REVIEW ARTICLE

Next-generation motion analysis and motion feedback for sports using omnidirectional cameras

Akinori Nagano, Akitoshi Makino

Objectives: Novel three-dimensional (3D) motion analysis methods using omnidirectional cameras are developed and a new framework is presented to integrate this analysis with immersive Virtual Reality (VR) motion feedback. This study addresses the limitations of sports motion analysis that relies on narrow-field-of-view conventional cameras.

Design: Employing a novel methodological and experimental design, new mathematical operations tailored to the spherical projection of omnidirectional cameras were developed and validated. Subsequently, the dual application of the design was demonstrated in quantitative analysis and experiential feedback.

Methods: New 3D reconstruction algorithms, inspired by the Direct Linear Transformation (DLT) and Non-Linear Transformation (NLT) principles but adapted for omnidirectional imagery, were developed. These methods utilize the longitude and latitude of celestial sphere images to determine the camera ray direction, thereby enabling the determination of the camera position/orientation (DLT-inspired method) or the relative position/orientation of the cameras (NLT-inspired method). A separate purely geometric method for minimal-calibration 2D position determination using two omnidirectional cameras was also proposed. Omnidirectional imagery data were then used to generate immersive 360° VR content for motion feedback using a Head-Mounted Display (HMD).

Results: The DLT-inspired 3D reconstruction method achieved an error of 0.22% relative to the calibrated space volume, and the NLT-inspired method achieved an error of 0.34%, both comparable to the accuracy of the gold standard methods. These methods drastically reduce the required number of cameras and technical complexity. Furthermore, omnidirectional recordings were successfully transformed into immersive VR content, enabling an embodied re-experience of movement.

Conclusions: Omnidirectional cameras have successfully overcome the field-of-view and complexity limitations of traditional DLT/NLT methods, achieving high-accuracy 3D motion analysis with minimal camera units. The integration of this precise analysis with immersive VR motion feedback results in a powerful, unified framework that accelerates motor-skill acquisition and performance enhancement. Thus, this study paves the way for the next generation of real-time mobile motion intelligence systems in sports science.

(*Journal of Trainology* 2025;14(2):15-20)

Key words: ■ DLT method ■ NLT method ■ Virtual reality ■ Augmented reality

INTRODUCTION

Motion analysis is widely used across the field of sports sciences, including training science.[1,2] The movement patterns of the body (kinematics) can be quantitatively determined through motion analysis. By calculating the forces and torques (kinetics) that generate these movements, strategies can be devised to improve physical performance and reduce injury risk. Additionally, procedures for capturing athletes' movements at a high resolution and providing rapid feedback are commonly employed, especially in the context of athlete development. In such procedures, feedback may be provided based solely on recorded movies or supplemented with the results of the motion analysis.[3] Hence, motion analysis and motion feedback techniques are essential to athlete development and are expected to evolve further with advancements in artificial intelligence (AI) and image processing/recognition technologies.[4]

To acquire three-dimensional motion recording and analysis, two well-established methods exist: Direct Linear Transformation (DLT) and Non-Linear Transformation (NLT). These two methods offer the highest accuracy and reliability for obtaining 3D coordinate data and are therefore considered the gold standard in the field of motion analysis. The DLT method was introduced in 1971,[5] followed by the NLT method in 1982[6]. Despite some revisions and changes in subsequent studies, the same set of equations have been in use since their introduction.

However, these methods present certain challenges. Both

Received November 11, 2025; accepted December 5, 2025

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Communicated by Takashi Abe, Ph.D.

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DLT and NLT are based on the structure of conventional optical cameras and rely on perspective projections that limit the field of view that can be captured. However, to obtain the 3D positional coordinates, it is necessary to record the subject simultaneously using multiple cameras. In particular, several cameras (10–20 units) may be required when analyzing dynamic movements, resulting in high costs and necessitating advanced technical expertise.

