FEATURES OF MODERN MOTION CAPTURE SYSTEMS

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Abstract. Introduction. In the present era, high-precision quantitative biomechanical analysis of human motor actions is conducted by motion analysis systems that employ both standard digital cameras and specialized high-speed cameras. Nevertheless, no studies have yet examined the characteristics of contemporary motion capture systems from the perspectives of hardware and software. The objective of this study is to present an analytical overview of the features of modern motion capture systems. The methodology employed in this study comprises a theoretical analysis, a systematic and generalised synthesis of contemporary scientific and methodological literature, and an examination of Internet resources pertinent to the research problem. As a result, the wide variety of motion capture systems can be classified according to several criteria, including those that use specialized cameras and those that use standard cameras. In the domain of software, motion capture systems can be classified into two main categories: those that offer qualitative, visual analysis of video clips (such as the ability to merge up to nine video clips into a single video clip or to create a single image with multiple superimposed images of a movement), and those that provide quantitative parameters of motor action. Optical motion capture systems that employ specialized cameras with passive and active motion capture markers facilitate high-precision, detailed biomechanical analysis, with automatic marker identification based on professional software for 3D video motion analysis using up to 256 digital cameras with a resolution of up to 26 megapixels. The potential of motion analysis and modeling technologies, particularly those incorporating artificial intelligence, to automatically trace the coordinates of human body points was considered. As a conclusion of this study, the capabilities of modern motion analysis systems were analyzed depending on the hardware and software. Modern motion analysis systems allow obtaining quantitative and qualitative data on human movements in an objective, informative and real-time manner. The plethora of contemporary motion analysis technologies enables precise evaluation and qualitative examination of an athlete's technique and motion patterns in both laboratory and field settings. The distinctive features of the BioVideo software for the biomechanical analysis of human motor actions through the use of video recording frames from a standard camera were presented.

Keywords: biomechanical analysis, human movement, modelling, sports technique, artificial intelligence.

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ОСОБЛИВОСТІ СУЧАСНИХ СИСТЕМ ЗАХОПЛЕННЯ РУХУ

Анотація. Вступ: Сьогодні високоточний кількісний біомеханічний аналіз рухових дій людини виконують системи аналізу рухів, які використовують як стандартні цифрові камери, так і спеціалізовані високошвидкісні камери. Проте дослідження, що аналізують особливості сучасних систем захоплення руху з погляду апаратного та програмного забезпечення, відсутні. Мета дослідження: представити аналітичний огляд особливостей сучасних систем захоплення руху. Методи: теоретичний аналіз, систематизація та узагальнення сучасної науково-методичної літератури, Інтернет-ресурсів. Результати: велику різноманітність систем захоплення руху можна класифікувати за кількома критеріями, зокрема залежно від апаратного забезпечення, на такі, що використовують спеціалізовані камери, і такі, що використовують стандартні камери. За програмним забезпеченням системи захоплення руху поділяються на такі, що забезпечують якісний візуальний аналіз відеокліпів (наприклад, поєднують до дев'яти відеокліпів в один відеокліп або створюють одне зображення з кількома накладеними зображеннями руху), та такі, що забезпечують кількісні параметри рухової дії. Системи оптичного захоплення руху, що використовують спеціалізовані камери з пасивними та активними маркерами, забезпечують високоточний детальний біомеханічний аналіз з автоматичною ідентифікацією маркерів на основі професійного програмного забезпечення для аналізу руху 3D-відео з використанням до 256 цифрових камер із роздільною здатністю до 26 мегапікселів. Розглянуто технології аналізу і моделювання руху, зокрема системи штучного інтелекту, які автоматично відстежують координати точок тіла людини. Висновки: проаналізовано можливості сучасних систем аналізу руху залежно від апаратного та програмного забезпечення. Сучасні системи аналізу руху дають змогу об'єктивно, інформативно та в режимі реального часу отримувати кількісні та якісні дані про рухові дії людини. Різноманітність сучасних технологій аналізу руху дає змогу проводити точну оцінку та якісний аналіз техніки рухових дій спортсмена як в умовах лабораторій, так і в польових умовах. Представлено особливості програмного забезпечення BioVideo для біомеханічного аналізу рухових дій людини за відеограмою зі стандартної камери.

