

Virtual Reality Racket Sports: Virtual Drills for Exercise and Training

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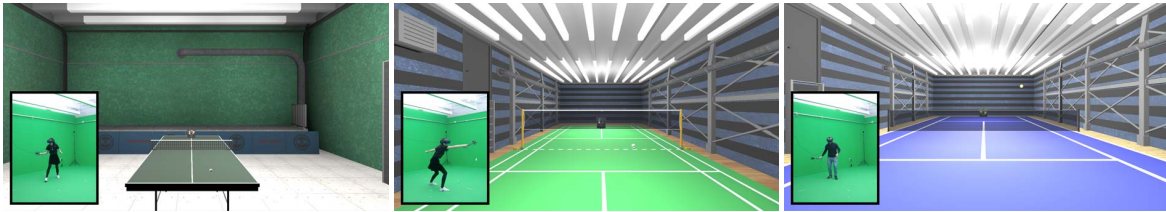


Figure 1: Our approach can optimize virtual reality exercise and training drills for different racket sports with minimal effort from the user. From left to right: table tennis, badminton, and mini tennis.

ABSTRACT

We have developed a modular virtual reality gaming application that can be used to synthesize exercise drills for racket sports. By defining cost terms that are related to the gameplay and the mechanics of the game, as well as by allowing a user to control the parameters of the cost terms, users can easily adjust the objectives and the intensity levels of the exercise drills. Based on the user-defined exercise objectives, a Markov chain Monte Carlo optimization method called “simulated annealing” was used to optimize the exercise drill. The effectiveness of the developed virtual reality gaming application was measured in two studies by using virtual reality table tennis as the evaluation tool. The first study investigated the potential usefulness of the developed virtual reality gaming application as an exercise tool by comparing its workout effectiveness at three intensity levels (low, medium, and high) through the collection of heart rate readings. The second study explored the potential utility of the virtual reality gaming application as a training tool by exploring whether there was any improvement in participants’ performance across the three conditions (no training, virtual reality training, and real-world training). The results indicate that a virtual reality gaming application, such as the examined virtual reality table tennis exergame, could indeed be used effectively as both an exercise and a training tool. Limitations and future research directions are discussed further below.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Applied computing—Computers in other domains—Personal computers and PC applications—Computer games

1 INTRODUCTION

Virtual reality has proven to be an excellent tool not only for entertainment purposes, but also for several other applications such as training [26, 28, 37, 52], rehabilitation [33, 61, 83], human behavior exploration [41, 60, 63], and visualization [1, 20]. The use of virtual

reality in these domains allows the user to observe and interact with the provided content in a highly immersive environment while also being entertained [31, 54]. With the widespread popularity of virtual reality devices and peripheral equipment, several real-world experiences can be converted into virtual ones and brought into one’s own living room. The use of virtual reality for exercise purposes can even have real-world benefits for some users. Specifically, by playing and simultaneously exercising, users can improve their physical health and fitness while being entertained [6, 18, 65].

Since quite a few people are interested in racket sports-related games¹ (e.g., table tennis, tennis, badminton, etc.), we decided to develop a modular virtual reality gaming application that can be used for exercise and training purposes by racket sports enthusiasts, focusing mainly on table tennis, badminton, and mini tennis. While the potential of virtual reality gaming applications for exercise and training is appealing, designing exercise drills may become tedious for the user, as the parameters have all been pre-set by the developer. Bearing this in mind, the virtual reality gaming application presented in this paper allows users to customize exercise drills, as our system is able to automatically optimize an exercise based on user-specified objectives.

The developed application was inspired by previous research on procedural content generation for exergames [45, 86, 87] and virtual reality applications related to racket sports [10, 55, 57, 75]. Our approach took into account several parameters related to racket sports games and represent these parameters as cost terms to a total cost function. Next, an optimization-based approach was used to synthesize the racket sport drill. By formulating the design of the racket sport drills as an optimization problem, in a few seconds, several exercise drills could be generated by our system which is designed to maintain a balance among different design schemes while ensuring the necessary variability between different generated drills. This variability is important for keeping the user engaged. As shown in Figure 1 and the accompanying video, our approach can be applied to different types of racket sports.

The focus of the paper is twofold: (1) develop an algorithm for automatically synthesizing exercise and training drills for racket sports, and (2) evaluate the impact of the synthesized exercise and training drills on human performance. The effectiveness of the developed application and the ability of our algorithm to efficiently synthesize exercise and training drills had to be evaluated, so two user studies were conducted to determine our method’s potential for use as an exercise and training tool. The results indicate that this type

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¹<https://www.worldatlas.com/articles/what-are-the-most-popular-sports-in-the-world.html>

of virtual reality application can indeed be used for both exercise and training purposes. However, aside from the advantages of exercising in virtual reality, there are also some limitations that should be taken into account by the research community, something that may spur the development of additional advanced virtual reality interfaces applicable to exercising and training in virtual reality racket sports.

The remainder of this paper is organized as follows. Related works are presented in Section 2. The methodology and implementation details are presented in Section 3. The first user study and results are presented in Section 4, and the second user study and results are presented in Section 5. Various limitations are presented in Section 6. Finally, the conclusions and potential for future research are addressed in Section 7.

2 RELATED WORK

Because traditional video games are generally associated with reduced energy expenditure on part of the players due to decreased physical activity [43], strategies that allow players to entertain themselves while also increasing physical activity have also been explored [27, 35, 50]. In response to the difficulty of developing effective strategies to promote physical activity [69], a category of games called exergaming [80, 84], or active video games [8], has been developed to incorporate virtual reality technologies into video games. Generally, exergames allow players to perform various exercise activities from the comfort of their living rooms. Such games require physical output as a means of interaction and engagement with the game. Aside from the capacity of such games to be used for exercise and fun, exergames are also considered a credible alternative to conventional training. This has made it possible for exergames to be used in sports training [13, 36], breathing training for increasing lung capacity [67], balance enhancement [44], weight control [82], and motor training [77].

