ingegneria sismica
International Journal of Earthquake Engineering
Anno XLIII - Num. 1 - 2026

The effect of virtual reality technology-assisted physical training in competitive sports performance

Lianlin Zhai[1] *and Yanan Liu*[2,*]

[1] Department of Physical Education, Qufu Normal University, Jining, Shandong, 273165, China
[2] Graduate School of General Studies, Dongshin University, Naju, 58255, Korea

SUMMARY: *In this paper, the octahedral model of an athlete during physical training is reconstructed in real time by means of sensor wearing and data acquisition to recognize the changes of his/her body parts during movement. Two pose description methods, Euler angle and quaternion, are used to calculate the athlete's actual motion position and the sensor reference position to locate the human motion position with high accuracy. Combine the occlusion processing method (DTP) and the action reconstruction algorithm (PE-DLS) to classify and complete the action reconstruction for different acceleration changes. The transformed action data are used to construct the action recognition model VT-AGCN, which accurately recognizes the actions in physical training. The athletes of the swimming team assisted by virtual reality technology have a greater improvement in stroke performance and leg striking performance, and the stroke performance is accelerated to 138.705-160.933 s, and the leg striking performance is accelerated to 190.158-208.846 s. Athletic training in the realm of competitive sports represents a vital factor for the development of superior athletes, and the employment of virtual reality technologies will be of great value in increasing the level of competitive ability of athletes.*

KEYWORDS: *DTP; PE-DLS; movement reconstruction; VT-AGCN; virtual reality; physical training*

1 Introduction

Competitive sports form an important part of the entire sporting environment in China [1]. In 2011, the General Administration of Sport of China developed the Olympic Competition Program Outline for 2011 – 2020. Later in 2016, the 13th Five-Year Plan for Sports Development and Competitive Sports were launched, thereby outlining a clear path towards the development of competitive sports and physical training in China. Over the years, China has exhibited a continuous and persistent interest in ensuring the healthy development of competitive sports in the country. From the development of strategic policies down to their implementation, and from the establishment of the national competitive sports system down to the selected approaches to the development of competitive sports in the country, the government has always taken targeted actions to meet its sports expectations [2]. Competitive sports in China have not only been an important part of the country's goal in achieving healthy China and becoming a dominant sports power, but also in fulfilling the Chinese dream of rejuvenation [3-5].

---

[*] hongjieliu8888@163.com

https://doi.org/10.65102/is2026425
Published: 30 April, 2026

The physical training of an athlete can be considered as the primary stage of preparation in each sport. The essence of the concept under discussion is to cultivate the athletic abilities of athletes comprehensively and hence increase the quality of athletic activities, optimize the body composition, and master skills in addition to their major area [6, 7]. Being an integral part of athletic training, physical training provides important prerequisites for the improvement of the technical and tactical qualities of athletes and for producing excellent achievements in competitions [8]. In doing so, it guarantees the comprehensive development of physical attributes, makes the body resistant to high loads during training sessions, and enables athletes to learn sophisticated techniques and improve their tactical abilities [9-11]. Thus, physical training plays an instrumental role in producing remarkable athletic achievements and prolonging the career of athletes. Owing to its importance, physical training has always been receiving great attention from the coaches working at international sport levels. Besides, it has become a hot topic among researchers across the globe [12]. In this context, virtual reality technology pertains to the construction of a simulated network space using computer systems, which would give rise to the experience of full immersion into a digitized environment [13]. Over the past years, considerable development was achieved in this field, and the application of this technology has been gradually integrated into multiple spheres of social life, ranging from the implementation of aerospace engineering worldwide to everyday entertainment purposes [14-16]. Virtual reality is far beyond a mere instrument for shaping and changing the perception of time and space in today's world. On the contrary, it provides new insights for the reform of existing methods of physical training [17]. What is more important regarding this issue, virtual reality technology offers the possibility for athletes to be trained in acquiring both theoretical and practical knowledge and skills as well as develop new ways to practice physical training [18, 19]. The intersection between virtual reality technology and physical training implies significant potential opportunities for the future. By utilizing the possibilities of virtual training, athletes will not only gain practical, lifelike experience of training but also foster their independent training mindset along with developing their critical, independent thinking skills. All of these aspects play a significant role in innovating the methods of physical training among athletes [20-22]. However, unlike sports training in general, the matter of how to employ virtual reality technology properly and create a new model of physical training on its basis still requires further investigation.

Relevant surveys show that injury is a key factor that causes athletes to be unable to sustain participation, which requires athletes to have good physical fitness, if the athletes do not have sufficient physical training, physical reserve is insufficient, The problem of injuries remains a constant factor during the training process and also while competing, and scientific physical training can improve the athletes' physical function and physical adaptability, and effectively prevent sports injuries [23-25]. Saunders et al [26] studied the physical training of stroke patients and designed cardiorespiratory training, resistance training, and a mixture of the two for the patients, cardiorespiratory training improved the walking ability of the patients, and the mixture of the training methods had a certain degree of influence on the balance ability, the conclusions of this research can be taken into consideration when dealing with the training process of athletes. Nygaard et al. [27] studied the influence of different kinds of physical training on changes in the orientation skills, including augmentative training, strength training, sprint training, and other single forms and combinations of forms, and all of the training modalities used resulted in varying degrees of enhancement in orienteering ability effect measures. In a study conducted by Lu et al. [28], the impact of physical training on the hitting skill of tennis players was analyzed through experimentation with 32 tennis professionals who were categorized into two groups based on the kind of training each received. The data obtained from the physical training was statistically analyzed using software, and it was established that physical training significantly improved the functional movement and hitting skills of the athletes. In another study done by Tian et al. [29], it was established that engaging in physical interval training before basketball training significantly improved the vertical jump and 20-meter sprint performance of male athletes, and it also has the same improvement effect on female athletes but to a lesser extent, so it is necessary to develop different physical training programs for different genders of athletes.

In relation to improvements in physical fitness among athletes, research by Xiao et al. [30] showed that functional training is a positive contributor, resulting in improvements in areas such as speed, muscle strength, power, balance, and agility. Lamberth et al [31] divided golfers into two groups for functional and traditional strength training, and the experimental data showed that the strength of the traditional strength group of athletes in the deep squat and leg raises was elevated high, while the vertical jump and swing speed and other specialized movements were not improved, while the functional training group was significantly improved in all data. The impact of elastic training on physical fitness was studied by Slimani et al. [32]. It was found that short term elastic training leads to improvement in jump height, sprinting, and agility performance. However, combining elastic training with specific sport training showed to be less effective compared to implementing elastic training alone. Akbar et al. [33] undertook an analysis of the effect of neuromuscular training on physical fitness in different sports, based on information obtained from 144 studies on the topic. concluded that neuromuscular training helps athletes to adjust their body movements according to their own situation and thus improve their performance in physical fitness indicators.

With the international deepening and development of physical training in the field of competitive sports as well as in the field of virtual virtual reality, progressive breakthroughs have been made in a number of research areas related to them [34]. Li et al [35] combined the use of VR technologies and smart sensors in physical training programs, resulting in the provision of training optimization, skill improvement, and psychological support to athletes. Such combination was able to overcome some shortcomings of current smart sensors during sports training. Ali et al [36] developed a virtual reality application for sports training, such as walking and running, and carried out a training effect test and survey to evaluate the effectiveness of the virtual reality program through body movements, voice commands, gesture control, and other interactive experiences to effectively improve the physical training effect of the testers. The virtual reality program provided an interactive experience through body movements, voice commands, gestures and other ways to effectively improve the physical training effect of the testers. Hong et al [37] designed a virtual reality-assisted convolutional neural network model for athletes to enhance the effectiveness of sports training, and the virtual reality-assisted provided athletes with real-time interactive environments, which enhanced the athletes' self-confidence and mastery of sports training knowledge. Donath et al [38] researched the effectiveness of virtual reality technology in increasing physical abilities of senior people. The results obtained showed that physical abilities of seniors, such as balance, mobility, were improved greatly after the use of virtual reality, helping reduce the probability of falling down in old age. Liu et al [39] obtained findings consistent with Donath et al, who pointed out that the immersive features of virtual reality technology play a key role in gait recovery of the elderly, and that weekly immersive training qualitatively improves functional mobility and balance in the elderly.

