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VolleyNaut: Pioneering Immersive Training for Inclusive Sitting Volleyball Skill Development

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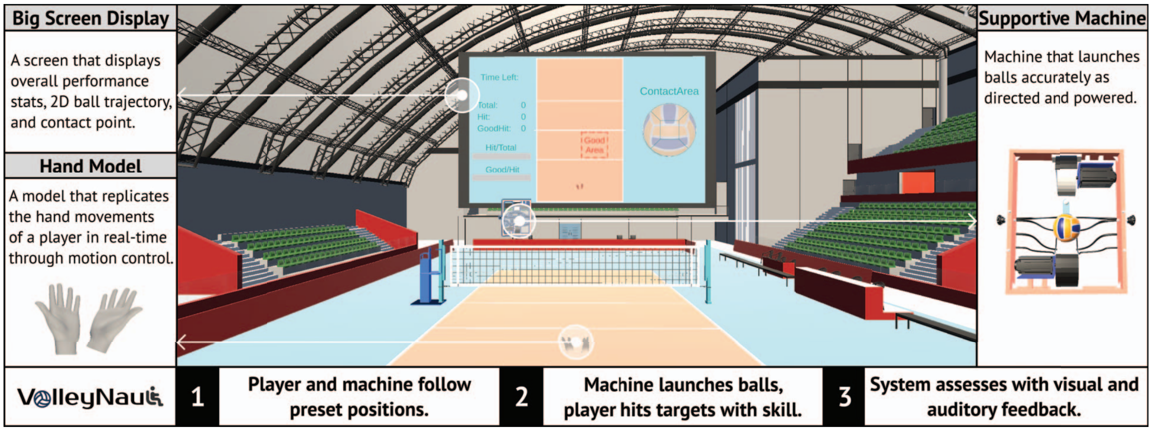

Fig. 1: Overview of VolleyNaut: An immersive simulation for accessible sitting volleyball training without spatial constraints

Abstract— Participation in sports provides individuals with disabilities opportunities for social inclusion, improved physical and mental health, skill development, and increased self-confidence, ultimately empowering them. Sitting volleyball, a popular para-sport adapted from traditional volleyball, has been played in more than 75 countries since its development in 1956. However, the limited availability of dedicated sitting volleyball courts creates a significant gap for individuals with disabilities interested in playing the sport. To address the challenges encountered by amateur sitting volleyball players due to the lack of specialized facilities, we encompass a pioneering design study on VR para-sports training and introduce VolleyNaut - an innovative virtual reality (VR) training system. Developed in close collaboration with professional coaches, this immersive system faithfully replicates the daily drills and realistic ball pitches experienced by players. It offers four specialized basic defensive drill scenarios, contributing to skill adjustment and enhancement. In our user study, we recruited volleyball players from college teams and clubs to assess the engagement factor of VolleyNaut, and we also included national sitting volleyball players and coaches to evaluate the system's effectiveness as a training tool. Our comprehensive analysis, combining quantitative and qualitative data, revealed consistently positive results across all user groups.

Index Terms—Sitting volleyball, virtual reality, inclusive training, immersive sports training, accessible communities, SportsXR

1 Introduction

Due to physical limitations, regular volleyball is not suitable for individuals with disabilities [4, 15]. Sitting volleyball represents an adapted version of traditional volleyball, retaining the fundamental skills and strategic aspects while incorporating crucial rule modifications to meet the players' needs. In this variant, players remain seated on the ground, using their arms and legs for movement. An essential rule requires at least one buttock to maintain contact with the floor while interacting with the volleyball. The playing court is smaller, and the net is set at a lower height compared to standard volleyball courts [35, 53].

However, the limited availability of dedicated sitting volleyball courts creates a significant gap for individuals with disabilities interested in playing the sport [13]. In the United States, where there are top-ranked women's and men's sitting national teams [36], only four clubs operate official sitting volleyball programs. Remarkably, just one of these clubs offers a dedicated court for sitting volleyball teams [51]. This situation places severe constraints on athletes' training schedules, limiting their ability to hone their skills. Furthermore, in regions lacking clubs dedicated to sitting volleyball, aspiring players often utilize local disabled sports or rehabilitation centers within their communities [17]. However, these centers typically need specialized training programs and resources for effective sitting volleyball development. Consequently, athletes face substantial challenges on their journey to mastering the sport, with limited opportunities to access the tailored support, facilities, and coaches necessary for their progress, ultimately hampering the growth of sitting volleyball as a sport of choice for individuals with disabilities [4].

In this paper, we aim to offer design guidelines for inclusive sports training in VR and offer an accessible sitting volleyball training environment to all volleyball amateurs by leveraging an immersive virtual setting. To this end, we followed a user-centered design approach during the study to address two key questions: "What are the needs and

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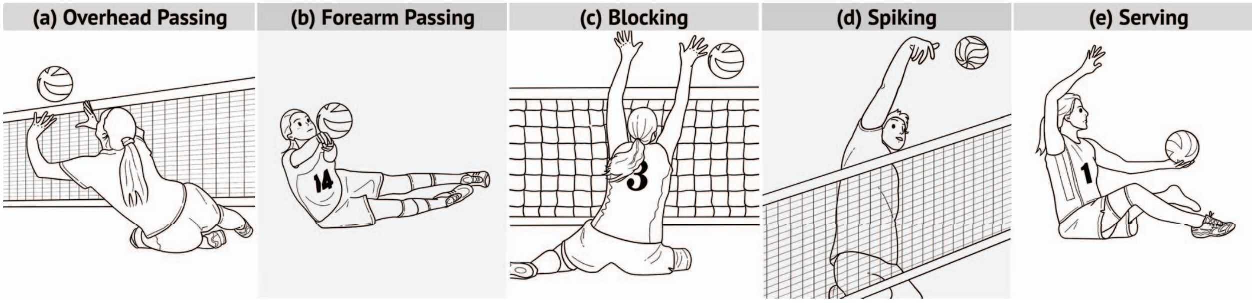

Fig. 2: Fundamental sitting volleyball skills: (a) Overhead passing, (b) Forearm passing, (c) Blocking, (d) Spiking, and (e) Serving

challenges for people in the accessible community to engage in sitting volleyball?" and "To what extent could an immersive training system supplement athlete's training and engage players of all skill levels?" A formative user study was conducted by collaborating with professional coaches to address our initial question. In total, we collaborated with six professional coaches, with four of them participating in the formative user study, while the others formed the coaches' group in our user study. Based on these discussions, we identified needs such as facility access, versatile training options, and adjustable training intensity. To address our second question, we developed VolleyNaut, a virtual reality-based (VR) training system that allows users to engage in four selected fundamental skills in Unity3D [48]. These skills are simulated using a data-driven task simulator, incorporating a supportive machine, a performance assessment module, and an interaction module to create training scenarios. Notably, users possess the flexibility to personalize their experience by adjusting the ball speed and controlling the duration of tasks to ensure accessibility for players of all skill levels. We showcase the outcomes of a quantitative and qualitative user study involving 14 active volleyball and sitting volleyball players across all levels and two national sitting volleyball team coaches. The study aimed to gauge the extent of engagement and utility experienced by the participants during training with VolleyNaut.