The idea of using exergames to improve the health of users has been increasingly promoted by the research, development, and health/medical communities [68, 73]. When comparing non-exergames with exergames, studies have indicated that the latter increase user enjoyment and intrinsic motivation levels [4, 5, 22, 58, 78]. So far, studies have validated the positive health effects of exergames [18, 46] on weight loss in adolescents and adults [6, 82], and on improved balance- and movement-related physical performance in the elderly [65, 85]. Moreover, it has been found that physical activity has positive effects on cognitive and also physical functions [15, 16, 25, 53, 64, 76]. A notable example of the above is the collaboration between West Virginia high schools and the KONAMI gaming company, through which the arcade dance-based video game “Dance Dance Revolution”² was included in the high school curriculum as a way to tackle youth obesity.³

When developing exercise games, an important factor a developer needs to take into account is the degree of physical exercise that is required by the user [66], since, according to a prior study, players derive more enjoyment from games that are neither too difficult nor too easy [81]. Though it is important to define physical exercise goals, when developing commercial games, customarily it is the developers who manually set these goals [23, 32]. Thus, a challenge arises for developers to design an exercise gaming experience that can be used efficiently by users of varying ages and fitness levels. Fitts’ law [48] and precision of difficulty [49] can be employed so that exercise parameters can be controlled by users. In the current implementation, we considered several parameters related to racket sports and ultimately provided users with control over the output of their exercise drills.

To automate the exercise or training drill synthesis process, procedural techniques can be efficiently applied [14]. Such procedural

²https://www.konami.com/games/asia/en/products/ddr_a/

³<https://www.sfgate.com/business/article/Video-dance-game-to-be-used-in-schools-West-2542902.php>

techniques allow the development of fast and scalable designs while variations across design outputs are also ensured. Note that such techniques have already been successfully implemented in various games [14, 29, 34, 79, 80]. Our developed procedural exercise drill design method was inspired by previous research and by recent approaches to automatic game-level synthesis for exercising [45, 86, 87]. Our application extends the current list of such exergames by proposing the use of racket sports, and evaluates the virtual reality table tennis exergame for its potential as an exercise and training tool.

3 SYNTHESIZING RACKET SPORTS EXERCISE DRILLS

A method was developed to synthesize exercise drills for virtual reality racket sports with respect to several factors defined as cost terms in a total cost function. Let $E = [s_1, s_2, \dots, s_N]$ denote an exercise drill, which consists of a number of $s_i \in E$ shots generated by our system (it is worth mentioning here that a virtual ball-throwing machine was used to generate the shots from the exact same position) and assembled in a sequential order, where s_i corresponds to any possible shot. The exercise drill E is designed by a total cost function $C_{Total}(E)$:

$$C_{Total}(E) = w_S^T C_S + w_P^T C_P \quad (1)$$

where $C_S = [C_S^{Dist}, C_S^{Speed}, C_S^{Freq}]$ is a vector of shot cost, and $w_S = [w_S^{Dist}, w_S^{Speed}, w_S^{Freq}]$ are weights that correspond to the cost terms. The C_S^{Dist} , C_S^{Speed} , and C_S^{Freq} terms encode the intensity of the exercise drill: C_S^{Dist} denotes the distance covered by the user to complete the drill and is expressed as the distance between two adjacent shots (the distance is computed between the position $P(s_i)$ and $P(s_{i+1})$ of the adjacent shot s_i and s_{i+1} , respectively), C_S^{Speed} denotes the speed of the shots, and C_S^{Freq} denotes the frequency with which the shots are generated. Note that each shot s_i is represented by a target position $P(s_i)$, speed $V(s_i)$, and frequency $\Phi(s_i)$.

The prior cost term $C_P = [C_P^{Dur}, C_P^{Var}, C_P^{Side}]$ includes the prior costs associated with the developed exergame, such as the duration of the exercise drill (C_P^{Dur}), the variations between the shots (C_P^{Var}) and the court side (C_P^{Side}), and the $w_P = [w_P^{Dur}, w_P^{Var}, w_P^{Side}]$ are weights assigned to the prior cost terms. It should be noted that aside from the proposed cost terms, various other cost terms can be examined by the developers, depending on the characteristics of the exercise drill. For the cost terms, we employed a Gaussian model in order to evaluate the distance between the given objective and the target objective of the exercise drill. The source code (Unity3D project) of our racket sports application is available at our GitHub repository: <https://github.com/Hearurt/VR-TableTennis-System>.

All cost terms presented in the below sections were computed by using normalized values that lie within the minimum and the maximum range of each individual target. In finding the targets, eight non-athlete healthy students (four males and four females aged 19-23) were required to exercise for 60 minutes by playing multiple variations of the exergame at varying exercise intensities. During that time, combinations of various target values for each cost term were tested, and the heart rate (beats per minute) of each participant was recorded by using a heart rate sensor, the Polar OH1+.⁴ Based on this initial data collection, we were able to define the range and the target values of the individual cost terms. Finally, it should be noted that the target objective of the optimization process was the manipulation of exercise intensity, which in our case will be later evaluated (see Section 4) by collecting heart rate data and self-reported perceived intensity rating.

Note that although a number of methods could be used to generate exercise and training drills, we choose to implement an optimization-

⁴<https://www.polar.com/us-en/products/accessories/oh1-optical-heart-rate-sensor>

based method to solve the exercise and training drill synthesis problem. For example, rule-based methods often fail to select appropriate parameters for the desired outcome (especially when multiple parameters should be fulfilled simultaneously) and, in most cases, synthesize the output in a product-appropriate manner [11]. However, optimization technique iterates through hundreds of systematic draws from the model parameter space to search for solutions that fit all constraints set by a user, no matter how complex the problem is, which makes it fairly reliable [71] and easy to implement new constraints/cost terms. Moreover, optimization techniques allow the estimation of complex solutions in a fast and scalable fashion, which rule-based techniques fail to do.

3.1 Shot Terms

The three shot terms responsible for generating a new exercise drill E are defined in this section.

