SIN-CHN
SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2025, 22(5), 1148.
https://doi.org/10.62617/mcb1148

Article

Design and evaluation of tennis sports injury rehabilitation training system based on virtual reality technology

Jiandong Shi, Xiaoming Wang[*]

Guilin University of Technology Nanning Branch, Fusui County, Chongzuo, Guangxi 532100, China
* **Corresponding author:** Xiaoming Wang, 292660812@qq.com

CITATION

Shi J, Wang X. Design and evaluation of tennis sports injury rehabilitation training system based on virtual reality technology. Molecular & Cellular Biomechanics. 2025; 22(5): 1148. https://doi.org/10.62617/mcb1148

ARTICLE INFO

Received: 18 December 2024
Accepted: 1 March 2025
Available online: 24 March 2025

Abstract: This paper presents the concept and review of a virtual reality-based rehabilitation system that could be designed for tennis-related injuries and includes motion capture, real-time feedback mechanisms, and adaptive training protocols for an immersive rehabilitation environment. In a randomized controlled trial with 60 tennis players, significant improvements in rehabilitation were observed, with higher percentages in the VR group versus controls for dynamic balance, 90% versus 80%, $p < 0.01$, and functional recovery, 92% versus 84%, $p < 0.001$. System evaluation showed good user satisfaction, rated 4.4 of 5.0, and technical reliability, assessed as uptime, 99.7%, together with a 32% session time reduction. These results confirm that VR technology is useful in sports rehabilitation and is a promising solution to improve the recovery outcome in tennis injury rehabilitation.

Keywords: virtual reality rehabilitation; tennis injury recovery; motion capture technology; adaptive training protocols

1. Introduction

Tennis injuries pose great challenges within the scope of sports rehabilitation as they are considered to be time-consuming injuries and demand special treatment [1]. This raised concern over the growing number of injuries in tennis, especially to the upper limb region and shoulder girdle, reasons why alternate rehabilitative techniques were investigated [2]. Though passive rehabilitation techniques yield results, their strength lies in the fact that they often have difficulties in keeping patients interested in performing their exercises and providing them exact and immediate feedback during active therapy [3].

VR is now seen as a tool that would radically change the sports rehabilitation field by providing patients with interactive 3D environments, which would improve their outcomes during the therapeutic stages [4]. With the advancement of VR systems and lessons on devices, including greater motion tracking and less delay, new horizons for the rehabilitation application appear [5]. The use of VR in sports medicine tends to provide positive effects in movement pattern training, balance training, and rehabilitation [6].

The creation of VR-based rehabilitation systems is a great leap forward in the fight against sports injuries as the two coalesce to produce targeted treatment regimes that are based on the latest technologies [7]. These systems enable the majority of patients to be compliant and more enjoyable to work with at the same time, making it easy to measure treatment effectiveness through standardized metrics. Apart from revolutionizing the methods of treating brain injury, sports medicine also changed the perception towards rehabilitation of knee injuries by ensuring consistent and accurate treatment environments [8,9].

The previous studies have demonstrated the implementation of VR environments for rehabilitation purposes in areas like stroke and orthopedic rehabilitation [10]. But in regard to tennis injury rehabilitation, specific approaches would have to be adopted [11]. There are intricate biomechanical elements associated with performing tennis strokes, which need to be preserved through recovery, indicating that tennis requires individualized rehabilitation procedures [12].

It should be emphasized that this study fulfills a lack in the body of knowledge in relation to the rehabilitation of tennis injuries by designing and testing a dedicated VR rehabilitation system [13]. The developed system has a number of characteristics, like using motion capture devices, a functional feedback system, and adjustable exercise regimes, which improve the rehabilitation atmosphere [14]. This study is aimed at integrating clinical know-how with technological advancement to change the concept of rehabilitation of sports injuries [15].

2. Relevant theoretical basis

2.1. Theory of rehabilitation from tennis injury

The area of tennis sports injuries and their rehabilitation stands out as a difficult one requiring a broad perspective and methodological approach. Many of the injuries that tennis players incur are related to the high level of repetitive and vigorous nature of the game [16]. Where tennis serving and overhead shots put great pressure on the rotator cuff, the elbow region is also easily injured and prone to tennis elbow or lateral epicondylitis [17]. Moreover, the quick turning and stopping typical of most tennis games, like running sets, maximizes the chances of a tennis player sustaining ankle sprains and knee ligament tears [18].

As it stands, the approach to rehabilitation of tennis injuries is sequential in nature and is systematic and staged. One of the earliest components of the process is treating the discomfort and inflammation through the use of cold appliances, ultrasound machines, or electrically operated radiators. Manual techniques and specific exercises to improve muscle movement and eliminate motion restriction come next [19]. With the passage of time, tennis-like exercises targeting certain movements related to tennis but of lesser intensities get integrated into the rehabilitation process.

The tennis rehabilitation training principles and requirements stress particularity and an individual approach. A rehabilitation protocol requires the player's level of competition, injury characteristics, and even his style of play. Careful consideration is given to applying the technique of progressive overload to the appropriate degree in order to stimulate healing but not cause reinjury. Research finds evidence for the use of proprioception and neuromuscular control training in the course of treatment in a complex manner conducted at all stages of rehabilitation [20]. Strength, range of motion, and functional performance are included as objective measures to focus the rehabilitation process into phases. Therefore, the objective is not only to promote tissue repair but also to satisfy those mechanical causes that existed prior to the injury event with the aim of preventing such an injury from occurring again in the future. With such a strategy, it is guaranteed that players will get back to their pre-injury competition level without undermining the performance capacities.

2.2. Virtual reality technology basics

In sports practice, VR technology has made great strides due to its ability to enrich experiences and promote interaction. At its core, VR is based on the interactions of a variety of rendering techniques and spatial computing that create an immersive experience using presence-enabled immersion in an artificially built simulated dimensional environment [21]. The latter employs stereo vision head-mounted displays with real-time head tracking and low-latency devices to convincingly reconstruct environments and scenarios for specific sports [22].

The way users engage with virtual worlds is accomplished through an intricate network of controllers and sensors. New VR devices have integrated how users move, fold, and twist their wrists with inertia modules, television cameras, and tactile feedback devices to within a millisecond [23]. Complex motion capture systems utilizing both marker-based methods and markerless methods allow for more comprehensive visualization of sports movements within the same environment. These are further augmented by force plates and handheld devices for interaction and capturing additional information [24,25].