In summary, our contributions encompass a pioneering design study that involved individuals from accessible communities in sports, with a specific emphasis on sitting volleyball. Additionally, we have created a simulated training environment and introduced VolleyNaut. This immersive training system caters to sitting volleyball players across all skill levels. Lastly, we have conducted evaluations of this immersive training system, collaborating with active volleyball players and coaches to assess its strengths and limitations.

2 Related Work

In this section, we review the existing literature and research related to our project, bridging two significant areas of study: VR-Based Sports Training and Incorporating Disabilities into Sports through VR.

VR-Based Sport Training. Virtual reality (VR) technology is rapidly advancing and finding diverse applications [38, 43, 47, 55], including in the sports domain [2, 6, 15, 19, 30]. VR sports products like All-In-One Sports VR [44] and Eleven Table Tennis [16] aim to create immersive sports experiences through VR games. A key advantage of VR is its ability to transcend geographical limitations. For example, during the COVID-19 pandemic that restricted access to sports facilities, Hanifah et al. [23] found that VR sports games helped sustain engagement. Similarly, Wu et al. [54] developed a VR skiing program to aid para-alpine skier training for the Beijing 2022 Winter Olympics when in-person preparation was challenging due to the pandemic. These examples demonstrate VR's potential to enable sport participation despite real-world constraints. Numerous studies have delved into the integration of virtual reality (VR) technology within various professional sports training disciplines. For example, Tsai et al. [50] developed a VR basketball training system focusing on tactics, and Bai et al. [5] introduced emotional virtual characters into a VR volleyball game to enhance engagement. Products like Neuro-Trainer and Beyond Sports [45, 49] help professional athletes improve decision-making and reaction times. These products mainly emphasize cognitive skills for elite athletes. Some VR products do focus on skill development, like StriVR [25]. StriVR partners with NFL, NBA, and ski teams to provide high-quality VR training environments that enable on-demand repetition while reducing injury risk. However, there are fewer VR approaches tailored to non-professional athletes that focus on skill training. Based on existing research, we aim to develop a VR system for athletes at all levels that centers on skill development and performance enhancement. The system offers customizable training tasks and performance evaluations for users across all skill levels.

Incorporating Disabilities into Sports through VR. Challenges stemming from physical limitations and resource constraints have historically impeded the participation of individuals with disabilities in sports (Stevenson, P. 2009, DePauw, K. P., and S. J. Gavron. 2005) [14, 34]. However, recent research by Fu and Ji [20] has illuminated a promising avenue for addressing these challenges. Their systematic review reveals that motor intervention for developmental disabilities can significantly benefit from virtual reality training. Furthermore, a study conducted by researchers from Flinders University demonstrates the potential of VR in promoting regular physical exercise among individuals with intellectual disabilities, with participants expressing enjoyment and a sense of engagement in sports. [33] These findings exemplify the transformative potential of VR technology in overcoming barriers to sports involvement for individuals with disabilities. While Byers et al. [7] have developed three Paralympic sports games—Boccia, Handcycling, and Sledge Hockey with a focus on designing inclusive games and interactions to empower young people with disabilities both socially and physically, the integration of VR applications for sports training purposes remains an untapped frontier in this context. This gap forms the backdrop for our project's exploration and development.

3 Background and rules

Sitting volleyball, established in 1956 as a rehabilitation sport for athletes with lower limb impairments, gained Paralympic status in 1980. As of 2023, it is played in over 75 countries worldwide [13, 53]. This sport closely follows traditional volleyball's objective: scoring points by landing the ball in the opponent's court. The game is played on a 10 x 6 meters court, with a net height of 1.15 meters for men and 1.05 meters for women. Teams comprise six players each and compete in best-of-five sets, where each set is played to 25 points, and the fifth set, if needed, to 15 points. A key rule in sitting volleyball is the requirement for players to keep their buttocks or torso in contact with the floor while playing the ball. Additionally, unlike traditional volleyball, blocking the serve is allowed [15, 35]. The sport emphasizes skills like overhead passing (setting), forearm passing, blocking, spiking, and serving, all requiring specific adaptations for seated play(Fig. 2).

4 Formative Study

In the development of a sitting volleyball training system tailored to accommodate physical limitations and facility constraints for individuals with disabilities, we undertook a comprehensive formative study involving input from professional coaches and players.

4.1 Pre-Design Studies and Insight Gathering

We engaged stakeholders through interviews and visits to the national training center, gathering insights into sitting volleyball players' challenges and training workflows, and informing our system's design.

4.1.1 Opening Meeting with Professional Coaches

We conducted a virtual meeting with four sitting volleyball coaches, each with over 15 years of experience at national and international levels. Discussions centered on the sport's current challenges, particularly the lack of community-level accessible courts. The coaches stressed the need for specialized training approaches and performance assessments adapted to the physical needs and rule differences of sitting volleyball.

4.1.2 In-depth interviews with Para-Olympic players

We interviewed six Para-Olympic sitting volleyball players, aged 21 to 45, to understand the experiences and challenges of disabled athletes. A notable finding was that 83% of these players hadn't played sitting volleyball before joining the Para-Olympic team. Additionally, 66% of initially inexperienced players considered quitting due to integration challenges. This underscores the need for structured pre-professional training and regular performance assessments to facilitate successful integration and development in sitting volleyball.

4.1.3 In-person Visit

An in-person visit to the national training center provided valuable insights into the adapted training environment. Observations of specialized training routines and equipment underscored the importance of skill-specific training designed for sitting volleyball.

4.2 Summary

Our study reveals three primary requirements for designing a VR-based training system for sitting volleyball:

- **R1: Accessible Dedicated Courts.** Sitting volleyball currently struggles with a severe lack of dedicated, accessible community courts, limiting participation for disabled individuals and keeping the sport niche. Addressing this, our study's designed virtual court targets specific sitting volleyball needs, focusing on space and accessibility issues.
- **R2: Coaching resources.** Given the physical and rule differences in sitting volleyball, accessible training drills and educational materials for all skill levels are crucial for skill development and self-coaching.
- **R3: Performance Assessment.** The absence of performance assessments in the sport hampers players' ability to monitor progress and set goals. Our system should provide immediate performance feedback and tracking of skill development to help players identify their strengths and weaknesses for measurable progress.

5 VOLLEYNAUT

To address the scarcity of dedicated sitting volleyball courts (R1), we developed VolleyNaut, a VR-based training system for sitting volleyball. This system features a realistic virtual arena and an interaction model that closely simulates real-life gameplay. The inherent capability of VR to simulate expansive spaces within a limited physical area makes VolleyNaut an effective solution for training in environments where access to large dedicated courts is constrained. We utilized advanced rendering techniques and physics simulations to ensure a high degree of realism. The court's dimensions, net height, and other physical attributes were defined using accurate scale models in the VR environment. Requiring only a 2x2 feet physical area for the user, VolleyNaut is accessible anywhere only with a VR device. To enhance realism and professionalism, we integrated a supportive machine inspired by those used by professional teams to launch balls during drills.