3.1.1 Distance Cost

In various exercise drills, user movement within a space is quite common and, according to sports science, locomotive movement while exercising presents various benefits [19, 74]. In order to calculate how much a user moves, it is assumed that there is a linear relationship between the distance of two adjacent shots (the distance of the positions of two balls the time point they bounce on the side of the user) and the distance that the user would need to cover when exercising. Thus, we defined a cost to compute the distance between the positions of two adjacent shots as:

$$C_S^{Dist}(E) = 1 - \exp\left(-\frac{\left(\frac{1}{|E|-1} \sum_{(s_i, s_{i+1})} D(P(s_i), P(s_{i+1})) - \sigma_D\right)^2}{2\sigma_D^2}\right) \quad (2)$$

where σ_D is the target distance covered between two adjacent shots, $D(P(s_i), P(s_{i+1}))$ denotes the distance between the positions $P(s_i)$ and $P(s_{i+1})$ of the two adjacent shots s_i and s_{i+1} , respectively, and $|E|$ denotes the total number of shots.

3.1.2 Speed Cost

According to sports science literature [7, 21, 56, 72], the speed in which a ball moves in racket sports enhances the intensity of the exercise, as the athlete needs to be prepared to quickly decide and adjust his/her movement toward the direction of a moving ball. Thus, we included a cost term to compute the speed intensity involved in the exercise drill:

$$C_S^{Speed}(E) = 1 - \exp\left(-\frac{\left(\frac{1}{|E|} \sum_{s_i} V(s_i) - \sigma_V\right)^2}{2\sigma_V^2}\right) \quad (3)$$

where σ_V is the target average ball speed in completing an exercise drill E , and $V(s_i)$ denotes the speed of the s_i shot.

3.1.3 Frequency Cost

The last term applied in our shot cost term is related to the frequency in which a new ball should be generated by the virtual ball-throwing machine. Based on various sources, we found that frequency is important in exercising, since high frequencies tend to keep an athlete vigilant as there is no time to rest between adjacent shots, resulting in a more intense workout [2, 3, 30, 40, 42, 47]. Thus, a frequency cost term was developed to compute the frequency intensity involved in the exercise drills:

$$C_S^{Freq}(E) = 1 - \exp\left(-\frac{\left(\frac{1}{|E|} \sum_{s_i} \Phi(s_i) - \sigma_\Phi\right)^2}{2\sigma_\Phi^2}\right) \quad (4)$$

where σ_Φ is the target average of the ball-throwing frequency in completing an exercise drill E , and $\Phi(s_i)$ denotes the frequency of the s_i shot.

3.2 Prior Cost

In this implementation, the prior cost terms were developed to control some of the features of game play. Various prior cost terms could have been employed, depending on the specific design requirements of an exercise. However, we limited the prior cost terms to those that are most important for this particular virtual reality gaming application: duration, variation, and court side.

3.2.1 Duration Cost

The duration cost is responsible to softly constrain the exercise drill to be of a certain duration, and it is defined as:

$$C_P^{Dur}(E) = 1 - \exp\left(-\frac{\left(\sum_{s_i} \tau(s_i) - \sigma_\tau\right)^2}{2\sigma_\tau^2}\right) \quad (5)$$

where $\tau(s_i)$ denotes the duration of a single shot and σ_τ denotes the target duration of the exercise drill.

3.2.2 Variations Cost

To keep the user engaged with the exercise drill—since an exercise without variation would become less interesting—a variation term was also implemented as an additional prior cost. When we perform exercise drills that require multiple repetitions of the same shot, the variation between repetitions should be minimized. Thus, the variation cost term ensures that the generated shots will or will not have the same characteristics, and it is defined as:

$$C_P^{Var}(E) = \frac{1}{|E|-1} \sum_{(s_i, s_{i+1})} \Gamma(s_i, s_{i+1}) \quad (6)$$

where (s_i, s_{i+1}) represents adjacent shots and $\Gamma(s_i, s_{i+1})$ returns 1 if the position and speed of shot s_{i+1} is identical to shot s_i (i.e., within a defined speed and position range); otherwise (s_i, s_{i+1}) returns 0 (the position and speed of shot s_{i+1} is different from shot s_i).

3.2.3 Court Side Cost

The court side cost is responsible for assigning a side to the synthesized drill, and it is defined as:

$$C_P^{Side}(E) = \frac{1}{|E|} \sum_{s_i} \Pi(s_i) \quad (7)$$

where $\Pi(s_i)$ returns 0 if the shot is generated at the chosen court side; otherwise $\Pi(s_i)$ returns 1. This cost term can be considered beneficial especially in cases where a racket sports enthusiast is willing to put in extra effort for a particular shot (e.g., forehand, backhand).

3.3 Optimization

An optimization approach was used to synthesize an exercise drill by generating a sequence of shots. Since an exercise drill could be generated by a variety of shots, an optimal solution for the user-defined target cost was searched in the solution space. Note that the target goal of the optimizer is to fit an exercise drill to user-defined exercise objectives and intensity levels. A Markov chain Monte Carlo optimization method, known as simulated annealing [39], with a Metropolis-Hastings state searching step [12] was used to optimize the exercise drill. To employ the optimization method, a Boltzmann-like objective function was defined:

$$f(E) = \exp\left(-\frac{1}{t} C_{Total}(E)\right) \quad (8)$$

where t denotes the temperature parameter of the simulated annealing process [39], set to decrease gradually during the optimization process. At every iteration, the optimizer chooses and applies a move to the current exercise drill E to propose an exercise drill E' . Based on the three components of the shot (position, speed, and frequency), seven different moves were developed to be chosen by the optimizer:

- change position;
- change speed;
- change frequency;
- change position and speed;
- change position and frequency;
- change speed and frequency; and
- change position, speed, and frequency.

At the beginning of the optimization process, the number of shots defined by the user is generated through random parameters of position (p), speed (v), and frequency (ϕ). At each iteration of the optimization, one of the shots and one of the moves are selected randomly. Then the move is applied to the selected shot and to the current exercise drill E to create a new exercise drill E' . For example, when the “change position” move is selected, a randomly chosen shot moves to a new position, and the system computes the cost of the new exercise drill E' . In our implementation, the selection probabilities of the moves were set to $Pr_p = .25$ for “change position,” $Pr_v = .25$ for “change speed,” $Pr_\phi = .25$ for “change frequency,” $Pr_{p,v} = .10$ for “change position and speed,” $Pr_{p,\phi} = .05$ for “change position and frequency,” $Pr_{v,\phi} = .05$ for “change speed and frequency,” and $Pr_{p,v,\phi} = .05$ for “change position, speed, and frequency.” Our optimization favors the individual changes for position, speed, and frequency.

