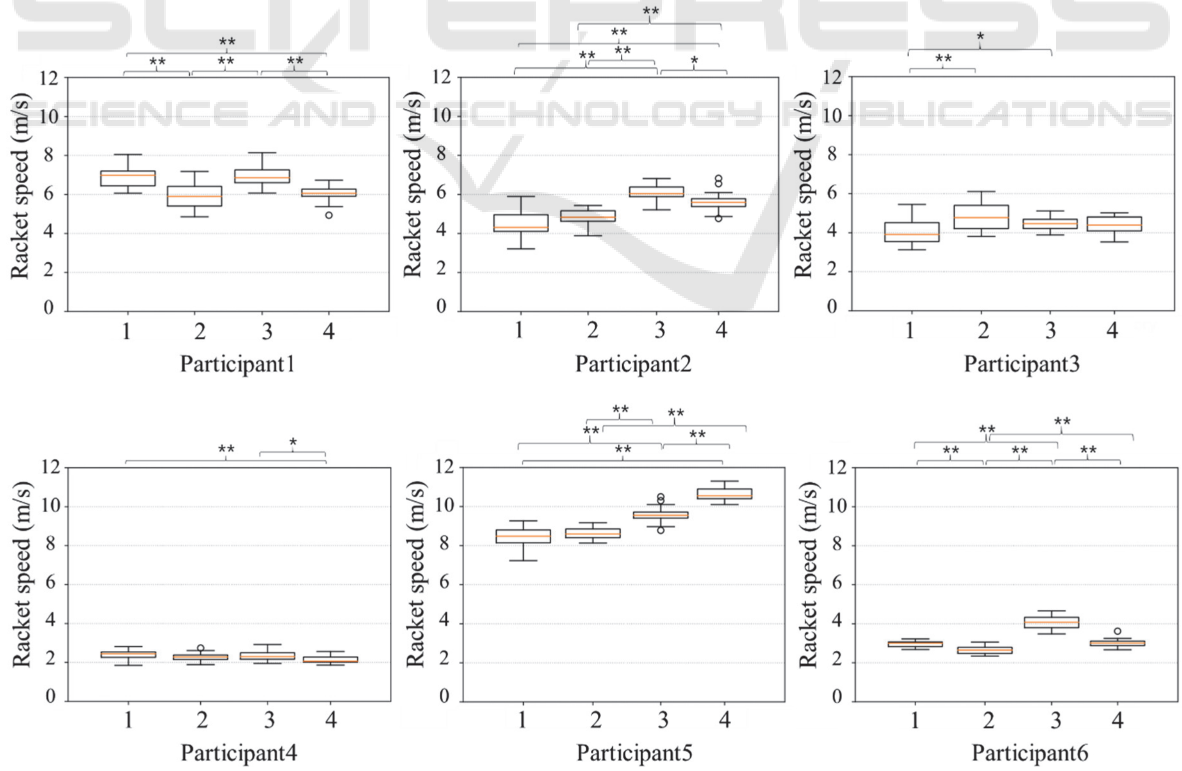

Figure 7: Racket speed of each participant (Tukey method *: $p<0.05$ **: $p<0.01$).

5 DISCUSSIONS

As shown in Figure 4 and 5, the analysis using the Bonferroni method hardly showed significant change across conditions. Therefore, Figure 6 and 7, which shows the results of the Tukey test, is the subject of the discussion.

5.1 Effect of Wearing the Assist Suit on the Swing

The effect of wearing an assist suit on the swing is examined by comparing the results of "No wear (before)" and "Without assist". In all participants except participant 6, there was no significant difference in the amount of waist rotation between "No wear (before)" and "Without assist". Therefore, it can be said that wearing the assist suit had less restriction on the lower body movement.

In addition, in participants 1 and 6, the racket speed was significantly decreased in the comparison between "Without assist" and "No wear (before)". About this, participant 1 said there was a feeling that the bag fixed on the back was misaligned. Based on this opinion, in each experiment of participants 2-6, the bag fixation was strengthened. In the result, a significant decrease was not observed except participant 6. Therefore, when the bag fixation was strengthened, it is considered that wearing the assist suit had little restriction of the upper body movement.

5.2 Support Effect for Waist Yaw Angle

The support effect of the assist suit is examined by comparing "With assist" and "No Wear (before)", "With assist" and "Without assist".

In all participants except participant 6, the amount of rotation of the waist increased significantly in the comparison between "With assist" and "No wear (before)". In addition, in all participants, the amount of rotation of the waist increased significantly in the comparison between "With assist" and "Without assist". From this, it can be said that the purpose of increasing the rotation of the lower body was achieved with the developed suit.