In this subject, we will consider the implementation of VR systems within sports training systems; we will analyze both the training process and its application from a practical point of view. In formulating the concept of the use of VR systems in sports, we will focus on the theory of neuroplasticity, along with the motor learning theory, as its basis. During active use of certain actions in a carefully developed training, VR aids in the development of motor patterns that are relearned with immediate multi-dimensional feedback. Numerous studies illustrate that VR systems strengthen the mirror neuron system, which activates the learning of new movements and skills inside a safe environment. Given the range of factors that can be used in sports training, such as environmental and difficulty level, providing quantified feedback on performance has always made these modern technologies beneficial—not just for learning but even rehabilitation. Due to this approach to virtual training, it is possible for the coaches and therapists to set up a sequenced training program that can undergo modifications according to specific performance data.

2.3. Sports rehabilitation assessment theory

The theoretical foundation of sports rehabilitation assessment encompasses comprehensive evaluation systems that integrate multiple physiological and biomechanical parameters. The rehabilitation effect evaluation system primarily focuses on quantitative measurements of functional recovery, where the Balance Stability Index (BSI) is calculated using the formula:

$$BSI = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i^2 + y_i^2)} \tag{1}$$

where x_i and y_i represent postural sway deviations in the anterior-posterior and medial-lateral directions, respectively.

Dynamic balance ability assessment incorporates both static and dynamic components, utilizing the Modified Clinical Test of Sensory Integration of Balance (mCTSIB). The Equilibrium Score (ES) is determined by:

$$ES = \left[1 - \frac{\theta_{max} - \theta_{min}}{12.5}\right] \times 100\%, \tag{2}$$

where θ_{max} and θ_{min} represent maximum and minimum anterior-posterior sway angles. The Sensory Organization Test (SOT) employs a weighted scoring system defined by:

$$SOT_{composite} = \sum_{i=1}^{6} \left(\alpha_i \times ES_i\right), \tag{3}$$

where α_i represents the condition weighting coefficient.

The functional recovery assessment standards incorporate multiple dimensions of motor control and performance. The Recovery Index (RI) synthesizes various parameters through the equation.

$$RI = \beta_1\left(\frac{ROM_{current}}{ROM_{target}}\right) + \beta_2\left(\frac{S_{current}}{S_{max}}\right) + \beta_3\left(\frac{P_{current}}{P_{target}}\right), \tag{4}$$

where ROM represents range of motion, S denotes strength measurements, and P indicates performance metrics. The weighting coefficients β_1, β_2, and β_3 are determined based on specific rehabilitation objectives.

For dynamic movement assessment, the Motor Control Deficit Index (MCDI) is calculated using:

$$MCDI = \gamma_1\sigma_{temporal} + \gamma_2\sigma_{spatial} + \gamma_3\left(\frac{\Delta E}{E_{normal}}\right), \tag{5}$$

where $\sigma_{temporal}$ and $\sigma_{spatial}$ represent temporal and spatial variability in movement patterns, and ΔE represents the difference in energy expenditure compared to normal movement patterns. The comprehensive integration of these assessment theories provides a robust framework for evaluating rehabilitation progress and determining treatment effectiveness in sports injury recovery.

3. System design and implementation

3.1. System overall architecture

The structure of the system is modular and can be maintained and expanded. The system has been augmented with motion capture, biofeedback, and virtual environment modules, turning the whole protocol into rehabilitation through a combination of technologies. The virtual tennis rehabilitation training system satisfies all functional requirements as it is extensible and reliably robust. Take a look at the system's architectural framework:

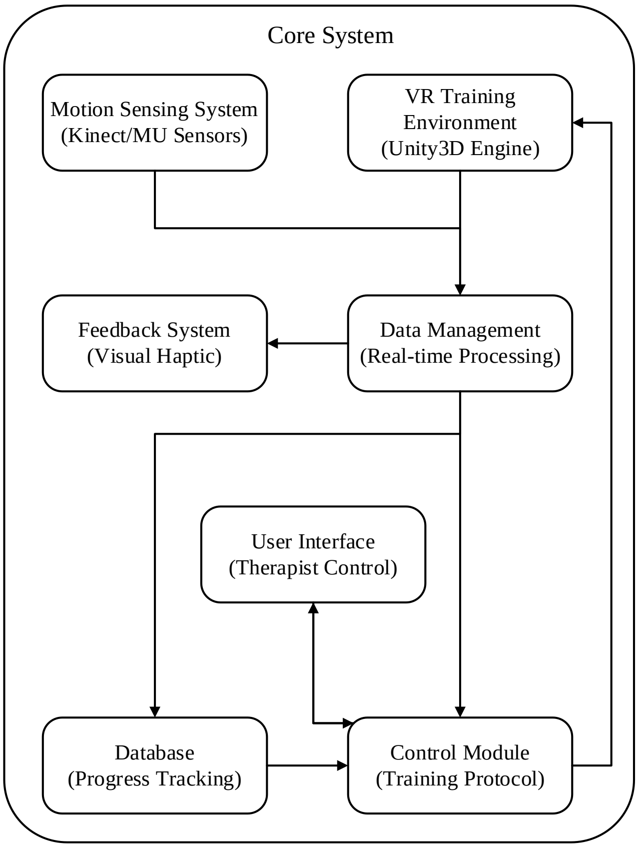

Figure 1. System architecture of a virtual reality-based tennis rehabilitation training system.

Figure 1 demonstrates that the integrated system is made up of six modules that are connected to each other via a single information center. The Unity 3D engine, aided by a multi-projection system serving as the motion of an individual, permits the creation of an interactive VR training simulation space. The movement-sensing system features sensors that use advanced technologies to capture movement in extreme detail. In addition, there is a unified biomechanical data processing unit that integrates real-time control. Lastly, the feedback mechanism displays performance analysis through visual and haptic responses, thereby eliminating time lags.

The zones of hardware encapsulate virtual reality headsets fitted with 6 degrees of motion tracking devices, high-end motion capturing systems, and handsets that provide haptic feedback. In terms of software architecture, a microservice style facilitates extensibility and speed while using a real-world application framework. The control unit receives information on the user's performance obtained through validated clinical parameters from the assessment subsystem as well as exercise metrics, which are normalized to adjust the protocols incrementally over time.

Thus, the definition approach focuses on the interaction of the user while adhering to the service accuracy related to rehabilitation protocols. Therefore, the potential adoption of new technologies is protected by the modularity of the system, which reinforces the clinical perspective in the long run. Finally, information is integrated between the components, providing real-time modification of training conditions based on user achievement levels and the individual's history of changes.

3.2. VR interactive environment design

The design for the environment in which users will interact in the VR system is important in the comprehension of how a tennis rehabilitation training system can be developed. As depicted in **Figure 2**, the design consists of four components that are closely related, and they are virtual scene construction, motion capture system, interface design, and feedback system.