To decide whether to accept a proposed exercise drill E' , our method compares the proposed total cost $C_{Total}(E')$ to the current total cost of $C_{Total}(E)$. The developed method accepts the proposed exercise drill E' based on the Metropolis criterion [12] denoted as:

$$Pr(E'|E) = \min\left(1, \frac{f(E')}{f(E)}\right) \quad (9)$$

To optimize different exercise drill design solutions, the simulated annealing method was employed. A temperature parameter t is first defined. When optimization begins, the temperature parameter t is represented by a high value, allowing the optimizer to aggressively explore the optimized results. As the iterations of the optimization evolve, the temperature parameter is reduced until it reaches zero. An initial temperature $t = 1.0$ was used in the current implementation at the beginning of the optimization and was reduced by .10 every 200 iterations. As the temperature parameter decreases, the optimizer becomes more greedy in finding the optimal solutions. The optimization process is completed when the total cost change is less than 5% in the past 50 iterations. Figure 2 illustrates how the total cost $C_{Total}(E)$ changes over several iterations.

Unless otherwise specified by a user, the weights assigned to the cost terms responsible for the shots are set to $w_S^{Dist} = 1.0$, $w_S^{Speed} = 1.0$, and $w_S^{Freq} = 1.0$, and the weights of the prior cost terms are set to $w_P^{Dur} = .10$, $w_P^{Var} = .50$, and $w_P^{Side} = .10$. Note that the user is allowed to control the weight values of both shot and prior cost terms to synthesize exercise drills by prioritizing differently the objectives of the drill. Moreover, the user is allowed to control the target values of the cost terms so that he/she can synthesize exercise drills with different levels of difficulty, intensity, and variability. Variations in exercise drills generated by the presented system, while keeping both the target values and weights constant, are shown in Figure



Figure 2: Total cost changes as the optimization process (iterations) evolves.

3, whereas shots of various distributions based on different target values are shown in Figure 4.

4 EVALUATION AS AN EXERCISE TOOL

This study investigates whether the developed virtual reality table tennis application can be used also as an exercise tool. Specifically, this study was conducted to evaluate whether our system can synthesize exercise drills that fulfill user-defined exercise targets. In this study, we considered intensity variations of the exercise drill and we captured heart rates to investigate whether exercise intensity differences are expressed as heart rate differences.

4.1 Participants

Participants were recruited through class announcements and emails. The participant group was comprised of 36 healthy undergraduate and graduate students. None of the participants were athletes. The students’ ages ranged from 19 to 26 years, with a mean of $M = 22.31$ ($SD = 2.65$). All participants had prior experience with virtual reality; however, none of the participants had experience with exercise sports games in virtual reality. No compensation was given to the students for their participation.

4.2 Setup and Implementation Details

The research team conducted this study at a lab space of our university. The lab space was 9 meters long and 7 meters wide, with a ceiling height of 4 meters. All tables and chairs were removed. The HTC Vive Pro head mounted display device was used to project the virtual reality content, and an HTC table tennis racket⁵ and HTC Vive tracker were used to control the virtual racket in the virtual environment. The virtual reality gaming application was developed in the Unity3D game engine version 2019.1.4 and ran on a Dell Alienware Aurora R7 desktop computer (Intel Core i7, NVIDIA GeForce RTX 2080, 32GB RAM). Note that the time required by our system to optimize an exercise drill that consists of 40 shots did not exceed 5 seconds.

A 3D virtual environment of a sports court was designed in 3Ds Max and imported into Unity3D (see Figure 5). The dimensions of the court were identical to those of the lab space. This was done so that the participants would be aware of their position in the real environment in order to eliminate potential accidents that might have occurred by colliding with the walls. The table tennis table was placed in the middle of the room, so the participants were at least three meters away from either wall. Finally, a Polar OH1+ optical heart rate sensor was used to capture the heart rates of the participants to determine how exercise levels of different difficulty, intensity, and variability affected them.

⁵<https://www.vive.com/us/VR-racket-sports-set/>

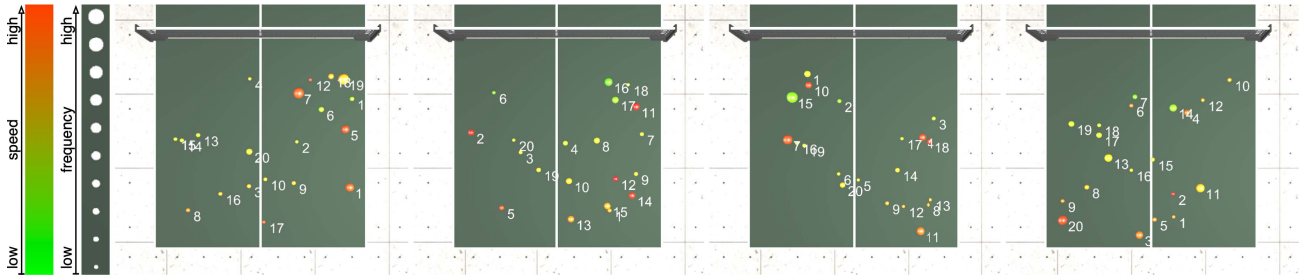


Figure 3: Variations in exercise drills generated by the presented system through keeping the target exercise amounts ($\sigma_D = .6$, $\sigma_V = .3$, and $\sigma_\Phi = .2$) constant. Numbers close to balls denote the sequence of shots. Note that for all four examples shown in this figure the weights of the shot and prior cost terms remained constant.

