Ultrasound-driven Curveball in Table Tennis: Human Activity Support via Noncontact Remote Object Manipulation

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Fig. 1. A) Schematic illustration of changing ping-pong ball trajectory using focused ultrasound and a controller, B) time-lapse photograph of a serve trajectory curved by ultrasound force and a photograph of a racket-shaped controller, and C) time-lapse photograph of a missed shot caused by a curveball during an actual table tennis rally. B and C were generated from actual videos recorded while playing table tennis. Note that the dotted line in C was overwritten based on the author's subjective perspective.

Augmented Human (AH) is a research field enhancing human physical abilities or supporting human activity using advanced technologies. As one of the AH approaches, previous studies have attached an actuator to a human body or tools used for an activity. The attached actuators are used to control their movements to support an activity. In this study, instead of attaching actuators, we propose to remotely present noncontact ultrasound force to a lightweight tool to manipulate it. The advantage of using noncontact force is that the

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users of AH system do not need to wear a specific device and to process tools used for the activity. As a proof-of-concept system, we developed an ultrasound-based curveball system by which table tennis players can shoot a curveball regardless of their physical ability. In the system, a moving ping-pong ball (PPB) is a target tool for the remote manipulation. The system curves the trajectory of a moving PPB by continuously focusing ultrasound on it. Users can control the curve timing and the curve direction (left or right) using a racket-shaped controller. In the user study, we conducted an actual table tennis match using the curveball system and qualitatively confirmed that the player using the system had the upper hand. Another user study using a ball dispenser quantitatively showed that the ultrasound-driven curveball increased the number of mistakes of the opponent player 2.95 times. These results indicate that the proposed concept is feasible.

CCS Concepts: • **Human-centered computing** → **Ubiquitous computing**.

Additional Key Words and Phrases: Augmenting physical skills, noncontact force, focused ultrasound, curveball, table tennis

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1 INTRODUCTION

Augmented Human (AH) is a research field supporting human activities and expanding human abilities by utilizing advanced technologies. One of the major approaches for AH is wearing a mechanical system to improve physical ability. For improving physical ability, previous studies have proposed increasing muscle strength using an exoskeleton [12] and supporting a ball thrown using a handheld robot arm [22].

Incorporating a mechanical system into a tool used by humans is another effective approach to augment human physical ability. The built-in mechanical system allows the user to control the movement of the tool to support their own physical activities. Since the system-incorporated approach does not require users to wearing any devices, it can reduce the physical burden on users of AH systems. Kianzad et al. incorporated a ball actuator into a pen [20]. The built-in actuator manipulates the pen and can support the user in drawing pictures. Nitta et al. incorporated a drone into a ball. They can control the trajectory of the ball and help a player pass it to another player [33, 34].

As a further advantage of the system-incorporated approach, the built-in mechanical system allows users to control the motion of the tools remotely, even if the tool is far from the user's hand. In other words, such a remote control can realize a physical ability that humans cannot achieve in the real world, similar to what we might see in comics. For example, the trajectory of a ball with a built-in drone can be freely controlled even after the ball has been thrown [33, 34]. Therefore, during a pass, even if the receiver moves before catching the ball, the trajectory can be modified according to the movement of the receiver. In a handheld AH device, the trajectory-changeable timing is limited to before throwing [22].

In this study, as a new AH concept, we propose the remote manipulation of a tool using an external noncontact force (e.g., focused ultrasound, airflow, or electromagnetic force) instead of incorporating a mechanical system. The advantage of using noncontact force is that users do not need to wear any devices and to process tools used for the activities. In other words, users can use their usual tools even if their physical abilities are augmented. Therefore, we believe that the augmentation strategy using noncontact force can enhance the user's physical skills without interfering with their original abilities or experience of activities.

For a noncontact force presentation, we adopted an airborne ultrasound phased array (AUPA) [3, 11, 18] in which ultrasound transducers are arranged in an array. An AUPA has two advantages compared to other methods: a high force propagation speed and high spatial controllability of the presented force distribution. The force presented by AUPA propagates at the speed of sound; thus, the force distribution can be presented and changed in real-time according to the movement of the user. The force distribution through ultrasound can be controlled with a high spatial resolution of 1 cm^3 ; thus, an AUPA can present a noncontact force to the target tool at a pinpoint [3, 11]. One of the disadvantages of an AUPA is that the presentation force is weak (a few grams force), but an AUPA can effectively augment human physical ability if the use case is selected appropriately.

1.1 Case Study in Table Tennis

We chose table tennis as an appropriate situation in which the proposed concept, the remote-manipulation approach for AH, is effective. We also chose a ping-pong ball (PPB) as a target tool for a force presentation. Since a PPB is light, ultrasound force can change its trajectory [29]. Moreover, table tennis is one of the major sports and there are many players all over the world. Therefore, an AH system for table tennis potentially has a high impact on society and we decided table tennis is an appropriate situation for evaluating our concept.