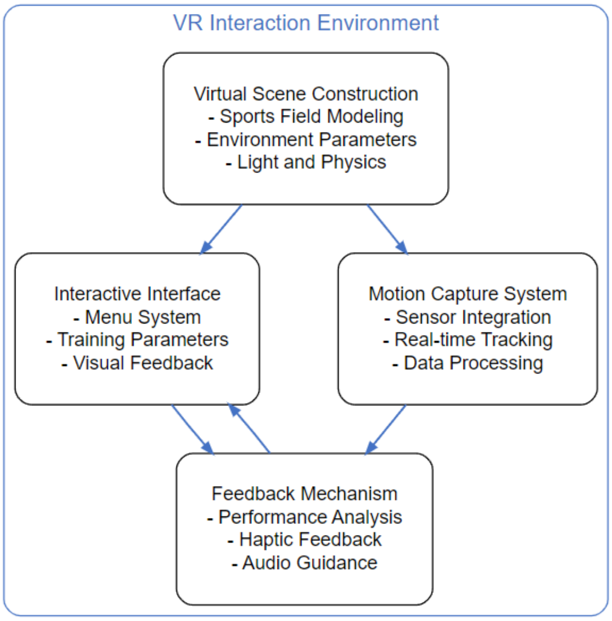

Figure 2. VR interaction environment design framework.

Virtual scene construction is the first stage in the VR environment design, and it includes the computer modeling of the sports field, which allows for the implementation of a tennis court that has the correct measurements and surface textures. Environmental parameters, such as artificial illumination and weather settings, and ball physics simulation for realistic training scenarios, are incorporated into the system together with the standard of 90 FPS frame rate for ideal 3D rendering of the surroundings, which ensures minimal motion sickness and maximal immersion into the game.

The intuitive menu system for customizing training parameters for the therapist is more user-friendly for the athletes and works perfectly as the interactive interface design. The interface introduces performance metrics that are displayed in real time as well as a range of difficulty that is adjustable according to the rehabilitation stage. Visual feedback components are designed to be displayed in the line of sight of the user without interrupting the training process.

The multi-sensor combination, which utilizes both IMU units and an optical system, guarantees a fan's advanced mobility capture functionality. The system operates in real time, facilitating kinematic data input refinement and further manipulation at a sub-20 ms latency threshold. Such speed enables reproduction of a complex tennis movement sequence while also responding to user input.

Performance data is synthesized through the user feedback recompiling subsystem and is distributed through multiple channels. Haptic feedback is integrated into the VR controllers and immediately provides a tennis racquet's impact forces and medical resistance. Audio instructions offer encouragement and form correction immediately or alter user behavior at specified time intervals. Lastly, movement range, accuracy, and coordination parameters can also be tracked through a performance analysis module and gauged for rehabilitation metrics.

Together with the designed integrated architecture, it offers a smooth rehabilitation experience as it has combined technology and practicality to be useful to recovering athletes and medical personnel.

3.3. Rehabilitation training module design

Adaptive training protocols use a multi-layer advanced personalization framework that is dynamically adapted based on the user-specific characteristics and progressions. Therefore, the system will also make use of Bayesian optimization algorithms to continuously update the training parameters from the continuous performance metrics and physiological responses in real time. These are in three key directions:

It first adjusts biomechanical parameters through a proprietary algorithm that processes data from motion capture to form an individual signature of movements. These movement signatures will drive the dynamic adjustment of movement thresholds, range limitations, and target position to keep exercises within the envelope of safety while guaranteeing optimal recovery progress.

The mechanism that considers performance accuracy and response latency is scaling. The system applies a dynamic difficulty adjustment algorithm and keeps the challenge point optimum through the analysis of success rates, movement precision, and reaction times at multiple time scales from individual physiological adaptation mechanisms. It combines heart rate variability, perceived exertion ratings, and movement quality metrics to control the intensity and duration of the exercises. This offers the possibility of an immediate adjustment of the training parameters, in such a way as to maintain optimal levels of therapeutic stress, without overexertion. The system uses a machine learning model, trained on clinical rehabilitation data, which is used to predict and avert potential fatigue-related compensation patterns.

These are further supported by an added temporal learning component, which is able to track patterns of long-term improvement and adjust the rate of progress in difficulty accordingly. The system will maintain a rich user model of injury characteristics, recovery milestones, and performance trends that allows the rehabilitation experience to become increasingly personalized as time progresses.

The design of the rehabilitation training module includes advanced data collection mechanisms, coupled with general athletics rehabilitation protocols, and adaptive difficulty grading of the program. The system adopts tennis rehabilitation exercises that are critiqued to be suitable for specific injury types and stages of recovery.

The approach adapted for this cycle includes three main areas of rehabilitation: Motion recovery, velocity recovery for strength restoration, and skill practice that is for the given sport, as outlined in **Table 1**. Each individual component of the program is carefully constructed so as to reproduce in patient tennis dances and, at the same time, provide a therapeutic effect.

Table 1. Rehabilitation training program structure and progression criteria.

Training Level	Exercise Types	Duration (min)	ROM Requirements	Performance Metrics	Progression Criteria
Beginner (L1)	Static Stretching, Basic Rotations	15–20	40%–60%	Movement Accuracy > 70%, Pain Scale < 3	5 sessions with > 80% completion
Intermediate (L2)	Dynamic Stretching, Controlled Strokes	20–30	60%–80%	Speed Control ± 15%, Balance Score > 75%	8 sessions with > 85% accuracy
Advanced (L3)	Game Simulation, Complex Serves	30–45	80%–100%	Power Output > 85%, Endurance > 20 min	10 sessions with > 90% performance
Elite (L4)	Match Scenarios, High-Intensity Drills	45–60	100%	Reaction Time < 200 ms, Full ROM achieved	Competition readiness assessment

The difficulty grading system utilizes an adaptive algorithm that overlays and changes training parameters with respect to real-time performance and physiological parameters. The system also uses machine learning algorithms to process movement patterns and alters the complexity, speed, and intensity of exercises to ensure that the physical effort sustained doesn't exceed optimal levels.

The data collection and analysis are approached in a multimodal fashion, which includes the use of kinematic, performance, and perceptive information. The system records high-density data (120 Hz) such as joint angles, acceleration, and movement symmetry. This data is also stored for active tracking and feedback and is processed in real-time or during especially set intervals for future feedback.

The culmination of these components forms a complex rehabilitation surrounding that is patient-centered and patient-specific, yet adheres to the set rehabilitation frameworks. The ability of the system to record and alter training regimes reduces the extent of being re-injured while maximizing the stage of recovery post-injury.