To tackle performance assessment needs (R3), VolleyNaut incorporates an assessment module with auditory feedback and visualizations to aid skill development. Responding to limited coaching resources (R2), we developed a data-driven task simulator in VolleyNaut. This combined the 3D sitting volleyball arena, supportive machine machine, interaction module, and performance assessment module. It currently features four selected fundamental skill training tasks. This compact setup enables users to engage in training from the comfort of their homes, effectively overcoming facility limitations, and significantly preparing the players with a VR environment before they enter the physical training phase.

5.1 Task Simulator

The VolleyNaut task simulator, created with Unity3D, features a 3D sitting volleyball arena, a specialized supportive machine, an interaction module, and a set of performance assessment rules. It uses input data to determine the player's position, the location of the supportive machine, the type of ball provided, and the suitable performance assessment model for each task. Upon entering the VR environment, users are greeted with a menu page that outlines all available tasks and their respective objectives. To enhance user experience, four distinct tasks have been implemented, allowing users to commence their training with a variety of challenges. These tasks are not only designed for skill development but also serve as valuable coaching resources, offering guided training experiences. Users can customize parameters such as ball speed and task duration before selecting and embarking on a specific task. This level of customization, combined with a user-friendly interface, ensures that VolleyNaut is suitable for a diverse range of users, from novices to elite athletes, establishing it as an inclusive and versatile training platform.

5.1.1 Tasks

Based on observations at a national training center and feedback from professional coaches, our VR system includes four core training tasks: Serve-receiving, Blocking, Digging, and Net Play. The first three focus on defensive skills, while Net Play offers realistic game scenarios. These tasks were selected for their fundamental importance and coach insights, although there is potential for future expansion. Our primary goal revolves around assessing the feasibility of VR as a skill training method, ensuring that it caters to individuals with disabilities across all skill levels, ultimately enhancing their engagement in sports. These tasks align well with this objective, establishing the VR system as a valuable asset in skill development and sports participation.

- **T1. Serve-Receiving Task** (Fig. 3a) This task simulates various serve scenarios with different speeds and placements using a supportive machine. The player's goal is to accurately pass the ball to a designated area, enhancing serve-reception skills in a game-like environment.
- **T2. Digging Task** (Fig. 3b) Here, the machine imitates opponent spikes, challenging players to defend and return the ball. This task aims to improve digging skills, focusing on handling difficult spikes typical in matches.
- **T3. Blocking Task** (Fig. 3c) In this task, the machine replicates spikes from opponents, and the player must block the ball to prevent it from crossing into their court. It concentrates on improving blocking techniques through positional adjustments.
- **T4. Net Play Task** (Fig. 3d) This task creates complex, net-close scenarios that are hard to replicate in physical training. It emphasizes strategic net passes, sets, and pushes, utilizing VR's capability to consistently replicate rare, in-game situations. This task highlights VR's effectiveness in specialized training.

5.2 Supportive Machine

In VolleyNaut, our main goal is to realistically simulate ball delivery for basic skill training. After consulting with professional coaches, we considered two options: a player avatar and a supportive machine, each with its own merits for an immersive experience.

The player avatar option offered increased engagement in gameplay, potentially improving the training. However, it had significant downsides. The avatar's movement might distract from basic skill training. Also, creating a realistic human avatar in VR posed issues like visual distortion and higher computational demands, impacting scalability and system performance in larger settings. The supportive machine, often used in professional training for skill development, proved to be a better choice. It delivers the ball precisely, allowing players to

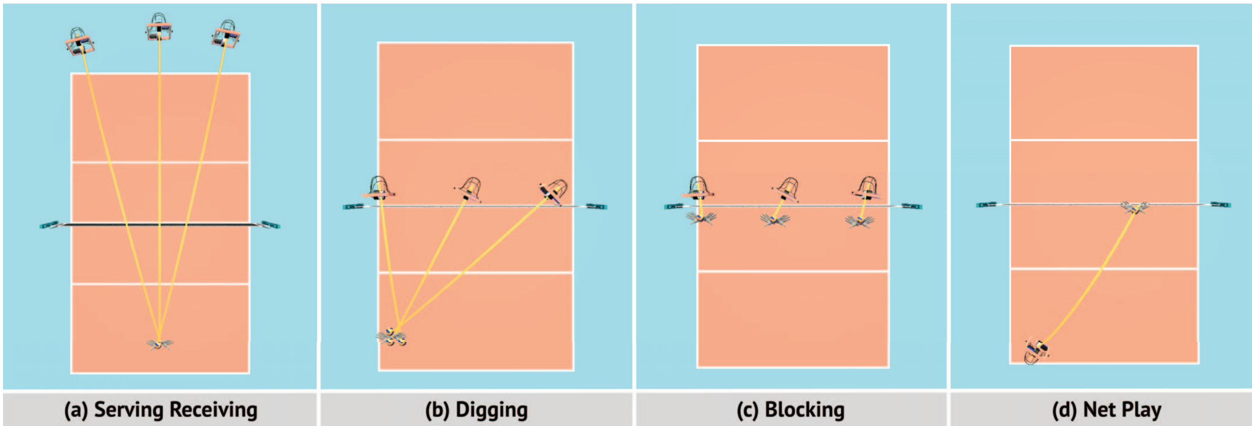

Fig. 3: Four training tasks offered by VolleyNaut, each featuring specific player and supportive machine positions. The machine accurately launches balls as directed and powered. (a) Serve Receiving **(T1)**, (b) Digging **(T2)**, (c) Blocking **(T3)**, and (d) Net Play **(T4)**.

focus more on the skill. Choosing this for VolleyNaut mimics professional training methods, concentrating players on the ball. Additionally, VR integration of the supportive machine is less resource-intensive, ensuring smoother performance and easier scalability [9, 46].

Therefore, we opted for a supportive machine (Fig. 4) similar to those used by professional teams[1]. For adaptation to sitting volleyball, where players are seated on the court, we modified the machine by removing its bracket. This left only the ball injection component, meeting the sport's specific needs and enhancing training focus while reducing technical challenges. The Supportive Machine is engineered for adaptability and ease of use, catering to a broad spectrum of skill levels in sitting volleyball. It seamlessly adjusts to different environments and user requirements. Key data inputs, such as its positioning, the intensity of the volleyball launch, and the desired ball trajectory, are processed to customize each session. This versatility ensures that the machine is equally beneficial for novice players and seasoned athletes, enriching the overall experience in the sport.

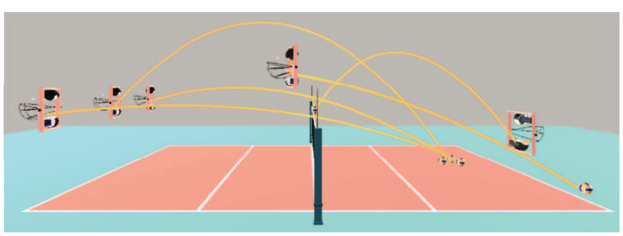

Fig. 4: Supportive machine can launch diverse balls from any position.