Ключові слова: біомеханічний аналіз, рухові дії людини, моделювання, спортивна техніка, штучний інтелект.

Introduction. Motion analysis systems are one of the leading areas of modern science [5, 14]. Motion capture is used to record the human movement in real time and replicate it in a virtual space generated digitally. Modern motion capture technologies are used in two main directions: the first – to measure and process information about the characteristics of movements (life sciences, human biomechanics & sports research, media and entertainment and engineering), and the second – to create movement models (robotics, virtual reality, animation) [4, 8, 20].

Systematization, classification, analysis, and identification of the main features of motion capture systems in biomechanics is an urgent problem in the field of physical education and sports, the solution of which will allow to expand the arsenal of possible scientific research, as well as to raise their methodological level. Understanding the possibilities of modern biomechanical technologies also has practical implications significance for physical culture and sports rehabilitation [5, 15]. However, no studies have yet analysed the features of modern

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motion capture systems from a hardware and software point of view.

The research objective of this study is to present an analytical overview of the features of modern motion capture systems.

Material and methods. Theoretical analysis, systematization and generalization of modern scientific and methodological literature, Internet resources on the research problem. The article was prepared based on the analysis of 57 references and 27 Internet websites.

Results. The big variety of the motion capture systems is possible to classify, in our opinion, by several criteria particularly depending on hardware on those using the specialized cameras and those using standard cameras. Under software the motion capture systems may be the following: those which provide the qualitative, visualized analysis of clips (for example, mix up to nine video clips into one single video clip or create a single image with several superimposed images of a movement) and those systems which provide the quantitative parameters of motor action (Figure 1). As a rule, the systems for the quantitative biomechanical analysis, work with non-standard, but with specialized cameras.

Depending on number of used cameras which work is synchronized, the biomechanical analysis can be carried out both in two (2D) or three dimensions (3D).

Optical motion capture, which can also be referred to as 'marker-based tracking', uses a set of cameras to track the coordinates of these markers to construct a detailed three-dimensional view of a moving subject.

Most motion capture systems use passive markers which 'bounce' light emitting from infrared light-emitting diodes (LEDs) circled around the cameras' lenses, while other marker sets may use active LEDs, which instead give off their own light. The brightness of these markers ensure that they are the only images the cameras can pick up, rather than the test subject or any background "noise".

Passive markers are usually retro-reflective and spherical, making it easier for a computer to work out their central points. When these central points are tracked by multiple cameras from different angles, they can be triangulated to produce 3D coordinates of the motion being performed. The resulting data can then be transposed onto a model or skeleton using mocap software. Camera's native speeds go up to 500 frames per second (fps), and as high as 10 000 fps.

Capture synchronized event data from multiple sources that integrated with third-party systems. Wide range of third-party equipment including multi-axis biomechanics force plates, EMG systems, Kistler Force Platforms and, analog to digital converters from 16 to 64 channels.

Optical motion capture systems using specialized cameras with passive & active mocap markers provide high precision detailed biomechanical analysis. For example, BTS Bioengineering (Italy) motion capture system (https://www.btsbioengineering.com) with automatic identification of markers produce professional software for 3D video-based motion analysis up to 256 digital cameras with resolution up to 26 megapixel. General characteristic of BTS Bioengineering system: accuracy <0.1mm. OptiTrack systems (USA) (https://optitrack.com/) typically produce less than 0.2 mm of measurement error, even across large tracking areas–even of those 10,000 sq ft or more. In smaller measurement areas, OptiTrack systems regularly produce errors of 0.1 mm or less [1].