In this study, as a proof-of-concept system, we developed a curveball system using AUPAs in which table tennis players can shoot a curveball regardless of their physical ability (Fig. 1). The curveball system curves the trajectory of a moving PPB by applying focused ultrasound. The ultrasound-driven curveball gives no sign for its trajectory change, unlike a curveball with a rotation that a normal table tennis player hits. In other words, our system allows a user to shoot super shots beyond the skill level of real-world players. Moreover, because the PPB does not undergo any physical processing, players can play table tennis just like a regular one e.g. hitting a smash strongly. We also developed a racket-shaped controller that enables players to control the curve timing of a PPB trajectory and its direction (right or left).

In the user study, we conducted an actual table tennis match using the curveball system and qualitatively evaluated whether the system augments the physical ability of players. During the match, only one player used the curveball system. For comparison, we also conducted a match without using the curveball system. Moreover, we quantitatively evaluated the performance of the system by counting the number of an opponent player's mistakes (error rate) induced by the curveball. Since the curveball system allows the player to shoot a curveball that is more difficult to receive than a straight ball, the error rate of an opponent player shows the quantitative system performance. We believe that the curveball system contributes to the development of an inclusive table tennis system, which players can enjoy regardless of their physical abilities. For example, in a match between a beginner and an intermediate player, if only the beginner uses the ultrasound-driven curveball, the skill gap between the two players can be filled. Moreover, because such a curveball cannot be realized in a normal table tennis match, the entertainment value of the game can be enhanced.

1.2 Our Contribution

Morisaki et al. previously showed that focused ultrasound can curve the trajectory of a thrown PPB [29]. However, they only changed the trajectory of the PPB under specific conditions (i.e., 60 cm away from the AUPAs, at a speed of 1.68 m/s), and did not develop an interactive curveball system. In the previous study, the curve timing could not be controlled, and the curve direction was only toward the left. We considered a curveball with a single direction to be insufficient to augment the skill of table tennis players. For example, if a single direction is used, the opponent player may become accustomed to this curve. The novelty of this study is the development of an

ultrasound-based interactive curveball system and its qualitative/quantitative evaluation through user studies. With this system, players can curve a PPB trajectory at arbitrary timing and control the curve direction (left or right).

Herein, we summarized our main contributions.

- We proposed new AH concept which is remote manipulation of a tool using noncontact external force.
- We developed an interactive curveball system for table tennis using focused ultrasound.
- We qualitatively and quantitatively evaluated the performance of the curveball system through the user studies.

2 RELATED WORKS

2.1 Augmenting Physical Ability using Mechanical Systems

2.1.1 Wearables. Some previous researchers proposed to attach robotic body parts and robotic exoskeleton to the human body. A robotic exoskeleton has been used for power assist [12], rehabilitation [46], and skill acquisition support [23]. Saraiji et al. attached robotic arms to a person which can be controlled by the toe of the person [38]. Goumelen et al. proposed to semi-automatically control the attached robot arms and work together them [10]. Maekawa et al. developed a handheld robotic arm that can grab a ball and automatically release it to control the landing position of the ball [22].

2.1.2 Controlling Motion of Tools. Support human activity by controlling the motion of tools has been proposed. Ohta et al. changed a ball trajectory using a build-in gas-jet unit [37]. Nitta et al. changed the trajectory of a ball with a build-in drone and support passing a ball [33, 34]. Fernando et al. and Kianzad et al. guided the motion of drawing pictures by a pen device with a build-in ball actuator [5, 20]. Yamaoka et al. develop dePENd which manipulates a tip of a commercial pen by magnetic force to support users' drawing motion [45]. In dePENd, a pen does not have a built-in actuator, but the pen is operated only at a user's hand. We propose to remotely control the movement of tools that are far from the user's hand.

2.2 Augmented table tennis

Some studies proposed to support table tennis players. Wu et al. predicted the future trajectory of a PPB using a long short-term pose prediction network [44]. Itoh et al. predicted the trajectory of a PPB and visualized it using an optical see-through head-mounted display [16, 17].

Enhancing table tennis as entertainment has been also proposed. Ishii et al. projected an interactive image on a table tennis table [15]. The projected image reacts to the sound of a PPB bouncing. Using a video conference system and a projector, Mueller et al. developed a table tennis-like game in which geographically separated players can play each other [31, 32].

2.3 Motion Control of Real Objects using Focused Ultrasound

In this paper, we used focused ultrasound to curve the trajectory of a PPB in noncontact manner. Here, we introduced other ultrasound techniques to control the motion of a real object. Focused ultrasound is generated by an airborne ultrasound phased array (AUPA) [3, 11, 18]; we and all studies introduced in this section used AUPAs to produce focused ultrasound. AUPAs was described in detail in section 3.2.1.

We targeted a moving PPB, on the other hand, static objects have been also manipulated by ultrasound. Furumoto et al. manipulated a floating balloon three-dimensionally by ultrasound plane wave and focus [6–8]. Marshall et al. manipulated a small sphere object two-dimensionally by surrounding the sphere with many ultrasound transducers [24]. Vi et al. manipulated small finely

chopped foods using ultrasound and delivery them to user's mouth [42]. Marzo et al. control the diffusion of liquid and drew pictures using ultrasound [27]. Sugiura et al. control the tilt of a carpet hair and drew pictures using ultrasound [39].

Some researchers levitated small particles and controlled their three-dimensional position by ultrasound standing wave [26, 28, 36]. Objects larger than the wavelength (sphere, and hexahedron) have been also levitated by designing proper pressure distribution [14, 25]. There is no research utilizing these motion control techniques for supporting a sports player.