5.3 Performance Assessment Module

In VolleyNaut, our Performance Assessment Module plays a pivotal role in enhancing the user's training experience by providing a comprehensive evaluation of their performance, both for individual ball interactions and overall progress. This module encompasses two key aspects: auditory feedback and embedded visualizations, each serving a distinct purpose to aid users in understanding their skill development [3, 56]. In the development of this module, we closely collaborated with coaches to establish assessment criteria that align with the specific nuances of sitting volleyball.

[1]A real photo of the supportive machine used by professional teams can be found at https://images.app.goo.gl/2MfWXFk6QmqC6zGf6

5.3.1 Auditory Feedback

We track every ball the user interacts with in VolleyNaut. If the user successfully touches the ball and meets the trajectory criteria for a "good hit," an audible "ding" sound triggers. This immediate audio reinforcement serves as feedback to encourage proper technique and skill development. Additionally, research shows audio feedback in sports can positively affect athletes' subjective perceptions [41]. By incorporating real-time auditory cues in VolleyNaut, we aim to increase confidence and motivation for individuals with disabilities engaging in sitting volleyball training. Much like the work conducted by Schaffert et al. [40], sonification helped swimmers improve their underwater dolphin kick execution, and our system's audio feedback provides tangible validation to empower users and reinforce their capacity to master key sport-specific skills. In this way, the integrated auditory performance evaluations may strengthen self-belief to encourage ongoing participation, which is important for disabilities.

5.3.2 Embedded Visualizations

Sitting volleyball currently faces a significant shortage of comprehensive data analysis and visualization tools. However, the nature of virtual reality (VR) allows us to collect extensive data, including crucial metrics like ball trajectory, landing spot, and contact points on the ball, which are essential for sitting volleyball analysis. Given the proven effectiveness of embedded visualization in empowering coaches and athletes to interactively analyze spatial data [11, 26, 27], we have made the decision to integrate this technology into VolleyNaut. This integration aims to provide users with a multi-dimensional understanding of their performance, enhancing their ability to assess and improve their skills in sitting volleyball. These visual aids include:

3D Situated Visualization. Previous research has shown that immersive visualizations can significantly assist athletes in adjusting their motion and gaining a deeper understanding of their performance from various perspectives [12, 28]. Building on these successes, we provide users in VolleyNaut with a 3D visualization of the entire ball trajectory (Fig. 5a), from the moment it is launched by the supportive machine to its landing spot. This visual representation serves to reinforce the user's comprehension of their ball placement and trajectory, aiding in skill refinement for sitting volleyball similar to how AR visualizations assisted basketball players. By leveraging situated VR technology, the trajectory visualizations in VolleyNaut aim to provide users with helpful feedback on their performance to support skill development.

Big Screen Display. We've identified three crucial data categories of interest to both players and coaches during tasks. Within the immersive environment, a dedicated large screen (Fig. 5b) is segmented into three sections, each serving a unique purpose:

1. **Overall Performance.** This section displays a summary of the user's performance metrics, such as the total number of balls

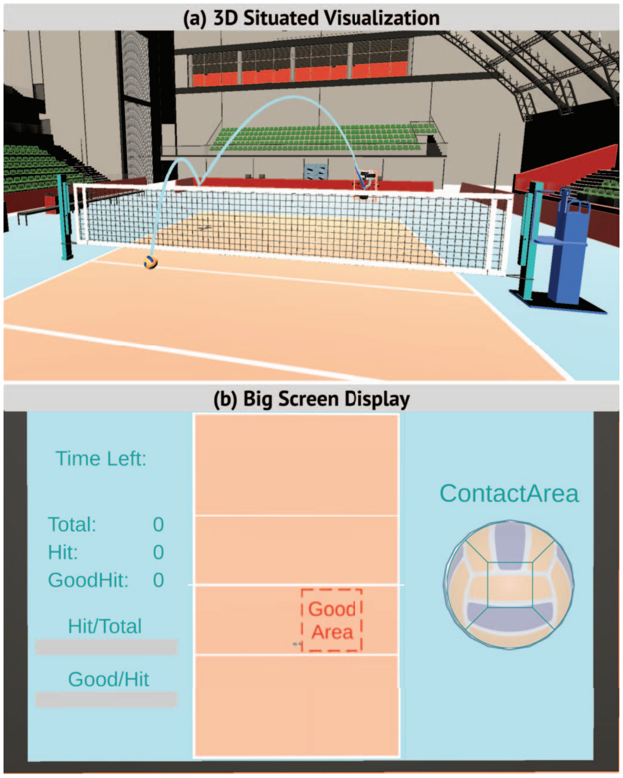

Fig. 5: Embedded visualizations in VolleyNaut: (a) Visualizing 3D ball trajectory, and (b) big screen displaying overall performance, 2D ball trajectory, landing spot, and contact point.

launched, hit, and good hits. It includes two horizontal capsule charts showing hit percentages for quick performance assessment.

2. **2D Ball Trajectory and Landing Spot.** A 2D representation of the ball's trajectory and landing spot compensates for VR's limited field of vision, allowing users to track the ball's path.
3. **Contact Point.** This section visualizes the contact point on the ball, helping users refine their hitting techniques for desired angles and improved precision [37].

Our Performance Assessment Module combines auditory feedback with comprehensive embedded visualizations, enabling users to gain profound insights into their performance.

5.4 Interaction Module

Realistic interaction must be highly precise and responsive. In our sitting volleyball game, we incorporated hand tracking to enhance realism and implemented reflection enhancement for more precise and responsive gameplay, catering to the sport's unique characteristics. The system should accurately detect and translate the subtle nuances of hand/arm gestures into ball behavior. Slight variations in angle, rotation, and force must produce different shots.

5.4.1 Hand Tracking Integration

Drawing inspiration from the VR game "Beach Volleyball VR" [8] and SetterVision [10], instead of traditional controller-based input methods, we choose to integrate the hand tracking interaction method from the Meta Interaction Software Development Kit (Interaction SDK) [25]. The hand-tracking model allows users to use their hands to interact with objects in the immersive environment. The hand tracking feature is supported by 5 external cameras in the Oculus Quest Pro, 3 facing forward and 2 facing downward, allowing us to accurately detect [1] and obtain hand information and visualize it in an immersive environment.

5.4.2 Force Reflection Enhancement

We implemented customized solutions to enable the nuanced hand interactions needed for sitting volleyball mastery in VolleyNaut. We used the PhysX engine in Unity to provide the fundamental physics simulation, allowing the system to simulate the motion of a volleyball effectively. Additionally, considering the rebound effect between the volleyball and the hand, we integrated a collision detection system to precisely identify the moment of hand-ball impact during hits. At the point of collision, we calculated the change in velocity of the hand over the 0.2 seconds before impact. Utilizing this velocity change data, we applied Newton's second law of motion to approximate the overall force vector exerted by the user's hand:

$$F = m \cdot \frac{\Delta v}{\Delta t} \tag{1}$$

Here, F represents the force applied to the volleyball, m is the mass of the virtual volleyball, Δv signifies the change in velocity, and Δt indicates the time interval during which the change occurred.

In this way, VolleyNaut moves beyond hand tracking alone to estimate impact forces. This enables nuanced force feedback for authentic sitting volleyball gameplay interactions within VR.