Recently, more and more motion capture systems provide the ability to perform biomechanical analysis using markerless technology. Innovative software complements optical motion capture system with inertial sensors and tracks the

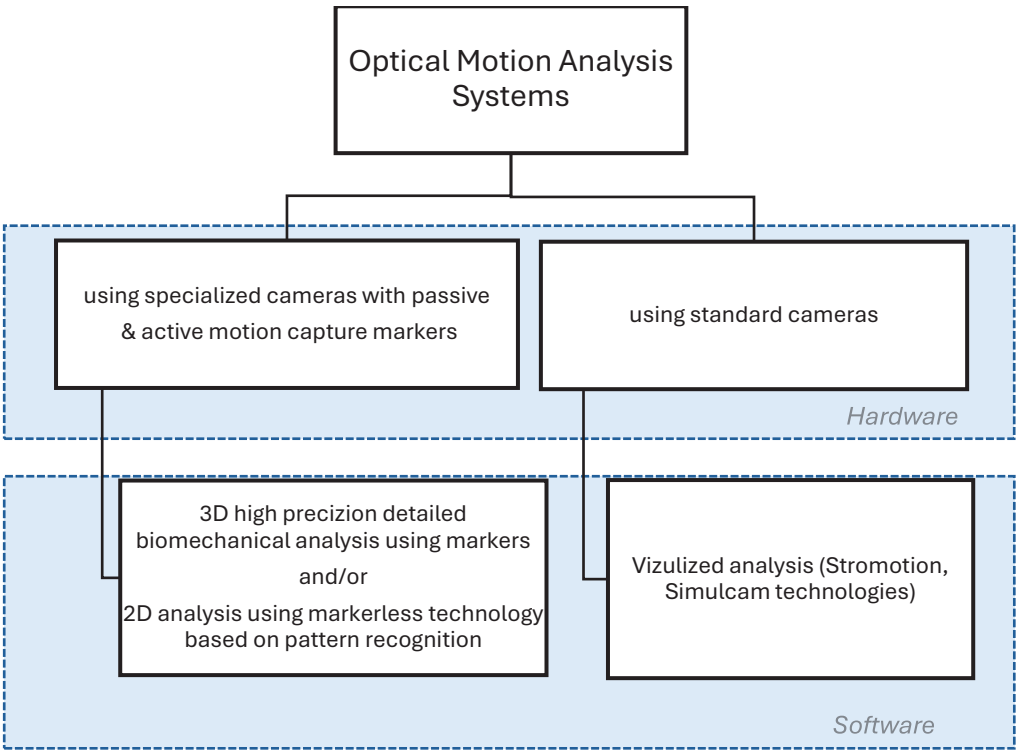

Figure 1. Classification scheme of motion analysis systems by hardware and software criteria

coordinates of points by solving the problem of artificial intelligence (AI) – pattern recognition. Markerless tracking with Contemplas software (Germany) (https://contemplas.com/) brings markerless tracking to Vicon. Thanks to Contemplas' Templo motion analysis software, it is possible to track and analyse subject's action in the lab, field, or pool. Such systems can supported with popular programming technologies – MATLAB, Python, LabView, or use ProCalc, free built-in application. To compute kinematical parameters, researcher can either use a pre-defined biomechanical model (such as Vicon Plug-in Gait) or create own model using Python programming language. Xcitex (USA) software (https://www.xcitex.com/) realize adaptive markerless feature tracking on different scale – from insect biomechanics to ballistic flight dynamics.

AI technology of pattern recognition is realised in Realtime Barbell Analyzer for Olympic Weightlifting (USA) (https://www.senbodi.com/). This complex allows you to obtain graphic and numerical characteristics of the movement structure of the "athlete-barbell" system on a PC immediately after the video recording of the athlete's movement actions: time and rhythmic characteristics of the movement; extremes of dynamic characteristics; force impulses in separate phases of movement; calculation of derivative indicators (force gradients, various coefficients); performance indicators, capacity; graphical representation of the dependence of force, speed, trajectory of the bar on time, etc.