We conceived a new approach for conducting 3D motion analysis using omnidirectional cameras. Omnidirectional cameras possess an extremely wide field of view and can capture spherical videos with a single unit. This allows for a significant reduction in the number of camera units required for motion analysis. Unlike conventional cameras, omnidirectional cameras do not use perspective projection, which makes it difficult to apply the DLT and NLT methods. We devised a set of mathematical operations that enables accurate motion analysis using omnidirectional cameras.[7,8,9]

Another application of omnidirectional cameras in sports and training science[10] is capturing full-sphere and hemispherical videos. By processing these images, virtual reality (VR) content can be generated. When viewed through a head-mounted display (HMD) or augmented reality (AR) glasses, viewers can experience the sensation of being present at the time and place of recording. Depending on the model, omnidirectional cameras can capture and generate separate images for the right and left eyes, enabling the creation of highly immersive 3D VR visuals. Our research team has been working toward the advancement of this technique and has achieved 3D VR feedback with short processing times.

This study focuses on omnidirectional cameras, presents the latest developments in motion analysis and motion feedback in sports settings, and discusses the future potential for research and development in this field.

Omnidirectional cameras

An omnidirectional camera, often referred to as a 360-degree camera or 180-degree camera, can capture visual information from all directions, either a full sphere (360°) or a hemisphere (180°) (Figure 1). Unlike traditional cameras that record a limited field of view, omnidirectional cameras often use multiple lenses (typically two ultrawide-angle fisheye lenses) to simultaneously capture the entire surrounding environment. Images or videos from each lens are then stitched together using specialized software, thereby creating a seamless panoramic or spherical view. When viewed through head-mounted displays (HMDs) or AR glasses, footage allows users to feel as if they are physically present at the recorded location, offering immersive experiences in sports, tourism, education, and various related settings. Researchers and developers are actively exploring methods to use omnidirectional cameras for rapid motion feedback, especially in sports science, where high-resolution real-time analysis can enhance performance and reduce injury risk.

An omnidirectional camera can capture images of an entire celestial sphere. Therefore, it addresses the challenges associated with the DLT and/or NLT methods owing to a narrow angle of view. Conventional cameras use perspective projection, and DLT and/or NLT methods are based on a Cartesian coordinate system. Because the omnidirectional camera does not use perspective projection like a conventional camera, the DLT and/or NLT methods cannot be applied. When processing images obtained using omnidirectional cameras, it is beneficial to use a polar coordinate system in addition to a