The practice of developing virtual reality systems for sports training has also become a feature of international research in the field of competitive sports. Cannavò et al [40] designed a virtual reality-based sports training system, which incorporates standardized movements for a variety of sports, such as basketball free throw movements, and improves the training effect of athletes on specific technical movements, and verified the system in training effectiveness testing experiments. The feasibility of the system was verified in the training effectiveness test experiment. Pastel et al [41] designed a virtual reality training system in order to achieve efficient karate technique training effects without the accompaniment of a coach, including the whole body visual presentation and forearm visual presentation of the two training modalities, and after a period of time training athletes all body parts of the training effect has been improved. Faure et al. [42] analyzed systematically the ways in which virtual reality technology is used in team ball sport training and provided a general assessment of the efficiency of these methods. As a result, the authors came to the conclusion about certain drawbacks associated with the use of virtual reality technology in sport training caused by the technical issues and imperfection of training programs. Cao et al. [43] studied the issue of virtual reality technology in sports training in detail. The results of the research have shown that virtual reality soccer training provides tactical situations for athletes in training and using artificial intelligence algorithms to analyze athletes' movement, decision-making increases the efficiency of training.

The upgraded breakthroughs of virtual reality technology such as VR and AR have brought more possibilities for the in-depth development of competitive sports. With the aim of improving the accuracy of physical training of athletes and their success in sports competitions, this paper applies virtual reality technology in detecting, reconstructing and recognizing athletes' training actions. The Euler angles and quaternion body postures of athletes during physical training are measured, and the spatial angular parameters and acceleration of each action data are calculated to locate the absolute and relative positions of the limb coordinates and to improve the accuracy of action capture. According to the changes of joint acceleration in the captured data, the occlusion processing method (DTP) and the motion reconstruction algorithm (PE-DLS) are categorized and applied to complete the reconstruction of the training motion. Afterwards, the human skeleton sequence data are input into the deep learning model VT-AGCN to recognize and classify each training movement to understand the athletes in physical training in real time.

2 Motion capture and analysis of physical training based on virtual reality technology

2.1 Human movement data monitoring

2.1.1 Human posture description methods

There are three principal methods for describing human posture, namely Euler angles, rotation matrices, and quaternions, each of which carries its own advantages, disadvantages, and applicable scope.

1) Euler Angle

Figure 1 illustrates how Euler angles describe the fixed-point rotation process. In the figure, $Oxyz$ and $Ox'y'z'$ represent the right-handed coordinate systems, and three angular parameters ψ, θ, φ are employed to express the relationship between the angular changes of a rigid body rotating around a fixed point, with $Oxyz$ serving as the reference coordinate system.

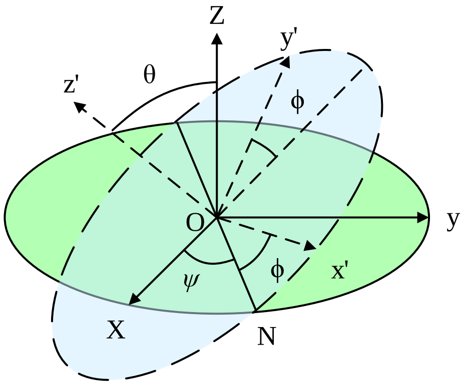

Figure 1: The diagram of rotation expressed by Euler angle

The angle from the fixed axis Oz to Oz' is the angle of chapter motion θ, and the perpendicular ON of the plane zOz' is the knuckle line, which is also the intersection of the planes $Ox'y'$ and Oxy. The angle from the fixed axis Ox to the nodal line ON is the angle of progression ψ, and the angle from the nodal line ON to the movable axis Ox' is the angle of rotation φ (ψ,θ,φ are all measured counterclockwise). The initial position is $Ox'y'z'$ coinciding with $Oxyz$, which is successively rotated $Z(\psi)$, $N(\theta)$, $Z'(\varphi)$ around the three axes of Oz, ON, and Oz', and $R(\psi,\theta,\varphi)$ is obtained after the rotation, and the transformation relationship is formulated as follows:

$$R(\psi,\theta,\varphi) = Z'(\varphi)N(\theta)Z(\psi) \tag{1}$$

The rotation operator in the rotation matrix representation demands the computation of numerous trigonometric values along with extensive matrix multiplication operations. The rotation operator: $N(\theta)=\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}$, $Z'(\varphi)=\begin{pmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix}$, $Z(\psi)=\begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$.

Euler angles can decompose the fixed-point rotation of a coordinate system into three successive rotations about a fixed axis. This method offers a more intuitive representation of the rotation angle of a rigid body or vector within a reference coordinate system.

2) Quaternion

A quaternion is composed of four elements, and its complex number form is expressed as

$$Q(q_0,q_1,q_2,q_3) = q_0 + q_1 i + q_2 j + q_3 k \tag{2}$$

where q_0 is the scalar of the quaternion representing the angle of rotation; q_1,q_2,q_3 are the vector parts of the quaternion; and i, j, k represent standard orthogonal vectors, which by the nature of the complex numbers can be shown to be $i \otimes i = -1.0$, $j \otimes j = -1.0$, and $k \otimes k = -1.0$, with the $\otimes$ symbol represents the multiplication of quaternions.

A quaternion can be thought of as a vector in four dimensions, or as a hypercomplex number. Where i represents a rotation from the x-axis positive to the y-axis positive in the plane where the x-axis intersects the y-axis, j represents a rotation from the z-axis positive to the x-axis positive in the plane where the z-axis intersects the x-axis, and k represents a rotation from the y-axis positive to the z-axis positive in the plane where the y-axis intersects the z-axis. The rotation relation of i, j, k can be described by multiplication of quaternions as

$$\left.\begin{array}{c} i \otimes j = k, j \otimes k = i, k \otimes i = j \\ j \otimes i = -k, k \otimes j = -i, k \otimes i = -j \end{array}\right\} \tag{3}$$

In the equation above, the multiplication of two distinct unit vectors by a quaternion conforms to the cross-multiplication properties of unit vectors. The addition and subtraction of quaternions follow the general laws and properties governing complex numbers.