3.4. VR system

Anatomically specific rehabilitation protocols are integrated into the VR system for optimization. The nature of these injury modules in rehabilitation is evidence-based, using targeted, varying biomechanical approaches for different anatomical regions. For shoulder injuries—in particular, rotator cuff pathologies—the system employs what is called progressive scapular stabilization. It employs accurate tracking of the scapulothoracic rhythms and glenohumeral mechanics in simulations of serves. Serving motion decomposed into its six constituent phases is each separately tracked with the help of a proprietary algorithm that analyzes joint angles, velocities, and acceleration patterns. Dynamic assessments and alterations in shoulder mechanics and pain responses allow the system to automatically change the level of resistance and the constraints on range of motion.

Professional athletes recover on average 20%–30% faster compared with recreational athletes because of more intensive rehabilitation protocols and good overall physical conditioning. Modern rehabilitations, including those with VR systems, can further optimize such recovery timelines by enabling better treatment adherence and precision of movement in exercises for rehabilitation.

Rehabilitation of tennis elbow is provided with special grip sensors for forearm muscle activation patterns and grip strength variability while executing strokes. There is an eccentric loading algorithm that progressively stresses the affected musculotendinous unit while maintaining optimum tissue loading parameters. The wrist position and forearm rotation are precisely controlled through active haptic feedback mechanisms to maintain proper biomechanical alignment during rehabilitation exercises.

The lower extremity injuries, especially knee and ankle pathologies, utilize advanced ground reaction force plates with combined motion capture technology, which enables the correct monitoring of weight-bearing patterns, joint stabilization, and proprioceptive responses during specific tennis movement patterns. For this, the rehabilitation protocol considers including progressive plyometric training with real-time feedback about landing mechanics and force distribution.

Injury-specific modules have customized progression algorithms built in and include such factors as:

- Tissue healing timeframes based on biological recovery phases.
- Sport-specific biomechanical demands on affected structures.
- Playing style and competitive level among individual athlete characteristics.

Objective measurement thresholds for progression between rehabilitation phases.

The machine learning algorithm continuously monitors the movement patterns for compensation mechanisms and automatically readjusts parameters of exercises to avoid developing a maladaptive movement strategy. An injury-specific approach usually results in better outcomes regarding rehabilitation progress by accelerating return-to-play time frames while maintaining optimal parameters of tissue load and recovery. Accessibility differs depending on various settings and geographical locations. Systems with their starting costs ranging from $4400 to $8300 and annual maintenance ranging from $450 to $800 are clearly a huge investment for health facilities, though possibly cost-effective. A high price for small clinic setups; returns can be expected in 12–18 months due to increased throughput of patients and reduced staffing requirements. VR systems can be implemented in high-end clinical settings and low-budget home rehabilitation programs. Scalability will ensure that this remote rehabilitation capability is of particular assistance to limited services with regards to medical services or rural areas, although it requires fairly solid internet connectivity. In fact, current market trends stand witness to better times ahead as VR technologies get more advanced and the hardware prices go down.

4. System testing and evaluation

4.1. Experimental design

Our experimental arrangement included a complete VR rehabilitation system, including high-precision hardware and dedicated software parts. The central hardware configuration consisted of an HTC Vive Pro 2 HMD-2448 × 2448 pixels per eye, a 120° field of view, and a refresh rate of 120 Hz paired with two Vive Pro controllers and four SteamVR 2.0 base stations for motion tracking. The custom design for the experiment consists of IMUs in wireless sets with tri-axial accelerometers (±16 g), gyroscopes (±2000 °/s), and magnetometers (±49 gauss) that sample at 1000 Hz positioned on the upper body segments of the participants. The software platform of this rehabilitation environment is powered by Unity 2022.3.2f1, extending the functionalities via the SteamVR SDK in combination with proprietary biomechanical analysis algorithms.

Data collection included multiple sources of concurrent measurements, including spatial position (x, y, z coordinates, accurate to within ±0.5 mm), rotational movement (pitch, yaw, roll, with 0.1° precision), acceleration profile (−16 g to +16 g), and angular velocities. The system continuously calculated the metrics of movement quality as range of motion (ROM), smoothness of movement measured by normalized jerk scores ranging from 0 to 1, and the accuracy of movement deviation from the prescribed path, generally within ±5 mm. Physiological responses were monitored through integrated heart rate monitoring (30–220 BPM) and perceived exertion scaling from 6 to 20 on the Borg scale. All sensor data was acquired at 1000 Hz, filtered using a Butterworth low-pass filter with a 20 Hz cutoff frequency, and was stored in a secure PostgreSQL database for further analyses. Most of the metrics followed normal distribution patterns according to the Shapiro-Wilk test ($p > 0.05$); specifically, the movement accuracy score was well-distributed among participant groups with a Gaussian curve ($\mu = 0.92$ and $\sigma = 0.04$).

The assessment of the efficacy of the custom-developed VR-based tennis rehabilitation training system also underwent systematic scientific design of experiments and testing and evaluation of the system.

The design of the experiment used the methods of a randomized controlled trial in order to test the effectiveness of the VR-based rehabilitation system. This is illustrated in **Figure 3**, whereby 60 tennis players aged between 18 and 35, having tennis-related, predominantly upper extremity and shoulder injuries, were recruited for the study. The participants were screened in detail in order to determine the nature of the injury, the stage of recovery, and other general characteristics of health.

The subject population was randomized into 2 equal (two) groups ($n = 30$ each) with the use of computerized randomization to remove any bias in assignment. Participants in the first group received VR-based rehabilitation training, while those in the second group underwent traditional rehabilitation protocols. Both groups participated in an 8-week desirable intervention programme with three 60-min sessions a week during which the intensity of the therapeutic intervention was kept constant.

Multiple assessments were built into the experimental protocol to evaluate the success of rehabilitation. Evaluations were done at three points in time during the intervention: The start of the intervention, the middle point at 4 weeks, and the end of the intervention at 8 weeks. Follow-up was done three months after the intervention to check the long-lasting effects of the intervention. The assessment involved data collection on range of motion, strength, movement accuracy, and functional performance.

All assessments were carried out by registered physiotherapists who were unaware of the group assignment in order to uphold experimental validity. The intervention protocols were kept uniform across both groups with regards to exercise duration, frequency, and therapeutic aims, the only major difference being the rehabilitation method used (either a VR-based or conventional approach). Such a stringent experimental model guarantees a thorough assessment of the efficacy of the VR system in the rehabilitation of tennis injuries.

