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COMPARATIVE STUDY OF NON-INVASIVE METHODS USED FOR MEASURING THE HUMAN JOINT ANGLES AND JOINT'S RANGE OF MOTION IN STATIC AND DYNAMIC CONDITIONS

Cristian Radu BADEA[1], Paul-Nicolae ANCUȚA[1], Sorin Ionuț BADEA[1], Florentina BADEA[1]

[1] The National Institute of Research and Development in Mechatronics and Measurement Technique (INCDMTM)

adresacontact@gmail.com; paul.ancuta@incdmtm.ro; sorin_ib@yahoo.com; mihaiflori@yahoo.com

Abstract: *The analysis of the human body motions, as well as the postural analysis, are extremely important activities because they provide essential information about human biomechanics, depending on which systems and corrective exercises can be created to allow both an increase in the efficiency of individuals in the various fields in which they are involved (military, lucrative, domestic or sports), as well as an improvement in their quality of life. The actions undertaken in this regard are generally limited by the impossibility of performing non-invasive, ultra-precise measurements of the various body segments. Therefore, estimating the positions of human anatomical elements can be done in several ways, each of which has both advantages and disadvantages. Starting from this fact, in the action of choosing between the currently existing movement analysis systems, one will have to take into account both the qualitative and quantitative aspects of the provided results.*

Keywords: *Motion analysis, inertial, video analysis, body landmarks, biomechanics, neuromuscular, human joints angles, joint's range of motion (ROM)*

1. Introduction

Estimating human position by analysing video images can be used in software applications for measuring and validating physical exercises and controlling gestures of the whole body. MediaPipe Pose Landmarker allows you to detect human body landmarks in an image or video. In this mode, key body locations can be identified to analyse posture and classify movements. MediaPipe pose uses machine learning (ML) models and provides body landmarks in image coordinates and 3D world coordinates [1].

Inertial motion analysis systems are extremely useful for determining the correctness of human biomechanics. The main advantage of these inertial systems is the possibility of determining the biomechanical parameters without requiring prior constraints regarding the degrees of freedom of the various anatomical elements (which leads to certain limitations by comparison with the natural human movements) and also the possibility of capturing all body segments without the occurrence of obturation phenomenon as is the case with motion analysis video systems. On the other side, determining the various anthropometric parameters as precisely as possible is extremely useful when it comes to the calibration of inertial motion analysis systems, which decisively depends on the quality of this type of information.

These motion analyses can be both quantitative in nature (for example: number of repetitions, speed of a body segment, etc.) and qualitative (for example: correct postural attitude assessment, performing the movement over the entire joint range of motion, gait analysis [2] etc.). Thus, each system and/or tool used in the determination of human biomechanics addresses a certain type of analysis, due to both its facilities and limitations.

2. Previous and related works

The paper [3] presents an introduction to the field of inertial motion analysis, focusing its attention on the analysis that is carried out with the help of modern mechatronic inertial motion capture systems, highlighting both the advantages and disadvantages of using such a system and

highlighting the main constituent elements of these systems as well as the necessary steps that must be performed to be able to perform such an analysis.
The paper[4] presents the most important aspects related to the occurrence of positioning errors that appeared during the motion analysis sessions carried out with the help of the Xsens MVN system, before and after the post-processing of the information captured by to the MEMS sensors of the system, located on the human body, and related to the scenario in which the action takes place at the floor level (considered as having an incompressible surface), this representing the only element of contact between the human subject under analysis and the environment.

3. Material and method

The experiments were carried out using the following hardware equipment: an inertial motion analysis system, a stereo vision type camera, a laptop, a digital protractor, a angle gauge, a roulette, a ruler, an fixed bars assembly and elements of props used as physical benchmarks for carrying out calibrations and respectively for ensuring the necessary framework for carrying out experiments under repeatability conditions. The software programs used are MediaPipe and OpenCV for video analysis and MVN Analyze for inertial analysis.