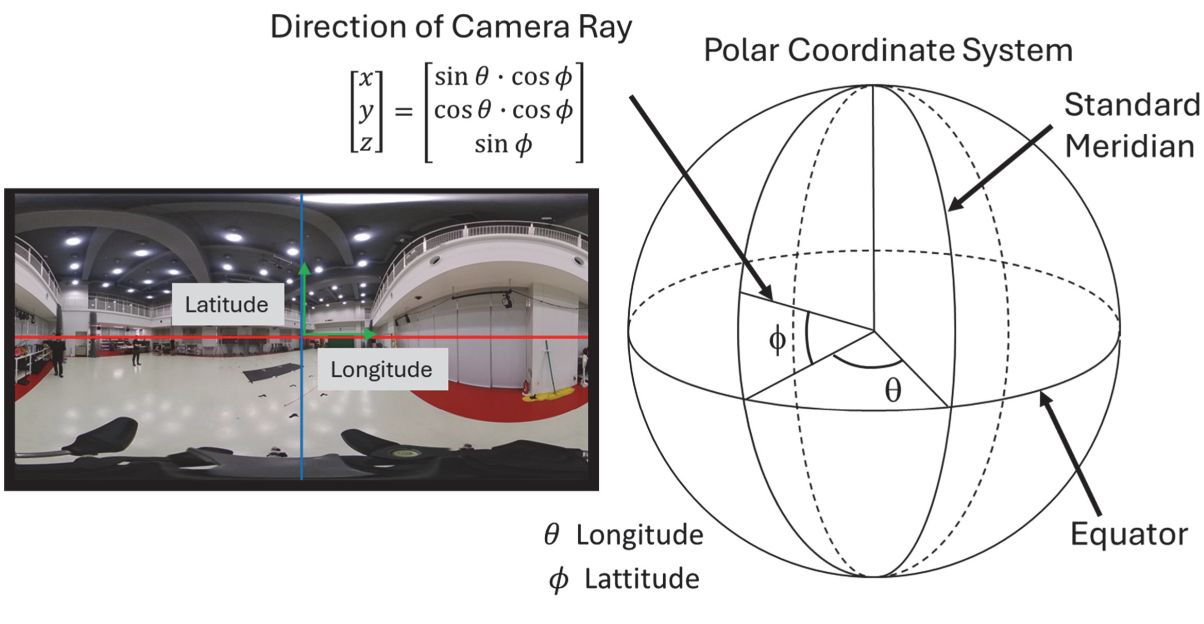

Figure 1. Omnidirectional image and the relationship between Cartesian and polar coordinate systems.
In the omnidirectional camera's polar coordinate system, θ and ϕ correspond to the longitude and latitude of the celestial sphere, respectively. The direction of the camera rays can be determined based on these angles.

Cartesian coordinate system (Figure 1). A celestial image from an omnidirectional camera can be presented in two dimensions using an equirectangular projection (or its equivalent). In an equirectangular projection, the horizontal and vertical positions within an image correspond to the longitude and latitude of the celestial sphere, respectively. Using this information and considering the polar coordinate system, the camera ray connecting the center of the camera to the point of interest can be determined. We used this mathematical operation to utilize omnidirectional cameras for motion analysis.[7,8]

DLT-inspired method

The direct linear transformation (DLT) is one of the most frequently used methods of motion analysis. Since its introduction in 1971, the method has been used in numerous studies[5]. In the calibration phase, the DLT method assumes that accurate three-dimensional position of the control points are available. At least six control points with known coordinates are required. This method is frequently used in sports training and competitions. The DLT method is based on the structure of conventional optical cameras in which perspective projection is used. Consequently, the camera can only capture a limited angle of view, which depends on the focal length and size of the image sensor, and rarely exceeds 90 °in either the horizontal or vertical direction. To cover a wide area of interest, it is necessary to either move the camera itself[11,12] or employ more cameras[13]. Both approaches impose technical and operational requirements including additional hardware, research staff, and funding. These requirements can also cause data inaccuracies.

In our previous study,[7] we proposed a three-dimensional (3-D) calibration and reconstruction method using omnidirectional cameras, which have significantly wider angles of view than conventional cameras. For the points of interest, the longitude and latitude of the celestial sphere were obtained from images captured using an omnidirectional camera (Figure 1). The direction of the points of interest relative to the camera's reference frame was determined by the longitude and latitude, considering the polar coordinate system. This concept and its mathematical operations are the unique and innovative aspects of this study. In the calibration phase, the position and orientation of the omnidirectional camera relative to the global reference frame were determined from the image of the control points with known 3-D coordinates. During the reconstruction phase, the intersection points of the rays from the cameras were determined.

The accuracy of the proposed method was validated via an evaluation experiment.[7] The evaluated resultant error was 0.22% relative to the volume of the calibrated space; this was within the range of error reported in previous studies that used the traditional DLT method (0.09–0.26%).[14] The wide-angle of view provided by omnidirectional cameras can be fully exploited using this method.

NLT-inspired method

Apart from the DLT method, the NLT method is the other method that is considered the gold standard[6]. In the NLT method, it is not necessary use control points of known coordinates. Control points of unknown coordinates are used, which makes the calibration process much easier than in the DLT method. On the other hand, in mathematical terms, it is required that all control points are observed simultaneously by multiple cameras at the time of calibration in NLT method. This requirement does not exist for the DLT method. However, in practical motion analysis settings, cameras are usually synchronized beforehand. Therefore, this additional requirement does not hinder the use of the NLT method. Because of this unique feature in which control points of unknown coordinates can be used, many automated motion capture systems currently utilize this method.

Like the DLT method, which is based on the perspective projection of ordinary cameras, the use of the NLT method is limited in some situations. In a previous study, we proposed a method for 3-D data collection method inspired by the NLT method using omnidirectional cameras that can capture images of the entire celestial sphere.[8] For the points of interest, the longitude and latitude of the celestial sphere were obtained from the image (Figure 1). The direction of the camera rays was then determined. This point is similar to that reported by Nagano[7] in the DLT-inspired omnidirectional method. Calculating the direction of the camera rays is essential for the proposed method. During the calibration process, the relative positions and orientations of the omnidirectional cameras were determined from the images of the control points with unknown 3-D coordinates. We determined the relative position of cameras by using the constraint condition: "each control point is simultaneously observed by multiple cameras."

