Design of Racket Game for People with Low Vision Using Drone

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This research presents a racket sport using a drone as a ball. There are few sports available for people with low vision than for sighted people. This leads to a loss of exercise opportunities of people with low vision, which often worsens their health conditions. They have difficulty in understanding their surroundings, and thus, there are only few ball sports. Especially in racket sports, many of processes to rally are dependent on vision and it is difficult for people with low vision to play. Increasing exercising opportunities for people with low vision will improve the health of many. In the study, instead of improving skills for sighted people, this study focuses on enabling people with low vision to be able to play racket sports. This research proposes to use a drone as a ball, which enables to operate its speed and trajectory, and its location is identifiable by flight noise. The device and game design was developed based on feedback from people with low vision. Experiments with participants with low vision was conducted to evaluate them. This research found that the system and game design was shown to be appropriate. We hope that this study will help increase exercise options for people with low vision.

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Chapter 1

Introduction

1.1 Background

There are only few sports available for people with low vision. They have difficulty in understanding their surroundings, and thus, there are only few ball sports. Especially in racket sports, there are three processes: (i) the player recognizes the position of the ball, (ii) the player starts swinging according to the speed and position of the ball, and (iii) the player hits the ball with the center of the racket. Many of these processes are dependent on vision and difficult for people with low vision to play. Racket sports designed for people with low vision have been made possible by making adoption to include a sound source and many bounces to increase the ease of identification. Therefore, it is common to change the method from hitting a flying ball in the original sport to hitting a rolling ball as shown in Figure 1.1.

1.2 Research Motivation

Since it has been difficult for people with low vision to recognize the position of it, these was lack of sport options. This leads to a loss of exercise opportunities. People with visual impairment are more likely to lack, which often worsens their health conditions[1]. In particular, the risks of depression, obesity, and poor self-esteem have been studied and are thought to be improved by communication and exercise [2, 3, 4, 5, 6, 7]. Health status with low self-esteem is also associated with high suicide rates in people with visual impairment [8]. According to the *WHO*, there are currently 220 million visually impaired people worldwide[9]. Increasing exercising opportunities for people with low vision will improve the health of many [10, 11, 12, 13]. People with acquired low vision can play upward-facing sports again that were previously possible, and congenital low vision will be able to play sports with movements they have never done before. In addition, they will be able to participate in sports which require the whole body movement in response to the movement of the ball. Therefore, this study proposes to develop a racket sport for people with low vision, in which they can recognize a moving ball in the air and play a rally, aiming to increase their exercise opportunities.

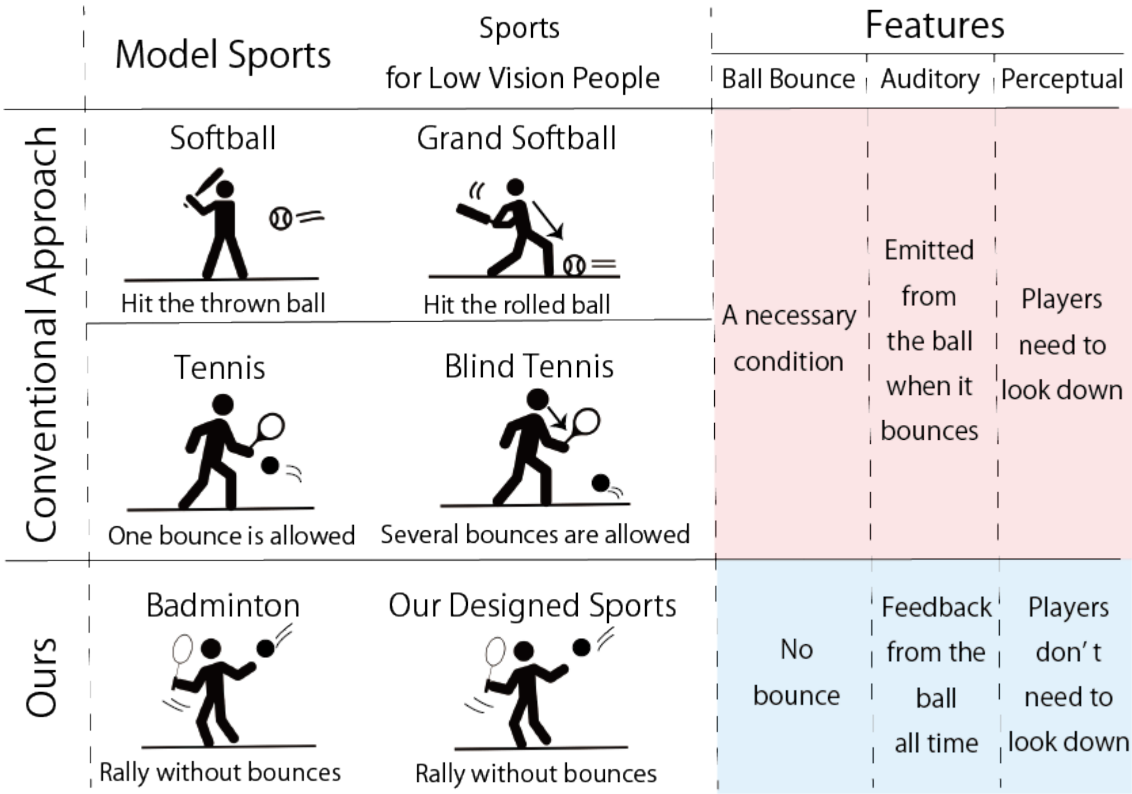

Figure 1.1: The Approach of this study differences from conventional approach

1.3 Proposal of This Research

First, interviews with the people with low vision and behavior observation were conducted since there is little research on racket sports for people with low vision. Therefore, the author participated in a futsal team for people with low vision for three months. the author asked the low vision futsal team to cooperate because, unlike blind soccer, they use a ball without a sound source without blindfolds, and these qualitative study investigated the difficulties in recognizing the flying ball. This study found three difficulties. The first is the size of the ball. The small size of the ball makes it difficult to recognize in mid air. The second is the speed of the ball. When the ball bounces, its speed decreases; however, when the ball is in flight, its speed is too fast for the player to hit it. The third is, it is difficult to recognize the location of the ball in the air. In sports where players recognize the ball in the air and rally, bouncing is often prohibited. Therefore, sports that require bouncing enable an update of the location based on the sound source, whereas sports that do not require bouncing do not. Goal of this study was to develop a racket sport using a ball that could solve all three problems.

There have been many studies that have focused on combining sports with technology inside advanced balls. For example, there are balls using visual effects [14, 15] and with a camera to allow viewing a point of ball view [16, 17]. It has also been proposed that drones can be used as a ball to develop sports that are different from traditional ball games because they can hover and change their speed [18]. In addition, drones are expected to be able to improve its visibility by attaching protectors and improve their auditory recognition as a ball because of the flight sound from it. However, these studies have focused on bridging the gap between the abilities and improving their skills for sighted people. In the study, instead of improving skills for sighted people, this study focuses on enabling people with low vision to be able to play racket sports.

1.4 Contributions

The main contributions of this study are the following:

- Conducted preliminary study which consisted interview and behavior observation to identify the difficulties of playing racket sports for people with low vision.
- Developed a prototype based on finding from the preliminary study
- Evaluated prototypes with people with low vision for feedback.
- Based on feedback, the device was improved and the game design was developed.
- Conducted the experiment to determine the efficacy of the developed system.
- Experiment found that developed system was effective and the game design was shown to be appropriate.

1.5 Thesis Outline

Chapter 2

In Chapter 2, a review of the published literature is presented. The literature review covers the application of localization assistance system for people with low vision, the preliminary sports design for people with low vision and the relation between human and drone.

Chapter 3

In Chapter 3, this section introduces the challenges of using a drone as a ball, the design to solve them, and the prototype of the racket and drone movement system using the SDK. The mechanism for rallying and the prototype of the racket were developed in collaboration with Tatsuya Minagawa, a member of the Digital Nature Group lab where this research was conducted. The drone's movement system and The holder for each device are developed by him. The author has developed all rapid prototyping. The author developed the system for judging the passage of drones in the frame, the selection of drones, and the system for communication during a drone and a PC.

Chapter 4

In Chapter 4, this section presents the preliminary study conducted to obtain feedback from participants with low vision on the system developed in Chapter 3. Four participants with low vision experienced drone movement prototype, evaluated the visibility of the drones and the usability of the rackets, and made suggestions for the game design. The evaluation was conducted qualitatively using interviews. The author designed the preliminary study, conducted, and analyzed data.

Chapter 5

In Chapter 5, the racket like device and the drone movement system was developed again based on the feedback from the preliminary study. The game using devices also designed. The game design, the components of the racket and the drone movement system using machine learning is explained. The drone movement system using machine learning and the racket like device were developed in collaboration with Tatsuya Minagawa. The racket consists of two parts, the grip and the frame, and the racket like device that is easier to use by players with low vision is developed. Since the preliminary study found it difficult to recognize the distance between the frame and the hand due to the handle, the grip using a 3d printer was developed by him. The author designed the racket, selected the frame, and created the trajectory of the drone.