3.1 Inertial motion analysis system

The tests carried out using the inertial motion analysis system Xsens MVN, were aimed on testing the facilities and limitations of such a system, as well as on the comparison between the this and a video analysis system. Xsens MVN is one of the best performing inertial motion analysis systems [5][6], based on a MEMS sensor network, each of which contains a combination of accelerometer, gyroscope and magnetic field sensors , whose signals are processed by a microcontroller, by means of advanced processing algorithms, in order to obtain information regarding the kinematics of the body segments of the individual under analysis and its global positioning, the data thus obtained being then transferred to a virtual biomechanical model, which reproduces, in real time, the movements of the person in question.
The hardware subassembly used in the study is called MVN Link and is a 3D kinematic analysis system, adapted to the human body, composed of a network of MEMS, interconnected by means of electrical cables, mounted/mountable, in predetermined positions, on a "Lycra" type of suit, the latter allowing the user to have maximum freedom of movement, but also having the role of reducing the time required for the positioning/repositioning of the MEMS. MVN Link can be used both indoors and outdoors, on rough terrain, in areas with low lighting. The results provided by MVN Link do not require post-processing, since the MEMS used do not suffer from the occlusion phenomenon, as in the case of optical markers. Also, the data provided by this system can easily be used by other software applications.
This system benefits from the presence of several extremely important elements, some of which are even innovations implemented for the first time by the manufacturer of this system, Xsens, namely:
- since the communication between the inertial system and the computer system, on which the motion analysis software is installed, is carried out wirelessly, the signal frequency is relatively low, around 100Hz, but this fact does not affect the quality of the analysis of movement due to the fact that the sampling frequency of the signal, by MEMS, is very high, of approx. 1000 Hz. In order to be able to maintain a high precision, the signal captured by the sensors that make up each MEMS is stored and transmitted incrementally, thus, in the event of a disruption in wireless communication, the data obtained by the MEMS are temporarily stored in a central sensory unit and then transmitted to computer, when communication is restored. Thus, the terminology used has undergone some changes regarding the sampling frequency (sampling rate), which has been replaced by "update/refresh rate";
- the signal transmitted by MENS is not influenced by distortions in the magnetic field, thanks to a function (named Magnetic Field Mapper), which allows the placement of MEMS on ferromagnetic surfaces, while maintaining the quality of the provided signal, as well as eliminating restrictions

regarding the working environment in that the system in question can be successfully used in motion analyses that are carried out inside the rooms with special metal reinforcement, in the car, plane, or train, or near the devices that use radio frequency;
- the high-resolution reprocessing engine, which allows offline reprocessing (or post-processing), of high-resolution information, which leads to an increase in the quality of the data provided by the system, by correcting the "slip" at the level of the foot, correcting the multi-point type contact, improving the consistency of the data, improving the accuracy of the data regarding joint angles and 3D kinematics and improving the accuracy of estimating the global 3D positioning;
- the possibility of including the analysed type of movement, in one scenario at a time, depending on the characteristics of the floor (incompressible, respectively compressible-elastic floor), on the performing the movement on different levels (as in the case of the analysis of the stairs climbing /descending, vertical walls climbing, etc.), or on the absence of a clear contact with the ground (as is the case with the analysis of skating and/or skiing);
- live detection of multiple contact points, which allows the analysis of walking in hands, of climbing and climbing stairs. In order to minimize positioning errors, the MVN Analyze software uses the contact points between the subject under analysis and the environment, which are usually anatomical protrusions considered to have the potential to physically interact with the environment, for example: the heel, elbow, knee [7]. Error minimization is achieved by combining the biomechanical model with advanced contact detection algorithms;
- the lack of orientation constraints, applied to the virtually modelled segments, as well as angular constraints applied to the joints, since the modelling of the joints of the virtual mannequin is based on the human anatomical structures that allow 6 degrees of freedom [8]. The information obtained is not manipulated by the system, to create the appearance of natural movements, but reflects exactly the values measured by the system's MEMS [9] [10].

3.2 Hardware and software used in the video analysis

The following components were used to perform the experiments:
Hardware components:
- Laptop DELL Vostro 15 3000 (two USB 2.0 ports, a USB 3.0 port, an Ethernet port, headphone/mic jack, DVD drive, VGA port, 15inch display 1366x768, core i5 8th Gen, 8 Mb RAM)
- Intel RealSense D435 Web Camera, which is equipped with a pair of depth sensors, an RGB sensor and an infrared projector and is connected via USB 3.0 Type-C.