We verified that the accuracy of the proposed method was comparable to that of the traditional NLT method[8]. The resultant error was 0.34% relative to the size of the calibrated field, which is larger than the error for the DLT-inspired method (0.22%), but still within the range of errors reported in previous studies. This again confirms that good accuracy can be achieved in motion analysis using omnidirectional cameras.

2D position determination with minimal calibration

This geometric method was proposed to determine the 2D position of a target object using two omnidirectional cameras with minimal calibration requirements. This method assumes that two control points with known coordinates are visible to both the cameras. Using these reference points, the relative positions of the cameras can be estimated, enabling subsequent localization of the target object[9].

Let the control points be P_1 (A) and P_2 (B) and the two cameras be C_1 (C) and C_2 (D). When the control points are projected onto the spherical images captured by each camera, the corresponding viewing directions are represented by angular parameters. By connecting these control points and camera centers, a quadrilateral *ABDC* is geometrically formed, where each vertex corresponds to the line of sight from the camera to the control point. The internal angles (θ_1 – θ_7) define the relative orientation of the cameras and control points (Figure 2).

Applying the law of sines to each constituent triangle yields

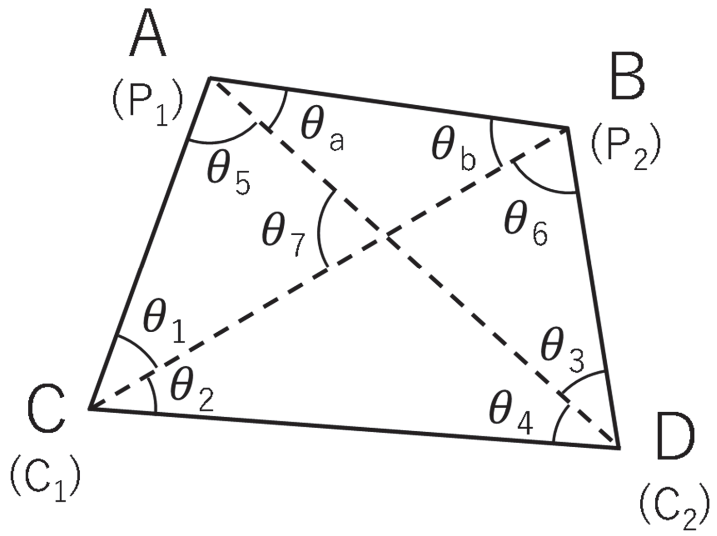

Figure 2. Geometric setup and notation for two-dimensional position determination.
Two omnidirectional cameras (C1 and C2) were used to observe the two control points with known two-dimensional coordinates (P1 and P2). The sight lines extending from each camera to each control point form a quadrilateral ABDC. Internal and external angles (θ1–θ7) define the relative orientation of the cameras and control points, while auxiliary angles θa and θb represent opposite interior angles used in the geometric derivation.

a series of relationships between side lengths and angles. These relationships allow the elimination of intermediate variables and lead to proportional relationships such as

from $\triangle ABC$ and $\triangle ABD$:

$$\frac{\sin\theta_b}{\sin\theta_a} = \frac{AB}{BD}\cdot\frac{1}{\sin\theta_3}\cdot\frac{AC}{AB}\cdot\sin\theta_1 = \frac{AC}{BD}\cdot\frac{\sin\theta_1}{\sin\theta_3} \tag{1}$$

from $\triangle ACD$ and $\triangle BCD$:

$$\frac{AC}{BD} = \frac{1}{CD}\cdot\frac{\sin\theta_6}{\sin\theta_2}\cdot CD\cdot\frac{\sin\theta_4}{\sin\theta_5} = \frac{\sin\theta_6\cdot\sin\theta_4}{\sin\theta_5\cdot\sin\theta_2} \tag{2}$$

combining (1) and (2):

$$\frac{\sin\theta_b}{\sin\theta_a} = \frac{\sin\theta_1\cdot\sin\theta_4\cdot\sin\theta_6}{\sin\theta_2\cdot\sin\theta_3\cdot\sin\theta_5} \tag{3}$$

These relationships provide the geometric constraints necessary to solve for unknown angles. Once these angles are determined, the shape of quadrilateral *ABDC* is uniquely defined, thereby determining the relative camera positions C_1 (C) and C_2 (D). Together with the external angle constraint $\theta_a + \theta_b = \theta_7$, this system allows θ_a and θ_b to be numerically determined. Once these values are obtained, quadrilateral *ABDC* is uniquely defined, which in turn specifies the relative positions of C_1 and C_2.