The possibility to urgently analyse the indicators of the barbell lifting technique and compare them with the indicators of the technique of previously performed lifting, which was entered in the database, is especially important.

Realtime Barbell Analyzer also send information via Bluetooth to app on a smart phone. This technology has been used by China National Weightlifting team for 3 years which won 7 gold medals in Tokyo Olympics 2021. Sensor data are captured at 100Hz. Video is at 120 or 240 fps.

Software development company Pixellot (Israel) (https://www.pixellot.tv/) is a focused-on creation of automatic video and analytics for the sports market. Here are some of the ways Pixellot is using AI in soccer:

Automated Camera Control: Pixellot uses computer vision algorithms to control cameras that capture the action on the field. The cameras are programmed to track the ball, players, and referees and adjust their position and angle automatically, ensuring that the footage is always focused on the most important aspects of the game [6, 7].

Real-Time Game Analysis: Pixellot's AI algorithms analyze the live footage to extract relevant data such as the position and movement of the players, ball possession, and game events such as shots on goal and fouls. This data is used to create real-time statistics and highlight reels that are displayed during the game and shared with fans and coaches after the game.

Automated Highlight Reels: Pixellot's AI algorithms are able to automatically create highlight reels from the game footage, using advanced editing techniques such as object detection and tracking, to identify key moments in the game such as goals, saves, and fouls. These highlight reels can be used for coaching, scouting, or for social media promotion.

Customized Viewing Experience: Pixellot's AI algorithms allow viewers to customize their viewing experience by selecting different camera angles or zooming in on specific players or areas of the field. The algorithms can stitch together footage from multiple cameras and create a seamless viewing experience for the user.

Multi-angle 8K cameras capture every drill at once. Patented Clipper software cuts sessions into clips of specific plays that can be reviewed and shared. Go panoramic for a full-field view. Review clips on our sports video analysis app for coaching on-the-fly. There's a reason that clubs like FC Barcelona, Bayern Munich and Real Madrid use Pixellot as their video coaching platform of choice.

Swiss-based company Dartfish (Switzerland) (www.dartfish.com) provided the motion capture system using standard cameras. Those cameras have a standard frame speed of 30 frames per second (fps) (NTSC) in North America and 25 fps (PAL) in Europe. If the camera records 25 pictures every second, one picture every 0.04 seconds.

Dartfish developed the SimulCam™ and by StroMotion™ technologies across industries such as sport, education, and healthcare. SimulCam™ technology allows video from multiple repetitions to be visually stitched into a single video, making direct comparisons between athletes possible, even when the camera is moving. StroMotion™ reveals the evolution of movement and gives trainers visual evidence of how the movement is performed from one stage to another. The computer vision involves allows to receive objective data (score, time on ice, player on ice etc.). Dartfish All-In-One Integrated Solution for Soccer – Filming, Coding and Publishing in one includes: live and post game coding, straight-forward graphical reporting, highlights publishing and sharing.

Modern market of biomechanical analysis systems is presented by applications for assessing biogeometrical profile of posture via photogrammetry techniques [2]. AI Posture Evaluation and Correction System (APEC) (France) (https://saneftec.com/) offers posture evaluation in frontal & sagittal planes; facial symmetry; Range of Motion (goniometer for custom angles). Such software could use to correct and prevent postural disorders though various exercises

The BioVideo software for the biomechanical video computer analysis was developed by kinesiology department, National University of Ukraine on Physical Education and Sports. This software can use to produce the biokinematical parameters of human motion: horizontal, vertical and the resulting linear velocities of the centre of mass (CM) and joint rotation centres; angular movement and angular velocities of segments. The user can create own model of human body by selection up to 100 points. A pre-defined model of the human support-motion apparatus consists of 20 points. This is a 14-segment branched biokinematic chain, the coordinates of the links of which, according to their geometric characteristics, correspond to the coordinates of the position in space of human body biolinks, and the reference points correspond to the coordinates of the joint centres. The BioVideo software consists of four modules: 1) construction module; 2) point's coordinates module; 3) calculation of motion characteristics module; 4) biokinematic scheme of human motor action module [10].