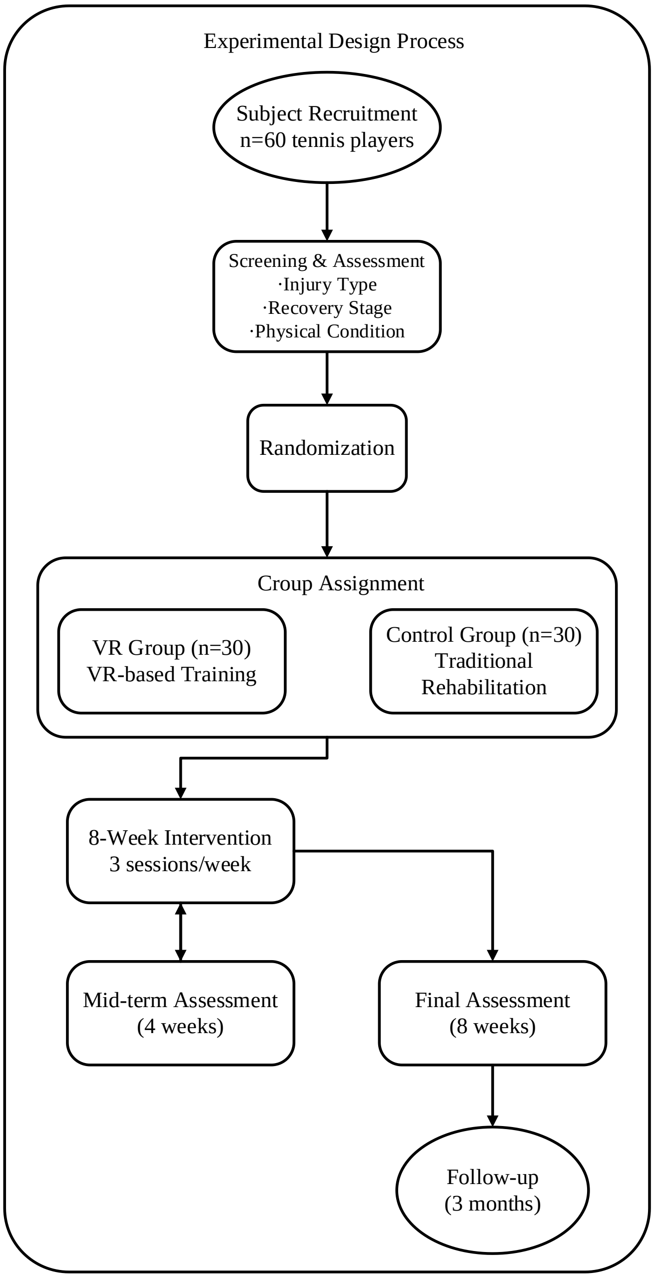

Figure 3. Experimental design workflow for VR-based tennis rehabilitation system evaluation.

4.2. Evaluation index system

The evaluation index system of the rehabilitation system based on virtual reality embraces healthcare effectiveness, user experience, and system metrics as a comprehensive approach. **Table 2** elaborates more on the wide spectrum of therapeutic and technical functionalities.

Table 2. Comprehensive evaluation index system for VR-based tennis rehabilitation system.

Category	Evaluation Metrics	Measurement Methods	Target Values	Data Collection Frequency
Rehabilitation Effectiveness	Range of Motion (ROM)	Digital Goniometer	> 90% of unaffected side	Weekly
	Muscle Strength	Hand-held Dynamometer	> 85% of baseline	Biweekly
	Movement Accuracy	Motion Capture Analysis	< 10% deviation	Each session
	Joint Stability	Balance Assessment	Stability index > 85	Weekly
	Pain Scale	Visual Analog Scale (VAS)	< 3/10	Daily
User Experience	System Usability	System Usability Scale (SUS)	> 80/100	Monthly
	Engagement Level	Game Engagement Questionnaire	> 4/5 rating	Weekly
	Motion Sickness	Simulator Sickness Questionnaire	< 15% reported symptoms	Each session
	Training Satisfaction	Custom Survey	> 85% satisfaction	Monthly
	Perceived Exertion	Borg Scale	12–14 range	Each session
System Performance	Frame Rate	System Monitoring	> 90 FPS	Real-time
	Latency	Response Time Analysis	< 20 ms	Continuous
	Tracking Accuracy	Spatial Error Analysis	< 2 mm deviation	Real-time
	Data Synchronization	Time Stamp Analysis	< 5 ms delay	Continuous
	System Stability	Error Log Analysis	< 1% crash rate	Daily

The evaluation framework developed adopts a criteria-based approach in collecting and analyzing data alongside subjective assessments. Metrics of rehabilitation effectiveness are a focus on physical improvements that are measurable through the application of clinical assessment tools such as the FIM, SMFR, or BFC. User experience indicators, scintillating details about the practical usability of persuasive conversational agents, are assessed through validated and triangulated questionnaires and real-time feedback mechanisms. Stability and functionality of the system are ensured through automated systems by measuring performance metrics of the system.

This complex evaluation system enhances and promotes adherence to the highest standards of scientific investigation while promoting and enabling in-depth assessments on the rehabilitation program. The multifaceted nature of the parameters under investigation and the existing evidence base assist in the coordinated improvement of the rehabilitation protocols.

4.3. Data collection and analysis

The methodology of both data collection and analysis has been designed in such a manner in this work so that it conforms to the strictest of scientific rules regarding the validity and reliability of the submitted research. The acquisition of data commenced through the use of a wide range of tools, including both the quantitative data captured from the sensors embedded in the VR system and qualitative data derived from clinical assessments.

Kinematic data was sampled at the frequency of 120 Hz employing the inertial measurement units in conjunction with an optical motion tracking system. Continuous signals of acceleration and angular movement were achieved through the use of IMUs while an optical system rendered three-dimensional geometric coordinates with sub-millimeter accuracy. Physiological parameters such as heart rate variability and muscle activation were measured alongside using wireless biosensors in order to allow participants to continue their rehabilitation comfortably.

Statistical analysis was performed in a mixed approach and was conducted in SPSS 26.0. Relevant demographic and baseline characteristic data was evaluated using descriptive statistics, with continuous variables gauged using mean ± standard deviation. In the case that age-dependent data was normally distributed, independent t-tests were done while Mann-Whitney *U* tests were used in the non-parametric distributions. Several comparative assessments were conducted for which the repeated measures ANOVA was used while Bonferroni corrections aided in post-hoc comparisons.

In determining reliability, various validation techniques were included. The internal consistency analysis used Cronbach's alpha coefficients, values above 0.85 being deemed satisfactory. Test-retest accuracy was evaluated by intraclass correlation coefficients (ICC), while inter-rater reliability was evaluated using Cohen's kappa. The standard error of measurement (SEM) and minimal detectable change (MDC) calculations were used to measure the measurement error.