Software components:
- UBUNTU operating system version 18.04.6 LTS;
- OpenCV software package version 4.7.0;
- The MediaPipe software package;
- Python version 3.10.5.

3.3 Types of biomechanical analyses performed and the imposed conditions

The biomechanical analyses carried out were structured in two sections, as follows:
- A static analysis section, necessary to perform a calibration of the two analysis systems used. In this section, the focus was on the capacity of the two motion analysis systems to determine in static conditions the joint angles at the level of the elbows and knees of the human subject;
- A dynamic analysis section. In this section, the focus was on the ability of the two motion analysis systems to determine, in dynamic conditions, the joint angles at the level of elbows and knees of the human subject, as well as the correct detection of joint's range of motion. Thus, this section was composed of:
    - a set of five sessions intended for the analysis of the flexion/extension movements of the right and left elbow joint respectively, consisting of ten movements (alternating biceps-triceps contractions, see Fig.1) having different amplitudes;
    - a set of sessions intended for the analysis of the flexion/extension movements of the right and respectively the left knee joint, consisting of ten movements (squats) with different amplitudes (see Fig.2).

In order to fulfil the proposed objective, certain conditions were imposed and respected, as follows:

- throughout the motion analysis sessions, the human subject was equipped with the sensory suit of the Xsens MVN inertial motion analysis system;
- during the analysis sessions, attention was focused on the knees and elbows joints;
- the analysis sessions carried out at the level of the elbow joint also included experiments in which the corresponding upper limb was wrapped in a red cloth, to increase the accuracy of the determinations by obtaining a colour contrast in relation to the sensory suit;
- the analysis sessions were carried out by reporting the positions of the human subject to fixed elements. Thus, a fixed bars assembly was used to ensure the necessary framework for performing motion analyses under repeatability conditions;
- both for the analyses intended for the elbow joint and for those intended for the knee joint, a set of five analysis sessions was created in which the entire body of the human subject was positioned angularly rotated in relation to the calibration landmark, by 0°, 15°, 30°, 45° and 60°;
- in order to be able to ensure obtaining and maintaining the joint angles as correctly as possible, necessary for the static analysis, a specially designed angle gauge was used so that it could be placed and maintained between the arm and forearm, respectively tibia and femur and having the angle of interest of 90°;
- in order to ensure a standardized measurement of the angles and the of joint’s range of motion, an electronic protractor with a resolution of 0.1° was used, mounted at the level of the studied joint, distally, on its lateral face.

A software application was written in order to create twenty *.avi* files during the flexion-extension exercise of the right elbow and the right knee for each position of the human subject's body using the video camera. These films were analysed frame by frame in order to identify the coordinates of the three points of interest (shoulder, elbow and wrist for the upper limb, respectively hip, knee and ankle for the lower limb) necessary to calculate the joint angle. At the same time during the movement cycles, the sensors positioned on the special training suit sent the acquired data to the inertial motion analysis software, this software determining the joint angle in real time. Figures 1, 2, 3 and 4 below show the dynamic and static video analysis sessions of the elbow and knee joints of the human subject.

Fig. 1. Successive positions of the human subject for measuring the right elbow joint flexion angle

Fig. 2. Successive positions of the human subject for measuring the right knee joint flexion angle

Fig. 3. Successive positions of the human subject carried out for the static determination of the flexion angle of the right elbow joint