Quaternion multiplication is defined by the symbol $\otimes$ and expressed as:

$$\begin{aligned} P \otimes Q &= \left(p_0 + p_1 i + p_2 j + p_3 k\right) \otimes \left(q_0 + q_1 i + q_2 j + q_3 k\right) \\ &= \left(p_0 q_0 - p_1 q_1 - p_2 q_2 - p_3 q_3\right) + \left(p_0 q_1 + p_1 q_0 + p_2 q_3 - p_3 q_2\right) i \\ &\quad + \left(p_0 q_2 + p_2 q_0 + p_3 q_1 - p_1 q_3\right) j + \left(p_0 q_3 + p_3 q_0 + p_1 q_2 - p_2 q_1\right) k \end{aligned} \tag{4}$$

The above equation is written in matrix form:

$$\begin{gathered} P \otimes Q = \begin{pmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & q_3 & -q_2 \\ q_2 & -q_3 & q_0 & q_1 \\ q_3 & q_2 & -q_1 & q_0 \end{pmatrix} \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{pmatrix} \\ \text{Or } P \otimes Q = \begin{pmatrix} p_0 & -p_1 & -p_2 & -p_3 \\ p_1 & p_0 & -p_3 & p_2 \\ p_2 & p_3 & p_0 & -p_1 \\ p_3 & -p_2 & p_1 & p_0 \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix} \end{gathered} \tag{5}$$

Quaternion multiplication satisfies the laws of distribution and combination:

$$P \otimes \left(Q + R\right) = P \otimes Q + P \otimes R \tag{6}$$

$$P \otimes Q \otimes R = \left(P \otimes Q\right) \otimes R = P \otimes \left(Q \otimes R\right) \tag{7}$$

Quaternion inverse: if $P \otimes R = 1.0$, then P and R are inverse to each other, denoted as $P = R^{-1}$ or $R = P^{-1}$, and the computational expression: $P \otimes P^* = \left(p_0 + p_1 i + p_2 j + p_3 k\right) \otimes$ $\left(p_0 - p_1 i - p_2 j - p_3 k\right) = p_0^2 + p_1^2 + p_2^2 + p_2^2 + p_3^2 = \|P\|$, is found:

$$P^{-1} = \frac{P^*}{\|P\|} \tag{8}$$

where P^* is the conjugate quaternion of P, and $\|P\|$ is the paradigm of the quaternion, which indicates the size of the quaternion.

2.1.2 Calculation of motion data parameters

1) Space angle (ω,θ,φ) calculation

In the calculation of joint range of motion, it is necessary to determine the relative positional relationship between neighboring upstream and downstream limbs through the measured attitude quaternion. The quaternion measurements output from the wearable inertial sensors $s1, s2$ are all based on each sensor's own coordinate system S as the reference system, and the relative position of the wearable inertial sensors $s1, s2$ with respect to the ground reference system G changes continuously throughout the process of motion. The ground reference system G is kept unchanged, and three or more node data are required to determine the attitude and perform the coordinate system transformation, so that the wearable inertial sensors $s1, s2$ both adopt the ground coordinate system as the reference system. The vector v_S in the S system is described in the S system coordinate expression v_G by Equation (9):

$$P^{-1} = \frac{P^*}{\|P\|} \tag{9}$$

where q is the conjugate quaternion of q^*, and $q^* = q^{-1}$ if $\|q\| = 1$.

$$\begin{aligned} Q = p \otimes q &= \left(p_0 + p_1 i + p_2 j + p_3 k\right) \otimes \left(q_0 + q_1 i + q_2 j + q_3 k\right) \\ &= \begin{pmatrix} p_0 & -p_1 & -p_2 & -p_3 \\ p_1 & p_0 & -p_3 & p_2 \\ p_2 & p_3 & p_0 & -p_1 \\ p_3 & -p_2 & p_1 & p_0 \end{pmatrix} \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix} \end{aligned} \tag{10}$$

According to the principle of quaternion synthesis, if quaternions p and q represent the first and second coordinate system rotations, respectively, the synthesized quaternion Q is described by Equation (10). It can be obtained that $q = p^{-1} \otimes p \otimes q = p^{-1} \otimes Q$, and if the quaternions of the upstream limb and the downstream limb measured by the wearable inertial sensors $s1, s2$ are Q_1 and Q_2, respectively, the coordinate system rotation relation ΔQ between the two quaternions is characterized by Equation (11) that

$$\Delta Q = Q_1^{-1} \otimes Q_2 \tag{11}$$

The quaternion $\Delta Q = \left(q_0, q_1, q_2, q_3\right)$ of the coordinate rotation of the upstream and downstream limbs is obtained according to Eq. (3), and the vector V represents the Oz'-axis negative direction vector $\begin{pmatrix}0 & 0 & -1\end{pmatrix}^T$ the matrix of coordinate transformations from the $Ox'y'z'$-system to the $Oxyz$-system is described by Eq. (12), the

$$V=\begin{pmatrix}V_x\\V_y\\V_z\end{pmatrix}=\begin{pmatrix}q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2+q_0q_3) & 2(q_1q_3-q_0q_2)\\ 2(q_1q_2-q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_0q_1+q_2q_3)\\ 2(q_1q_3+q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2\end{pmatrix}\begin{pmatrix}0\\0\\-1\end{pmatrix} \tag{12}$$

To find the reference vector $\vec{n}=\begin{pmatrix}V_x\\V_y\\0\end{pmatrix}$, the y-axis vector $\vec{m}=\begin{pmatrix}0\\1\\0\end{pmatrix}$, and according to Euler's formula for the angular rotation angle, it can be found that (ω,θ,φ) is described by equation (13):

$$\left.\begin{aligned}\omega&=\arccos\left(\frac{\vec{n}\cdot\vec{m}}{|\vec{n}||\vec{m}|}\right)\\ \theta&=\arccos\left(\frac{\vec{n}\cdot\vec{V}}{|\vec{n}||\vec{V}|}\right)\\ \varphi&=\arctan\frac{2(q_0q_1+q_2q_3)}{q_0^2-q_1^2-q_2^2+q_3^2}\end{aligned}\right\} \tag{13}$$

2) Acceleration Calculation

Assuming that the attitude vector in the S system is V_s and remains constant, and the coordinate system S is rotated to the G system as the conjugate quaternion q^* of q, the accelerations a_x^s, a_y^s, a_z^s measured by the sensor are based on the S system, and the G system is used as the reference system. The calculation process is as follows: the acceleration vector is expressed in the coordinates of the S system as $A^S=(a_x^s,a_y^s,a_z^s)$. If the vector is fixed, the coordinate system rotates the S system to the G system, and the new coordinates of the acceleration vector are:

$$A^G=(a_x^G,a_y^G,a_z^G)=q^{*-1}\circ A^S\circ q^* \tag{14}$$

2.1.3 Trainer Virtual Octahedron Model Acquisition

Human body parts included the pelvis, left thigh, right thigh, left calf, right calf, left foot, right foot, chest and abdomen, neck, head, left upper arm, right upper arm, left lower arm, left hand, right lower arm, and right hand. Based on the actual paste locations of marker points related to the same limb segment and the 3D spatial coordinates of the collected marker points, each part was represented by an octahedron. Exactly which MARKER points are used to represent which part of the body is to be measured by visualization.

For the position of the marker points depicting the same body segment, there are differences between subjects due to the disparity in physical attributes. Referring to the case of the RFHD marker situated on the front portion of the right side of the simulated human head, the values for its world coordinate for a person of smaller physical dimensions are (13, 11, 1645), whereas those of a person with higher physical dimensions have been found to be (13, 8, 1800). In terms of physical size difference, this has been evident in the values associated with the z-coordinate of the mentioned point. Based on the three-dimensional coordinates of the marker points denoting particular body segments, it will then be possible to obtain octahedral models that accurately represent the physical sizes of the human trainees with varied body sizes.

This virtual human head will be used as a representative example for demonstrating how an octahedral model can be obtained for the particular person undergoing training.

Three marker points have been placed for the virtual head: RFHD, LFHD, and LBHD, indicating the right front, left front, and left back portions of the head. First, the position of the head end center is calculated using the spatial coordinate points for these three marker points. After that, the center point of the neck and head joint is obtained by considering the chest landmark CLAV and the upper back landmark C7 points. An octahedral model can now be developed for the virtual human head based on the proper angular rotation and scaling of these two centers.