6 User Study

To assess the user engagement and effectiveness of the designed VolleyNaut, we conducted user studies with respect to both standard volleyball players and sitting volleyball players at different proficiency levels, as well as some professional coaches. Standard volleyball players are also under the rules of sitting volleyball.

6.1 Experiment Set-Up

In the VolleyNaut user study, participants trained in a compact 2x2 feet area, safeguarded by protective mats and a yoga mat for comfort and stability. This confined space was chosen to evaluate VolleyNaut's effectiveness in simulating sitting volleyball training within limited physical constraints, testing the participants' adaptability and focus.

The study utilized the Quest Pro Head-Mounted Display (HMD), eliminating the need for controllers as all interactions were gesture-based. Participants, wearing VR headsets, engaged in virtual sitting volleyball by using hand movements to strike a virtual ball served by a computer-generated ball machine. This setup offered a realistic volleyball experience, allowing participants to refine their techniques through immediate, multifaceted feedback from the assessment module. This feedback included audio cues, 3D situated visualization, and display on a large screen, enhancing the training's effectiveness and interactivity.

6.2 Participants

We targeted participants who have prior volleyball or sitting volleyball experience to ensure the user study can effectively assess VolleyNaut. To ensure the diversity of the study, we recruited 20 participants including both male and female players, ages from 18 to 27. 8 of them are from a university team, 8 from a university club team, and 4 Para-Olympians. With such formulation of the participants, we can study the effectiveness of the designed system to different professional levels of volleyball players. 15 participants reported playing volleyball or sitting volleyball for 10 years, 3 for 5-10 years, and 2 for 1-5 years.

In addition to the players, we engaged 2 national sitting volleyball team coaches (Male=1, Female=1; Age: 36-45; Years in coaching: 10-17) to experience our system for providing feedback from a seasoned coach's perspective.

6.3 Design and Procedures

The VolleyNaut study employs a within-subject experimental design to evaluate user engagement and effectiveness across four distinct volleyball tasks: Serve-Receiving, Blocking, Digging, and Net Play. This design ensures each participant experiences every aspect of the experiment, thereby minimizing individual differences' impact on the outcomes. Participants spend a uniform duration of five minutes on

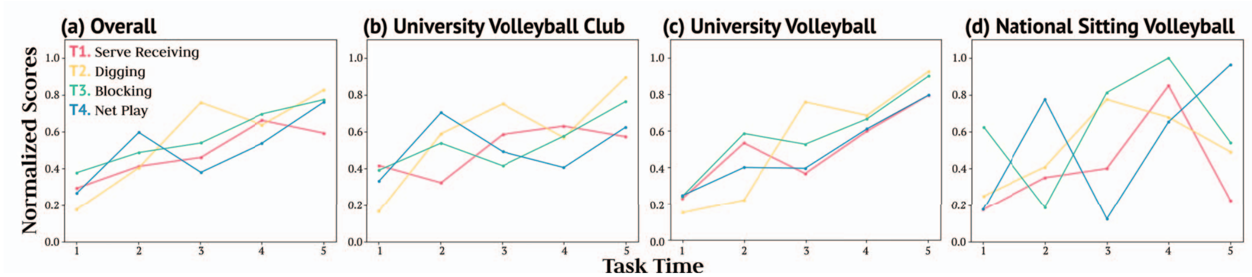

Fig. 6: Performance metrics over time for each participant group: (a) all participants, (b) University volleyball club team, (c) University volleyball team, and (d) National sitting volleyball team. The x-axis represents time in one-minute intervals, with '1' denoting the first minute and '5' the last, of the five-minute duration for each task as per Section 6.2. This normalized score progression demonstrates the enhancements or declines in skills such as serve receiving, digging, blocking, and net play over the course of the evaluation period.

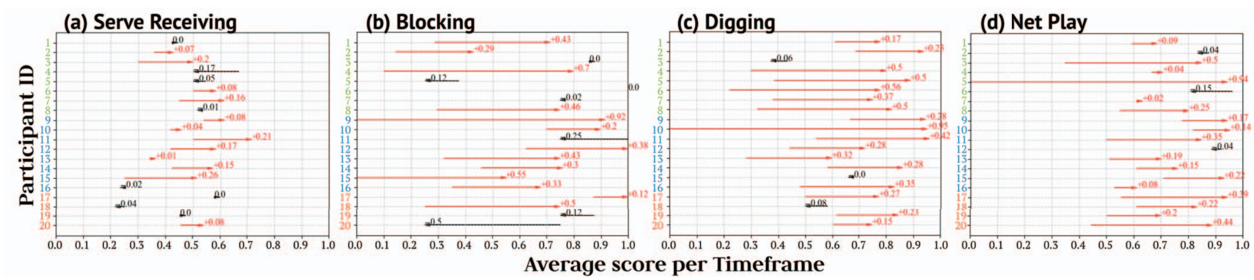

Fig. 7: Comparison of score difference between the first timeframe and the last timeframe for each task among all participants by task. In digging and net play, more than 85% of participants demonstrated improved performance by the end of the training task. In blocking and serve-receiving, over 60% of participants exhibited enhanced performance.

each task, ensuring consistent exposure and controlled comparison across tasks. This standardization is crucial for accurately assessing each task's engagement and effectiveness.

Initially, participants engage in a 180-second introductory scenario to familiarize themselves with the virtual environment, mitigating performance biases due to unfamiliarity with the VR setup. This acclimatization is vital for ensuring subsequent interactions with the tasks accurately reflect true engagement and capabilities within the VR environment. Participants proceed through tasks sequentially, starting with Serve-Receiving, then Blocking, Digging, and Net Play. This order allows for focused assessment of each task, isolating and analyzing the impact of each on user engagement and effectiveness. Feedback is gathered using two mechanisms: the Sports Engagement Scale (SES) and a 5-point Likert Scale, providing both quantitative and qualitative data, enabling comprehensive evaluation of the VR system's efficacy. The SES measures sports-specific engagement, while the Likert Scale offers nuanced feedback on system usability and overall experience.

In contrast, coaches in the study have an unrestricted timeframe to explore the VR environment, reflecting their unique role focusing on an in-depth examination of the system's training potential. Following their exploration, structured interviews are conducted using a predefined questionnaire, blending open-ended exploration with structured feedback. This approach seeks to obtain thorough insights into the system's effectiveness for athlete training, utilizing coaches' expert knowledge.

The total duration of the study for each participant, including players and coaches, is approximately 40 minutes. Each participant receives a $10 incentive as a token of appreciation.

6.4 Measures

To establish that VolleyNaut delivers a high level of user engagement and benefits players of all skill levels in sitting volleyball training, we conducted a comprehensive evaluation. This evaluation encompassed both qualitative analysis, derived from participants' feedback, and quantitative analysis, which utilized data collected during the player group's task performance, as well as the users' ratings of the system.

6.4.1 Quantitative Analysis

Our quantitative analysis consists of three components: 1) evaluating task performance, 2) assessing user perceptions of VolleyNaut, and 3) measuring VolleyNaut's ability to engage users.