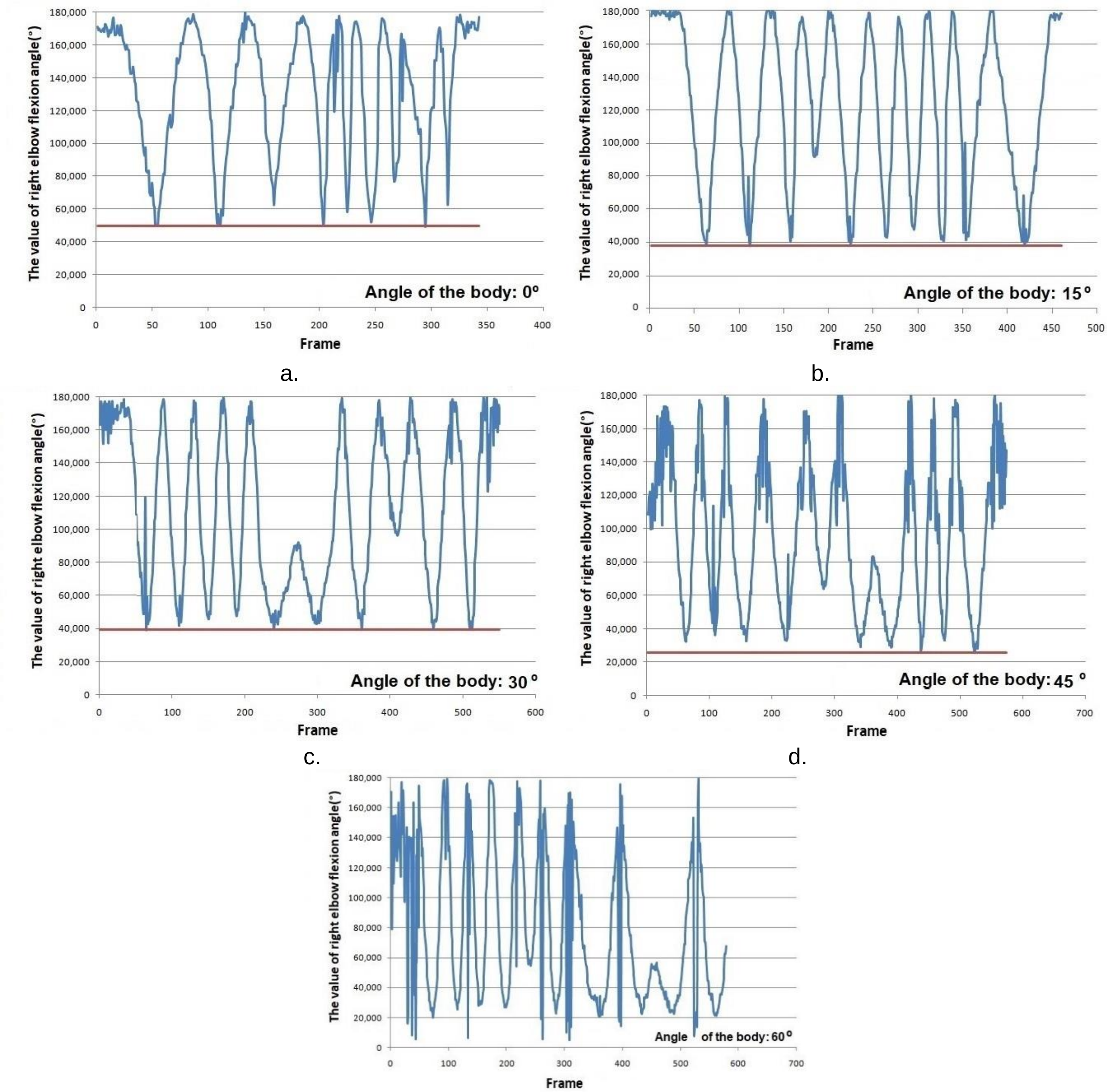
Fig. 4. Successive positions of the human subject carried out for the static determination of the flexion angle of the right knee joint

4. Results

The numerical results obtained were analysed and represented in the form of graphs of variation of the measured size, namely of the angles of the joints of the elbows and respectively the knees of the human subject under analysis.

4.1 Monitoring the right elbow flexion

The variation of the flexion/extension angles value of the right elbow as it is extracted from the processed frames is shown in the graphs in Fig.5.



e.

Fig. 5. The results obtained after processing the video frames of flexion/extension movements at the level of the right elbow joint

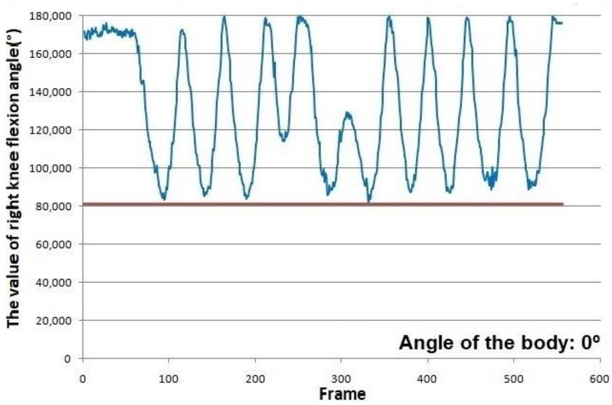
There were image frames in which human body landmarks could be detected by software and therefore the flexion/extension angle was not represented on the graphs. This was the case of the set of frames associated with the rotation position of the human body at 60°, where the dispersion of the data did not allow the quick detection, using software successive comparisons, of the minimum value of the flexion/extension angle. Table 1 shows the data processing situation for the flexion movement of the right arm, as it was monitored by the video application.