Morisaki et al. showed that focused ultrasound can curve the trajectory of a throw PPB [29]. However, they changed the trajectory of a PPB in only one direction and did not conduct a user study. In another study, they partially demonstrate an ultrasound-based interactive curveball system but its technical detail and performance were not evaluated [30]. In this study, we developed an interactive curveball system for table tennis and evaluated its performance through user studies.

3 DESIGN OF ULTRASOUND-BASED CURVEBALL SYSTEM FOR TABLE TENNIS

In this section, we developed and introduced an ultrasound-based curveball system for table tennis shown in Fig. 2. The system can curve the trajectory of a PPB to the right or left by continuously presenting a focused ultrasound onto the moving PPB. We also developed a racket-shaped controller shown in Fig. 3. Using the controller, players can control the curve timing and the curve direction.

3.1 Noncontact Force Presentation Method

There are three typical methods for remotely presenting a force: midair focused ultrasound [7, 26, 35, 43], airflow [2], and electromagnetic force [19, 21]. Among these, we adopted focused ultrasound in this study because we considered that ultrasound is particularly suitable for AH systems for the following three reasons: 1) ultrasound can apply a force to most material, 2) the propagation speed of the force is high (sound velocity), and 3) the presented force distribution can be controlled with a high spatial resolution.

3.1.1 Covering most materials. Focused ultrasound can be used to apply force to any object that reflects sound waves. Therefore, an AH system using ultrasound covers most of the tools used in human activities. By contrast, materials that can be influenced by electromagnetic forces are limited.

3.1.2 Propagation speed. Because focused ultrasound propagates at the sound velocity, ultrasound force can be applied to the target tool at an extremely high speed. Therefore, the AH system using ultrasound is capable of reflecting users' intentions or input in the movement of the target tools in real-time. The propagation speed of airflow generated by a typical blower is much slower than that of ultrasound.

3.1.3 Spatial resolution. Focused ultrasound can narrow the presentation force distribution to approximately 1 cm^3 [11]. Therefore, even when the target tool is near a human user or the user is holding the tool, the force can be applied only to the target tool without applying it to the human. Since the airflow gradually diffuses after output, the presentation of a selective force is difficult to achieve.

3.2 Hardware Properties

The configuration of our curveball system and its coordinate system is shown in Fig. 2. The coordinate system was a right-handed system with an origin at the center of the right camera lens. The system consists of 18 AUPAs (nine units on each side) applying force to the PPB, two high-speed cameras measuring the three-dimensional position of the PPB (Ximea MQ003CG-CM),

Fig. 2. System configuration of ultrasound-based curveball system. This system consists of 18 AUPAs (nine units on each side) applying force to the PPB, two high-speed cameras measuring the three-dimensional position of the PPB. The coordinate system was a right-handed system with an origin at the center of the right camera lens.

and a Windows PC (Panasonic Let's Note CF-SZ6) controlling the AUPAs based on the images from cameras.

The nine AUPAs were arranged on both sides of the player to curve the PPB to the right or left. The nine AUPAs on the same side were driven simultaneously, and each side was driven individually. Here, the AUPA is placed only on one player's side, not in the center of the table because participants preliminarily reported that the difficulty of table tennis was increased by curving the PPB trajectory near the player's hand. In the previous system, only nine AUPAs were arranged on left side [29].

3.2.1 Airborne Ultrasound Phased Array. In this section, we introduce an ultrasound beam focusing by AUPAs [3, 11, 18]. We used it to present force to a moving PPB because it can produce a high-pressure spot smaller than a PPB in mid-air.

An AUPA is a device in which airborne ultrasound transducers are arranged in an array (Fig. 4). The phase and the amplitude of each transducer can be controlled individually [3, 11, 18]. By controlling the phase to focus ultrasound at a single point, a localized noncontact force is generated at that point. The noncontact force is based on a nonlinear acoustic phenomenon called an acoustic radiation force [47]. The ultrasound focus diameter can be reduced to approximately the ultrasound wavelength [11].

The AUPA unit used in this study consists of 249 transducers of 40 kHz ultrasound [13, 41], thus, the ultrasound focus diameter is approximately 1 cm^3 . The focus size was smaller than half the size of a PPB with a diameter of 40 mm. For this reason, focused ultrasound can only stimulate a

Fig. 3. Function assignment of racket-shaped controller. Pressing the A button causes the right AUPAs to be driven, allowing players to hit a left curveball. Pressing the Y button drives the left AUPAs, allowing players to hit a right curveball.

Fig. 4. Airborne ultrasound phased array and schematic illustration of focusing ultrasound on single point

moving PPB without damaging the environment or the player. The AUPAs were connected to each other using LAN cables and communicated via the EtherCat protocol.

For all experiments conducted in this study, the AUPAs were driven at the maximum output.

3.2.2 Stereo High-speed Camera. The setup of the stereo high-speed camera used in this research is the same as that used in the previous research [29]. Its mean measurement error in the x -axis is 0.72 mm, in the y -axis it is 0.76 mm, and in the z -axis it is 1.96 mm.