After the camera geometry is established, each camera's viewing direction toward the target can be expressed by azimuthal angles θ_{C1} and θ_{C2}, measured on the omnidirectional images. The target's 2D coordinates are then obtained as the intersection of two rays extending from C_1 and C_2 along these azimuthal directions. This purely geometric computation enables position estimation based entirely on angular information, without requiring any prior calibration of distance, lens parameters, or camera alignment except for obtaining the position coordinates of two control points.

With the camera geometry fixed, the azimuthal directions from each camera toward the target object can be identified on the spherical images as θ_{C1} and θ_{C2}. The intersection of the two rays extending from C_1 and C_2 along these directions defines the 2D coordinates of the target. This approach requires no elaborate camera calibration or 3D reconstruction, and relies solely on angular information derived from omnidirectional imagery. We verified the accuracy of a new image analysis method using an omnidirectional camera. An indoor flat area measuring 5 m (X-axis) × 5 m (Y-axis) was prepared. Control points with known coordinates were placed at 1 m intervals along both the X and Y axes, including their intersections. The positional errors between the actual and estimated coordinates were 0.020 m along the X-axis, 0.031 m along the Y-axis, and 0.039 m overall. The relative error ratios with respect to the target area were 0.4% and 0.6%, respectively.[9]

VR motion feedback

Motion analysis using omnidirectional cameras is an established method for quantifying human movements in sports and health sciences. In addition to their analytical use, such recording data can be transformed into immersive VR content, thereby enabling a novel form of motion feedback that combines biomechanical accuracy with experiential learning. This dual applicability allows the same visual data to serve as both a research tool for precise kinematic evaluation and a training resource for intuitive self-referential feedback. Thus, VR motion feedback using omnidirectional cameras extends