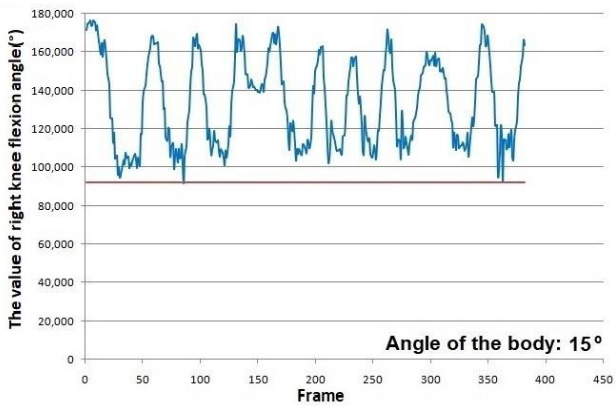
Table 1: The data acquired and processed by the video application for the movement of the right elbow

The position of the body relative to the fixed reference on the floor	Total number of frames	Number of frames having detected Landmarks	Minimum flexion angle (°)
Rotation: 0°	672	342	49.83
Rotation: 15°	536	461	38.07
Rotation: 30°	601	551	39.36
Rotation: 45°	588	574	25.75
Rotation: 60°	615	614	Not detected

4.2 Monitoring the right knee flexion

The variation of the flexion/extension angles value of the right knee as it is extracted from the processed frames is shown in the graphs in Fig.6.





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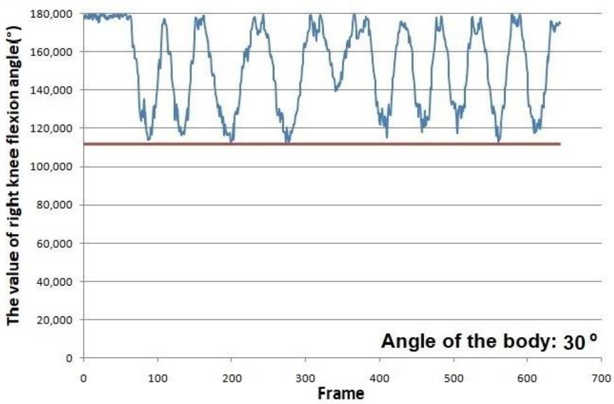

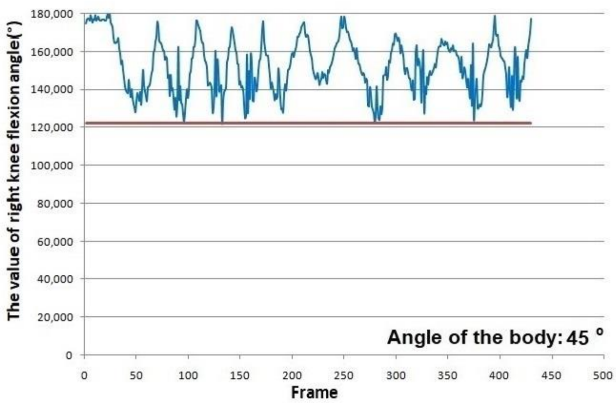

c.