2.2 Reconstruction of key modules based on virtual reality technology

2.2.1 Data pre-processing

Before real-time motion capture starts, the offset between the body parts and the corresponding sensors should be obtained through pose calibration, so as to get the position $p_i^b(t)$ and rotation $q_i^b(t)$ of the corresponding joints of the virtual human. In this paper, we use the “T” pose calibration method. When the calibration program starts, the user needs to assume the “T” pose. The virtual human model is scaled according to the ratio of the height of the head-mounted display and the height of the virtual human head, r_{scale}, so as to ensure that the virtual human and the real human body are the same size.

$$r_{scale} = \frac{p_{head,y}^s}{p_{head,y}^b} \tag{15}$$

The sensor position and rotation in the “T” attitude are defined as 3D vector $p_i^s(t_0)$ and quaternion $q_i^s(t_0)$, respectively, and the position and rotation of the corresponding body joints are defined as $p_i^b(t_0)$ and rotation $q_i^b(t_0)$, respectively, so that the positional and rotational offsets p_i^{off} and q_i^{off} of the VR device and the body parts, respectively, are calculated as follows:

$$q_i^{off} = q_i^s(t_0)^{-1} \cdot q_i^b(t_0) \tag{16}$$

$$p_i^{off} = p_i^b(t_0) - p_i^s(t_0) \tag{17}$$

where t_0 denotes the calibration moment. $q_i^s(t_0)$ and $q_i^b(t_0)$ denote the rotation of the sensor and the rotation of the corresponding joint of the digitizer, respectively, at the time of calibration. The $p_i^s(t_0)$ and $p_i^b(t_0)$ denote the position of the sensor and the position of the corresponding joint of the digitizer at the time of calibration, respectively. The calibration method is based on two assumptions, one is to assume that the virtual human and the real human body have the same bone length ratio, and the motion retargeting with different bone length ratios is out of the research scope of this paper. In this paper, the virtual human model is adjusted to maximize the alignment between the user and the virtual human bone length ratio. Second, it is assumed that the offset between the VR device and the human body is fixed after the calibration is completed.

The VR Grip has interactive buttons and haptic feedback, supports teleportation, and other features, so in practice, the HTCVIVE trackers for both hands can be replaced with the VR Grip for more interactive features. It should be noted that if a VR grip is used instead of a two-handed tracker, the user needs to hold the grip tightly after calibration to prevent the grip from sliding and introducing large errors. Although the calibration results based on the above assumptions have unavoidable errors with the real situation, the experimental results show that this method is a simple and effective way to calibrate.

In real-time operation, based on the position and rotation offsets of the VR device and body parts obtained from the calibration, the original sensor data can be transformed to the virtual human model coordinate system, so as to obtain the position $p_i^b(t)$ and the rotation $q_i^b(t)$ of the corresponding joints with the following transformation formula:

$$q_i^b(t) = q_i^s(t) \cdot q_i^{off} \tag{18}$$

$$p_i^b(t) = p_i^s(t) + q_i^s(t) \cdot q_i^s(t_0)^{-1} \cdot p_i^{off} \tag{19}$$

where $q_i^s(t)$ and $p_i^s(t)$ denote real-time sensor rotation and position data, respectively.

2.2.2 Motion Reconstruction

In order to improve the real-time, accuracy and robustness of action reconstruction, this paper integrates a high-precision, real-time action reconstruction algorithm (PE-DLS) and an occlusion processing method (DTP) in the action reconstruction module.The DTP algorithm is mainly aimed at the occlusion problem, and it is essentially a deep learning method, which is limited to generalization in real-time motion capture due to the complexity and diversity of the human body movements. The PE-DLS algorithm, as a generalized high-precision, real-time action reconstruction algorithm, has a performance that is not limited by the type of action and scene, but it cannot deal with the occlusion problem. Therefore, in this paper, the DTP method is used for reconstruction when it may suffer from the occlusion problem, otherwise the PE-DLS method is used to reconstruct human actions, which can improve the performance and efficiency of the algorithm.

This paper introduces a simple and effective determination method for occlusion processing: when there exists any joint i such that $\Delta a_i > \Delta a_i^{\max}$, the system is reconstructed by using the DTP method, otherwise it is reconstructed by using the PE-DLS method. Under normal circumstances, the human body movement continuity is good and the acceleration change is small. When the sensor suffers from occlusion by the human body or the surrounding environment, the data affected by the occlusion usually jumps, so when the acceleration change is faster, it is likely to suffer from the occlusion problem. In this paper, we characterize the continuity of the data by calculating the acceleration change of the sensor in $\mathrm{m/s^3}$. When the acceleration change is greater than a certain acceleration change threshold, the DTP method is selected for motion reconstruction, otherwise the PE-DLS method is used for motion reconstruction. The joint acceleration change of normal human natural motion is usually very small, and the acceleration change threshold does not have a fixed value, which is usually related to the type of motion. In this paper, the maximum joint acceleration change value $\Delta a_i^{\max}$ of the root node and the end node in all the motion sequences is calculated based on the large human motion capture dataset AMASS as the threshold value, and the joint acceleration change value Δa_i at the moment of t is calculated as follows:

$$\Delta a_i = \frac{p_i^b(t-2) + p_i^b(t-2) - 2p_i^b(t-1)}{(\Delta t)^3} \tag{20}$$

where $p_i^b(t)$, $p_i^b(t-1)$ and $p_i^b(t-2)$ denote the joint positions of the current frame, the previous frame and the last two frames. In this paper, the system is stabilized at 55FPS, so $\Delta t = 1/55$.

Because the training of the deep learning model in the DTP framework is based on the AMASS dataset that uses a right-handed coordinate system, whereas the collected data using the Unity3D engine is represented in a left-handed coordinate system, the coordinate transformation is inevitable. That is, the collected position and orientation data should be converted from the left-handed to right-handed coordinate system before reconstruction, and then the reconstructed motion of the entire body should be converted from the right-handed to left-handed coordinate system again before its usage in the DTP algorithm. In the Unity3D engine, the three-dimensional coordinate system uses a left-handed system where the positive x-axis is in the right-hand direction, the positive y-axis in the upward direction, and the positive z-axis in the frontward direction. On the contrary, the AMASS dataset uses a right-handed coordinate system where the positive x-axis is toward the left-hand direction, the positive y-axis in the upward direction, and the positive z-axis in the frontward direction. The transformation process from one coordinate system to another can be performed by converting the quaternion q into the rotation matrix R using Rodrigues' formula:

$$R = I + \hat{\omega} \cdot \sin\theta + \hat{\omega}^2 \cdot \left(1 - \cos\theta\right) \tag{21}$$

where $I \in \mathbb{R}^{3\times3}$ is the unit matrix. $\omega \in \mathbb{R}^3$ denotes the rotation vector form of the quaternion q and θ denotes the angle of rotation. The $\hat{\omega}$ is the antisymmetric matrix generated by the rotation vector ω:

$$\hat{\omega} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \tag{22}$$

Taking the left-handed system as an example, the position and rotation under the left-handed coordinate system F^l are defined as the three-dimensional vector $p_i^l(t)$ and the rotation matrix $R_i^l(t)$, and the position and rotation under the transformed right-handed coordinate system F^r are defined as the three-dimensional vector $p_i^r(t)$ and the rotation matrix $R_i^r(t)$, respectively. In this paper, the transformation from the left-handed coordinate system F^l to the right-handed coordinate system F^r is realized by flipping the x-axis direction of the left-handed coordinate system. The position data $p_i^r(t)$ under F^r can be obtained by inverting the x-component of the 3D position vector under F^l as:

$$p_i^r(t) = S_T \cdot p_i^l(t) \tag{23}$$

where $S_T = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ denotes the three-dimensional vector transformation matrix from F^l to F^r. Suppose a point p^l in the left-handed coordinate system F^l is transformed by rotating $R_i^l(t)$ to obtain a new point $\tilde{p}^l$ as:

$$\tilde{p}^l = R_i^l(t) \cdot p^l \tag{24}$$

Substituting Eq. (24) into Eq. (25) yields:

$$S_T \cdot \tilde{p}^r = R_i^l(t) \cdot (S_T \cdot p^r) \tag{25}$$

A point p^r in the right-handed coordinate system F^l is rotated $R_i^r(t)$ to obtain a new point $\tilde{p}^r$ as:

$$\tilde{p}^r = R_i^r(t) \cdot p^r \tag{26}$$

According to Eqs. (25) and (26), the rotation matrix $R_i^r(t)$ in the right-handed coordinate system F^r is related to the rotation matrix $R_i^l(t)$ in the left-handed coordinate system as follows:

$$R_i^r(t) = S_T^{-1} \cdot R_i^l(t) \cdot S_T \tag{27}$$

Given the inherent symmetry between left-handed and right-handed coordinate systems, the procedure for converting from a right-handed system to a left-handed system is identical to that for converting from a left-handed system to a right-handed system, and is therefore not repeated here.