Chapter 6

In Chapter 6, ten people with low vision experienced the game developed in Chapter 5. This section presents the experiment and the Demographic Information of the participants. This chapter clarified the relevance of the drone as a ball, the usability of the racket, and the evaluation of the game design. The evaluation was conducted quantitatively using a Likert scale and qualitatively using interviews. The author designed the experiment, conducted, and analyzed data.

Chapter 2

Related Work

This study refers to research in human-computer interaction. Therefore, this section discuss the assistive technologies for people with low vision. Aspects of spatial skills and sports technology for them was reviewed. Finally, this section presents related studies on drone and human Interaction.

2.1 Localization Assistance for People with Low Vision

Many studies have been conducted to support people with low vision in localizing objects using sound [19, 20, 21]. These studies mainly focused on supporting the ability of visually impaired people to gain awareness of their surroundings by measuring the auditory localization of the blind people and people with low vision. It has been observed that people who lost their vision at a younger age have a better ability to localize sound sources. It is also possible to obtain cross-modal sensation in adults, and the cross-modal approach to the auditory and tactile vision considered in this study may be successful over a long period of time. Because visually impaired people are usually supported by sound assistive technology, voice assistive technology is very beneficial in this case [22]. There are numerous studies on navigation assistance [23, 24, 25, 26, 27]. These studies to navigate to a destination using only voice promote to take spontaneous action of the people with visual impairment. In addition to navigation, research has been conducted to support the localization of moving objects and sound sources in a three-dimensional virtual space [28, 29, 30]. These studies have shown that, when the subject is stationary, the location of the sound source can be determined only by auditory feedback in the horizontal direction. Most of these studies have focused on the ability to gain awareness of their surroundings in daily life. Few research have been investigated why people with low vision have difficulty recognizing a flying ball in sports, especially ball games.In particular, support techniques for visually impaired people consist of three patterns: sound, touch, and cooperation from others [31].

2.2 Sports Design for People with Low Vision

Several studies have been conducted to support the movement of the visually impaired using senses other than sight [32, 33]. In the human-computer interaction field, assistive technologies for the visually impaired have been flourishing in the fields of sports, entertainment, and games [34][35][36]. These studies have shown that even with limited vision or field of vision, such people still have the visual ability to guide their movements, and the development of techniques to use this ability effectively can help them in their daily lives. There is a genre of video games called "*exergame*," in which the player moves and the avatar on the screen moves in response to the movements of the player, allowing the player to play sports in a virtual space. To support the movement of visually impaired children, studies have been conducted to make this *exergame* possible without the need for vision by using auditory and tactile feedback [37, 38, 39, 40, 41]. There is also a tennis game that does not rely on vision by using a keyboard [42]. However, these studies have shown that the *exergame* requires more waiting time than actual competition, and the amount of exercise is not different from that in daily life [43]. Another study to realize badminton as a virtual competition used speakers to create a competition that can be enjoyed to the same extent by both sighted and visually impaired people [44]. In the study, the shuttle on a computer is moved by a bare swing of the racket and the trajectory of the movement is emulated by the speakers, thus realizing badminton without the use of a shuttle. However, most of the studies on exercise promotion have been conducted in a virtual space. In virtual space, there are limitations of the required space to play the game. Moreover, it is possible to experience the similar game that people with acquired low vision has been able to play before they became amblyopic in the real world. This study proposes a system that uses a ball and racket to perform exercise in the real world.

Several efforts have been made to introduce technology to develop new sports [45, 46, 47, 48]. The benefits of using technology include the ability to recreate movements that were previously impossible and allows the development of sports with completely new designs. Augmented Reality markers have been used to develop ball games that can be played without using a ball [49]; the study incorporates elements unique to a virtual space, such as player power-ups and the presence of an invisible ball, while simultaneously integrating virtual and real sports, as the game is played in the real world. *Nitta* et al. named such technology-enhanced competition "*augmented sports*" [18].

There were also studies in which people with visual impairment can walk around the environment in Virtual Reality(VR) by using special equipment [50]. There were also studies on the use of VR games to allow people with visual impairment to enjoy them[51]. In these studies, they used sound and vibration feedback to enable people with visual impairment to enjoy games. By using programmed ball movement and sound support, users can play video games that cannot be achieved with a regular ball. Systems that support sound localization with 3D audio have also been developed. They need to wear headphones to allow the system to recognize the left and right ears. In addition, by using a tracking function in the VR headset, it is possible to realize the difference in the way the sound was heard depending on the viewpoint. Based on the results, the use of VR may lead to more opportunities for people with visual impairment to increase their exercise. However, it is difficult to move the legs in VR because the movement must be done while wearing a headset. Therefore, it is designed to minimize the movement as much as possible. Another problem is the delay caused by the network connection. Therefore, Sports in the real world, where the entire body can be moved was focused on.

2.3 Human Drone Interaction

UAV technology has advanced rapidly in recent years and has become ingrained in people's daily lives [52, 53]. The relationship between UAVs and sports has grown closer in recent years, with the most notable development being UAV-based photography. This technology enables viewers to obtain more realistic images from viewpoints that only a UAV can provide [54, 55, 56, 57]. Furthermore, it is expected that analyzing one's own movements from the viewpoint of a third-party using UAV filming would improve athletic performance [58]. A research field known as *Human-Drone Interaction* that focuses on the relationship between UAVs and humans has emerged [59, 60, 61]. Studies in which humans control UAVs with their own body movements or gestures have been conducted [62, 63, 64, 65, 66, 67]. In addition, Introduction to existing efforts that have revealed the relationship between UAVs and people with low vision will be also presented. UAVs are useful for people with low vision as cameras are attached to the UAVs. For example, there are studies in which UAVs are used as walking guides [68, 69, 70]. There is also a study where UAV assist people with low vision to run [71]. There is also a study examining the relevance of using a drone as a ball with blindfolded sighted participants [72]. This study discusses the possibility of recognizing the position of a drone. Thus, studies to incorporate drones in the field of sports and the life of people with visual impairment are focused on.

Chapter 3

Design

This section describes the development of the racket game prototype with a drone as a ball. The difficulties in suggested sport with drones, and a prototype system that solves them are presented.

3.1 Design of the Present Racket Game

The idea of a racket ball game using a drone as a ball came up from interviews and behavior observations of people with low vision. However, there is no racket game that uses a drone as a ball. This section present the difficulties involved in using a drone as a ball and explain the kind of game design should make.

Research question is clarified through a three-step approach: First, this study developed a prototype in this section and conducted preliminary studies in Phase I to obtain ideas about the direction of the device and the game from participants with low vision. After that, the author developed an improved device and game design based on the feedback in Phase II and conducted experiments to evaluate the concept and game design proposed in Phase III. Finally, the challenges and the system and game design that should be developed based on the feedback was discussed.

3.2 Prototyping a Device that can Function as a Racket

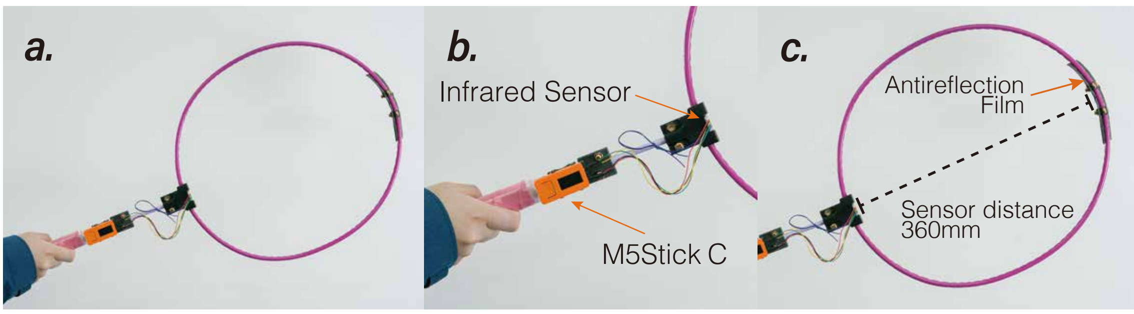

Figure 3.1: Overview of the racket design. (a) Assembly view of the racket. (b) Detailed view of grip. Infrared sensor is connected to *M5Stick C* (c) Infrared sensor measures the distance between the sensor and the anti-reflection film. The distance reads 360 mm when undisturbed.