The system detects the three-dimensional position of a PPB using a binarization color filter. The detail of the detection algorithm was described in the previous research [29] and we here summarized it. First, a picture was taken by each camera. Second, areas of orange color in the pictures were acquired by a binarization color filter. We defined the center of gravity of the acquired area as the PPB position in the pixel coordinate. Third, the pixel-position were converted to the two-dimensional positions of the PPB in the real world by calibration parameters acquired in advance. Lastly, the three-dimensional position of the PPB was acquired by triangulation.

3.2.3 Racket-shaped Controller. We developed a racket-shaped controller so that players can curve a PPB trajectory by ultrasound at their voluntary timing.

The developed racket-shaped controller is shown in Fig 3-upper. The device consists of a table tennis racket and a commercially available game controller (Nintendo Switch Joy-Con). The controller was connected to the control PC via Bluetooth. The functions assigned to the controller are shown in Fig 3-below. Pressing the A button causes the right AUPAs to be driven, allowing players to hit a left curveball. Pressing the Y button drives the left AUPAs, allowing players to hit a right curveball.

Fig. 5. Results and schematic illustration of evaluating shooting range of stereo high-speed camera. We measured five PPB positrons. The shooting range is the area surrounded by the points.

3.3 Driving Algorithms for Phased Arrays

In this section, we introduced the driving algorithms for the AUPAs.

First, the curveball system waits for the input from the racket-shaped controller. After getting the input, the system starts to search the three-dimensional position of a PPB using the stereo high-speed camera. If a PPB was not found, the AUPAs were not driven. Second, the detected PPB position was converted to a predicted value taking into account system delays. The types of delay were sound velocity, communication delay between Windows PC and the AUPAs, and processing time to obtain the position of a PPB from the image. In order to predict the PPB position, a linear function was fitted to the horizontal movement of the PPB, and a parabola was fitted to its vertical movement. The prediction algorithm is the same as that used in the previous study [29]. Lastly, the AUPAs focused ultrasound at the predicted position. The frame rate of our system was 250 fps.

4 PERFORMANCE EVALUATION OF CURVEBALL SYSTEM

In this section, we evaluated the performance of our curveball system at a table tennis table from the following points of view: 1) shooting range of its stereo camera, 2) the displacement of a changed trajectory corresponding to each ball bounce position on a table, and 3) the change in the displacement with respect to a PPB speed. Morisaki et al. evaluated the displacement of a moving PPB by ultrasound but, the bounce position and ball speed were fixed to one condition (60 cm away from AUPAs, speed of 1.68 m/s) [29].

4.1 Shooting Range of Stereo Camera

We examined the shooting range at a table tennis table of the stereo high-speed camera measuring the three-dimensional position of a PPB. We measured five PPB positrons (referred to as p_0 - p_4) and assumed that the shooting range is the area surrounded by the points. The schematic illustration of the shooting range is shown in Fig. 5.

First, the closest PPB position to the stereo camera in the shooting range was recorded. The PPB was manually manipulated. Next, the PPB was placed at the right and left ends of the table on the opposite side of the camera. Here, the left and right sides are the directions seen from the camera. The PPB was moved up and down at the ends and the maximum and minimum heights at which the PPB can be captured were measured, respectively. The closest measured point to the camera is referred to as p_0 . The maximum and minimum height at the left are referred to as p_1

Fig. 6. A) Experimental setup for evaluating displacement of curved trajectory on each grid, B) example of experiment (bouncing ball at grid 2, left curve). The bounce position of a thrown PPB was adjusted by manually manipulating the dispenser position. The PPB trajectory was measured by a depth camera.

and p_2 , respectively. The maximum and minimum height at the right are referred to as p_3 and p_4 , respectively.

The results are shown in Fig. 5. The results show that $p_0 = (-0.12, 0.62, 0.36)$ m, $p_1 = (0.35, 0.57, 0.17)$ m, $p_2 = (0.37, -0.11, 0.17)$ m, $p_3 = (-0.9, 0.58, 0.16)$ m, $p_4 = (-0.9, -0.12, 0.17)$ m. The range can cover the half of the table tennis table. There were some unreasonable measured value, for example, p_1 and p_2 had different z and x positions. This may be due to the human error of the manual manipulation and the measurement error of the stereo camera. These unreasonable values were smaller than a PPB size thus, we judged that the errors had no problem evaluating the shooting range.

4.2 Trajectory Displacement by Ultrasound According to Each Bounce Position of a Ball

We evaluated how much our system changes the trajectory of a PPB to right and left. Especially, we examined the relationship between a ball bounce position on a table and the displacement. Fig. 6-B shows an example of the experiment that is grid 2-bounced case.

We only focused on the bounce position in this experiment. The reason for this is that the main factor of the displacement may be the distance between a PPB and AUPAs since the ultrasound force decreases as the distance from the AUPA increases [47]. Moreover, the relationship between the displacement and bounce position is practically useful because it can show which part of the table surface players should target in order to shoot a curveball by ultrasound.