2.2.3 Motion Recognition

After preprocessing the motion capture data, more complete and realistic motion data are obtained. By inputting these data into the deep learning model, the sports training movements can be recognized and evaluated. Due to the existence of many complex movement features in sports training movements, such as the turning movement, the general deep learning model cannot accurately recognize sports training movements. This is because in the motion capture of sports training, for the same action, the difference in viewpoints will lead to a large difference in the motion capture data. Taking the selfie action as an example, under different viewpoints, there are large differences in the skeleton representation of the human action.

To address this problem, the study proposes a VT-AGCN model. The action recognition process of this model is as follows: according to the features of sports training, a reasonable angle is obtained by using the viewpoint adaptation subnetwork, and the transformation of consistent viewpoint is realized. The transformed data is input into the classification model and the model is trained. In a human skeleton sequence, let the number of joints be n and the number of frames be m, n joints form a vertex set $V=\{v_{ti} \mid t=1,2,\cdots,m,i=1,2,\cdots,n\}$, and the edge set connecting the vertices is E. The E is categorized into two kinds of spatial trajectories E_S and temporal trajectories E_F, as shown in Eq. (28) and Eq. (29).

$$E_S=\{v_{ti}v_{tj} \mid (i,j)\in H\} \tag{28}$$

$$E_F=\{v_{ti}v_{(t+1)i}\} \tag{29}$$

In Equation (29), H is the set of natural connections of human joints. By obtaining E_S and E_F, the spatio-temporal topology graph can be constructed, so as to obtain the global and local representations between a node and the neighboring nodes, and then extract the multi-dimensional features. Figure 2 shows the spatio-temporal topology of the human skeleton.

The nodes in the topology graph are classified into three categories, which are source points (nodes themselves), proximal points (nodes close to the center of gravity of the human body), and distal points (nodes far away from the center of gravity of the human body), and are assigned with different weights of 0.0, 1.0, and 2.0. The definition of each node is shown in Eq. (30).

$$l_{ti}\left(v_{tj}\right)=d\left(v_{ti},v_{tj}\right)=\begin{cases}0, & r_j=r_i\\ 1, & r_j<r\\ 2, & r_j>r\end{cases} \tag{30}$$

In Equation (30), r_i is the average clustering of the center of gravity to the joint i in all frames of the training set. With Eq. (30), centripetal and centrifugal motions can be distinguished more clearly. Through Eq. (30), the human motion data is divided into bone information and joint information, which are input into the respective classification networks for training, and the two outputs are summed to finally output the action categories. Synthesizing the above, the sports training action capture and recognition model based on VT-AGCN is constructed.

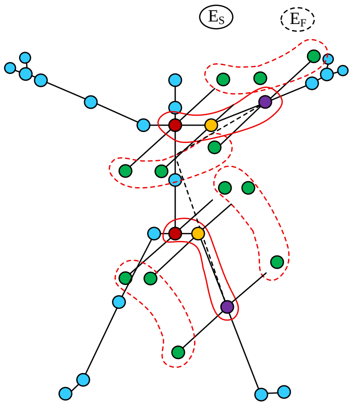

Figure 2: Spatiotemporal topological structure of the human skeleton

3 Performance testing and application practice of virtual reality technology

3.1 Simulation of Joint Movement Training

A simulation experiment was set up to verify the effectiveness of the proposed virtual reality technology in reconstructing and recognizing changes in body parts during physical training. A competitive sports athlete was invited to wear sensors and other tools to complete several physical training sessions. The motion data of this athlete was collected and input into a deep learning model for recognition and evaluation. Figure 3 shows the simulation trajectory of the athlete's elbow joint kinematic training simulation. Figure 4 is the simulation trajectory of the athlete's knee joint sports training simulation. In the simulation process of physical training, the virtual coordinates of the three axes of X-Y-Z of the athlete collected and restored by the system are more consistent with the actual coordinates. For example, during the movement of the elbow joint, the coordinates of the X-axis only showed an error of about 0.06m in frames 2-8 (i.e., during the physical training process), and the axes of the rest of the joints also showed smaller errors.

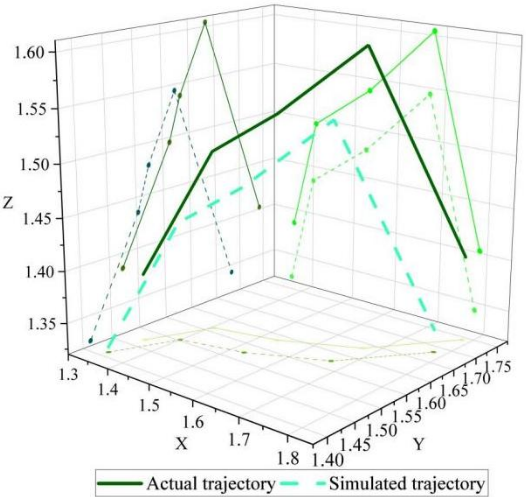

Figure 3: Simulation trajectory of elbow joint motion training

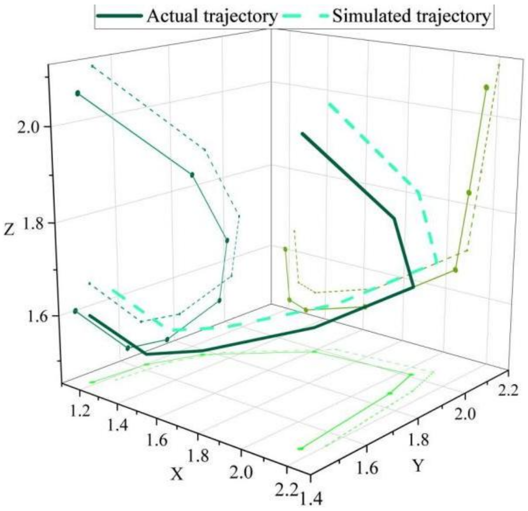

Figure 4: Simulation trajectory of knee joint motion training

3.2 Performance test of the model in physical training

3.2.1 Training Motion Capture Speed Comparison

From the simulation trajectory of joint movement training simulation, the model in this paper can capture and restore the training movements of athletes more accurately. In order to better reflect the application value of the proposed method, the algorithm (DTP+PE-DLS) and model (VT-AGCN) used in the action reconstruction module and action recognition module are examined. Table 1 shows the results of the comparison of the reconstruction speed of human motion training actions with different algorithms. In the reconstruction experiments with different numbers of training movements, the algorithm chosen in this paper, DTP+PE-DLS, consistently maintains a reconstruction speed of 25-29 movements/min, which is faster than that of Pw3D++ (13-16 movements/min), RGB-D (10-13 movements/min), and LVA (10-12 movements/min). In terms of reconstruction real-time, DTP+PE-DLS achieves faster reconstruction speed and better experience in the actual virtual restoration of human body movements due to the simple determination of the motion occlusion that exists during the training process, and the consequent selection of appropriate DTP/PE-DLS algorithms to realize motion reconstruction.