Tasks Performance. In addition to collecting subjective ratings, we also gathered data on participants' performance in the training tasks. For each training task, users received points based on the following criteria: 0 points for a ball not hit, 0.5 points for a successful hit, and 1 point for a ball classified as a "good hit." These data enable us to track performance trends over time and assess whether participants' skills improved during the training period.

To analyze the data effectively, we divided each training task into 5 timeframes and assigned a score to each timeframe based on the previously mentioned scoring criteria. Following this, we performed a normalization of the total score for each timeframe. This normalization process provides an understanding of the trend in an individual's performance scores over time. In essence, it allows us to discern whether a participant's performance improved, remained consistent, or declined throughout the training sessions. Finally, we calculated the average normalized score for all participants in each timeframe for every task and visualized these data as a line plot, where each line represents a task (Fig. 6). We could see that, on average, participants performed better over time in all tasks, although there were some fluctuations in the third timeframe for both Serve-Receiving, Net Play, and Digging. Furthermore, a noteworthy observation is that participants from college teams and club teams exhibited significant improvement throughout the training sessions. In contrast, participants from national teams did not demonstrate as substantial improvements.

Additionally, we conducted a comparison of the score difference between the first timeframe and the last timeframe for each task among all participants (Fig. 7). As shown in Fig 7c and Fig. 7d, in the Net Play and Digging tasks, the majority of players demonstrated significant improvements. In the case of Serve-Receiving (Fig. 7a) and Blocking (Fig. 7b), over 60% of the players exhibited substantial progress.

User Perceptions of VolleyNaut. Users provided subjective ratings

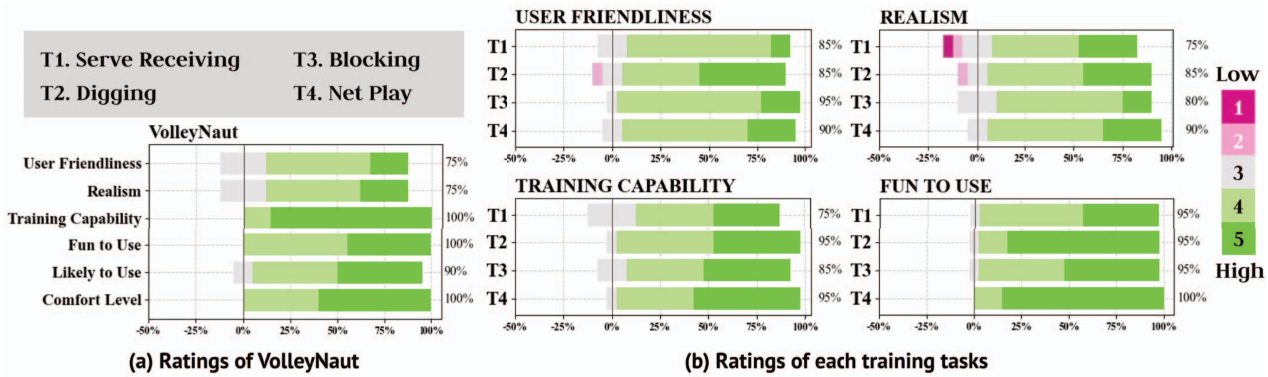

Fig. 8: Participants' rating for each task and the overall system. Regarding the evaluation of participants' experience, the ratings for each task and the overall system were consistently positive. Initially, (a) participants found VolleyNaut to be user-friendly, realistic, effective for training, fun to use, and expressed a willingness to use it in the future, with comfort in using it (Mdn ≥ 4). Subsequently, (b) participants rated each task favorably in terms of user-friendliness, realism, training capability, and enjoyment (Mdn ≥ 4).

for VolleyNaut across six dimensions: 1) User Friendliness, 2) Realism, 3) Training Capability, 4) Fun to Use, 5) Likely to Use, and 6) Comfort Level. The ratings were conducted using a 5-point Likert Scale, with the "Likely to Use" and "Comfort Level" dimensions evaluated for the overall system, while the remaining dimensions were assessed for both individual tasks and the overall system. Fig. 8a revealed that the majority of participants provided positive ratings for the overall system ($Mdn \geq 4$) across all dimensions. For all four training scenarios, participants expressed satisfaction with their user-friendliness ($\geq 85\%$), perceived realism ($\geq 75\%$), and enjoyment($\geq 95\%$). In terms of training capability, 95% found Blocking and Net Play useful, Digging received a rating of 85%, and Serve-receiving was rated positively by 75% of participants. None of the participants gave negative ratings on the comfort level of the VR headsets.

VolleyNaut's Ability to Engage Users. To measure the level of engagement among VolleyNaut users, we employed the Sport Engagement Scale (SES) [21]. The SES is a widely recognized tool for evaluating sports engagement and has been used in various studies [18,22,24,52]. It is an adaptation of the "Utrecht Work Engagement Scale" (UWES) [42], designed to assess engagement in a sports context, particularly among athletes. SES quantifies athletes' engagement and emotional experiences during their sports activities, defining engagement as a positive mental state characterized by vigor, dedication, and absorption during sports participation. SES consists of 15 questions in total, with each dimension comprising five questions. Upon analyzing all the SES surveys (Table 1), we found that, on average, all dimensions received positive feedback. Vigor had an overall average rating of 5.6, dedication scored 5.7, and absorption achieved a rating of 6.2. These high scores, given on a 7-point scale, demonstrate that VolleyNaut has successfully engaged players in sitting volleyball training.

6.4.2 Qualitative Analysis

Interviews were conducted with all participants to gather qualitative feedback on VolleyNaut's effectiveness as a volleyball training tool.

Overall, coaches unanimously agreed that creating an immersive training environment like VolleyNaut using VR holds great promise. They particularly appreciated several aspects of VolleyNaut. One standout feature that coaches found highly valuable was the performance assessment module. They emphasized that the 3D visualizations and real-time data provided by the system can significantly help players make adjustments to their techniques, such as refining their hand shape and adjusting angles for ball passes. Another noteworthy aspect was the controllable environment, allowing coaches to create specific scenarios like net plays. The consistent delivery of balls by the supportive machine to the same landing spot was seen as highly beneficial for training players' decision-making skills in a practical context.

Coaches also highlighted the suitability of VolleyNaut for beginners. The system's ability to start with low-speed balls and offer self-guided practice was seen as a valuable resource for players who may not have access to coaching or facilities. However, coaches did point out two significant limitations in our system: the absence of haptic feedback and the lack of arm detection.

In the context of sitting volleyball, muscle memory plays a pivotal role in mastering the sport. However, during our evaluation of VolleyNaut, it became evident that the absence of tactile feedback, accurately representing the force of the ball on the arm, poses a significant challenge. This limitation hinders the system's ability to fully replicate the sensory feedback that players rely on for muscle memory development.

Interviews with the player group further emphasized these issues. In addition to the concerns raised by coaches, some players reported experiencing muscle soreness and fatigue during training, occasionally taking short breaks for their arms. While all players agreed that achieving a good hit made them feel successful, they expressed a desire for more system feedback during successful hits.

Additionally, the player group reflected that the limitation of the hand tracking technology which incorporates only the hand, wrist, and a limited section of the forearm slightly affected players' performance.