The proposed game design identified four racket-related problems. The first problem is the gut. If the gut is used to hit the drone as in conventional racket sports, the gut can damage or break the drone, engaging the player. The gut part from the frame of the racket was removed and an infrared sensor to the connection between the frame and the handle was fixed as shown in Figure 3.1 (a). By placing a light-absorbing paper at the diagonal of the sensor at the tip of the frame, the distance measured by the infrared sensor was fixed at approximately 360 mm (approximate length of the frame). For evaluating the passage of the drone, the threshold was set to 330 mm. This value was chosen such that sensor value has some tolerance for error. By adopting this design, a racket sport using a drone as a ball were able to be realized. By using a racket-shaped device, participants would be able to understand that it was a new but familiar ball game. Another advantage of using the frame is that the reflective paper can be fixed at the tip of the frame which is necessary for stable measurement of IR sensor.

The second problem was the frame size. The size of the frame of the conventional racket makes it difficult to pass the drone through the frame when the proposed system is adopted. Therefore, this racket prototype decided to use a toy badminton racket for children with a large frame: 30 cm width, wide enough for the 17 cm width of the drone. Since this game design has a possibility of recognizing and hitting a ball above the body, a lightweight badminton racket that is easy to swing was used.

The third problem was the communication module to wirelessly transmit the infrared sensor connecting to the PCas shown in Figure 3.1 (b). The small wireless module textitM5Stick C [1] from M5Stack was decided to use as shown in Figure 3.1 (c). It was equipped with an *ESP32* microcomputer and a 6 ToF IMU (*SH200Q*) to acquire acceleration and angular velocity. This module was connected to a PC via wirelessly using the UDP communication protocol. The *M5Stick C* also allowed unique IDs to be assigned to each player. This system moved the UAV in the forward direction when the ID was 1, and in the reverse direction on the same trajectory when the ID was 2. Even if the player sent duplicate commands (e.g., accidentally puts a hand through the frame), the UAV flew in the correct direction.

Finally, a holder for the infrared sensor, light-absorbing paper, and *M5Stick C* was designed to securely attach each component to the frame. The holder was manufactured using a 3D printer (*Raise3D N2 Plus*)

3.3 Prototyping the Motion of the Drone

DJI's Tello [2], a small and programmable toy UAV whose SDK is publicly available, making it a relatively easy to program was used as shown in Figure 3.2 (a). Protectors, available from third parties, were attached to the drone for safety.

Furthermore, the trajectory of the drone was specified by preparing a csv file with four columns and multiple rows. The first, second, third, and fourth rows represented the degree of left/right, the degree of forward/backward, the degree of rotation, and the degree

[1] https://m5stack-store.myshopify.com/collections/m5-core/products/stick-c (last accessed : December, 22th, 2021)

[2] https://www.ryzerobotics.com/jp/tello (last accessed : December, 13th, 2021)

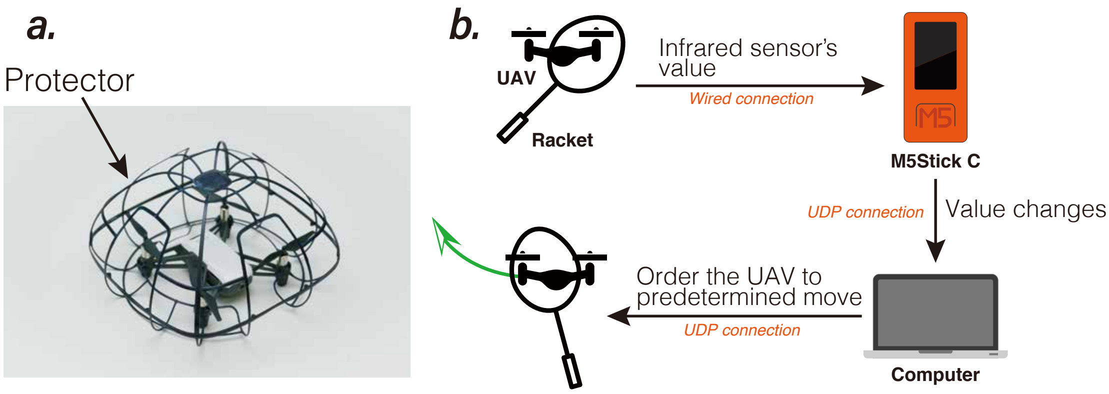

Figure 3.2: Overview of the UAV system (a) Assembly view of the UAV. (b) Overview of the prototype architecture.

of up/down, respectively. It was possible to specify trajectory of the drone by preparing multiple rows, one row as one frame. The drone's movement was replayed on a PC, and a single trajectory could be selected from the PC using the GUI to reproduce the trajectory when the drone passed through the frame as shown in Figure 3.2 (b). The trajectory preferred by people with low vision has not been determined; therefore, the author prepared two simple trajectories in a preliminary study: a linear trajectory that moves horizontally and a semicircular trajectory. The two types of trajectories were tested in a preliminary study to determine which one to adopt. Therefore, a trajectory as a simple system was prepared. In a rally between two players, waiting for drone to turn 180 degrees to face front of the drone back to other player would be time consuming. Therefore when a drone flies from player ID 1 to 2, the trajectory was played backward given varied swing signal has been produced by player ID 2.

Chapter 4

Phase I: Evaluation of Prototypes and Verification of the Direction of Game Design

They still require improvement based on the opinions of people with low vision because the devices were developed by sighted people. Therefore, the initial design in Chapter 3 was tested to obtain their opinions regarding the devices and game designs. Four people with low vision participated in the qualitative evaluation of the prototypes and game design. The device and the game design are improved in Phase II based on the difficulties and requests clarified in this section.

4.1 Method

4.1.1 Participants

Four male participants were recruited, aged between 22 and 35 years old (M=28.75, SD=6.26), from a local football club for people with low vision in the preliminary study. They all were physically active. This preliminary study could not control for gender bias. As participants were selected among the contacts of the author. P3 had congenital low vision and the rest had acquired low vision. Table 4.1 shows the demographic information of participants.

4.1.2 Apparatus

The participants used the prototype rackets in the swing and rally practice session. The power (on/off) of the M5Stick C attached to the racket and set the player ID was checked. Tello drone was used, and we turned the power on/off, replaced the batteries, and checked if there is any damage to the Tello. Two drones and eight batteries contingency were prepared.

4.1.3 Procedure

The purpose of this preliminary study was to familiarize the participants with the UAV and the racket, and obtain feedback from them.

The preliminary study started with an explanation of the study by gathering four participants simultaneously. Only the final rally session was conducted between two par-

Table 4.1: Demographic Information of Participants in the preliminary study

ID	Age	Gender	Diagnosis	Age diagnosed
P1	35	Male	Leber Hereditary Optic Neuropathy	26
P2	35	Male	Leber Hereditary Optic Neuropathy	16
P3	23	Male	Optic Atrophy	<1
P4	22	Male	Leber Hereditary Optic Neuropathy	18

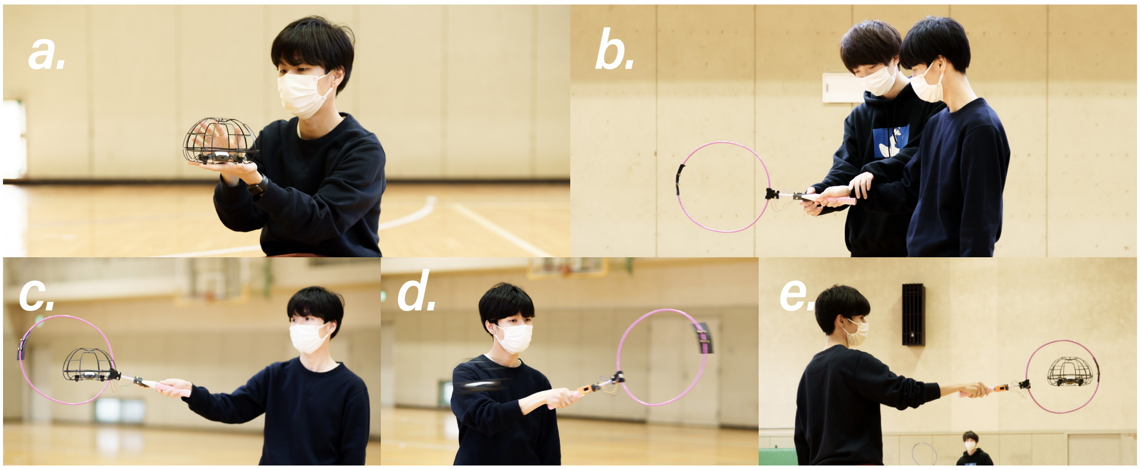

Figure 4.1: Flow of the preliminary study (a) Understand shapes using hands. (b) Learn how to swing. (c) Pass a floating UAV through the frame. (d) Pass a UAV that is moving straight ahead through the frame. (e) Two participants rally.

ticipants, but the other sessions were conducted one at a time. All the participants heard about the existence of drones but had never seen or touched one before. Therefore, the participants touched the drone used in the experiment to familiarize themselves with its shape, size, and hardness as people with low vision often touch things with their hands to recognize the shape of objects. The movement, color, and shape of the drone and protector were explained while the participants ware allowed to touch them as shown in Figure 4.1 (a). This introduction session lasted between 5 to 10 min.