4.2.1 Procedure. Fig. 6-A shows an experimental setup. A PPB was thrown straight by a ball dispenser in the positive x -axis direction. The PPB trajectory was measured by a depth camera (Microsoft Kinect V2). The surface of the table was divided into $4 \times 4 = 16$ grids. The length in x -axis direction of the grid was 300 mm and its length in z -axis direction was 380 mm. The PPB was thrown 25 times to bounce on each grid. The thrown PPB was curved to the left (driving the right AUPAs) and to the right (driving the left AUPAs). The AUPAs were automatically driven when the PPB is within the shooting range of the high-speed cameras. Here, the left and right sides

Fig. 7. The difference between the displacement of {the left curve and the right curve} and that of the straight ball. We used the displacement of the trajectory in straight condition as baseline. *Right* and *left* means the displacement of the right curveball and the left curveball, respectively. The left and right sides are the directions seen from the ball dispenser.

Fig. 8. Ping-pong ball trajectory and result of linear regression when a ping-pong ball bounced at the grid 2

are the directions seen from the ball dispenser. We also measured straight conditions that did not use ultrasound force for comparison. The PPB was thrown 16 positions $\times$ 3 conditions $\times$ 25 trials = 1200 times.

Before throwing the ball, its bounce position was adjusted by manually manipulating the dispenser position. The dispenser threw the PPB by rotating a motor located under the PPB, and the motor speed was fixed to keep the ball speed constant. The actual ball speed was 1.98 m/s (SD = 0.17) calculated from the measured trajectory after this experiment. If the thrown ball did not go straight and clearly deviated from the planned trajectory before the ultrasound force was given, those trials were not counted. This unintended trajectory was caused when the ball dispenser missed throwing the PPB. This decision was based on the author's subjective view.

4.2.2 Result. The evaluation results are shown in Fig. 7. Error bars show standard deviations (SD). We calculated the average trajectory displacement on each grid that was the difference in a PPB position between the center of the table ($x = -0.33$) and the end of it ($x = 0.57$). We also used the displacement of the trajectory in straight condition as baseline thus, we actually plotted the difference between the displacement of {the left curve and the right curve} and that of the straight ball in Fig. 7.

Since the maximum frame rate of our depth camera was low (30 fps), the z -positions at $x = 0.57$ m and $x = -0.33$ m was not measured directly. To complement the measured data, we conducted linear regression using a least-squares method to the data in the range of $x = 0.37 \pm 0.6$ m and $x = -0.93 \pm 0.6$ m, respectively. From the regressing, z -position at $x = 0.57$ m and $x = -0.33$ m were calculated, respectively. Fig. 8 shows that an example of linear regression when the PPB bounced at grid 2. If there were no more than two measurement data points within the specified range, the corresponding trajectories were excluded from the calculation. 22 out of 1200 trajectories were excluded. The average coefficient of determination (R^2 value) of the regression was 0.888 (SD = 0.235).

Under the left curve condition, the PPB trajectory had the largest displacement when it bounced on grids 1 and 2. The displacement at grid 1 was especially over 40 cm. One of the reasons for this, we conjectured that the apex of the trajectory at which y -directional ball speed is lowest is near the center of the right AUPAs when the PPB bounces on grid 1 and 2.

Although grids 4, 8, 12, and 16 were close to the left AUPAs, there was little change in the PPB trajectory on them. This may be because the PPB was too close to the high-speed stereo camera and out of its shooting range. When a PPB is close to the stereo camera, the time that the PPB is in the recognition range of the camera is shortened. To extend the shooting range, for example, it is conjecture that the position of the camera is changed to just above the table tennis table. Adding extra cameras can be also considered.

4.3 Trajectory Displacement according to Ball Speed

We measured the PPB displacements according to the ball speed. The bounce place was fixed to grid 2 where the average displacement of the left curve was the second largest and that of the right curve was the third largest. The setup was the same as shown in Fig. 6. A PPB was thrown 25 times and it was curved to the left and right. The PPB was also thrown in straight condition. The PPB speed was increased two levels by increasing the motor speed of the ball dispenser. The actual ball speeds were 2.3 m/s (SD = 0.41) and 2.77 m/s (SD = 0.18) calculated from the measured trajectory. The total number of throwing PPB was 2 speed $\times$ 3 conditions $\times$ 25 trials = 150 times.

Fig. 9 shows the difference in the z -position between the average displacement of the straight ball and that of both curveballs. The displacement was calculated between z -position at $x = 0.57$ m and $x = -0.33$ m. We also plotted the displacements at the ball speed 1.98 m/s that have been plotted in Fig. 7. The z -position was obtained from the result of linear regression. In the regression process, 31 trajectories were excluded.

Fig. 9. Difference between displacement of {left curve and right curve} and that of straight ball at grid 2 with ball speed 1.98, 2.3, and 2.77 m/s. Error bars mean standard deviation.

Fig. 10. Snapshot of trial play of curveball system in actual table tennis match

The results show that the displacement decreased as the PPB speed increased, but the average displacement was approximately 0.1 m even when the speed was 2.77 m/s.

5 USER STUDY1: TABLE TENNIS MATCH WITH ULTRASOUND-BASED CURVEBALL SYSTEM

In this section, the participants played table tennis matches using the curveball system. From the results and participants' comments, we evaluated the performance of the system in actual table tennis from the following perspective: 1) whether the ability of the table tennis player was augmented, 2) whether the fun of table tennis was enhanced. These two evaluation points can contribute to the realization of sporting events that can be enjoyed regardless of physical ability, which is the basic motivation of AH in sports (called augmented sports).