Table 1: Comparison of Rebuilding Speed of Human Movement Training Actions

Number of training exercises	Action reconstruction speed (minutes per unit)			
	DTP+PE-DLS	Pw3D++	RGB-D	LVA
50	25	14	10	12
100	27	13	12	12
150	28	15	10	11
200	26	16	11	10
250	28	14	11	11
300	29	13	13	12
350	27	15	11	10
400	26	15	12	10

3.2.2 Loss Function and Recognition Accuracy Analysis

In terms of action recognition, since it is necessary to input the preprocessed action data into the VT-AGCN model to complete action recognition and classification, the recognition effect of the VT-AGCN model is crucial for the later training strategy adjustment and so on. Figure 5 shows the loss function and training accuracy of the VT-AGCN model obtained after 500 iterations. Figure 6 shows the recognition rate results of the VT-AGCN model for different training actions. The model iterates for 500 times, with a sudden change at the 122nd time, and stabilizes the rest of the time, and finally stabilizes at a lower loss value (0.1244) i.e. by the 250th time. The model accuracy increases with the number of iterations and eventually stabilizes at a higher accuracy of around 0.9904. And the recognition rate of the model is always above 95% in the recognition of four different training actions. Among them, the recognition rate of the paddling action is the highest, reaching 99.60%-99.95%, which is close to 100%. This is followed by the recognition rate of the leg striking action, which reaches the range of 99.24%-99.58%. The recognition module chooses the VT-AGCN model to recognize and classify the action data, which has a more stable recognition effect and higher recognition accuracy.

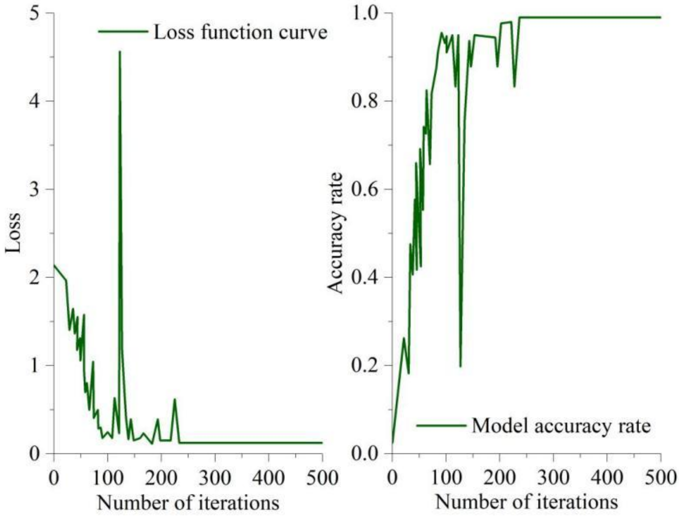

Figure 5: The loss function of VT-AGCN and training accuracy

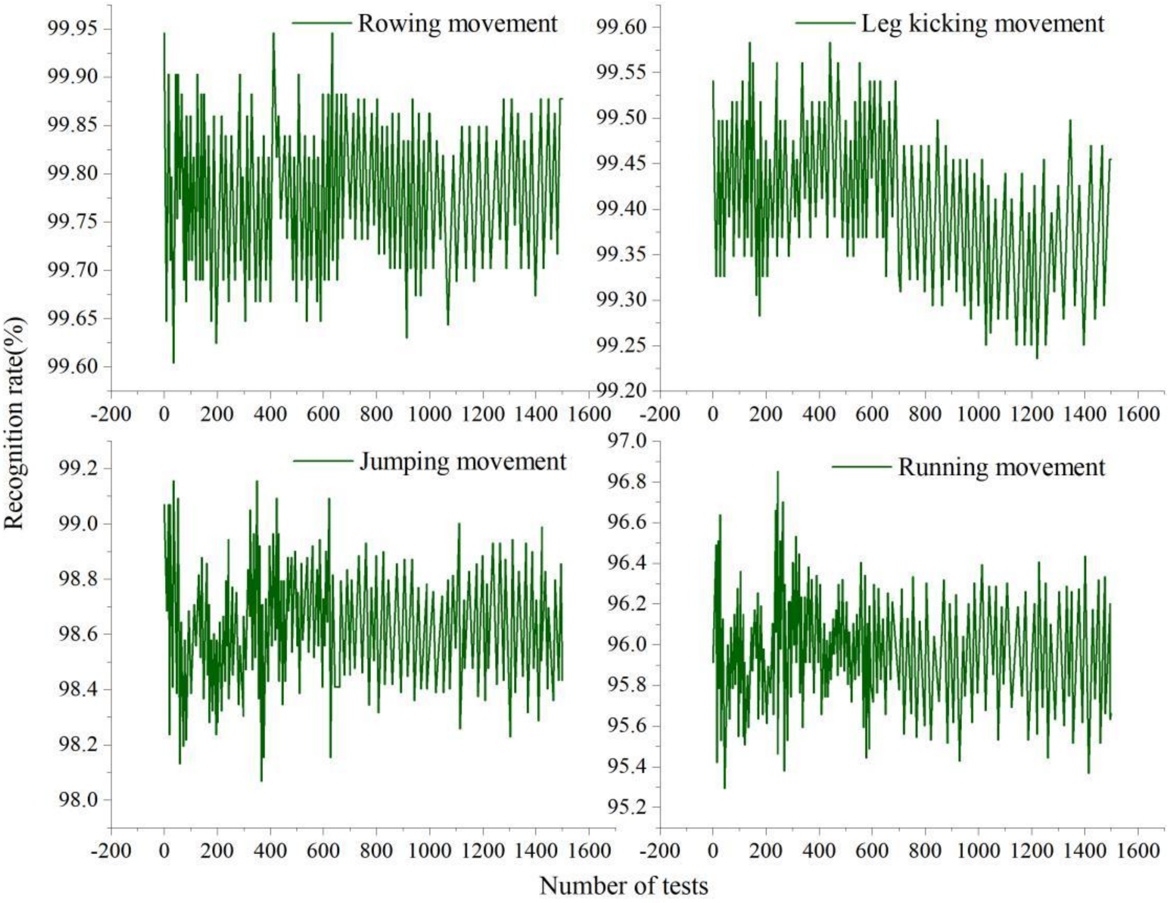

Figure 6: Recognition rate of VT-AGCN for different training movements

3.3 Comparison of athletes' physical training performance assisted by virtual reality technology

3.3.1 Comparison of rower performance

After validating the efficacy of the suggested technique, virtual reality technology was utilized for the physical training of the swimming team at Sport D College, experimenting. The swimming team is a women's swimming team with 40 athletes and alternates, and the daily physical training includes stroke training and leg beating training. Before and after the experiment, the athletes' rowing and hitting scores were collected through the test, the results obtained before and after the experiment were analyzed to measure the influence of virtual reality technology on the physical training result. This experiment was carried out for one semester, covering 16 weeks altogether.

Graph 7 shows the results of the athletes' strokes performed before and after the experiment. The stroke performance of 40 swimmers before the experiment was around 101.680-122.245s. After 16 weeks of virtual reality technology-assisted practice, the stroke performance of these 40 athletes accelerated to 138.705-160.933s, and the hand pain caused by irregular training movements was reduced.