The initial data for BioVideo are frame files of 2D single-plane video recording of a human's motor action (BMP,

DIB, WMF, EMF, GIF, JPG, JPEG formats). The user identifies the coordinates of human body points on the recording frame.

The construction module creates the object's scheme model. Model may include the points of human body or his separate segments. The calculation of human motor actions characteristics module provides quantitative biomechanical characteristics: kinematic and dynamic parameters of points, joints, segments; energetical parameters (mechanical potential and kinetic energy and power) in any movement frame or in phase analysis. The module of human motion biokinematic scheme gives the opportunity to view the centers of masses (CM) both human total body, and his separate bioparts in every frame of motor action, to construct trajectories of movement on each of the chosen points, of the CM segments and of general centre of masses. As an example, the BioVideo biokinematical scheme of the diagonal stride performed by a highly skilled cross-country skier with hearing impairment [8] is presented by Figure 2.

Discussion. The global 3D Motion Capture market size was valued at USD 303.66 Million in 2023 and will reach USD 629.52 Million in 2030, with a CAGR of 12.92% during 2023-2030 (https://www.industryresearch.biz/). Majority of powerful corporations for example as Vicon (United Kingdom) (https://www.vicon.com), Motion Analysis Corporation (USA) (https://www.motionanalysis.com), Qualisys (Sweden) (http://www.qualisys.se), have 30-40 years of experience in the field of biomechanical research.

Nowadays the 3D Motion Capture technology is used widely in different science areas: for gait analysis, sports biomechanics, therapy, neuroscience, animation and robotics [5, 18]. 3D Motion capture market by types divided into following segments: hardware, software, service. 3D Motion capture market by applications divided into following segments: life sciences, biomechanical research and rehabilitation, engineering & ergonomics, education [4, 15, 19].

Our study presents the classification of motion analysis systems according to hardware and software criteria.

As a rule, systems that can conduct quantitative biomechanical analysis work not with standard, but with specialized cameras. Features of practically all modern motion analysis systems using specialized cameras and markers are the high acquisition of data in real time [14, 16]. The disadvantage of these systems is that they work exclusively in the laboratory. In case of application of motion analysis systems at competitions, where the use of markers is impossible, the coordinates of the points are recognized with the help of artificial intelligence software by pattern recognition [3, 13, 21].

Many software products on motion analysis using standard cameras can be achieved on a mobile phone, personal computer, or tablet [17].

As the analysis of a special literature has shown, now in the market of motion capture systems there are not those systems which would work with standard video cameras and at the same time provide the quantitative biomechanical characteristics of human movement. The BioVideo software for the biomechanical analysis has just those features [9, 10, 15].

The feature of BioVideo software is that one allows you to perform an analysis of motor action based on video frames, which can be produced at any speed allowed by the hardware, since the user can set this speed programmatically (it is taken into account in BioVideo when determining all quantitative characteristics). In most movements, 25 fps are sufficient to drive biomechanical analysis, when there is no need to analyse precise movements.

BioVideo modules determine not only kinematic, but also dynamic characteristics of motor action. In BioVideo, dynamic characteristics are determined in the same way as kinematic ones, using a videogram, which makes it possible to control the athlete's competitive activity. A distinctive feature of BioVideo compared to existing motion analysis software is that BioVideo provides for determining the biomechanical characteristics of the CM of biolinks and the GC of the human's entire body, as well as performing a phase analysis of motor action [8, 11, 12].