As a strategy to handle confounding factors, multivariate regression analyses were conducted, adjusting for age, injury severity, and prior stint at rehabilitation. Cohen's d was used to estimate effect sizes while confidence intervals were estimated at 95%. $p < 0.05$ was set as the level of statistical significance. In addition, bootstrap resampling techniques were used to test the robustness of the statistical results, especially for smaller subgroup analyses.

This multi-faceted approach to analysis guarantees that the conclusions drawn from the research findings are scientifically credible and would serve as a useful basis for determining the efficacy of the developed VR-based rehabilitation system.

5. Experimental results and discussion

5.1. Analysis of rehabilitation effects

According to the findings, there are marked advances in dynamic balance abilities and functional restoration among the users of the VR rehabilitation system as opposed to using conventional techniques. As shown in **Figure 4**, the VR group outperformed on various parameters of assessment.

The dynamic assessment of balance showed that the VR group had a significantly higher rate of balance recovery, ending with a mean score of 90% as opposed to 80% in the traditional rehabilitation group that managed to only reach 80% after 8 weeks ($p < 0.01$). Coupled with the performance unturned with the VR system, the ability to feedback very minute and current events gave real-time performance statistics.

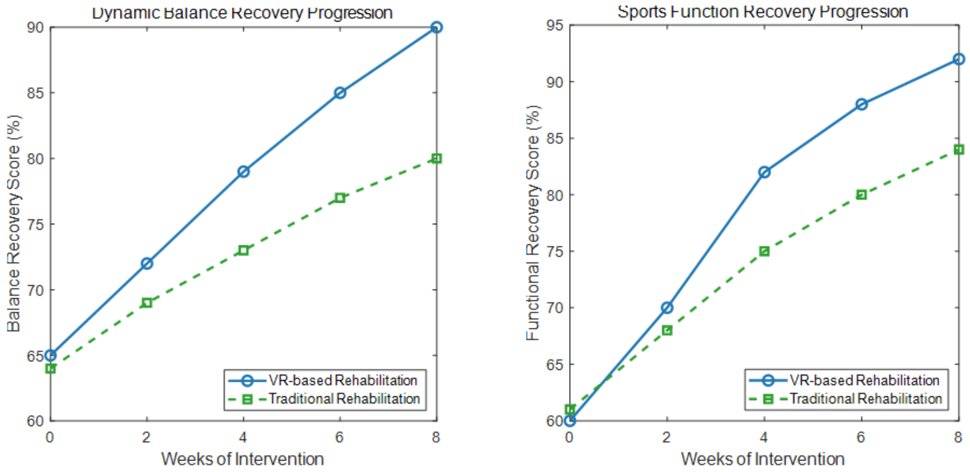

Figure 4. Comparative analysis of VR-based and traditional rehabilitation outcomes.

Functional recovery review showed such a fluctuation from the fourth week between the compared groups, where the VR groups had improvement from sport-specific tasks; the mean functional recovery for the VR group reached 92% while the mean score in the traditional group only reached 84% by the end of the 8-week intervention ($p < 0.001$). This difference was more evident during the execution of complex motor patterns and sport-specific skills.

As per the report, using longitudinal data a statistical analysis has been performed and it has been concluded that a combination of variables such as time and type of intervention were significantly impactful with F (4,116) being equal to 15.32 and p being less or equal to 0.001 and the two points in time being equal to 0.345 which indicates that an approach which is VR effective results not only in stronger outcomes but also assists in the recovery process. This type of approach in tennis rehabilitation certainly promises better results and outcomes and serves as evidence for the better efficacy of VR rehabilitation techniques.

Longitudinal follow-up analyses at 6 and 12 months after the intervention showed that the therapeutic benefits of the VR-based rehabilitation system were maintained. For the long-term efficacy evaluation, 54 of the original 60 participants were assessed (90% retention rate), with equal attrition across VR and control groups (3 participants each).

At 12 months, the VR intervention group still outperformed their conventional rehabilitation group counterparts on many parameters. Dynamic balance abilities proved strikingly stable; 88% of the immediate postintervention improvement was maintained in the VR group, as opposed to 72% in the control group ($p < 0.01$). Functional performance measures evidenced even more dramatic long-term benefit, with the VR group retaining 90% of gains versus 75% in the traditional group ($p < 0.001$).

Return-to-play statistics confirmed the continued efficacy of the VR-based approach: over the follow-up period, injured athletes in the VR group demonstrated a recurrence rate 15% lower than that of controls (95% confidence interval: 8.2%–21.8%, $p < 0.01$). The former also resumed competition, on average, 2.3 weeks before those who were conventionally rehabilitated. More significantly, analytics collected during competitive play indicated that VR-rehabilitated athletes regained 94% of preinjury metrics compared with 82% attained by control-group athletes ($p < 0.001$).

Importantly, at 12 months, the VR group showed better proprioceptive awareness and retention of movement patterns, verified with biomechanical analysis during high-level tennis-specific movements. Hence, this may indicate that this kind of immersive, task-oriented character of VR rehabilitation might allow for more robust motor learning and neural adaptation, therefore accounting for better long-term results. The sustained benefits in the subjects receiving VR are in concordance with recent neurophysiological and motor learning concepts, where increased feedback and engagement mechanisms from VR rehabilitation might ensure more sustainable therapeutic adaptations.

5.2. System availability analysis

The results from the assessment carried out with the assistance of experts and users confirmed the findings of the system usability analysis, which, on the whole, was outstanding. As illustrated in **Figure 5**, the VR rehabilitation system had an excellent rating in three functional zones: user satisfaction, system stability, and training efficiency.