5.1 Procedure

The participants played table tennis matches with and without the curveball system. Six males (aged 22-26) participated in this trial play; thus, there were three pairs to play a table tennis match. All participants had previous table tennis experience but were not advanced. Each pair first conducted a warm-up rally for approximately five minutes with one participant using the controller. After the warm-up rally, the participants performed a match. The first player to score five points was the winner in this match. After the match, the player using the controller was shifted to the other player, and a warm-up rally and the match were conducted again. Finally, both players in the pair played a game without using the curveball system. All players commented freely about the experience after the game.

5.2 Result and Discussion

Table 1. Result of actual table tennis game with or without curveball by ultrasound

(a) P1 vs P2						(b) P3 vs P4						(c) P5 vs P6					
Curveball		Score		Result		Curveball		Score		Result		Curveball		Score		Result	
P1	P2	P1	P2	P1	P2	P3	P4	P3	P4	P3	P4	P5	P6	P5	P6	P5	P6
-	used	3	5		win	-	used	2	5		win	-	used	5	3		win
used	-	2	5		win	used	-	5	4		win	used	-	5	4		win
-	-	5	0		win	-	-	4	5		win	-	-	5	4		win

5.2.1 Ability of table tennis player. The results of the table tennis matches are shown in Table 1. From the results and participants' comments, we conjectured that the player who used the ultrasound-driven curveball had the upper hand. P1 defeated P2 with a score of 5-0 without a curveball, but P2 won the match when P2 used the curveball. In the match between P3 and P4, the participants who used the curveball won the game, respectively. P1, P2, and P6 reported that the curveball caused the missed shots. P1 also commented that "I could not hit the ball hard and return it to the desired position on the table because its trajectory curved unpredictably. As a result, my opponent player could return the ball easily, and I lost the match."

On the other hand, there were some cases where using a curveball could work as a disadvantage. P1 was defeated even when using the curveball. As the reason for this, P1 commented that "I wanted to actively use the curveball, so I tried to return the ball to the front of the table (corresponding to grid 1-3 shown in Fig. 7) many times in order to greatly change the trajectory. However, I sometimes conducted it even when returning the ball was difficult due to the ball position or my posture. At this time, I failed it." This problem can be solved by expanding the workspace, as mentioned in section 4.2.

Moreover, P2, P4, and P6 reported that they sometimes could not concentrate on the match because their attention was distracted by the controller operation. P3 and P4 also reported that the operation of the controller was difficult. A user-friendly interface will be an area of future work, and one way to design such an interface is to monitor the movements of players and to provide ultrasound force automatically according to the monitored situation.

Although not mentioned in the comments, it is possible that the participants' mistakes were caused not only by the curved trajectory but also by the change in the ball speed. If the original moving direction of the PPB was tilted with respect to the table tennis table, a participant who received it would feel that the PPB was not only curved but also accelerated.

5.2.2 Enjoyment. The participants' comments suggest that the curveball system improves the enjoyment of table tennis. All participants commented that the experience of shooting a curveball using ultrasound was enjoyable. P2 commented that the curveball system expanded the range of strategies available in table tennis. P3 and P4 commented that the displacement of the ball trajectory was larger than that imagined. Moreover, all participants commented that they enjoyed the match even when they did not have the controller. In other words, they enjoyed the experience of being induced mistakes by the ultrasound-driven curveball. For this reason, we conjectured that the experience of sudden changes in the PPB trajectory cannot be experienced with normal table tennis.

6 USER STUDY2: QUANTITATIVE EVALUATION OF NUMBER OF INDUCED MISSED SHOT

The results of user study1 indicate that the ultrasound-based curveball system can augment the skill of table tennis players because the curveball induced mistakes of the opponent player several times. In this section, to quantitatively evaluate the augmented skill level, we counted the number of missed shots of the opponent player induced by the curveball. For the reproducibility of this evaluation, we used a ball dispenser to throw a PPB.

6.1 Procedure

The experimental setup is shown in Fig. 11-A. The PPB was thrown using a ball dispenser. The dispenser was manipulated such that the PPB bounced at the center of the grid 2, 3, 6, and 7 (Fig. 11-B). If the PPB bounced outside the specified range (grid 2, 3, 6, and 7), it was not counted. The motor speed of the dispenser was the same as that described in section 4.2.

Fig. 11. Experimental setup for counting miss shot. Participants hit and returned a thrown ball to the target area.