The mechanism of the racket was explained and the participants was taught how to swing it as shown in Figure 4.1 (b). Unlike common racket sports, it was recommended to swing the racket perpendicular to the ground without tilting the surface to prevent the drone from colliding with the frame. Since each participant has a different way of seeing, they swung in a way that was the easiest for them. After that, the participants pass the drone through the frame with the power turned off, which held in the author's hands. The swings were performed five times each. The drone was fixed by hand at the left and right positions around the participant's waist and practiced the swings. This swing training session lasted about 10 min.

The participants practiced swinging and passing the drone through the frame as it hovered near their bodies as shown in Figure 4.1 (c). At this time, the drone did not have the setting turned on to move as it passed through the frame. This session was performed five times for drones fixed at the right and left sides of the body near the waist and above the head. The overhead standard setup was near the elbow when the participant raises their hand to rule out the cases where the drone went up and out of reach due to wind. The participant did not need to move, and the location of the drone was adjusted. This swing training session lasted approximately 10 min.

The participant stood at a designated position, and the UAV was moved in a straight-line trajectory from a fixed location 12 m away as shown in Figure 4.1 (d). At this time, the drone did not have the setting turned on to move as it passed through the frame. Each participant was asked to practice swinging the racket five times as it approached them. In the practice of passing the drone through the frame, the practitioner, a sighted person, had the drone play a predetermined movement on the PC. In this practice, the UAV was moved in a straight line from the participant's waist position to the left and right and the participant's wrist position when the participant's hand was raised, as in the previous swinging practice. This swing training session lasted approximately 10 to 15 min.

Finally, two participants, spaced 12 m apart, played a rally. When the drone passed through the racket, it automatically moved in the direction of the opponent as shown in Figure 4.1 (e). The drone was set up for two participants, and the rally started after the drone took off. The player who started the rally was chosen randomly. In this session, the drone trajectory ended when each player had performed 10 rallies for horizontal movement on the ground and 10 rallies for semicircular movement. This rally training session lasted approximately 10 and 15 minutes.

4.2 Phase I Findings: Evaluation of the Racket Device.

In the preliminary study, a racket with a length of 35 cm and a width of 32 cm was used. Regarding the size of the frame, P3 and P4 stated: *The size of the frame was fine for me.*, while P1 and P2 stated: *It was a little small for me.* These suggest that there is a need to develop scalable rackets for each participant, as people with low vision have different vision symptoms. There was another reason for the difficulty in passing the drone through the frame. Three participants(P2, P3, P4) said: *The handle of the racket makes it difficult to recognize the distance between the frame and my hand.* This is related to the fact that people with low vision usually recognize the shape and distance of objects by touching them with their hands. Therefore, it is necessary to reduce the impression caused by the sense of distance from the frame due to the handle.

4.3 Phase I Findings: Evaluation of Drone as a Ball

P2 fixed the racket vertically next to his body and placed his non-racket hand in front of his body, such that he could feel the approaching wind and sound of the UAV with his hand and recognize the distance and swing. P3 and P4 swung their rackets quickly when the drone approached and were able to pass the drone through the frame, but had more collisions than the other participants. P1 swung the racket in a similar manner to P2, waiting for the UAV to come closer and trying to swing carefully. In the interview, P1 and P2 mentioned that it was more difficult to recognize the position of the UAV compared to P3 and P4 because there were moments when the UAV was in a difficult-to-see positions because of the loss of viewing angle.

Not all participants could clearly recognize the drone's position. Therefore, they would swing their rackets when the sound of the drone was close and when the object, which appeared to be a black blur, was approaching. All of them found it difficult to look up and swing at a drone that was above their bodies. This indicates that when an object is above the body, it was difficult to estimate the distance to the object. In addition, all the participants stated that they were not used to looking upward because they rarely had the opportunity to look up in daily life. Player can exercise using muscles that they don't usually use by playing the proposed racket sport, which may lead to an increase in the amount of exercise. P3 and P4 suggested that a sound be used as feedback when a drone approaches. All participants also asked for more flexibility in operation, such as changing the drone's movement to match the direction of the racket swing.

4.4 Phase I Findings: Suggestions for Game Design

All participants indicated that they were familiar with physical contact from playing futsal daily and that they had no fear of the drone hitting them. This suggests that feelings may change depending on whether the participant is experienced in sports or not. One participant(P3) said: *I didn't have any fear because the protector made it seem safe to hit me.* Three participants(P1,3,4) said that because the drone was hard to see, the tension of whether or not they could successfully pass it was fun, and they enjoyed it because they could not see it. Furthermore, concerning the movement of the drone, two participants(P3,P4) noted that the semicircle trajectory was more varied and better than the straight line. Although one participant (P1) said: *Since various movements of the drone can be reproduced, there is no need to make it an ordinary ball-like movement.* All of them also wanted the players to be able to decide how to operate the drone.

This preliminary study brought two drones and eight batteries, and prepared an environment where the drones could operate for a long time with the batteries always charged. However, the drone stopped working in the middle of the rally sessions due to the large number of times the participants hit the drone with their rackets. The maximum flight time of the Tello was 13 minutes, and even with multiple batteries, the drone would stop working if it hit the racket and fell multiple times. Tello has a safety feature that automatically stops the propeller movement when it hits an object, such the drone do not fly erratically and collide with the participants. One of the participants (P2) commented: *It would be nice if the drone could recover immediately, if it hits and falls every time, the rally becomes boring.* Therefore, it is necessary to consider the specifications for operating the drone for a long period and develop a system or rules to prevent the drone from hitting the frame.

Chapter 5

Phase II: Devices and Game Design

This section describes the system development based on the feedback in Chapter 4 and aims to improve racket and related system design (e.g. game design).

5.1 The Device that can Function as a Racket

The racket in Phase II was improved based on the result in the Phase I as shown in Figure 5.1.

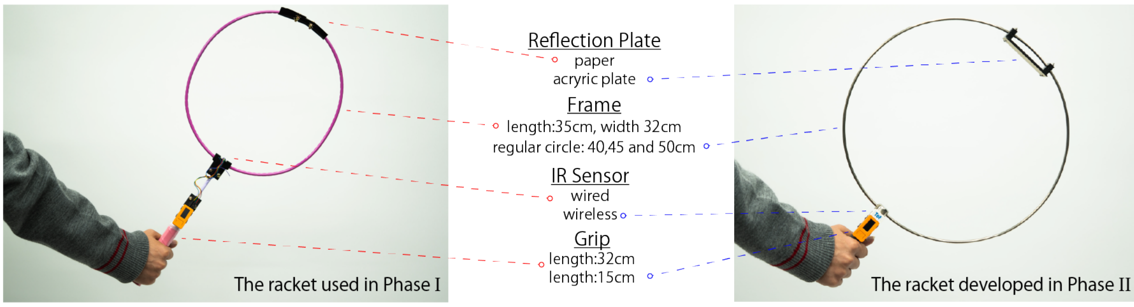

Figure 5.1: Differences during the rackets used in Phase I and developed in Phase II

5.1.1 Frame Part

This section improved the racket design based on the feedback from the preliminary study. Since the appropriate size of the racket frame and grip vary between users, a racket with an adjustable frame and the grip was developed. Users could choose their preferred size of the frame and attach it to their preferred grip.

When a prototype racket like devise was used in the Phase I, half of the participants indicated that they were not dissatisfied with the size of the frame, while the other half indicated that the frame size was too small. The racket prototype used a racket with a length of 35 cm and a width of 32 cm. Therefore, three titanium frames shaped in regular circles with diameters of 40 cm, 45 cm, and 50 cm was prepared and each player was allowed to choose the preferred frame as shown in Figure 5.2 (a). Titanium frames was chose because

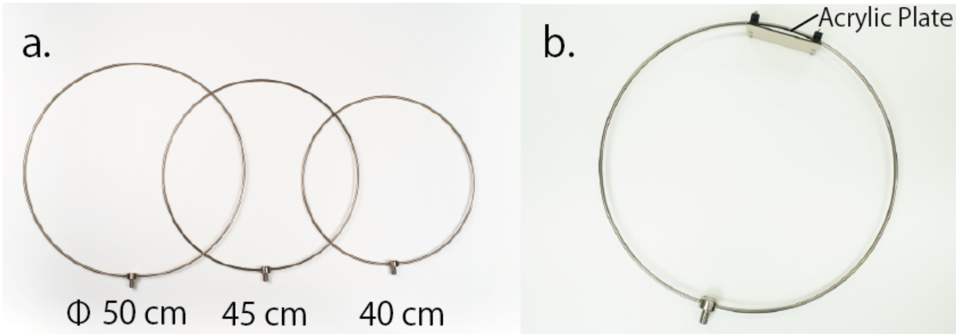

Figure 5.2: Two frame images designed for the Phase III experiment. (a) Three types of racket frames. (b)An acrylic plate for IR reflection

its light weight makes it suitable for swinging with one hand and its high strength prevents damages from a full swing.