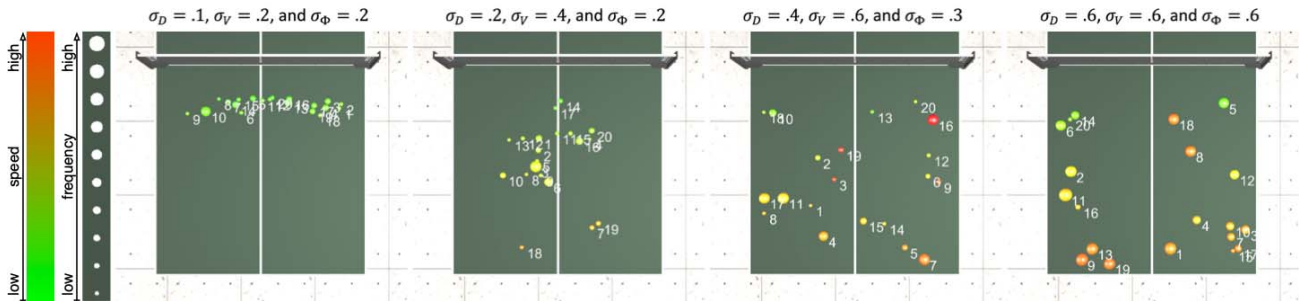


Figure 4: Distribution of shots when varying the target values (σ_D , σ_V , and σ_Φ) of the shots cost terms. Numbers close to balls denote the sequence of shots. Note that for all four examples shown in this figure the weight of the shot and prior cost terms remained constant.



Figure 5: The virtual table tennis court that was designed and used for the purpose of the study.

4.3 Conditions of the Study

Three conditions were tested to determine whether the developed virtual reality gaming application could be used as an effective exercise tool. Note that this is a between-group study, which means that all participants experienced all of the three developed conditions. The conditions were:

- **Low Intensity:** The user does not need to move much, the balls move with low speed, and the shots are generated with a low frequency. The target values were set as: $\sigma_D = .2$, $\sigma_V = .2$, and $\sigma_\Phi = .2$. Based on the set target values, the heart rate of participants was expected to reach 110 beats per minute (BPM).
- **Medium Intensity:** The user is called to perform small steps to hit the ball, the balls move a bit faster, and the shots are generated with a medium frequency. The target values were

set as: $\sigma_D = .5$, $\sigma_V = .5$, and $\sigma_\Phi = .5$. In this condition, the heart rate of participants was expected to reach 120 bpm.

- **High Intensity:** The user is called to perform more intense movements to hit the ball, the balls move even faster, and the shots are generated with a high frequency. The target values were set as: $\sigma_D = .8$, $\sigma_V = .8$, and $\sigma_\Phi = .8$. The heart rate of participants was expected to reach 130 bpm.

Finally, we would like to mention that for all three examined conditions the weights assigned to the shot and prior cost terms remained constant. By changing the target values of each shot-related cost term, we were able to generate on demand an exercise drill with different objective goals and consequently with different target exercise intensity levels expressed through heart rate indicators. Thus, each of the abovementioned conditions made requests to our optimizer in terms of distance, speed, and frequency objectives, and ultimately specified the intensity level for each synthesized table tennis exercise drill.

4.4 Measurements

To evaluate the prospect of using a virtual reality table tennis application as an exercise tool, the heart rate of the participants was measured using the abovementioned heart rate sensor. Specifically, the mean heart rate of participants was computed after each trial of the exercise segment of the study. Note that high heart rate values correspond to higher fatigue [59, 62]. For each condition (there were 10 trials in total for each intensity level), the first 30 seconds of the heart rate data were deleted, as this was considered a warm-up period. After the exercise segment of the study the participants were asked to provide a rating of perceived exertion (RPE), as developed by Borg [9]. The RPE scale measures the intensity of an exercise by asking participants to rate the perceived intensity of an activity. We used a seven-point scale in which 1 indicated “not high at all” and 7 indicated “very, very high.”

4.5 Procedure

We followed a within-group study design, and we asked the participants to partake in a three-day session. The participants experienced a different condition on each day of the study. Note that the participants were aware of this process before the beginning of the first session.

Once the participants arrived at the lab space, the research team provided information about the project, and the participants were asked to sign a consent form that was approved by the Institutional Review Board of our university. During that time, the participants became aware that they would be attending tree sessions. Then, the participants were asked to complete a demographic questionnaire. In the next step, the research team helped the participants with the virtual reality equipment. Once the virtual reality gaming application started, the research team asked the participants to move to a position close to the table tennis table within the virtual environment. The participants were also told that the walls of the virtual space corresponded to the walls of the real space and that they should be careful when moving toward any of the walls. None of the participants collided with any of the walls during the study. When the participants indicated that they were ready, the researcher switched on the virtual ball-throwing machine. In total, the participants experienced 10 variations of the game at the same intensity condition classification. We developed 10 variations for each condition to ensure that the participants did not lose interest while playing the exergame.

For each variation of the training session, the participants were exposed to a trial in which 40 virtual balls were placed in the ball-throwing machine. Each variation of the condition (trial) lasted no more than two minutes. Note that in between the trials, participants were allowed to take up to a two-minute break. To eliminate the first-order carry-over effects between the trials of the condition, Latin squares [38] for balancing were used. Thus, each participant experienced a different sequence of each of the variations. After the end of the exercise segment, the participants were asked to fill in the perceived exertion scale. At the end of the final trial (day three of the study), the participants were informed that the research team would answer questions about the study. To standardize the study, each participant came to the lab on the same day and time respectively for each of the three sessions that occurred during three consecutive weeks. The Latin squares [38] ordering method was used to ensure a balance across all conditions (low, medium, and high intensity levels). Thus, each participant experienced a different level of exercise intensity in each of the visits. Finally, we would like to note that each participant spent no more than a total of 120 minutes in the lab for the total of the three sessions (40 minutes per session).

4.6 Results

A one-way repeated measuring analysis of variance (ANOVA) was used to determine the differences across the three developed intensity levels of the exercise. The normality assumption of the collected data was evaluated graphically using Q-Q plots of the residuals [24]. The Q-Q plots indicated that the obtained data fulfilled the normality criteria. A $p < .05$ value was deemed statistically significant. Boxplots of the obtained results are shown in Figure 6.