Only in participant 6, there was no significant difference in the amount of rotation of the waist with the comparison between "With assist" and "No wear (before)". In this regard, in participant 6, the amount of rotation of the waist reduced in "No wear (after)". So, there is a possibility that participant 6 generated the opposite force against the support force of the device.

5.3 Training Effect of Assist Suit

The training effect of the assist suit is examined by comparing "No wear (before)" and "No wear (after)".

In the results of the comparison of waist rotation amounts, there is no significant difference in participants 1 and 4, but a significant increase in participants 2 and 5, and a significant decrease in participants 3 and 6.

In the results of the comparison of racket speed, there is a significant decrease in participants 1 and 4, a significant increase in participants 2 and 5, and no significant difference in participants 3 and 6.

From the above, it can be said that the improvement of the swing ability by training with the assist suit was observed in participants 2 and 5, but not observed in participants 1, 3, 4, and 6.

To identify whether there are any characteristics specific to those who have benefited from the suit, the difference between participants 2, 5 and other participants is discussed. On considering about difference, participant 1 whose bag on his back was fixed weakly than other participants and participant 6 who was not able to get support with the assist suit are excluded. In the comparison of the waist rotation amounts of "Without assist" and "With assist", there are significant increases in all four participants. However, in the racket speed, there are significant increases in participants 2 and 5. Therefore, it is considered that participants 2 and 5 were able to transmit the waist increase movement to the racket.From the above, there is the possibility that this assist suit gives a great effect to participants who are able to coordinate the twisting motion of the waist and the movement of the racket well.

Figure 8 shows each average of waist yaw angular velocity in "No wear (before)" and "No wear (after)". In participants 2 and 5 who had a training effect, Waist yaw angular velocities of both "No wear (before)" and "No wear (after)" were large. The same character is also seen in participant 1. So, there is a possibility that participant 1 got a positive training effect if the method of fixing the bag was the same as that of other participants. On the other hand, in participants 1, 3 and 6, waist yaw angular velocities of both "No wear (before)" and "No wear (after)" were small. From this, training effect may be seen in participants with large waist yaw angular velocities before training. Also, increases of waist yaw angular velocities is not seen for participants with small waist yaw angular velocities before training.

From the above, there is a possibility that the developed assist suit is effective by introducing a mechanism which supports transmitting the increased movement of the lower body to the racket movement and reproducing the movement with large waist yaw angular velocity without the suit after training. In addition, the total training time is short since participants hit the ball 20 times for each condition. So, it is necessary to confirm whether the training effect will be produced even in participants with small waist yaw angular velocity if the number and duration of training increase.

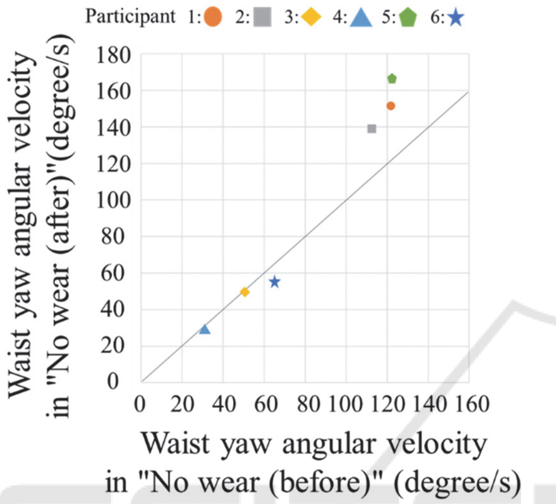

Figure 8: Relation of the average of waist yaw angular velocity between "No wear (before)" and "No wear (after)" in all participants 1-6. The plots over the diagonal line indicate increases in waist yaw angular velocities from "No wear (before)" to "No wear (after)".

6 CONCLUSIONS

In this study, the assist suit that assists the twisting exercise of the lower body during the forehand swing of table tennis was developed. Then, the assistive and training effect for table tennis beginners were verified. As a result, it was found that the developed assist suit can increase the twisting motion of the lower body and there are individual differences in the improvement of swing ability by training with the assist suit.

In the future, the number of participants will be increased and the changes in experimental conditions, such as long-term training and expansion of the age range of participants, will be conducted to evaluate the performance of the suit more accurately. Furthermore, it is necessary to develop a mechanism for the wearer to be able to link the movements of the lower and upper body.

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