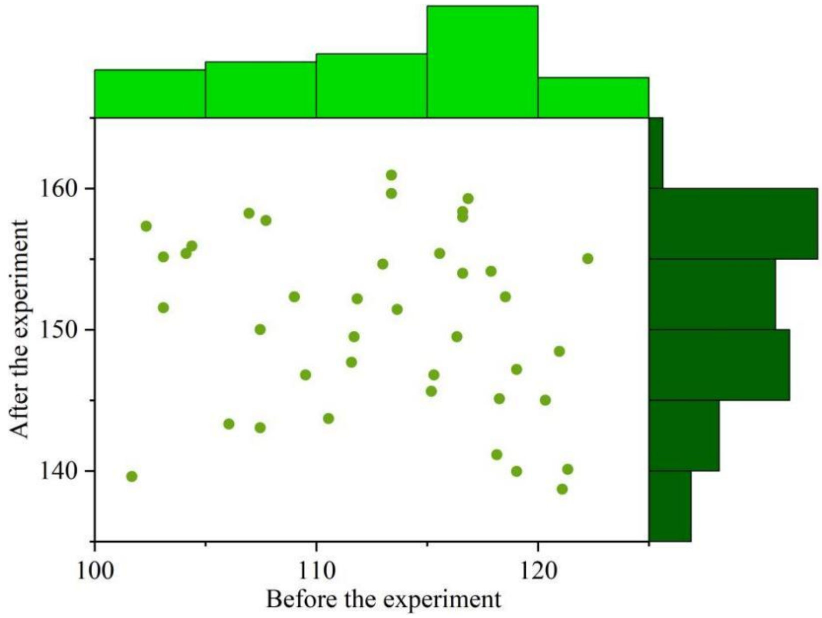

Figure 7: Rowing performance of the athletes before and after the experiment

3.3.2 Comparison of leg striking performance

Figure 8 shows the comparison of the athletes' leg striking performance before and after the experiment.The leg striking performance of 40 swimmers was accelerated from [131.742,176.810]s before the experiment to [190.158,208.846]s after the experiment, and the athletes of the sports team were more average. The use of virtual reality technology to assist the practice can be real-time view of the athlete's paddling hand, leg striking posture, etc. whether to comply with the norms as well as the specific location of the error occurs, so as to facilitate the coach to quickly adjust. This also reduces the risk of injuries that may occur in the process of physical training of athletes and improves their performance in competitive sports.

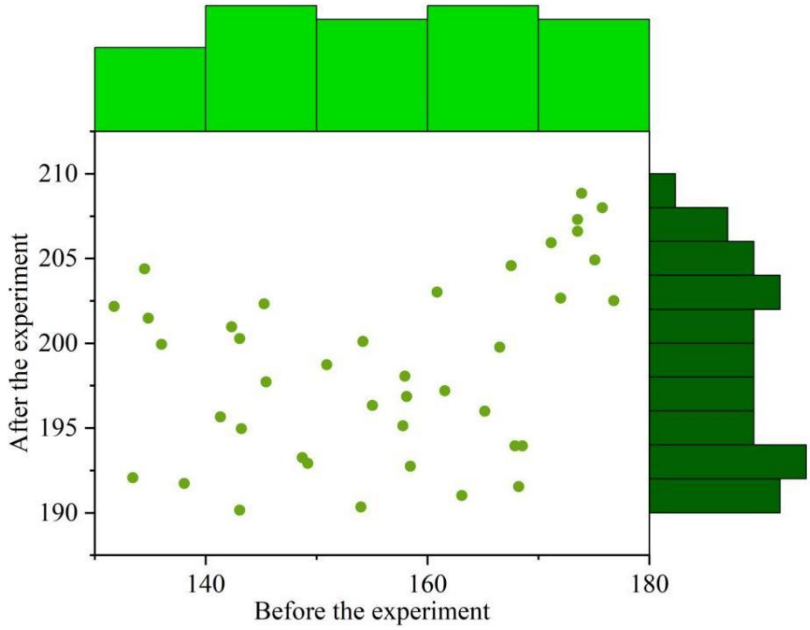

Figure 8: Leg-strengthening performance of athletes before and after experiment

4 Conclusion

In this paper, virtual reality technology is utilized to capture and recognize athletes' physical training movements to provide data references for improving movement standardization. The reconstruction speed of training movements of DTP+PE-DLS algorithm reaches 25-29 movements/min, which is able to complete the reconstruction of training movements very quickly. Meanwhile, the recognition model VT-AGCN has a recognition accuracy of more than 95% for different actions. The fast and accurate recognition makes the physical training performance of the swimming team assisted by the virtual reality technology improve greatly. 40 swimmers' rowing and leg striking performance is accelerated from [101.680,122.245]s, [131.742,176.810]s to [138.705,160.933]s, [190.158, [208.846]s after the experiment. 208.846]s.

The application of virtual reality technology to physical training provides a real-time reference basis for coaches and athletes to facilitate the rapid completion of error correction exercises and optimization of training, which also leads to better athletes' competitive sports performance.

Funding

This research was supported by the Optimize the allocation of sports resources to promote physical activity of children and adolescents (Project No.: 19CTYJ08).

References

[1] Zhang, X., Zhou, A., & Ryall, E. (2021). Philosophy of sports in China: an overview of its history and academic research. Sport, Ethics and Philosophy, 15(4), 556-571.

[2] Shao, J., & Li, L. (2015, January). Strategy Study of Coordinated Development between

Mass Sports and Competitive Sports. In International Conference on Education, Management, Commerce and Society (EMCS-15) (pp. 456-460). Atlantis Press.

[3] Jiang, B., & Wang, S. (2024). Research on the scientific connotation and practical path of the construction of sports power. Quality in Sport, 33, 57206-57206.

[4] Huang, J., Wang, S., & Jiang, B. (2024). Shape the international discourse of Humanities Exchange in China's sports events within The Belt and Road Initiative. Quality in Sport, 36, 56423-56423.

[5] Zhao, M., & Liu, T. (2016). Study on the impact of bid for Winter Olympics on the development of Chinese Winter Sports. Journal of Sports Science, 4, 175-181.

[6] Makhmadaliyevich, R. S. (2025). The use of various methods in the process of special physical training of volleyball players. The American Journal of Interdisciplinary Innovations and Research, 7(03), 28-30.

[7] Satyanarayana, K., Mohan, N., & Pallavi, A. (2020). The importance of physical training in team sports. International Journal of Health, Physical Education and Computer Science in Sports, 39(2), 24.

[8] Zheng, B., Xu, Q., & Zhang, J. (2025). Combining HIIT with Small-Sided Soccer Games Enhances Cardiometabolic and Physical Fitness More Than Each Alone in Overweight Youth: A Randomized Controlled Study. Journal of Sports Science & Medicine, 24(1), 104.

[9] Safronov, R. V., Vanina, E. S., Pershikov, S. V., & Nemchenko, I. A. (2025). Analysis of the negative dynamics in the level of physical training of medical university students in the first four years of study. Theory and Practice of Physical Culture, (3), 61-63.

[10] Pazzianotto-Forti, E. M., Moreno, M. A., Plater, E., Baruki, S. B. S., Rasera-Junior, I., & Reid, W. D. (2020). Impact of physical training programs on physical fitness in people with class II and III obesity: a systematic review and meta-analysis. Physical therapy, 100(6), 963-978.

[11] Parviainen, J., & Aromaa, J. (2017). Bodily knowledge beyond motor skills and physical fitness: a phenomenological description of knowledge formation in physical training. Sport, Education and Society, 22(4), 477-492.