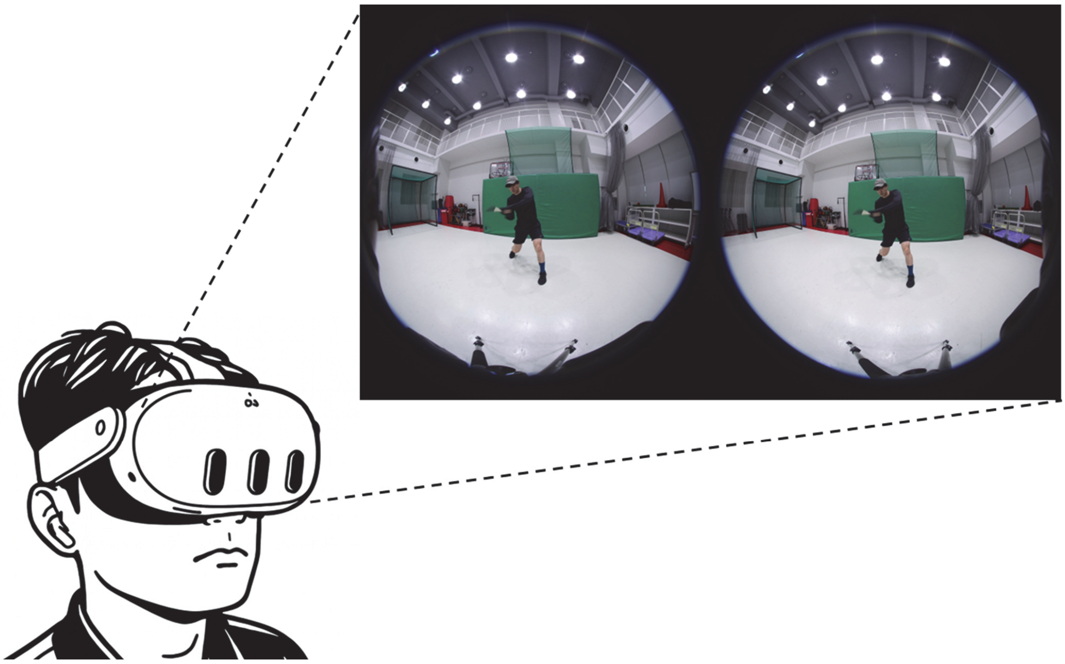

Figure 3. Immersive motion feedback using omnidirectional video and a head-mounted display (HMD).
Recordings captured by omnidirectional cameras can be replayed as immersive 360° video content in a VR environment. The data used for motion analysis can thus also be utilized for embodied re-experience through an HMD, enabling intuitive self-evaluation and feedback on movement performance within the original real-world context.

the role of motion analysis beyond measurement to immersive re-experience.

Traditional biofeedback and video replay provide limited 2D information that is often detached from a performer's embodied experience. In contrast, VR motion feedback reproduces the spatial and sensory context of movement by integrating visual, vestibular, and proprioceptive cues to enhance sensorimotor adaptation.[15] When omnidirectional footage is viewed through an HMD, the performer can re-experience their movement from a first-person or external perspective that dynamically responds to head motion. This promotes an immersive experience, body ownership, and spatial coordination, which are the key factors in both motor learning and rehabilitation.

Clinical and experimental studies have demonstrated that immersive VR feedback improves postural control, balance, and upper limb precision more effectively than conventional feedback methods.[16,17] Similarly, interactive or game-based VR environments encourage repetition and focused engagement, thereby facilitating neural reorganization and skill acquisition.[18] From a sports perspective, omnidirectional VR feedback enables athletes to analyze and re-experience their performance within a lifelike environment, supporting technical refinement, tactical awareness, and overall performance enhancement.[19,20]

Moreover, tracking head orientation through an HMD provides valuable information about where the performer directs their attention and how they align their body relative to the environment. When combined with kinematic data from omnidirectional recordings, this information enables a detailed analysis of the facing direction and spatial awareness throughout movement execution.[17] Such integration of quantitative motion data with immersive replays bridges biomechanical analysis and perceptual feedback, establishing a unified framework for embodied motor learning and performance improvement. Building on the prior work that established optimal filming techniques (e.g., camera settings, composition, and equipment) in various sports contexts, this study contributes to advancing research aimed at developing training protocols utilizing HMDs and enhancing motor learning, through real-time feedback using AR technologies.

Conclusion and future perspectives

This paper demonstrates the revolutionary potential of omnidirectional cameras to overcome the long-standing limitations of conventional motion analysis, which relies on field-of-view-restricted DLT and NLT methods. By devising novel mathematical operations tailored to the spherical projection of an NLT-inspired 3D reconstruction methods. Both methods achieved high accuracies, comparable to the established gold standards (errors of 0.22% and 0.34%, respectively), while requiring fewer camera units and a less complex setup. This study also introduced a highly practical 2D position-determination method with minimal calibration, relying purely on geometric constraints. The same omnidirectional data serve a dual purpose: facilitating precise biomechanical analysis and enabling rapid immersive VR motion feedback. This integration offers an embodied learning experience that is superior to traditional 2D video replay, which can accelerate motor-skill acquisition and performance enhancement in sports.

In the future, this research will be integrated and automated. First, we focus on automating the entire analysis pipeline, from capturing omnidirectional footage to generating an interactive VR environment overlaid with quantitative kinematic data. This involves leveraging AI for automated feature tracking and the real-time computation of key performance metrics, making high-precision analysis instantaneously accessible to coaches and athletes. Second, the current methodology can be extended to multi-person analysis in highly dynamic and unpredictable environments, such as team sports. This requires optimization of the reconstruction algorithms for robustness against occlusions and complex background clutter. Finally, the VR feedback loop was enhanced by incorporating AR, allowing athletes to see their optimal motion trajectories overlaid onto a real-world practice environment. This transition from laboratory-based 3D analysis to a fully integrated, real-time, and mobile motion intelligence system marks the next frontier in training science, promising the democratization of elite-level motion analysis and feedback.