The light-absorbing paper used in the prototype deteriorates after a long period of use. Thus, an acrylic plate was molded into 6×10 cm, and fixed it to the tip of the frame as shown in Figure 5.2 (b). Acrylic plate was used because of its weather resistance and light weight. Paper was attached to the plate to improve IR reflection. The apparatus used to fix it to the tip was fabricated using a 3D printer.

5.1.2 Grip Part

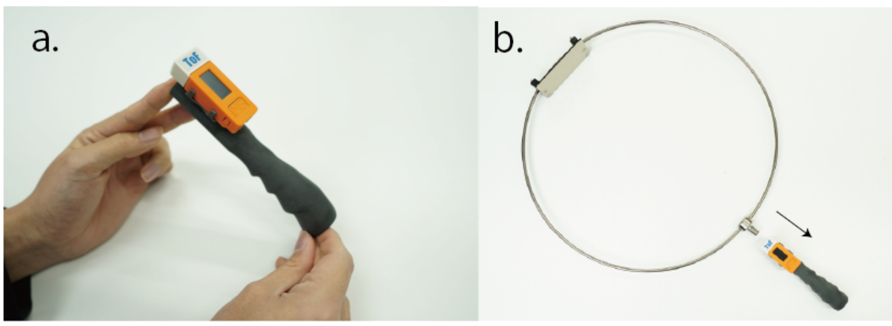

Figure 5.3: Two images for grip and racket designed for the Phase III experiment. (a) Shape of Grip (b)Racket and Grip

The racket prototype used a racket with a handle length of 17 cm and a grip length of 15 cm. This had a distance of about 30 cm between the hand and the frame. The handle widening the distance between the hand and the frame was one of the factors that made it difficult to pass the drone through the frame. The long and resilient properties of the handle were necessary in normal racket sports to achieve high ball speed and altitude. However, in this game, there is no need for such a handle because there is no gut. Therefore, a grip without a handle was developed as shown in Figure 5.3 (a). The total length of the grip is 15 cm, and the M5Stick C, is installed within that range. This is the same as the length of the prototype grip. The diameter of the grip is about 3.2 cm. The grip, with a holder shaft for the M5Stick C, was made using a selective laser sintering 3D printer (Sinterit Lisa Pro). The material used is Nylon 12. As a result, the joint strength between the frame and the shaft was improved compared to the one output by FDM. In addition, this system classifies the swing and changes the trajectory of the drone. Therefore, if the user constantly changes the way they hold the grip, it becomes difficult to determine the swing direction. By modeling the grip part to match their fingers, the racket made it easier for the player to maintain a consistent grip holding style as shown in Figure 5.3 (b).

The prototype used an infrared sensor, and the sensor was connected to the M5Stick C to obtain distance information. However, the wire between the sensor and the M5Stick C frequently disconnected or break. The M5StickC ToF Hat was used, an infrared sensor module released by M5Stack to solve this problem.

5.2 Drone's Moving System

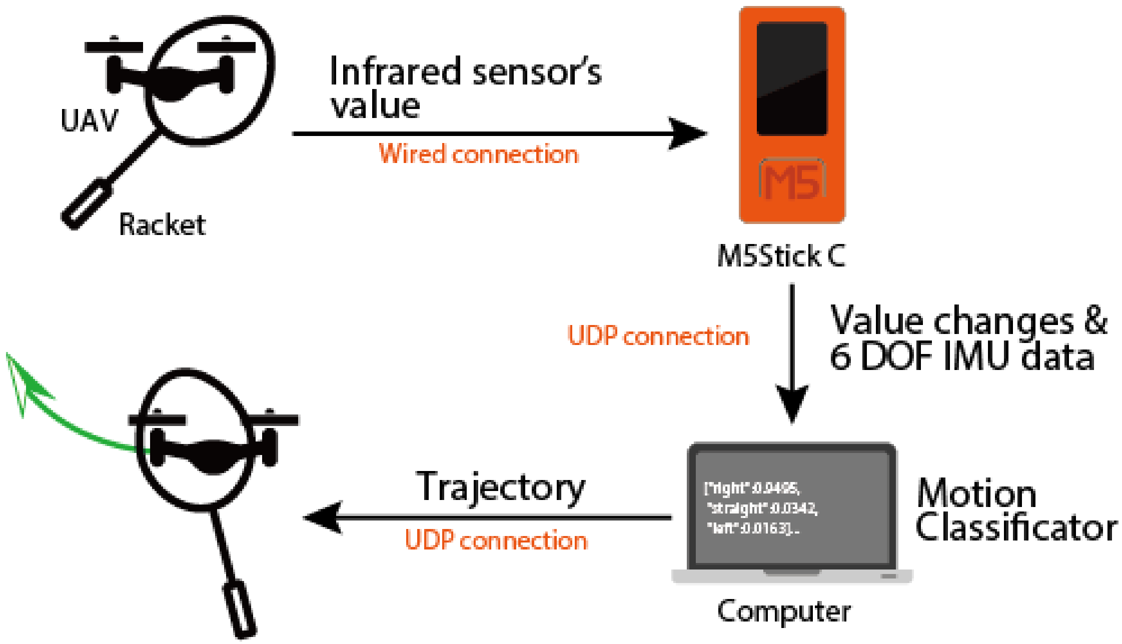

Figure 5.4: Overview of the system architecture.

In the preliminary study, one type of csv file with the trajectory of the drone was played back as the drone passed through the frame. Therefore, the drone could only fly one type of trajectory. However, participants wanted drone movements that could be controlled from the player side. Therefore, using machine learning, four types of trajectories was prepared to match the swing, and were able to achieve three directions: left, right, and straight lines, for each as shown in Figure 5.4. There are small individual differences in the racket swing

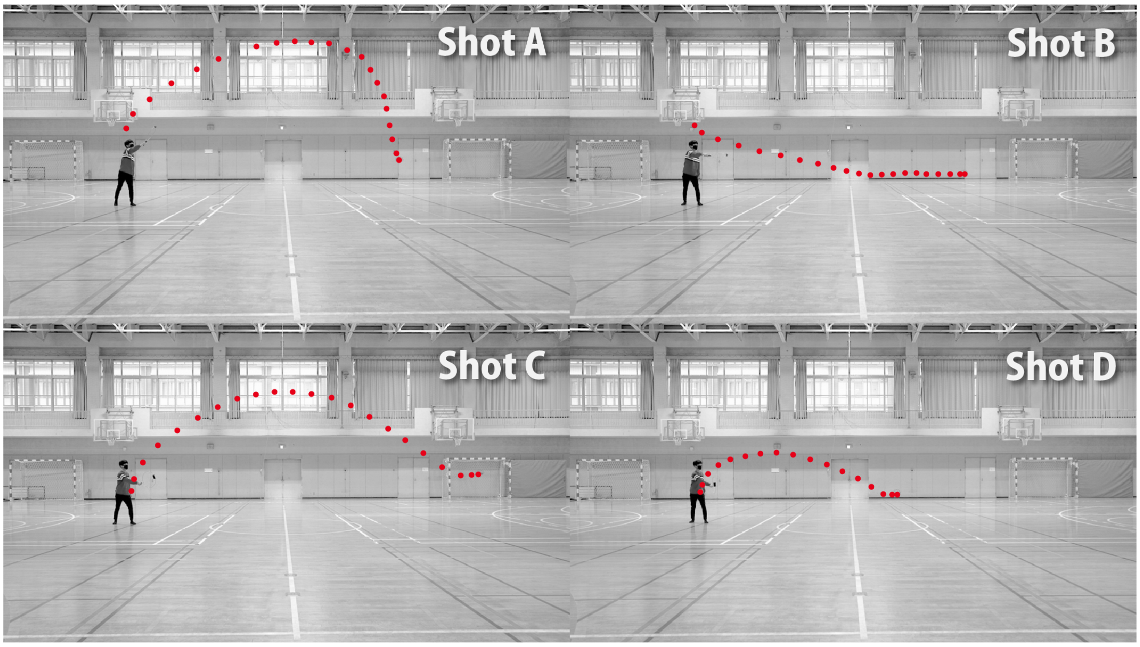

Figure 5.5: Trajectory of each of the four shots. The drone's trajectory is plotted at 0.5 second intervals.

motion. Therefore, it is difficult to build a discriminator that classifies into multiple classes based on the numerical values sent from the IMU without machine learning. Participants can operate the drone according to their swing by using machine learning and determining the swing for each shot. Players can determine the drone's trajectory from among the four types according to the swing, and can change it to any one of the three directions according to the direction of the swings as shown in Figure 5.5. The semicircular movement, not the straight movement, was adopted as the drone's trajectory in response to the feedback from the preliminary study.