By analyzing the **heart rate** data, we identified significant differences across the three examined conditions [$\Lambda = .189$, $F(2, 34) = 72.900$, $p < .0001$, $\eta_p^2 = .811$]. Post-hoc comparisons using the Bonferroni correction revealed that the mean heart rate during the low intensity condition ($M = 108.41$, $SD = 6.48$) was significantly lower than that of the medium intensity condition ($M = 118.08$, $SD = 4.87$) at the $p < .0001$ level and that of the high intensity condition ($M = 125.58$, $SD = 4.81$) at the $p < .0001$ level. Moreover, the mean heart rate during the medium intensity condition was significantly lower than that during the high intensity condition at

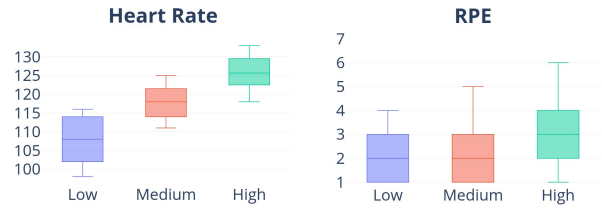


Figure 6: Boxplots of the obtained results regarding the usage of the developed method as an exercise tool. Boxes enclose the middle 50% of the data. The median is denoted by a thick horizontal line.

the $p < .001$ level.

By analyzing the **RPE** data, we also identified significant differences across the examined conditions [$\Lambda = .616$, $F(2, 34) = 10.576$, $p < .0001$, $\eta_p^2 = .384$]. Post-hoc comparisons using the Bonferroni correction revealed that participants reported that the low ($M = 1.89$, $SD = .82$) and medium ($M = 1.94$, $SD = .86$) intensity conditions were less intense than the high ($M = 3.05$, $SD = 1.45$) intensity condition, both at the $p < .0001$ level. No significant difference was found between the low and medium intensity conditions.

4.7 Discussion

The heart rate of the participants differed across the three exercise levels and, therefore, the three exercise intensity levels worked as expected. Moreover, the heart rate data revealed that it is indeed possible to develop racket sports-related virtual reality gaming applications that can be used for exercise purposes. The developed exercise design approach also revealed that it can automatically generate table tennis exercise drills that can allow users to exercise at user-specified intensity levels in the comfort of their own living rooms.

Specifically, the collected data has shown that our system can optimize exercise drills that are able to trigger the heart rate of participants close to the target heart rate value that was anticipated for each condition. For instance, the target heart rate value for the low intensity was expected to be 110 BPM and the mean heart rate value of the participants was found to be 108.41 BPM, the target heart rate value for the medium intensity was expected to be 120 BPM and the mean heart rate value of all participants was found to be 118.08 BPM, and the target heart rate value for the high intensity was expected to be 130 BPM and the mean heart rate value of all participants was found to be 125.58 BPM. Based on these findings, it can be said that participants' mean heart rate was closer to the target heart rate when exposed to the low and medium intensity exercise drills compared to the high intensity exercise drill. We believe that the difference between the expected and the actual heart rate could be adjusted by synthesizing exercise drills that take into account the gender, age, and physical health of the users. However, all things considered, our findings indicate that users who are willing to exercise from the comfort of their living rooms while being exposed to a fun activity, such as playing a virtual reality game, can indeed achieve exercise goals significantly close to their desired ones. Finally, we would like to mention that although VRT can help people improve their performance, it does not provide a training experience similar to a real-world one. However, this fact does not invalidate the ability of VRT to help racket sports enthusiasts improve their skills.

Regarding the self-reported intensity of the exercises, on the one hand, we found that the perceived difficulty of the easy and medium intensity drills was lower than that of the high intensity drill. This finding shows that participants were only partially able to distinguish across the intensity levels they were exposed to, since we were not able to find differences between the low and medium intensities. A possible explanation is that the intensity level of

an exercise drill can be related to various other participant-related factors (e.g., someone who spends 2-3 days per week at a gym might rate the medium intensity as easy compared to someone who barely exercises). However, each user can tune the intensity of the exercise by triggering the respective target values of the shots cost terms. This way, the developed method can be used to generate exercise drills even for demanding tasks and users who want to exercise at a more advanced level. However, the fact that we were not able to find differences between the low and medium intensities is the most interesting result of this study. This finding indicates that while the medium workout resulted in a significantly higher heart rate over the low workout, it did not result in a significantly higher perceived exertion. From our point of view, this finding indicates that while the level of exercise intensity increased, the discomfort of participants stayed at low levels.

After the study, we asked participants about their experiences. Almost all of the participants said that they really enjoyed exercising in a virtual reality environment, and many said they liked the way the virtual reality application was designed. We believe that the participants' levels of enjoyment were the reason they did not rate the medium intensity level workout with a higher RPE. This insight (increased levels of enjoyment) could be considered in implementing exercise-related virtual reality applications as a guideline for raising the level of exercise without raising discomfort. Another participant said that including a virtual coach or an opposing player might have also been interesting. However, for the purpose of this study, the motion and the presence of an opposing player might have distracted the user. Finally, it is worth noting that none of the participants reported dizziness or any form of cybersickness.

5 EVALUATION AS A TRAINING TOOL

A second study was conducted to evaluate the usefulness of the developed virtual reality gaming application as a training tool. For this evaluation process, the performance of our participants was evaluated in three training conditions: no training, virtual reality training, and real-world training. Details on this study are given in the below subsections.

5.1 Participants

The participants were recruited through class announcements and emails. The participant group was comprised of 42 healthy undergraduate and graduate students. It should be noted that none of the participants were athletes. The participants' ages ranged from 19 to 29 years, with a mean of $M = 23.75$ ($SD = 2.64$). All participants had prior experience with virtual reality. None of the participants of this study had participated in the first study, so they were unaware of the gaming application and its mechanics. No compensation was given for participation.

All participants signed a consent form that was approved by the Institutional Review Board of our university. The participants were randomly divided into three groups: 1) the no training (NT) group, the group of participants that did not receive either virtual reality or real-world training; 2) the virtual reality training (VRT) group, the group of participants that received virtual reality table tennis training using our application; and 3) the real-world training (RWT) group, the group of participants that received real-world table tennis training in our recreation center. It should be noted that each group was comprised of an equal number of participants ($N = 14$, nine males and five females in each group). As this study was divided into multiple sessions (details are given in the next section), the consent form and demographic questionnaire were administered during participants' first visits.