Twelve males (aged 22-29) participated in the user study. P2, 3, and 6 in user study1 also participated in this experiment. All participants had played normal table tennis but were not advanced. The participants were instructed to return the thrown PPB to the instructed target area on the table. In this experiment, the target area was the right and left halves from the table edge to 0.75 m, which was 0.572 m^2 (target-L and target-R). The size of the target area was determined based on a preliminary experiment. This area was sufficiently wide such that beginners can hardly fail to receive a PPB when an ultrasound-driven curveball was not used. The target areas are shown in Fig. 11-B. The PPB was thrown 15 times under an experimental setting in which the trajectory was changed at random timing (set-A). The PPB was also thrown 10 times in an experimental set in which its trajectory was not changed (set-B). In set-A, a right curveball, left curveball, and straight ball was thrown five times each. The AUPAs were automatically driven when the PPB was within the shooting range of the high-speed cameras. From the above, each participant returned the PPB $2 \times (15 + 10) = 50$ times. For counterbalance, half of the participants first conducted set-A, and the other half first conducted set-B. Similarly, half of the participants first targeted target-L, and the other half first targeted target-R. Therefore, there are four types of experimental order: AL-BL-AR-BR, AR-BR-AL-BL, BL-AL-BR-AR, and BR-AR-BL-AL where A, B mean set-A and -B, and L, R means target-L and -R, respectively. The reason why the straight ball was thrown in set-A was that we aimed to maximize the effect of the curveball on causing a missed shot. The participants preliminarily reported that the curveball at random timing made players feel a sense of tension.

The participants first practiced returning a straight ball and a curveball for approximately three minutes with knowledge regarding which type of ball was coming. When the target was changed, the participants practiced with the new target again. After the practice session, the participants were informed of the experimental set type (A or B) then, they conducted it. The throwing timing was also indicated to participants. The interval between throwing was approximately 10 seconds, which was sufficient for the participants to return to their original posture. After all sets, the participants commented freely regarding the experience.

6.2 Result

The number of types of returned PPBs is shown in Fig. 12 and in Table 2. We categorized the returned PPBs into three types: miss-1 (out of the table), miss-2 (out of the target range), and success (inside the target). In set-A where a curveball was used, the number of the total misses was 127 out of 240 and that of the miss-1 was 75. A straight ball was excluded from the result. In set-B, the number of the total misses was 43 out of 240 and that of the miss-1 was 26.

Fig. 12. Number of the types of returned ping-pong ball. The returned PPB was categorized into three types: miss-1 (out of the table), miss-2 (out of the target range), and success (inside the target).

Fig. 13. Rate of missed shot

Table 2. Number of the types of returned ping-pong ball for each participant. “A” means the curveball condition. “B” means the straight ball condition. The returned PPB was categorized into three types: miss-1 (out of the table), miss-2 (out of the target range), and success (inside the target).

Participant	A, miss-1	A, miss-2	A, success	B, miss-1	B, miss-2	B, success
P1	5	7	8	2	0	18
P2	5	2	13	1	0	19
P3	6	7	7	1	4	15
P4	6	7	7	0	3	17
P5	12	4	4	3	3	14
P6	3	6	11	7	0	13
P7	8	3	9	2	1	17
P8	2	4	14	0	1	19
P9	8	3	9	0	0	20
P10	9	2	9	7	2	11
P11	5	5	10	1	1	18
P12	6	2	12	2	2	16

We analyzed the effect of the curveball and the order of the experimental set on the rate of missed shots. The boxplot of the miss rate is shown in Fig. 13. The median value of the miss rate of set-A and -B were 60% and 20%, respectively. First, the averages of the miss rate were calculated for each participant and divided into four groups ({the miss rate of set-A or that of set-B} in a group where {set-A or set-B} was first conducted). Second, in the Shapiro-Wilk test, the hypothesis that the results follow a normal distribution was not rejected in all four groups ($p > 0.05$). Third, we applied two-way ANOVA to the groups of the miss rate with the three factors: the set type (with/without the curveball), the set order, and the interaction between them. We observed that only the set type had significant effect on the miss rate ($F(1, 20) = 30.0, p < 0.05 \times 10^3$). As a posthoc test, we compared set-A and set-B in the miss rate with Wilcoxon signed-rank test. The comparison results showed that the miss rate of set-A is significantly higher than that of set-B ($p < 0.005$).

6.3 Discussion

The evaluation provides one of the quantitative evidences that the ultrasound-based curveball system can augment the skill of a table tennis player. The results show that the curveball can cause

players to miss the returning task. The curveball increased the number of total miss shots 2.95 times in that experiment. Through observation of the participants' behavior, we found three types of miss induced by the curveball: 1) players swung at a PPB and missed, 2) a PPB hit an unintended racket position, 3) players could not adjust their posture according to the changed PPB trajectory. P6 commented, "When a PPB trajectory was changed to leave from a racket, the task was more difficult." P2 commented, "I could not respond to the trajectory change."

Interestingly, P1, 2, 3, and 7 reported that the returning task in set-A was more difficult even when a PPB trajectory was not changed. Therefore, we conjectured that the curveball can increase the tension in a table tennis match.

As with user study1, the free comments in study2 indicated that even the opponent player that was induced to miss by the curveball system still enjoyed table tennis. All comments on enjoyment were positive and implied that the experience of the induced missed shot was fun. P4 commented "The experience of swinging and missing was fun because it had been never experienced in normal table tennis," and P11 commented, "When I swung and missed, I was disappointed. However, I enjoyed the experience."

7 LIMITATION

7.1 Experimental Design

There are two limitations in the experimental design: imbalance in the number of throw PPB, and the skill of participants.

In user study2, to maximize the number of missed shots, we mixed straight balls with set-A. This caused a problem that the number of throwing PPB was not equal between set-A and set-B. Therefore, in order to more accurately evaluate the effect of the curveball, it is future work to compare set-B to the new experimental set which consists only of the curveball.