5.2.1 System Architecture

This section explains the mechanism of acquiring sensor values and the timing of swing to acquire sensor values. First, the accelerometer and gyroscope sensors built into the M5Stick C were connected to a PC to acquire values in each direction during a swing (six data sets: acceleration and angular velocity in the X-, Y-, and Z-axes). These directional data were sampled at 16.7 Hz, and a queue was created to store 50 sets of six different data as one set. The data in the queue was continuously updated, and when a drone passed through the frame, the latest data in the queue was sent to the PC for machine learning via UDP communication. The k-nearest neighbor algorithm was used to build the model. The model used K-Neighbors-Classifier[1] to classify the motion sensor data. The classifier concatenated six-axis data with a window size of 50 and trained the data with a length of 300 as one sample. The accuracy was 91%. The trajectory data of any of the 12 types of trajectories obtained in the output was sent to the PC that served as the server to determine the trajectory to be played by the drone according to the results.

[1]https://github.com/scikit-learn/scikit-learn

5.2.2 Shots and How to Swing

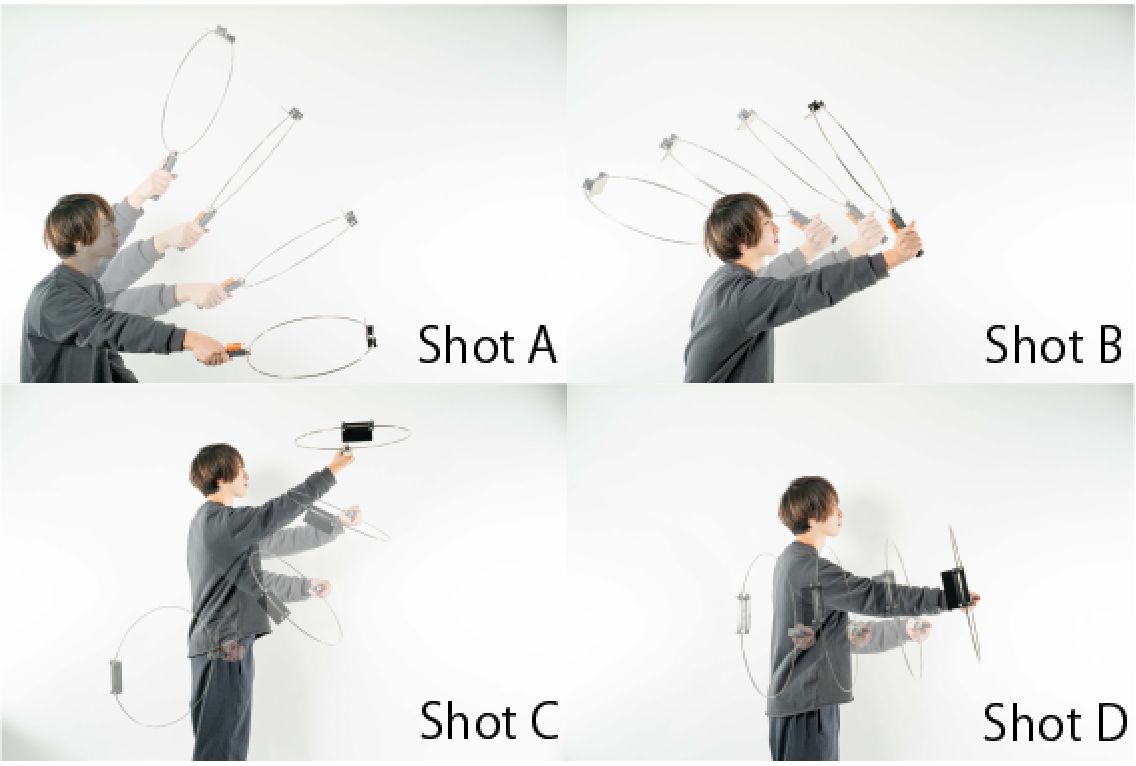

Figure 5.6: Each swing for four shots

Figure 5.7: Each swing for three directions

This system has two types of swings: one going down and the other going up as shown in Figure 5.6. In this system, the player can swing down and swing up. Therefore, for each shot, shots that makes the opponent player look up and look down were created. First, the swing of the shot from above was present. There are two types of shots that swing from above: Shot A that moves in a semicircle like a ball, and Shot B, which moves downward toward the opponent's feet. Shot A has a maximum altitude was 4.13m, and a flight distance was 6.49m. Shot B has a flight distance was 6.26m. Shot A requires an upward swinging motion with the frame facing up. Shot B requires a downward swinging motion with the frame facing down. The player moves the drone in the left direction by swinging from the right direction to the left; to move the drone to the right, the player swings from left to right, holding it in such a way that the back of their hand is visible to their opponent. By swinging in a straight-line trajectory the drone moves in a straight line as shown in Figure 5.7. Two shots result from swinging from below: shot C that moves in a semicircle like a ball, and shot D, which makes a short downward movement. The average speed of shot C has the maximum altitude is 3.40m, and the flight distance is 8.48 m. Shot D has a flight distance of 4.79m. Shot C requires a swinging motion from below upward with the face of the frame facing upward. Shot D requires a horizontal swinging motion with the face of the frame pointing horizontally to the ground.

5.3 Game Design

The game was designed to be played until a player scores three points, with a maximum of five rallies. The standard point was tested beforehand with a sighted person and was set with the assumption that the game would take 15 minutes. Since the maximum flight time of the drone was 13 minutes, the match time set 15 minutes in consideration of the non-flying time. In some cases, the drone did not move even though it had passed through the racket. In that case, the trajectory of the drone was determined based on the player's swing and replayed the trajectory of the drone. This rule was not conveyed to the participants.

5.3.1 Rules of Swing

There are two rules about swinging. The first rule is that players can only swing once; swinging many times increases the risk of collisions which can break the drones. Therefore, a limit on the number of swings was set to reduce the risk of colliding with the drone. The second is, after the swing, the racket should be fixed in front of the body. If the racket is left in place after the swing, there is a risk that the racket collides with the drone moving back in the direction of the opponent.

5.3.2 Rule of Score

There are five rules for scoring. The first is when the drone and the frame collide and the drone crashes. This rule was set up to solve the problem of drones breaking when they collide with the frame during the preliminary study. The second is a miss. The purpose of this rule is to have the participant swing carefully and reduce the risk of the drone breaking. The third is when the drone collides with the participant's body. This is to prevent the participant from hitting the drone with their body, and then swing after it stops moving. The fourth is when the operating drone collides with a wall. Colliding with a wall could cause the drone to crash, and this rule for scoring points was set in this case. The last is when the drone was unable to swing before 10 s had passed from the time a drone was hovering. This penalizes disturbing the game tempo.

In addition, there is a case that the rally may take too long to end. In that case, the participants may get distracted and not enjoy the game. Therefore, after 10 successful rallies, a point is given to both participants. The reason for this is to keep the tempo of the game going by giving points to each participant. If both participants get three points at the same time, the game is considered a drawn match.

5.3.3 Rule of Rally

During the rally, each participant cannot tell the other, the type of their swing or the direction of movement of the drone. This avoids getting external auxiliary information for later qualitative evaluation of one's visibility and ability to localize the drone's sound source.

Chapter 6

Phase III: Evaluation of Devices and Game Design

This section describes the experiments to evaluate the device and game design developed in Chapter 5. Ten people with low vision participated in the quantitative and qualitative evaluations of the devices and game design.

6.1 Method

6.1.1 Participants

Ten participants were recruited, aged between 20 and 35 years old (M=23.1, SD=4.46; 9 males, 1 female), from a football club for people with low vision. They all were physically active. The experiment could not control for gender bias. As participants were selected among the contacts of the first author. Eight people had congenital low vision and the others had acquired low vision. Table 6.1 shows the demographic information of participants.

6.1.2 Apparatus

Each participant used one of the developed rackets in the swing and rally practice session. We checked the power on/off of the M5Stick C attached to the racket and set the player ID. Tello was used, and we were responsible for turning the power on/off, replacing the battery and checking the damage of the Tello. 10 drones were prepared for contingency. Ten batteries were also prepared because one set of experiments was expected to take one hour.