7 Discussion

In this section, we assess system usability and limitations from the user study, compare VR sports training to real-world sports training, and emphasize unique aspects of inclusive VR sports training.

7.1 Usability of the Tool

Our study reveals that VolleyNaut serves as an effective training system, engaging participants in sitting volleyball effectively. However, we encountered certain usability issues during our investigation.

One issue we identified was participant muscle fatigue and a noticeable decline in performance during the tasks, particularly in sessions 3 or 4. This performance decline can be attributed to the fixed task time of 5 minutes maintained for consistency throughout the study. To address this, we suggest implementing a feature that allows users to customize the task duration. By providing flexible task durations that users can set in the menu before entering a training scenario, we can mitigate issues related to participant fatigue and performance decline.

Another important observation pertains to the use of the forearm in sitting volleyball, primarily due to physical limitations. The hand tracking technique integrated into our system, relying on Oculus technology, tracks only a portion of the forearm. This limitation explains why national sitting volleyball team players did not exhibit significant improvements compared to college and club team players during training tasks. Additionally, the absence of haptic feedback hindered muscle memory development. Hand tracking's blind spot also emerges as a usability concern. This limitation occurs because Oculus's hand tracking relies on headset cameras, resulting in certain areas not being adequately covered. This can lead to a failure in detecting hand positions and touch input, affecting the system's usability.

In addition, as coaches mentioned, our current system primarily caters to individual skill practice. To expand the utility of VR in sports training, it is essential to develop a more interactive system that enables collaborative training among multiple players.

7.2 The Impact of VolleyNaut on Perception and Cognition

Our research investigates the role of virtual reality (VR) in sports skill enhancement, building on studies [29, 31, 32, 39] that underscore VR's impact on real-world sports performance. This exploration is crucial for both conceptualizing our VR system and understanding its practical applications. Our findings add to evidence that VR training effectively enhances physical sports skills, offering safe skill repetition and heightened presence and immersion, crucial for improving spatial awareness and motor skills.

The design of our system is rooted in the principles of embodied cognition, which posits that cognitive processes are deeply intertwined with the body's interactions with its environment. This theory is reflected in our system's hand tracking and force reflection module, demonstrating the significant impact of physical interaction in VR on cognitive processing and skill acquisition in sports training.

Our performance assessment module integrates three key components to enhance training effectiveness. The Auditory Feedback, with its "ding" sound for successful hits, leverages human auditory perception for attention and emotional engagement, crucial in skill development, and provides positive reinforcement essential for learning. The 3D Situated Visualization, by tapping into human depth perception and spatial awareness, aids players in skillfully evaluating and adjusting their actions. Finally, the Big Screen Display presents performance data in a visually appealing, expansive format, facilitating quick comprehension and action adaptation based on clear, concise metrics. These combined elements significantly contribute to an immersive and effective training experience.

Our user study results affirm the effectiveness of these components. Participants reported increased confidence due to the auditory feedback, a heightened spatial understanding of ball trajectories from the 3D visualization, and the large screen display provided immediate insights into their performance. These factors collectively contributed to improved awareness and decision-making capabilities during training.

7.3 VR Sports Training vs. Real World Sports Training

When comparing VR sports training to traditional training methods, we can identify several advantages and limitations.

7.3.1 Advantages

Accessible Anywhere. VR sports training offers accessibility, allowing individuals to train anywhere with the right equipment. This convenience is particularly valuable for those lacking access to traditional sports facilities. Moreover, the spatial efficiency of VR environments enables expansive training scenarios within a limited physical space, enhancing accessibility for users with limited room or facility access.

Controllable Scenario. Another notable advantage lies in the degree of control afforded by VR in training scenarios. VR enables users to practice various situations, replicating real-game scenarios, and facilitating skill development and decision-making abilities.

Energy Conservation. Furthermore, VR training offers notable advantages in terms of energy conservation for athletes. In traditional sports training, athletes often expend substantial physical energy during practice sessions, potentially affecting the quality of their training. In contrast, VR sports training allows athletes to engage in intensive practice without the same physical demands. This is particularly valuable for individuals recovering from injuries or beginners who may not yet have the stamina for extended physical training. By conserving energy, athletes can maintain a higher level of focus on key skills and strategies throughout their VR training sessions.

Performance feedback. VR training's real-time feedback and visual data offer athletes a profound understanding of their techniques and strategies. Athletes can make immediate corrections and adjustments during training sessions, accelerating skill development. This visual feedback empowers athletes to dissect their performance with unparalleled clarity, identify areas for improvement, and track their progress over time. Beyond individual techniques, visual data aids in strategic insights for team sports, enabling anticipatory decision-making and optimized positioning. The engagement factor is enhanced as athletes can witness tangible improvements, fueling motivation. In essence, the incorporation of 3D ball trajectories and visual feedback within VR training revolutionizes the training experience, fostering skill mastery and strategic excellence for sitting volleyball.

7.3.2 Limitations

Lack of Haptic Feedback. Limitations emerge when applying VR sports training to sports heavily reliant on equipment interaction, like volleyball, primarily due to the absence of haptic feedback. Athletes in sports like volleyball rely not only on visual and auditory cues but also on the tactile sensations of handling the ball and equipment, a crucial aspect of developing muscle memory. In the virtual environment, this tactile feedback is lacking, making it challenging for athletes to replicate the precise timing, angle, and power required for skill development in volleyball. While VR systems can simulate ball movements and interactions to some extent, the absence of real-world equipment hinders the complete translation of these skills to the actual game.

Movement Restriction. It's also important to acknowledge a significant limitation of VR sports training: the physical constraint imposed by wearing VR headsets. Currently, most VR headsets are relatively bulky and can restrict a player's freedom of movement. This limitation can hinder the full replication of real-world sports movements, particularly in dynamic sports like volleyball that involve rapid and varied physical actions, including jumping.

7.4 Implications for inclusive sport training in VR

Identifying specific needs based on sports type and skill levels. Our study underscores the importance of tailoring VR-based inclusive sports training programs to meet the unique needs of individuals based on their sport type and skill levels, as exemplified in the context of sitting volleyball. For non-professional athletes, the key need is easy access to courts and coaching resources, with the need to overcome logistical barriers such as proximity to training facilities. On the other hand, professional athletes require more comprehensive resources, including advanced training modules, expert coaching, and sophisticated performance assessment and feedback tools. These resources are essential for skill refinement and peak performance maintenance. By recognizing and addressing the distinct needs of athletes at various skill levels within a sport, VR-based inclusive sports training programs can be finely tuned and customized, enhancing the overall training experience and contributing to the development and success of athletes, regardless of whether they are beginners or seasoned professionals.

Customizable Training Scenarios. Sports training for disabled athletes presents unique challenges due to physical limitations. For example, Participant 12 had restricted forward movement due to a hip disability. This made forearm passing difficult in Digging and Serve Receiving. Overhead passing from a forward position better accommodated their needs. However, our confined study space hindered their ability to move forward, negatively impacting their performance in Digging and Serve-Receiving tasks over time. This demonstrates the need to enable court positioning customization in VR training for accessibility. Players could choose locations tailored to their capabilities and limitations. Customizable scenarios would allow players like Participant 12 to properly position themselves and maximize skill development despite disabilities.