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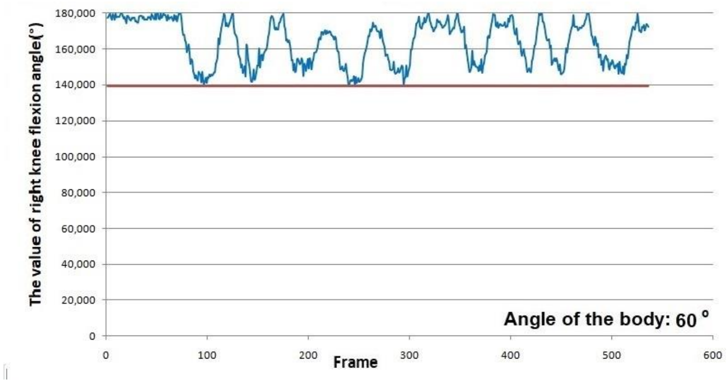
Fig. 6. The results obtained after processing the video frames of flexion/extension movements at the level of the right knee joint



e.

Fig. 6. The results obtained after processing the video frames of flexion/extension movements at the level of the right knee joint

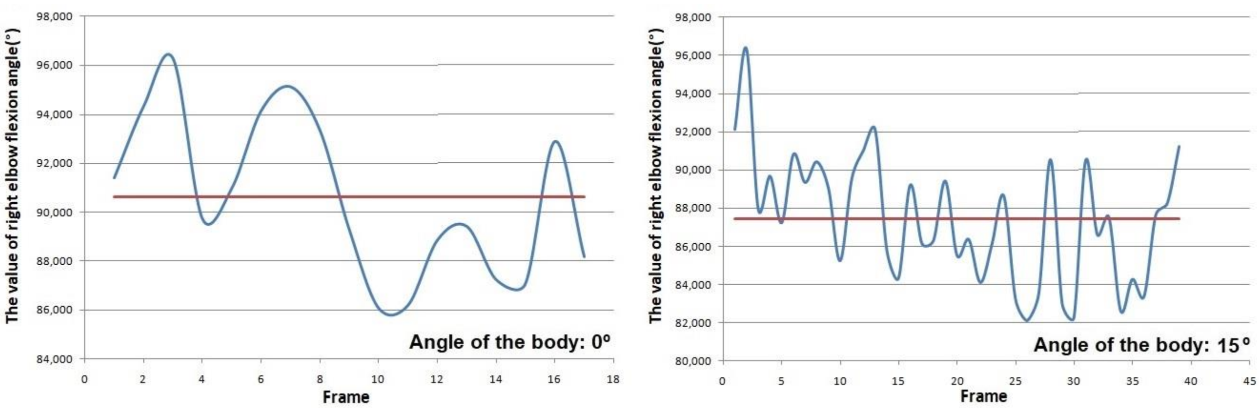
There were image frames in which human body landmarks could be detected by software and therefore the flexion/extension angle was not represented on the graphs. Table 2 shows the data processing situation for the flexion movement of the right knee, as it was monitored by the video application.

Table 2: The data acquired and processed by the video application for the movement of the right knee

The position of the body relative to the fixed reference on the floor	Number of frames	Number of frames having detected Landmarks	Minimum flexion angle (°)
Rotatie 0°	571	556	81.16
Rotation: 15°	532	382	91.87
Rotation: 30°	667	644	111.82
Rotation: 45°	569	430	122.10
Rotation: 60°	581	536	139.66

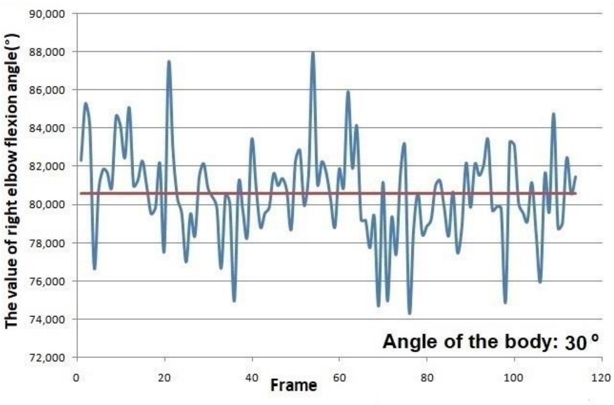
4.3 Monitoring the right arm fixed position

The measurement of the 90° flexion angle of the right elbow joint depending on the processed video frame is shown in the graphs in Fig.7.



a. b.