6.1.3 Procedure

An explanation of the study was started to a pair of participants at a time. The rally practice sessions and game sessions were conducted with two participants, but the other sessions were conducted with one player. The pair was determined by the degree of each visual impairment. All the participants knew about the existence of drones but had never seen or touched one before. Therefore, the participants touched the drone, fitted with a protector, used in the experiment to check its shape, size, and hardness. The movement,

Table 6.1: Demographic Information of Participants in the experiment

ID	Age	Gender	Diagnosis	Age diagnosed
P1	21	Male	Pigmentary Degeneration of the Retina	<1
P2	21	Male	Retinoschisis	<1
P3	21	Male	Leber Hereditary Optic Neuropathy	14
P4	21	Male	Macular Hypoplasia	<1
P5	20	Male	Retinopathy of Prematurity	<1
P6	20	Male	Optic Nerve Hypoplasia	<1
P7	21	Female	Retinoblastoma	<1
P8	35	Male	Leber Hereditary Optic Neuropathy	18
P9	24	Male	Dominant Optic Atrophy	<1
P10	27	Male	Cone Monochromatism	<1

color, and shape of the drone and protector were explained, while the participants touched them.

Each participants selected the preferred size of the frame between the three types while passing the drone through the frame in their hands.This introduction session lasted between 5 to 10 min.

The 12 different shots were explained, and the participants practiced swinging each shot twice. Since the participants had low vision, their hands were held and taught them how to swing by movement and orally. The drone was held by hand, and the participant practiced swinging the shot that the author orally told them to swing and passing the drone through the frame after the swing explanation. This swing practice was done twice for each swing, and if the participant made a wrong swing, they were taught by moving the racket while holding the participant's hand. This swing training session lasted approximately 5 minutes.

Participants practiced rallying twice at 12 m apart operating the drone in a straight line. There was no limit to their shots during the rally. At the end of the first rally practice, the players switched positions and practiced the rally again. This rally training session lasted between 10 to 15 min.

The participants played the game according to the rules outlined in chapter 5.3 after practicing the rally. The participants decided whether they had the right to serve during the rally or to choose the location. The drone was set up and the game was started after the drone took off. This game session lasted approximately 15 min.Each pair of participants gathered and answered a questionnaire after the game.

Two participants gathered and answered a questionnaire after the game.

6.2 Phase III Findings: The Relevance of Using a Drone as a Ball

To design sports of this study, it is necessary to confirm whether a drone is appropriate as a ball sports for people with low vision. The fundamental question is how recognizable the drone was and how well it could pass through the frame. A questionnaire designed was conducted to obtain more detailed answers using a seven-point Likert scale with a bi-polar

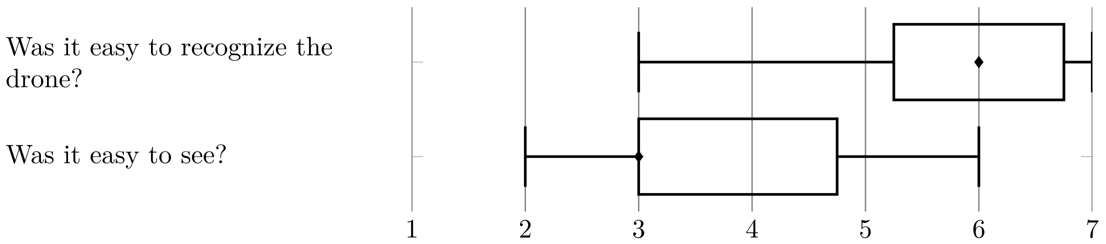

Figure 6.1: Results of the questionnaire about the relevance of using a drone as a ball by a five-point Likert scale (above:1 “I was easy to recognize it very much,” 7 “I was uneasy to recognize it very much”)(below:1 “I was easy to see it very much,” 7 “I was uneasy to see it very much”)

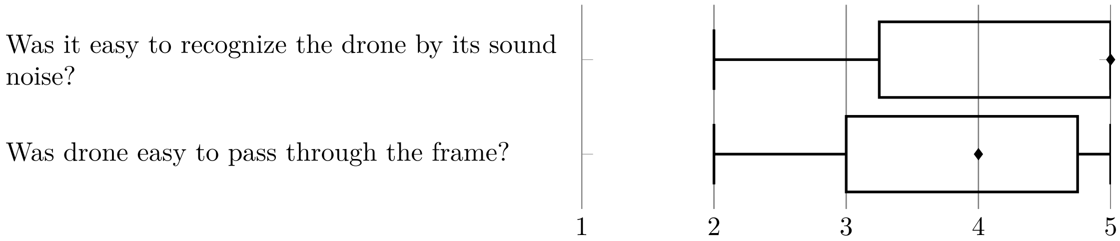

Figure 6.2: Results of the questionnaire about the relevance of using a drone as a ball by a seven-point Likert scale (1 “I fully disagree,” 5 “I fully agree”)

scale for visibility of the drone and location recognition, which were critical issues in the preliminary study. A five-point Likert scale was used for the questionnaire regarding the flight noise of a drone and the ease of passing the drone.

This study found out that recognizing and passing the drone was easy. The results of visibility of the drone, the localization of its flight noise, the recognition of the drone’s location using sound and vision senses, and the ease of passing the drone through the frame are shown in Figure 6.1. A high score was obtained for drone location recognition with the participant’s vision and hearing senses (Mean=5.6, SD=1.43). However, it was found that the visibility of the drone was relatively low (Mean=3.6, SD=1.28 on Likert scale). The drone location recognition by the drone’s flight sound was found to be quite recognizable (Mean=4.1, SD=1.22) as shown in Figure 6.2. The drone could be recognized even when hardly visible due to the drone’s flight noise. In addition, the fact that there were times when the drone hovered may have also led to this result. As a result, a high score was also obtained for the result on whether it was easy to pass the drone (Mean=3.7, SD=1.1). Regarding the visibility of the drone, there was an issue of visibility depending on the location; P1 said: *It was difficult for me to see the drone when it was high up.* P2, P3, P5, and P8 found it difficult to see when the drone was covered with lights. Regarding the visibility of the drone itself, P1, P2, P8, P9, and P10 believed that it would be easier to see if something like an LED was attached to the drone. Although regarding the light emission, P10 said: *Some people have difficulty seeing if it’s too bright, so you need to investigate best light emission colors and color contrast.* Further study on how people with low vision see drones will help create something easier to recognize and develop more competitive game designs.

6.3 Phase III Findings: Evaluating the Usability of Racket

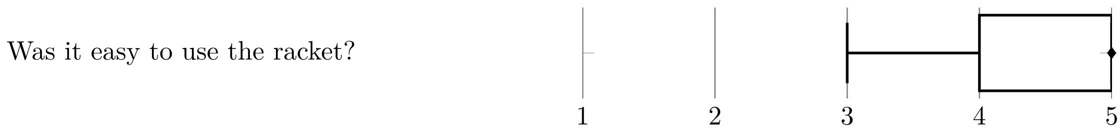

Figure 6.3: Results of the questionnaire about the usability of a racket-like device (1 "I fully disagree," 5 "I fully agree")

In this study, a racket like device without gut and with a sensor attached have been developed to use a drone as a ball. The usability of the racket developed in this study was evaluated through a questionnaire survey using a five-point Likert scale.

The results of the survey are shown in Figure 6.3. The device without the gut and with the sensor was found to be easy to use (Mean=4.4, SD=0.8). Regarding the racket, there were several comments about the design of the grip. A grip design was adopted that eliminated the handle to solve imprecision caused by the distance between the hand and the frame. However, the P7, P8, and P10 found the handle was too short. The P8 and P9 found that the handles were so thin that they were difficult to hold. Regarding the frame, P5 and P6 feared that the frame would hit the drone, so they could not swing it as hard they wanted to. P6 and P10 were concerned about the drone that falls upon colliding with the frame, as a result, they could not swing as fast as they wanted to. Regarding the swing, P2 said: *At first, it was difficult to have a sense of distance with an unfamiliar racket. However, I got used to it after practicing rallies continuously, so I think other people will get better if they keep practicing.*

6.4 Phase III Findings: Evaluation of Game Design

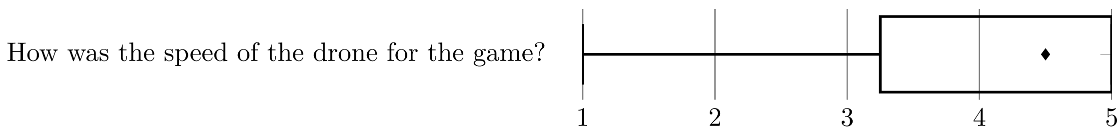

Figure 6.4: Results of the questionnaire about the Game Design by a five-point Likert scale (1 "I fully disagree," 5 "I fully agree)

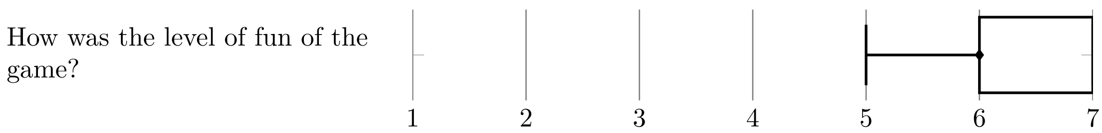

Figure 6.5: Results of the questionnaire about the Game Design by a seven-point Likert scale(1 "I feel boring very much," 7 "I feel fun very much")

This game design is in its early stage based on the developed devices. It was necessary to use models for evaluation. Therefore, the speed of the drone and the level of fun of the game were evaluated. Questionnaire surveys using a five-point Likert scale and seven-point Likert scale on drone speed and fun were conducted, respectively.