In user study1 and 2, we did not control the skill level of participants. From the authors' subjective view, there was no big skill gap between each participant. To evaluate the effect of skill level, in the future, we plan to conduct user studies on groups with very different skills and compare them e.g. beginner, amateur, and professional.

7.2 System Performance

The participants' comments pointed out two limitations of our curveball system: insufficient trajectory displacement and audible noise.

Some participants reported the curveball system sometimes did not work correctly. As the reason for this, the bounce position and the ball speed for sufficient trajectory change were limited as evaluated in section 4. In user study2, P2 commented that the displacement of the trajectory was sometimes small and in such cases, it is easy to receive the PPB. P3 and 8 also commented that in some cases they did not feel the effects of the curveball. As we described in section 4.1, expanding the shooting range of the stereo high-speed cameras is one of the solutions. In addition to this, expanding the workspace of AUPA using a concave reflector would be also effective [1].

In user study2, P3 and 5 commented that they were sometimes surprised by the audible sounds generated by the AUPAs. An AUPA produces audible noise when changing ultrasound focus position and this phenomenon has been pointed out by previous research [9, 11]. This problem can be solved using a gradual phase shift method proposed by Suzuki et al. [40] or by applying a low-pass filter to a driving signal of ultrasound transducers [41].

Finally, although no participants pointed out, we should consider whether the AUPAs blocked the playspace of the participants. In the conducted user studies, we considered that the current AUPA placement did not interfere with the players and did not affect the experimental results. There

was no comment that the AUPAs blocked the playspace through all the user studies. However, if advanced players use this system in the future, this arrangement may interfere play significantly. Therefore, in the future, it will be necessary to search for a new AUPA layout that does not block the playspace. For example, it is conceivable to arrange AUPAs near the center of the table tennis table.

8 SAFETY OF CURVEBALL SYSTEM USING FOCUSED ULTRASOUND

In this section, we discuss the safety of our curveball system producing high-intensity ultrasound. First, we conjectured that the ultrasound force by our curveball system rarely hit people because the system recognized the ball position and focused ultrasound only toward it. There are no reports that the force hit participants during the user studies.

Herein, we additionally discussed the safety in terms of the presented acoustic power. We drove the nine AUPAs at the maximum power thus, the maximum radiation pressure is 0.0388 N/cm^2 [29] and the acoustic power is 6.59 W/cm^2 . Because the human body reflects the sound energy by 99.9% [11], the sound power of 6.59 mW/cm^2 is finally transmitted into the human body. The transmitted power is approximately 1/15 of 100 mW/cm^2 which is sufficient for safety standards provided by the American Institute of Ultrasound Medicine [4]. In addition, the ultrasound exposure time is not long. Assuming that players lean forward to a table tennis table and are recognized as a PPB, the players can be exposed to ultrasound for up to 0.63 s. Here we assume that the PPB speed is 1.98 m/s, which is the lowest speed evaluated in this paper. We also assumed that the PPB was in the shooting range of the stereo camera for the longest period (1.25 m).

Note that if the system focuses just on the ear holes, the possibility of damaging the eardrum can not be denied. Such cases are rare since the size of an ear hole is less than 1 cm, but there are two additional safety measures: wearing earplugs and detecting a person's face.

9 FUTURE WORK

9.1 Game Design with Ultrasound-driven Curveball

In this paper, we developed an ultrasound-driven curveball system and augmented the capabilities of table tennis players. In the future, we will use the curveball system to adjust levels between players in a table tennis match. To adjust, it is conceivable to limit the number of times the curveball can be used. Moreover, indicating the sign of the curveball and its direction can be considered. In actual table tennis, the movement of enemy players and the rotation of a PPB is used as the sign to predict the future trajectory of the moving PPB. To reproduce it, for example, we plan to optically project the curved direction of a PPB onto a table tennis table and to adopt a user's specific motion as a trigger (interface) for hitting a curveball (driving AUPAs).

9.2 Control of Curveball Trajectory

In the future, we control a PPB trajectory using a closed-loop system to further augment the ability of table tennis players. In this paper, closed-loop control was not used, and the AUPAs were derived at the maximum output while the controller button was pressed. For example, it is possible to automatically guide a moving PPB to a position where hitting the PPB is difficult for the opponent player. Moreover, contrary to hit a curveball, it is conceivable to guide a PPB to an arbitrary position to receive it easily.

10 CONCLUSION

In this paper, we proposed a new concept for augmenting human ability, which is to remotely control the motion of tools using noncontact external force. As a proof-of-concept system, we

developed a curveball system in table tennis using airborne ultrasound phased arrays (AUPAs). The system allows table tennis players to shoot a curveball regardless of their physical ability.

In the user study, we conducted an actual table tennis match with the curveball system. The participants' comments implied the player using the curveball had the upper hand. Especially, they reported that the curveball induced mistakes in an opponent player. We also quantitatively evaluated the frequency of the induced mistakes. The results showed that the curveball increased the miss rate of the participants 2.95 times.

We concluded that the ultrasound-based curveball system can enhance the skill of table tennis players and the proposed concept, human activity support via noncontact remote object manipulation, is feasible. We hope that our concept provides new strategies for researchers to design human augmentation systems and further expand the potential of human capabilities.

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