Confidence. Confidence is an important point for engaging disabilities in sports. As Participant 11 stated, *"I love the sport, especially spiking the ball successfully into the opponent's court. It's a daily thrill!"* Participant 13, who had experienced a life-altering accident, shared a similar sentiment: *"Following the loss of my right leg in an accident, I fell into a state of depression. When my coach reached out to my parents with the suggestion of trying sitting volleyball, they*

Dimension	Question	Mean	Sample SD
Vigor	1. I am able to train for long periods of time	5.9	0.8
	2. I am very persistent in my sport activity	5.3	1.5
	6. I feel full of energy during my training and matches	5.6	1.6
	7. When I get up in the morning I look forward to going to train	6.1	0.7
	8. I am strong and vigorous in my sport activity	5.1	1.3
	Overall	5.6	1.3
Dedication	3. My sport activity is a self challenge	5.0	1.6
	4. I am enthusiastic about my sport activity	6.1	0.7
	5. I am proud of the work I do	6.1	0.7
	9. My sport activity is full of meaning and resolve	5.9	1.0
	12. I feel inspired whilst carrying out my sport activity	5.4	1.1
	Overall	5.7	1.1
Absorption	10. I am carried away by my sport activity	6.3	0.7
	11. I am happy when I am engrossed in my sport activity	6.4	0.7
	13. I am oblivious to everything going on around me when I train	5.8	1.1
	14. I am absorbed in my sport activity	6.1	0.7
	15. Time flies when I am training or competing	6.4	0.5
	Overall	6.2	0.8

Table 1: The Sport Engagement Scale (SES) result. On a 7-point scale, participants averaged 5.6 in vigor, 5.7 in dedication, and 6.2 in absorption, suggesting that participants were highly engaged while using the VolleyNaut system for sports training.

decided to enroll me in the sport. Initially, I faced challenges due to my lack of prior volleyball experience, but as I immersed myself in this new endeavor, I found a sense of success and purpose." These quotes, coming from national team players with disabilities, demonstrate that to engage individuals with disabilities in sports, it's crucial to provide challenging training experiences that allow them to taste success. When they achieve success in their training, it not only boosts their confidence but also fosters a sense of accomplishment and belonging.

7.5 Real world application

VolleyNaut has the potential for widespread use in the real world. As coaches have suggested, individuals can leverage VolleyNaut in various ways to enhance their sitting volleyball experience. Beginners can use the system to get acquainted with sitting volleyball, explore the sport, and gauge their interest. Moreover, VolleyNaut can serve as a valuable tool for honing basic defensive skills before joining team practices, facilitating a smoother transition into the team environment. For more advanced players, VolleyNaut offers opportunities to refine their decision-making abilities. They can engage in scenarios like net play, where balls are consistently directed to specific spots. Here, players can experiment with different techniques, such as pushing the ball up with a single hand to set up teammates or directing it to the opponent's backcourt for an attack. The system also aids in adjusting defensive positions and refining passing angles and power. By simulating game scenarios and allowing players to experiment with various strategies, VolleyNaut becomes an indispensable tool for skill development in sitting volleyball.

7.6 Multi-Player VR Training System

In our pioneering design study tailored for sports for the disabled, we initially focused on developing a single-player training system using virtual reality (VR) for sitting volleyball. The results from our user studies indicated that integrating VR into training significantly boosts skill development for athletes with disabilities. As we mentioned in Section 5.2, this system includes a supportive machine specifically designed for basic skill training. However, given the team-oriented nature of sitting volleyball, it becomes crucial to extend this approach to a multi-player training system.

The benefits of our multi-player VR training system are manifold. Firstly, it facilitates remote participation, which is invaluable for athletes who have difficulty accessing physical training facilities. This feature not only broadens access to training but also fosters a sense of community among players. Secondly, the system enhances mental agility and situational awareness, crucial for developing teamwork skills. By simulating real-life scenarios, athletes can practice and adapt to various in-game situations, emphasizing the importance of collaborative strategies in team sports. Thirdly, VR technology offers an accessible platform for athletes with disabilities, effectively overcoming physical and logistical barriers commonly found in traditional sports settings. This feature is instrumental in promoting social inclusion and deeper engagement in sports.

For multi-player VR training, a pivotal feature is the use of avatars that represent real people. This allows players to see their teammates' body movements through these avatars, thereby mimicking the feel of an actual game. This aspect of the system is particularly significant in para-sports, where avatar design must reflect the specific characteristics of the sport. For instance, in sitting volleyball, leg movements are less influential, which allows us to potentially omit them from the avatar design. This decision is driven by a need to balance computational resources and visualization costs within the VR environment. Additionally, it's vital to provide customization options for these avatars, enabling players to create representations that reflect their own physical conditions, such as having one arm. This level of personalization ensures inclusivity and enhances the overall VR experience. Implementing such a system is not without its challenges. Ensuring seamless, real-time interaction in VR demands a robust network infrastructure capable of handling significant data loads. Synchronization is essential for a consistent and immersive user experience, requiring advanced techniques to align players' actions with the virtual environment. Furthermore, managing latency is critical; excessive delays can detract significantly from the immersive quality of VR.

In conclusion, the introduction of a multi-player VR training system in sitting volleyball marks a significant advancement in sports training for the disabled. By focusing on inclusivity, personalization, and the unique characteristics of para-sports, we aim to revolutionize how athletes with disabilities engage in sports, making training more effective, accessible, and adaptable to individual needs and preferences.

8 Conclusion and Future Work

This paper aims to offer insights into the application of VR to engage individuals with disabilities in the training of sitting volleyball, providing an accessible training solution that can be utilized anywhere, overcoming the limitations posed by traditional sports facilities. The result suggested that, first, VR can provide highly engaged and effective training to players; second, the controllable characteristic of VR can help cover training scenarios that can hardly be duplicated in real life; third, the real-time visual feedback supports users to make adjustments and coaches to design further training plans accordingly. Overall coaches and players all favored VR in inclusive sports training.

As the first comprehensive study on the application of VR to sitting volleyball training, our insights serve as a foundational point for future research in immersive sports skill development. Future work should focus on customizing VR training for various sports and skill levels, particularly for athletes with diverse disabilities. It's also essential to create VR experiences that foster players' sense of achievement and confidence, thus enhancing their engagement in sports. These challenges present significant research opportunities in human-computer interaction, promoting VR's application in disability sports training.

From a technical perspective, the introduction of applications supporting multi-player collaboration would greatly benefit team sports players. Advancements in hand-tracking technology are required to achieve complete coverage, eliminating blind spots and improving the precision of hand movements. Additionally, the creation of haptic feedback devices that can replicate the sensation of hitting a volleyball without hindering the player's ability to perform actions is crucial. Furthermore, the development of lighter VR headsets capable of accommodating a wider range of physical actions, including jumping, is essential to further enhance the effectiveness of VR sports training.

These endeavors hold the promise of further enriching the field of sports training for individuals with disabilities, ensuring that they can experience the joy and benefits of sports participation to the fullest.

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