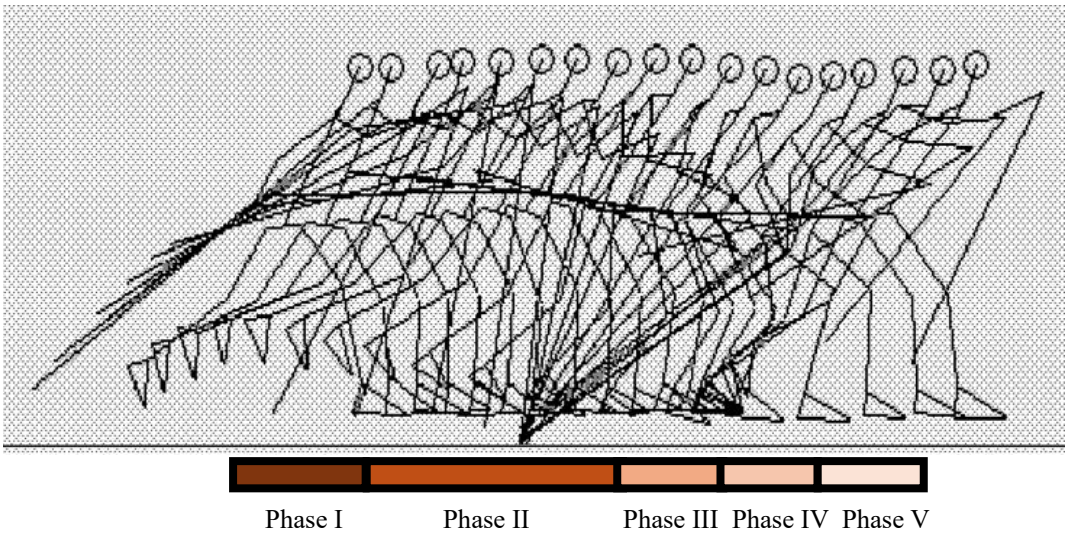

Figure 2. The biokinematical scheme of a highly skilled cross-country skier with hearing impairment in phases of diagonal stride: phase I – a free unidirectional glide on the left ski, phase II – gliding with the straightening of the support (left) leg in the knee joint, phase III – gliding with the sinking on the left foot, phase IV – gliding with a squat on the supporting leg and phase V – repulsion with the straightening of the pushing (left) leg

BioVideo modules determine not only kinematic, but also dynamic characteristics of motor action. While most of the biomechanical analysis systems provide the dynamic characteristics based on the data from force plates, the dynamic characteristics with BioVideo are also defined as well as kinematic under the motion capture in sports and physical rehabilitation.

Most video computer analysers are expensive products. Over the past 20 years, there has been a trend towards an increase in the share of software in the total cost of motion analysis systems compared to the first motion analysis systems, in which the main cost was hardware. Taxes and additional charges vary according to user's country of residence. In this regard, BioVideo software is of undoubted value as free tool for analysing motor action from video frames recording by standard camera.

Conclusions

1. A classification scheme for motion analysis systems has been developed according to the hardware and software criteria.

2. The capabilities of the modern motion analysis systems depending on the hardware and software were analyzed. Modern motion analysis systems allow to obtain quantitative and qualitative data on the human motor actions objectively, informatively and in real time. The variety of modern motion analysis technologies allows for accurate assessment and qualitative analysis of a human movement both in the conditions of laboratories and fields.

3. The distinctive features of BioVideo software for biomechanical analysis of human motor actions by video frames from a standard camera were presented.

Prospects for further research are in the analysis and generalization of artificial intelligence systems which are used for modelling in sports and physical culture & rehabilitation.

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Authors' Contribution. *Irene Khmelnitska* – Study design, Data collection, Statistical analysis, Manuscript Preparation; *Gennadii Lisenchuk* – Study design, Data collection, Manuscript Preparation; *Konstantin Bogatyrev* – Study design, Data collection, Statistical analysis; *Gennadii Zhigadlo* – Data collection, Statistical analysis; *Svitlana Krupenya* – Data collection, Statistical analysis; *Volodymir Zaloylo* – Data collection.

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ІНФОРМАЦІЯ ПРО АВТОРІВ

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