DISCLOSURE STATEMENT

The authors report no conflicts of interest.

ACKNOWLEDMENTS

This study was supported by the Leading-Edge Research Project for Sports Medicine and Science, Japan Sports Agency.

REFERENCES

1. Robertson D. G, Caldwell G. E, Hamill J et al. Research Methods in Biomechanics, 2nd Edition, Champaign, Human Kinetics, 2014.
2. Winter D. A. Biomechanics and Motor Control of Human Movement, 4th edition, John Wiley, Sons, New Jersey, Inc. Hoboken, 2009.
3. Hribernik M, Umek A, Tomažič S, Kos A. Review of Real-Time Biomechanical Feedback Systems in Sport and Rehabilitation. *Sensors (Basel)* 2022; 22: 3006.
4. Leddy C, Bolger R, Byrne P. J et al. The application of Machine and Deep Learning for technique and skill analysis in swing and team sport-specific movement: A systematic review. *Int J Comp Sci Sport* 2024; 23: 110-145.
5. Abdel-Aziz Y. I, Karara H. M, Hauck M. Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. *Photogrammetric engineering & remote sensing* 2015; 81: 103-107.
6. Dapena J, Harman E. A, Miller J. A. Three-dimensional cinematography with control object of unknown shape. *J Biomech*. 1982; 15: 11-19.
7. Nagano A. Three-dimensional videography using omnidirectional cameras: An approach inspired by the direct linear transformation method. *J Biomech* 2021; 128: 110722.
8. Nagano A, Kudo S. A Method of Three-Dimensional videography using omnidirectional cameras with control points of unknown coordinates. *International Journal of Sport and Health Science* 2024; 22: 1-4.
9. Makino A, Minoura S, Tahara T et al. December. Verification of a new motion analysis method using omnidirectional cameras. Paper presented at *the 37th Annual Meeting of the Japan Society of Training Science for Exercise and Sport* 2024; Okayama, Japan. [in Japanese]
10. Kittel A, Cunningham I, Larkin P. Editorial: 360° VR in sport and physical activity - it is very real. *Front Psychol* 2023; 14: 1342533.
11. Yanai T, Hay J. G, Gerot J. T. Three-dimensional videography of swimming with panning periscopes. *J Biomech* 1996; 29: 673-678..
12. Yu B, Koh T. J, Hay J. G. A panning DLT procedure for three-dimensional videography. *J Biomech* 1993; 26: 741-751.
13. González-Frutos P, Veiga S, Mallo J et al. Spatiotemporal Comparisons Between Elite and High-Level 60 m Hurdlers. *Front Psychol* 2019; 10: 2525.
14. Hinrichs R. N, McLean S. P. NLT and extrapolated DLT:3-D cinematography alternatives for enlarging the volume of calibration. *J Biomech* 1995; 28: 1219-1223.
15. Catania V, Rundo F, Panerai S et al. Virtual Reality for the Rehabilitation of Acquired Cognitive Disorders: A Narrative Review. *Bioengineering (Basel)* 2023; 11: 35.
16. Corbetta D, Imeri F, Gatti R. Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review. *J Physiother* 2015; 61: 117-124.
17. Bateni H, Carruthers J, Mohan R et al. Use of Virtual Reality in Physical Therapy as an Intervention and Diagnostic Tool. *Rehabil Res Pract* 2024; 2024: 1122286.
18. Elor A, Kurniawan S, Teodorescu M. Towards an immersive virtual reality game for smarter post-stroke rehabilitation. In *2018 IEEE International Conference on Smart Computing (SMARTCOMP)* , Taormina, IEEE, 2018.
19. Borghesi F, Mancuso V, Pedroli E et al. From virtual reality to 360 videos: upgrade or downgrade? The multidimensional healthcare VR technology. Chapter 12, *In Handbook of research on implementing digital reality and interactive technologies to achieve society 5.0*, Eds. Popovis D, Ito Y, Hershey, IGI Global, 2022.
20. Mancuso V, Borghesi F, Bruni F et al. Mapping the landscape of research on 360-degree videos and images: A network and cluster analysis. *Virtual Reality* 2024; 28: 101.