5.2 Study Details

This study attempted to determine whether the developed virtual reality gaming application could be used for training purposes. To

at this end, it measured whether the performance of the participants was improved after participating in virtual reality training sessions. In addition, this study attempted to investigate whether the performance of participants exposed to virtual reality training differs from the performance of participants exposed to real-world training, or no training. The RWT condition was added to investigate whether virtual reality training differs from real-world training. The no training condition was included since we realized that some training would take place during the initial performance evaluation in the recreation center. Thus, this initial assessment alone might have inadvertently led to an improvement in the post-training evaluation. For this reason, we decided to include the no training condition to investigate whether the changed performance of the VRT group depended on the initial performance evaluation or on the actual virtual reality training.

This study is divided into three parts for the VRT and RWT conditions, and into two parts for the NT condition. For all conditions, all participants were asked to attend two 30-minute sessions (a pre- and a post-training session) at the table tennis court at the recreation center. The pre- and post-training performance assessment of the participants was performed using a medium-intensity exercise drill. During the performance evaluation sessions, the participants were free to take multiple breaks if needed. For the performance evaluation process, the participants were exposed to 10 trials in which 20 balls were placed in the ball-throwing machine. The machine used was the iPong V300⁶ table tennis ball-throwing machine. The total duration of the performance evaluation process lasted 30 minutes, including short breaks that the participants took between the study trials. Note that the table tennis table at the recreation center was located in a space of 7 meters long by 4 meters wide.

To evaluate the performance of the participants two measurements were captured: 1) lost shots (the number of balls each participant was unable to hit with the table tennis racket), and 2) mistakes (the number of balls that were either stopped by the net on the table or bounced outside the table after the player hit the ball). Note that since our primary intention was to evaluate the potential improvement in participants' performance, our computations focused on the difference (subtraction) between the post- and pre-training data collected for each participant, which were later used for our statistical analysis process.

The participants that were assigned the NT condition did not receive any further training. They were only asked to attend the final performance evaluation session. However, the participants that were assigned the VRT condition were asked to participate in three training sessions, each for the duration of 30 minutes. This group of participants trained using the developed virtual reality table tennis application, and the training sessions were conducted in our department's lab space. During the first two sessions the participants were trained on low-intensity table tennis exercise drills, and during the third session the participants were trained on a medium-intensity exercise drill (see Section 4 for more details on the low- and medium-intensity exercise drills).

The participants that were assigned to the RWT group took part in three training sessions at the recreation center where they trained in real-world table tennis. The participants of the RWT condition were trained on low-intensity table tennis exercise drills during the first two sessions, and on a medium-intensity exercise drill during the third session. The duration of each session was 30 minutes, including short breaks. A table tennis expert (the coach of a local table tennis club; male, 44 years old with 18 years of experience as a table tennis coach) helped us tune the ball-throwing machine (iPong V300) that was used at the recreation center. The tuning of the ball-throwing machine was performed by the expert after experiencing multiple trials of both low and medium exercise intensities in our virtual reality table tennis application.

⁶<http://www.ipong.net/joomla/index.php/ipong-models/ipong-v300>

In conclusion, we would like to note that all participants were aware that they would be attending multiple training sessions before they began the first session; this was made clear when the consent form was handed to them. Moreover, all participants followed the same scheduled day pattern: pre-training performance evaluation on Tuesday, first training session on Thursday, second training session on the following Tuesday, third training session on Thursday, and a post-training performance evaluation on the final Tuesday. Each participant came to the lab or recreation center at the same time on each scheduled day. This scheduling process helped us to standardize the study. Finally, regarding the NT condition we would like to note the following. Since participants were asked to take part in only two sessions, we tried to standardize the gap between these sessions. Thus, considering that the last training sessions on both the VRT and RWT were on Thursday and the post-training evaluation session was on Tuesday (a five-day gap), we decided that the performance evaluation session for the NT condition should also be five days after the initial performance evaluation session.

5.3 Results

We used the one-way between-group ANOVA to compare the performance of our participants. We used the three conditions (NT, VRT, and RWT) as our independent variables and the performance improvement on lost shots and mistakes (the difference between post- and pre-training scores) as our dependent variables. The obtained results are summarized in Figure 7. Since we conducted a between-group study, before analyzing our results we decided to explore the homogeneity of our participants by using as dependent variables the three participant groups (the three conditions), and as independent variables the age, height, and weight of the participants. Note that, as mentioned before, each group was comprised of nine males and five females. The one-way between-group ANOVA indicated no significant difference for **age** [$F(2, 39) = .901, p = .421$], **height** [$F(2, 39) = 1.188, p = .137$], or **weight** [$F(2, 39) = 1.463, p = .254$] across groups. Based on the obtained results and the male/female ratio per group, it can be said that all three groups were homogenous.

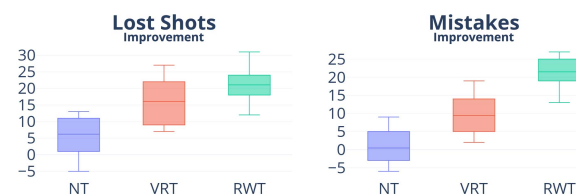


Figure 7: Comparison across the three examined conditions (NT: no training, VRT: virtual reality training, and RWT: real-world training) used to evaluate the developed virtual reality table tennis application. Negative and low values indicate that our participants' performance did not improve at the post-training session. Positive values indicate that participant performance improved. Boxes enclose the middle 50% of the data. The median is denoted by a thick horizontal line.

By analyzing the performance improvement data for **lost shots**, we found significant differences across the three examined conditions [$F(2, 39) = 21.804, p < .001$]. Post-hoc comparisons using the Bonferroni corrected estimates revealed that the mean performance improvement during the NT condition ($M = 6.43, SD = 5.62$) was significantly lower than that of the VRT condition ($M = 14.64, SD = 7.19$) at the $p < .002$ level, and that of the RWT condition ($M = 21.35, SD = 4.92$) at the $p < .001$ level. Moreover, we also found that the performance improvement for the lost shots during the VRT condition were significantly lower than that of the RWT condition at the $p < .05$ level.