[12] Zouhal, H., Ben Abderrahman, A., Khodamoradi, A., Saeidi, A., Jayavel, A., Hackney, A. C., ... & Jabbour, G. (2020). Effects of physical training on anthropometrics, physical and physiological capacities in individuals with obesity: A systematic review. Obesity reviews, 21(9), e13039.

[13] Guo, Q., Xu, H., Wu, J., & Fang, Z. (2025). Investigating the impact of indoor wood element combinations on human subjective thermal perception in cold region using virtual reality technology. Journal of Wood Science, 71(1), 41.

[14] Seybold, C., & Mantwill, F. (2021). 3D sketches in virtual reality and their effect on development times. Proceedings of the Design Society, 1, 1-10.

[15] Tadeja, S. K., Seshadri, P., & Kristensson, P. O. (2020). AeroVR: An immersive visualisation system for aerospace design and digital twinning in virtual reality. The Aeronautical Journal, 124(1280), 1615-1635.

[16] Bermejo-Berros, J., & Gil Martínez, M. A. (2021). The relationships between the exploration of virtual space, its presence and entertainment in virtual reality, 360º and 2D. Virtual Reality, 25(4), 1043-1059.

[17] Ali, S. F., Azmat, S. A., Noor, A. U., Siddiqui, H., & Noor, S. (2017, November). Virtual reality as a tool for physical training. In 2017 First International Conference on Latest trends in Electrical Engineering and Computing Technologies (INTELLECT) (pp. 1-6). IEEE.

[18] ZHANG, S. (2024). Intelligent physical education: an exploration of virtual reality applications in college martial arts courses. APPLIED MATHEMATICS, 9(1).

[19] Niu, Y., Dong, Y., Zhang, J., Zhang, S., & Cao, Y. (2025). The value of athletics class with the use of virtual reality games for better communication and socialization of students. Education and Information Technologies, 30(1), 693-714.

[20] Akbaş, A., Marszałek, W., Kamieniarz, A., Polechoński, J., Słomka, K. J., & Juras, G. (2019). Application of virtual reality in competitive athletes–a review. Journal of human kinetics, 69, 5.

[21] Mikami, D., Takahashi, K., Saijo, N., Isogawa, M., Kimura, T., & Kimata, H. (2018). Virtual reality-based sports training system and its application to baseball. NTT Technical Review, 16(3).

[22] Mahalil, I., Yusof, A. M., & Ibrahim, N. (2020, August). A literature review on the effects of 6-Dimensional virtual reality's sport applications toward higher presense. In 2020 8th International conference on information technology and multimedia (ICIMU) (pp. 277-282). IEEE.

[23] Edouard, P., Navarro, L., Pruvost, J., Branco, P., & Junge, A. (2021). In-competition injuries and performance success in combined events during major international athletics championships. Journal of science and medicine in sport, 24(2), 152-158.

[24] Farley, J. B., Barrett, L. M., Keogh, J. W., Woods, C. T., & Milne, N. (2020). The relationship between physical fitness attributes and sports injury in female, team ball sport players: a systematic review. Sports medicine-open, 6(1), 45.

[25] Hicks, A. L., Martin Ginis, K. A., Pelletier, C. A., Ditor, D. S., Foulon, B., & Wolfe, D. L. (2011). The effects of exercise training on physical capacity, strength, body composition and functional performance among adults with spinal cord injury: a systematic review. Spinal cord, 49(11), 1103-1127.

[26] Saunders, D. H., Sanderson, M., Hayes, S., Kilrane, M., Greig, C. A., Brazzelli, M., & Mead, G. E. (2016). Physical fitness training for stroke patients. Cochrane Database of systematic reviews, (3).

[27] Nygaard Falch, H., Guldteig Rædergård, H., & van den Tillaar, R. (2019). Effect of

different physical training forms on change of direction ability: a systematic review and meta-analysis. Sports Medicine-Open, 5(1), 53.

[28] Lu, L., Wu, D., & Lei, Y. (2025). Physical Function Training Strategies for Improving Tennis Players' Baseline Movement Stroke Ability. Applied Bionics and Biomechanics, 2025(1), 7898511.

[29] Tian, L., Jie, C., & Guo, H. (2025). Sequencing Effects of Sprint Interval Training Applied Before or After Regular Basketball Training on Sex-Specific Physical Performance Adaptations in Young Athletes. International Journal of Sports Physiology and Performance, 1(aop), 1-11.

[30] Xiao, W., Soh, K. G., Wazir, M. R. W. N., Talib, O., Bai, X., Bu, T., ... & Gardasevic, J. (2021). Effect of functional training on physical fitness among athletes: a systematic review. Frontiers in physiology, 12, 738878.

[31] Lamberth, J., Hale, B., Knight, A., Boyd, J., & Luczak, T. (2013). Effectiveness of a Six-Week Strength and Functional Training Program on Golf Performance. International Journal of Golf Science, 2(1).

[32] Slimani, M., Chamari, K., Miarka, B., Del Vecchio, F. B., & Cheour, F. (2016). Effects of plyometric training on physical fitness in team sport athletes: a systematic review. Journal of human kinetics, 53, 231.

[33] Akbar, S., Soh, K. G., Jazaily Mohd Nasiruddin, N., Bashir, M., Cao, S., & Soh, K. L. (2022). Effects of neuromuscular training on athletes physical fitness in sports: A systematic review. Frontiers in physiology, 13, 939042.

[34] Cho, H., & Sohng, K. Y. (2014). The effect of a virtual reality exercise program on physical fitness, body composition, and fatigue in hemodialysis patients. Journal of physical therapy science, 26(10), 1661-1665.

[35] Li, X., Fan, D., Deng, Y., Lei, Y., & Omalley, O. (2024). Sensor fusion-based virtual reality for enhanced physical training. Robotic Intelligence and Automation, 44(1), 48-67.

[36] Ali, S. F., Noor, S., Azmat, S. A., Noor, A. U., & Siddiqui, H. (2017, December). Virtual reality as a physical training assistant. In 2017 international conference on information and communication technologies (ICICT) (pp. 191-196). IEEE.

[37] Hong, F., Wang, L., & Li, C. Z. (2024). Adaptive mobile cloud computing on college physical training education based on virtual reality. Wireless Networks, 30(7), 6427-6450.

[38] Donath, L., Rössler, R., & Faude, O. (2016). Effects of virtual reality training (exergaming) compared to alternative exercise training and passive control on standing balance and functional mobility in healthy community-dwelling seniors: a meta-analytical review. Sports medicine, 46(9), 1293-1309.

[39] Liu, M., Zhou, K., Chen, Y., Zhou, L., Bao, D., & Zhou, J. (2022). Is virtual reality training more effective than traditional physical training on balance and functional mobility in healthy older adults? A systematic review and meta-analysis. Frontiers in

Human Neuroscience, 16, 843481.

[40] Cannavò, A., Pratticò, F. G., Ministeri, G., & Lamberti, F. (2018, February). A movement analysis system based on immersive virtual reality and wearable technology for sport training. In Proceedings of the 4th international conference on virtual reality (pp. 26-31).

[41] Pastel, S., Petri, K., Chen, C. H., Wiegand Cáceres, A. M., Stirnatis, M., Nübel, C., ... & Witte, K. (2023). Training in virtual reality enables learning of a complex sports movement. Virtual Reality, 27(2), 523-540.

[42] Faure, C., Limballe, A., Bideau, B., & Kulpa, R. (2020). Virtual reality to assess and train team ball sports performance: A scoping review. Journal of sports Sciences, 38(2), 192-205.

[43] Cao, Q., & Yu, Q. (2025). Application analysis of artificial intelligence virtual reality Technology in Fitness Training Teaching. International Journal of High Speed Electronics and Systems, 34(02), 2440084.