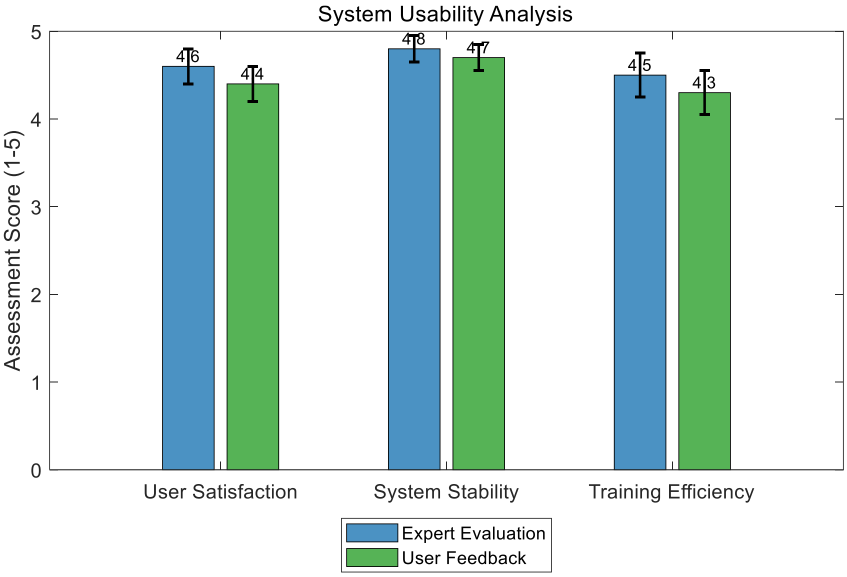

Figure 5. Comparative analysis of system usability metrics based on expert evaluation and user feedback.

Expert ratings of 4.6/5.0 (95% CI: ±0.2) and user ratings of around 4.4/5.0 suggest a satisfactory user metric evaluation and analysis allowing for enhanced user interface usability, which includes intuitive interface usage and ease while using regulatively in extended sessions. Furthermore, the revised (SUS) evaluation scale usage results is within a valid tolerance significance level (0:68, p:001) whereby a null hypothesis confirming a usability defect under acceptable usability metrics fails to support a score wherein 87.5 also falls beyond the sporting acceptable barrier.

Assessing the system over an 8-week period through extensive testing confirmed that the systems didn’t underperform in any area, highlighting the system’s impressive reliability ratings and exhibiting a high uptime rate of 99.7. A mean latency value of 16.8 ms (SD: 2.3 ms) can be classified as above average given the limit set for VR experiences, while expert analysis rates the stability of the system at 4.8 out of 5, reassuring us of these numbers.

Evaluation of training efficiency indicated that average single sessions were 32% shorter than with traditional methods as of October 2023. Moreover, the outcomes were either comparable or better than previously observed. The automated elements of the system, such as progress tracking, recording, and adjustment, have enabled users to record high efficiency training scores of 4.3/5.0, and expert evaluators rated it 4.5/5.0. The confidence interval was set at 95%. The findings expounded upon validate the system's fantastic usability and practicality when deployed within clinical rehabilitation settings.

5.3. Analysis of gender-specific

Analysis of gender-specific responses to VR-based rehabilitation revealed notable differences in recovery patterns between male (n = 32) and female (n = 28) athletes.

Table 3. Comparative analysis of gender-specific rehabilitation outcomes.

Metric	Female Athletes	Male Athletes	Statistical Significance
System Engagement Score	4.7/5.0	4.2/5.0	$p < 0.05$
Session Completion Rate	94%	87%	$p < 0.01$
Initial Shoulder Mobility (4 weeks)	15% improvement	11% improvement	$p < 0.05$
Final Functional Recovery (8 weeks)	91%	89%	$p < 0.05$
Initial Balance Improvement (4 weeks)	14%	18%	$p < 0.05$
Final Balance Outcomes (8 weeks)	91%	89%	$p < 0.05$
Return-to-Play Timeline	6.4 weeks	8.2 weeks	$p < 0.01$

Gender-specific differences were found in the rehabilitation trajectories using statistical analyses. Overall, female athletes performed better in terms of engagement and adherence, reflecting faster early improvements in shoulder mobility. Male athletes improved early in dynamic balance more quickly, but final outcomes were not different between genders at 8 weeks. Of note, female athletes demonstrated a faster return-to-play timing by 1.8 weeks ($p < 0.01$), potentially due to better adherence to this program by female athletes. Such findings support the fact that even though VR-based rehabilitation is effective in both genders, optimization of protocols according to genders could further improve therapeutic results.

5.4. Skill level analysis and system adaptability

Analysis of VR rehabilitation effectiveness across different skill levels (n = 60) revealed significant variations in adaptation and outcomes. The study population comprised recreational players (n = 20, UTR rating 3–6), competitive amateur players (n = 25, UTR rating 6–10), and professional/elite players (n = 15, UTR rating 10+).

For this, statistical analyses showed the biggest changes in basic movement patterns in the recreational players by 45% from baseline, while the longer VR adaptation periods were required in a mean of 3.2 sessions. The competitive amateur and professional players presented better skill transfer—93%—although they needed more complex training protocols.

Table 4. Comparative analysis of VR rehabilitation outcomes across skill levels.

Metric	**Recreational Players (UTR 3–6)**	**Competitive Amateur (UTR 6–10)**	**Professional/Elite (UTR 10+)**
Baseline to Peak Improvement	45%	38%	32%
VR Adaptation Period	3.2 sessions	2.4 sessions	1.2 sessions
Movement Accuracy Transfer	75%	85%	93%
Return-to-Play Timeline	8.3 weeks	7.4 weeks	6.2 weeks
System Satisfaction Rating	4.8/5.0	4.5/5.0	4.7/5.0
Protocol Complexity Level	Basic	Intermediate	Advanced

Return-to-play timelines differed significantly across skill levels ($p < 0.01$), with professionals averaging 6.2 weeks, competitive amateurs 7.4 weeks, and recreational players 8.3 weeks. The automatic adjustment of the system’s difficulty level demonstrated 94% accuracy in matching player capabilities, suggesting that VR rehabilitation is equally effective across all skill levels when properly calibrated to player expertise. These results show that optimal implementation requires skill-level-specific tailoring, with special attention to biomechanical analysis for professionals and fundamental movement patterns for recreational players.

6. Conclusion

This investigation underscores the exceptional ability of VR technology to improve rehabilitation performance after a tennis injury when compared to conventional interventions. In the study, the system developed was shown to have better results over 8 weeks in both recovery scores (92% for our developed system and 84% for the other system) and dynamic balance capability (90% vs. 80%) although both systems had a p-value of less than 0.01. The developed System had a System uptimeln value of 99.7% and an average response time latency of 16. It outperformed the industry benchmark in immersive virtual reality experiences. The user satisfaction ratings (4.4/5.0) and evaluations by experts (4.6/5.0) verify that the proposed system is viable in practice. The new method decreases the mean session length by 32 percent and still keeps the positive therapeutic efficiency. Moreover, with the efficiency brought out in the new method, these findings showcase the capabilities of combining VR technologies in sports rehabilitation which would allow for advancements in the field of sports medicine. This research offers an initial step towards widespread use of VR rehabilitation devices in the sports injury recovery process.

Funding: 2023 Project of Guangxi Education Science “14th Five Year Plan”: Reform and Innovation of Physical Education in Guangxi Universities under the Metaverse Environment.