By analyzing the performance improvement data for **mistakes**, we identified significant differences across the three examined conditions [$F(2, 39) = 54.824, p < .001$]. Post-hoc comparisons using the Bonferroni corrected estimates showed that the mean performance improvement of mistakes during the NT condition ($M = 1.71, SD = 4.54$) was significantly lower than that of the VRT condition ($M = 9.35, SD = 5.77$) at the $p < .001$ level, and that of the RWT condition ($M = 21.28, SD = 4.53$) at the $p < .0001$ level. Moreover, we also found that the mean performance improvement of mistakes for the VRT condition was significantly lower than that of the RWT condition at the $p < .001$ level.

5.4 Discussion

The measurements of lost shots and mistakes revealed that our method can automatically generate training drills that can help table tennis enthusiasts improve their skills. By comparing NT with VRT it can be said that by attending the VR training sessions participants were able to improve their scores on lost shots. This indicates that the training sessions taught that participant group to anticipate the ball and react more appropriately when the ball approached them. Similarly, the participant group that was exposed to virtual reality training had a reduced number of mistakes. This may also be a result of the first finding (reduction of lost shots). Because the participants were anticipating a shot, they were better prepared to react and hit the ball appropriately. Therefore, they were able to perform better overall after receiving the virtual reality table tennis training.

Significant results were also found for both lost shots and mistakes measurements when comparing the VRT and RWT groups. These significant differences are perhaps the most interesting result of the study. The significant results indicate that the RWT group improved their performance even more than the VRT group. It is shown that even if this virtual reality table tennis can be used as a training tool, it is still less effective than RWT. However, considering that we also found a significant improvement in participants' performance when compared to the NT condition, virtual reality training can also be considered as an option for table tennis enthusiasts who wish to improve their skills without having to search for a table tennis coach or partner, or attend training sessions at a gym. Although we found that the VRT training results were lower than the RWT results, it could be said that virtual reality training is still a reasonable and alternative way to train for various reasons. First, people can learn how to play table tennis and improve their skills without needing to actually be in the gym. Second, the virtual reality training for racket sports can be done remotely, saving time and money. Third, virtual reality offers an immersive experience that promotes repetition and retention. It is for these reasons we believe that virtual reality training for sports has multiple potentials for peoples' health and well-being.

Upon completion of the study, we asked participants about their experiences. All the comments we received for the table tennis virtual reality application were quite positive, suggesting that virtual reality table tennis could become a training tool for racket sports enthusiasts. Several participants said that they were not expecting the use of virtual reality to help them improve their skills and reduce the number of mistakes they made. Please note that after the end of the post-training sessions all participants were informed of their performance. Almost all the participants said that the virtual reality training helped them to become more vigilant. Others said that the virtual reality training helped them better position themselves in the court and that the virtual reality training helped them to react more quickly. Finally, it is worth noting that none of the participants reported dizziness or any form of cybersickness.

6 LIMITATIONS

There are a few limitations that we would like to note. First, the weight and balance of the table tennis racket that was used in these

studies may be problematic. A table tennis paddle weighs between 150 g and 250 g. However, the HTC table tennis racket is 226 g, and with a Vive tracker (89 g) attached it weighs 315 g. Although this weight differential may not be as significant for beginners, we assume that it could be problematic for more experienced and professional table tennis players. We believe that experimentation with fabricating and printing 3D gaming interfaces [70] might solve this problem. Moreover, because the science and technology related to virtual reality is rapidly evolving, we assume that future table tennis paddles for virtual reality experiences will be more similar to actual paddles in terms of weight specifications.

A second limitation is related to missing tactile feedback. Tactile feedback is an important factor that provides an additional parameter to consider when hitting balls [17,51]. To overcome this issue, the use of a tactile actuator might partially solve the tactile feedback problem; however, such a device would add additional weight to the table tennis paddle.

A third limitation is related to the physical space required for a player to use the virtual reality gaming application. Although, as mentioned above, virtual reality racket sports can be experienced from the comfort of one's living room, a large play area with no obstacles would be required in order to achieve an optimal experience without injuring oneself or damaging objects within the real space.

A fourth limitation is that only participants with little or no table tennis experience participated in this study. Unfortunately, we were not able to recruit intermediate or advanced table tennis players. However, it would have been interesting to evaluate our exergame with more experienced table tennis players so we could explore whether the findings of our studies would also apply to them.

The last limitation we would like to mention is related to the head-mounted display that was used for the studies, as some participants commented on it. Specifically, we used the HTC Vive Pro headset. Participants mentioned that the combination of the wire that connects the headset to the computer, the weight, and the size of the headset itself all made them more concerned and uncomfortable when moving around during game play. We assume that a wireless head-mounted display such as the Oculus Quest might provide a better exergame experience to virtual reality users.

7 CONCLUSIONS AND FUTURE WORK DIRECTIONS

We developed a virtual reality racket sports gaming application and a method for synthesizing exercise drills. In this method, the user may change the parameters of the cost terms and our system will automatically generate an exercise drill that meets these user-specified objectives. Two user studies were conducted to evaluate the effectiveness of the developed application as an exercise and training tool for the table tennis application. The results indicate that virtual reality can be a solution for users who would like to exercise and achieve specified exercise goals. The virtual reality gaming application can also be used to improve user skills. Lastly, the flexibility of the developed gaming application in handling different types of racket sports with minimal changes and effort is another advantage.

Future work might include the development of other virtual reality gaming applications that can be used for exercise and training purposes. An example might be martial arts exercises and training in virtual reality, in which the user could interact with an intelligent virtual coach. In addition to the algorithmic development that automates the exercise and training sessions, exploring the effects of virtual reality exercising and training on long-term health benefits, such as weight loss and rehabilitation, is another interesting direction for future research. Considering the popularity and attractiveness of virtual reality, we can assume that it will be used in the future as a tool that not only entertains users, but also helps them improve their physical functions and overall health.

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