The results of the drone speed for the game and the enjoyment of the game design are shown in Figure 6.4. For most participants, the speed of the drone in the game was evaluated as adequate (Mean=3.9, SD=1.37).

The evaluation of whether the participants enjoyed this game was quite high as shown in Figure 6.5 (Mean=6.3, SD=0.64). The fact that the minimum value is 5 indicates that all participants enjoyed the game. P5 and P6 said: *Because of the rule that we were only care to make a mistake, shot A was easy to pass the drone and I almost use it. It would be better to give the attackers more advantages.* P8 also said, *It's good that both sides get a point after 10 s of hovering, but 10 s seems like a long time.* P3, P4, and P10 wanted to try swinging the drone at a faster speed. On the other hand, P5 said. *I have never been able to participate in tennis or badminton because of the speed of the balls. It was the first time for me to swing at a ball in the air, and it was fun.* P6 said, *The slow speed made it possible for me to enjoy it even though I am not an athletic man.* P10 also gave some advice on how to popularize the game in the future, saying, *It might be more popular if it was fun to watch.* P9 said: *It would be more popular if this sport can be played with a smartphone application not to use a computer.* If the game is improved in response to feedback from people with low vision, it could become a sport that can support more visually impaired people.

Chapter 7

Discussion

This study proposed a racket game using a drone as a ball to expand the range of games for people with low vision. A racket-like device and a drone movement system using the drone as a ball were developed and a game design was made. Experiment with people with low vision was also conducted to obtain their feedback about systems and game design. Based on the results, discussions on the following two points were organized: First, the devices were developed, in particular, the relevancy of using a drone as a ball and the racket-like device. Second, the game design; the game design based on game design in an early stage and the feedback from participants were discussed.

7.1 Improvement to the Racket like Device

This study proposed a racket-like device with three types of frames and a self-made grip made using a 3D printer. As a result of the preliminary study, it was found that the size of the frame varied depending on the participant's sight, and the handle made it difficult to recognize the distance. The results of the survey on the usability of the racket developed in phase II were positive. Since this is the first racket sports which combined racket and drone, further variation of the system can be envisioned. However, this design is still in its early stages of development and needs more time before implementation for the benefit of people with low vision. Some participants said that the 15 cm grip without the handle was too short and thin for the large hands of adult males. In addition, the machine learning data set was made for right-handed people, which is the common hand orientation. Since all the participants were right-handed, there were no problems. However, it is necessary to develop a more flexible trajectory system and to make grips for left-handed people together with more personalized grips in the future. Since the target players are people with low vision, it is difficult for them to know whether they were able to pass the drone. Therefore, it is also difficult to recognize whether the other player was able to pass the drone. Providing feedback in vibration and sound when the drone passes through the frame would make rallying more enjoyable.

7.2 Toward a Drone-based Design Approach

7.2.1 Improvements to the Drone Itself

There is a possibility of the drone hitting the player; therefore, the small and lightweight Tello were chosen, which has minimal danger. The participants touched the Tello and showed no signs of fear in operating it as a ball. The drone recognition got a high evaluation, as the flight noise was coming from the drone, and hovering and low speed were adopted. This validates the use of the drone as a ball. This study selected drones that are commercially available and are suitable for the purpose of this study. However, the development of optimal drones is essential for the development of a better game design.

In this study, the white airframe Tello was fitted with a black protector and used as a ball. How people with low vision can recognize flying drones was not studied yet. However, there are various ways of seeing in low vision, and it depends considerably on the individual in terms of field of vision, color, visual acuity, and level of vision. This study adopted a simple design, Tello and the protector, and investigated the recognition. For small drones, the balance and the stability of the center of gravity are quite relevant to the flight. LEDs or other light-emitting components were not used because their weight and position could interfere with the flight. Since the preliminary study was able to confirm that the visibility of the drone was possible, the study proceeded to conduct experiments with the same drone to investigate their positional recognition. LEDs are used in many situations to improve visibility for people with low vision. In the experiment, there was a negative opinion about the visibility, and it can be said that the position recognition was enabled by the flight sound and the speed of the drone. Therefore, future studies on the visibility of drones for people with low vision may lead to the development of drones as better balls.

The maximum flight time of the Tello is, officially, 13 min. Therefore, the duration of the proposed game was set to 15 min to reduce the possibility of changing the battery of the Tello in one game. However, some of the drones frequently used had a flight time of 13 min or less. When the battery was changed, the drone had to connect the PC wirelessly again. A drone suitable for this game should have a longer flight time.

There is also need for improvement in the durability of the drone. In the preliminary study, there were many cases that participants hit the drone as hard as they could and broke it. 10 drones were prepared and only three drones were broken during the five matches and multiple rally practice sessions. Many participants commented that they wanted to swing as hard as they could to enjoy the game. Therefore, it is necessary to adopt and develop protectors for drones that are less likely to break even if they hit the frame and continue to improve the game design to make it more satisfying for players.

7.2.2 Drone's Moving System

A system that uses sensor data and replays the drone's trajectory by machine learning was adopted. In the preliminary study, there was feedback from participants for more freedom in drone operation, so systems were developed to determine four types of shots and three types of movement directions by machine learning. By adopting these drone movement methods, the experiment was able to see each participant trying out different shots. In addition, by setting the drone speed to a low speed and adopting the specification of hovering after movement, many participants indicated that it was easy for the drone to pass through the frame. However, some participants wanted improvements on the trajectory of the drone. In particular, a system that changes the speed and movement distance of the drone to match the player's swing would provide a more operable sport. Based on the acceleration obtained by the M5Stick C, these movement systems are possible. It is necessary to construct a system that can simulate movement according to sensor values. Since drones are used, there were calls for a special trajectory that cannot be achieved with ordinary balls. Special trajectories that are unique to drones could be fun for the audience also.

7.3 Improvement to Game Design

The participants rated the enjoyment of the game highly, suggesting a high potential for a racket game using a drone as a ball, which strongly supports idea of this study. In particular, the experience of swinging a racket at a ball floating in the air is scarce for people with low vision. The congenital participants enjoyed playing for the first time, and the acquired participants were happy to be able to perform the action they were once familiar with. Therefore, we believe that by developing this initial game design, it would be possible to greatly increase the variety of games for people with low vision. In particular, the feedback by the participants indicated several improvements related to the environment. This game design mainly focused on rackets and drones, and there was not much support for the court where the game was played. Instead of providing support by recognizing the court for people with low vision, we considered the entire gymnasium as the court and set up the game. The purpose of this was to consider the large space of the gymnasium as a court so that the game could be evaluated without being restricted to the court. Therefore, in the future, by setting up the court and narrowing down the scope of the game, it will be possible to realize a sport with more strategy in selecting shots. The success rate of recognizing and passing drones were improved by using a lower speed, but other participants wanted a faster tempo. Therefore, by adding an improvement that changes the speed according to the user, the difficulty level can be varied, and more users can enjoy the game.

Chapter 8

Conclusion

First, a survey was conducted to find the problems of options of racket sports for people with low vision. After that, the prototype was developed of using a drone as a ball and developed a prototype of a device with a sensor instead of a gut and a drone movement system, and conducted a preliminary study with four participants with low vision. The preliminary study conducted an interview survey and obtained feedback on the future direction of this concept and suggestions for the game design. The system was improved, the game design was developed based on the feedback, and conducted another experiment. As proved by the 10 participants, it was possible for people with low vision to use the drone as a ball, and the game design was highly appreciated. The performance of this system exceeded the participants' expectations in terms of position recognition of the drone, usability of the racket, and the fun of the game.

In the future, we plan to improve the drone battery performance and reduce the possibility of crashes. We will review the system and improve the game design. Finally, we hope that this study will help increase exercise options for people with low vision. For people with low vision, more exercise options and opportunities are critical to improving their health. This study has the potential to greatly increase the range of racket sports for them.

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Appendix

Game Contents and Pass Rates in Phase III

Pairing	Rally 1	Rally 2	Rally 3	Rally 4	Rally 5	Result	Pass Rate
P1	1					1	87%
P2	1	2	3			3	100%
P3		1	2		3	3	86%
P4	1			2	3	3	86%
P5		1	2	3		3	96%
P6	1	2				2	91%
P7			1			1	88%
P8	1	2	3			3	100%
P9	1	2	3			3	100%
P10	1		2			2	96%