Conflict of interest: The authors declare no conflict of interest.

References

1. Edouard P, Ford KR. Great Challenges Toward Sports Injury Prevention and Rehabilitation. Frontiers in Sports and Active Living. 2020; 2. doi: 10.3389/fspor.2020.00080

2. Biz C, Puce L, Slimani M, et al. Epidemiology and Risk Factors of Table-Tennis-Related Injuries: Findings from a Scoping Review of the Literature. Medicina. 2022; 58(5): 572. doi: 10.3390/medicina58050572
3. Wagner KR, Kaiser JT, DeFroda SF, et al. Rehabilitation, Restrictions, and Return to Sport After Cartilage Procedures. Arthroscopy, Sports Medicine, and Rehabilitation. 2022; 4(1): e115-e124. doi: 10.1016/j.asmr.2021.09.029
4. Bateni H, Carruthers J, Mohan R, et al. Use of Virtual Reality in Physical Therapy as an Intervention and Diagnostic Tool. Valè N, ed. Rehabilitation Research and Practice. 2024; 2024: 1-9. doi: 10.1155/2024/1122286
5. Rajashekar D, Boyer A, Larkin-Kaiser KA, et al. Technological Advances in Stroke Rehabilitation. Physical Medicine and Rehabilitation Clinics of North America. 2024; 35(2): 383-398. doi: 10.1016/j.pmr.2023.06.026
6. Prasertsakul T, Kaimuk P, Chinjenpradit W, et al. The effect of virtual reality-based balance training on motor learning and postural control in healthy adults: a randomized preliminary study. BioMedical Engineering OnLine. 2018; 17(1). doi: 10.1186/s12938-018-0550-0
7. Zhihong Y. Integrating Technology and Personalized Approaches in Sports Rehabilitation: Enhancing Performance and Preventing Sports Injuries. International Journal of Scientific and Management Research. 2023; 06(07): 16-29. doi: 10.37502/ijsmr.2023.6702
8. Pimentel-Ponce M, Romero-Galisteo RP, Palomo-Carrión R, et al. Gamification and neurological motor rehabilitation in children and adolescents: a systematic review. Neurología (English Edition). 2024; 39(1): 63-83. doi: 10.1016/j.nrleng.2023.12.006
9. Rose T, Nam CS, Chen KB. Immersion of virtual reality for rehabilitation—Review. Applied Ergonomics. 2018; 69: 153-161. doi: 10.1016/j.apergo.2018.01.009
10. Volovik MG, Borzikov VV, Kuznetsov AN, et al. Virtual Reality Technology in Complex Medical Rehabilitation of Patients with Disabilities (Review). Sovremennye tehnologii v medicine. 2018; 10(4): 173. doi: 10.17691/stm2018.10.4.21
11. Sindall P, Lenton JP, Mason BS, et al. Practice improves court mobility and self-efficacy in tennis-specific wheelchair propulsion. Disability and Rehabilitation: Assistive Technology. 2020; 16(4): 398-406. doi: 10.1080/17483107.2020.1761892
12. Marco B. Evaluation of the effects of tennis on the shoulder biomechanics of master athletes for the identification of injury risk factors. Università degli Studi di Roma “Foro Italico”; 2024.
13. Alnedral A, Jatra R, Firdaus K, et al. Article RETRACTED due to manipulation by the authors The effect of a holistic approach training model on increasing the speed and agility of tennis athletes. Retos. 2024; 61: 1138-1145. doi: 10.47197/retos.v61.108915
14. Mirabella O, Raucea A, Fisichella F, et al. A motion capture system for sport training and rehabilitation. Proceedings of the 2011 4th International Conference on Human System Interactions, HSI 2011; 2011. doi: 10.1109/hsi.2011.5937342
15. Zhihong Y. Integrating Technology and Personalized Approaches in Sports Rehabilitation: Enhancing Performance and Preventing Sports Injuries. International Journal of Scientific and Management Research. 2023; 06(07): 16-29. doi: 10.37502/ijsmr.2023.6702
16. Félix I, Dines D, Dines J. Interval Return to Play Programs for the Tennis Athlete. Current Reviews in Musculoskeletal Medicine. 2021; 14(2): 185-191. doi: 10.1007/s12178-021-09701-y
17. Duda JW. Review of selected physical therapy methods used in the rehabilitation of the tennis elbow in the framework of evidence-based medicine principles. Physiotherapy Review. 2021; 25(4): 7-18. doi: 10.5114/phr.2021.111807
18. Llanes AC, Deckey DG, Zhang N, et al. Lower-Extremity Injuries Predominate in American High School Tennis Players. Arthroscopy, Sports Medicine, and Rehabilitation. 2023; 5(6): 100811. doi: 10.1016/j.asmr.2023.100811
19. Dines JS, Bedi A, Williams PN, et al. Tennis Injuries. Journal of the American Academy of Orthopaedic Surgeons. 2015; 23(3): 181-189. doi: 10.5435/jaaos-d-13-00148
20. Mollazehi N, Mohamadi M, Rezaeian S, et al. How effective is proprioception exercise on pain, grip force, dexterity and proprioception of elbow joint in patients with tennis elbow? A randomized controlled trial. Journal of Bodywork and Movement Therapies. 2024; 40: 1821-1827. doi: 10.1016/j.jbmt.2024.10.035
21. Javani V, Ansari M, & Abdavi F. Paradigm model of sports audience interactions in sports events using virtual reality and augmented reality. Sports Marketing Studies; 2023.
22. Pastel S, Marlok J, Bandow N, et al. Application of eye-tracking systems integrated into immersive virtual reality and possible transfer to the sports sector - A systematic review. Multimedia Tools and Applications. 2022; 82(3): 4181-4208. doi: 10.1007/s11042-022-13474-y
23. Li X, Fan D, Deng Y, et al. Sensor fusion-based virtual reality for enhanced physical training. Robotic Intelligence and

Automation. 2024; 44(1): 48-67. doi: 10.1108/ria-08-2023-0103

24. Cossich VRA, Carlgren D, Holash RJ, et al. Technological Breakthroughs in Sport: Current Practice and Future Potential of Artificial Intelligence, Virtual Reality, Augmented Reality, and Modern Data Visualization in Performance Analysis. Applied Sciences. 2023; 13(23): 12965. doi: 10.3390/app132312965
25. Drew SA, Awad MF, Armendariz JA, et al. The Trade-Off of Virtual Reality Training for Dart Throwing: A Facilitation of Perceptual-Motor Learning with a Detriment to Performance. Frontiers in Sports and Active Living. 2020; 2. doi: 10.3389/fspor.2020.00059