Fig. 7. The comparative results obtained after processing the video frames for the angles of the right elbow joint, having the angle gauge mounted on its inner face



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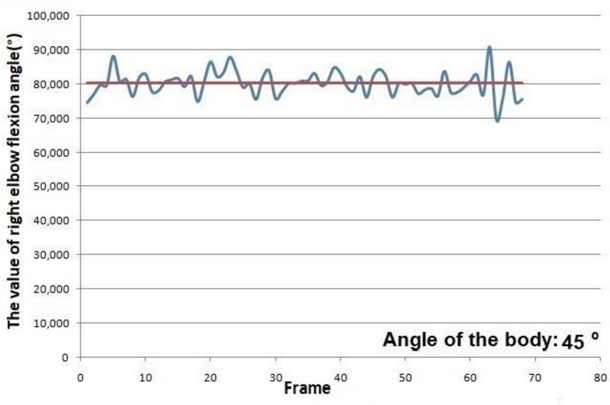

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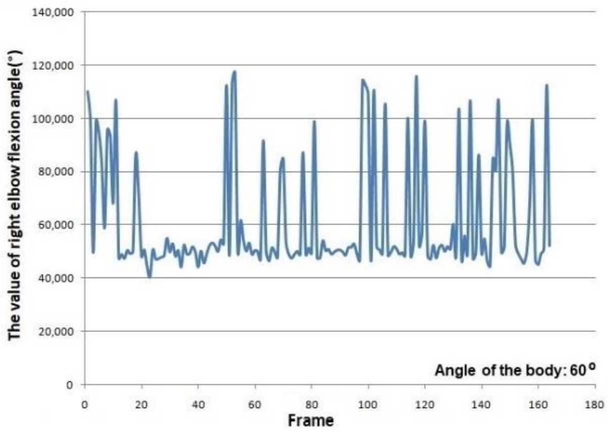


e.

Fig. 7. The comparative results obtained after processing the video frames for the angles of the right elbow joint, having the angle gauge mounted on its inner face

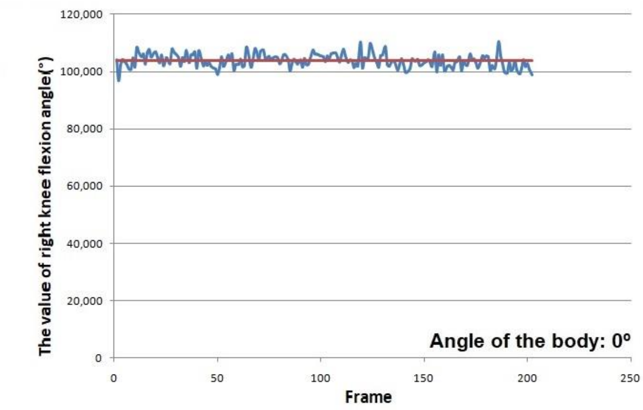
There were image frames in which human body landmarks could be detected by software and therefore the flexion angle was not represented on the graphs. Table 3 shows the data processing situation for the angular position in static conditions of the right elbow joint, as it was monitored by the video application.

Table 3: The data acquired and processed by the video application for the static flexion position of the right elbow joint

The position of the body relative to the fixed reference on the floor	Number of frames having detected Landmarks	Average value of flexion angle (°)
Rotation: 0°	17	90.61
Rotation: 15°	39	87.43
Rotation: 30°	114	80.56
Rotation: 45°	68	80.17
Rotation: 60°	164	N/A

4.4 Monitoring the right foot fixed position

The measurement of the 90° flexion angle of the right knee joint depending on the processed video frame is shown in the graphs in Fig.8.



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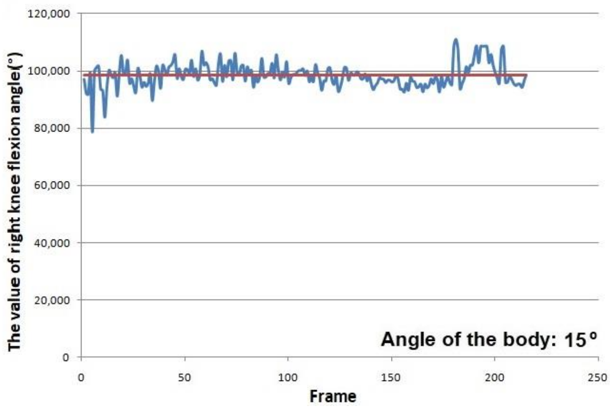

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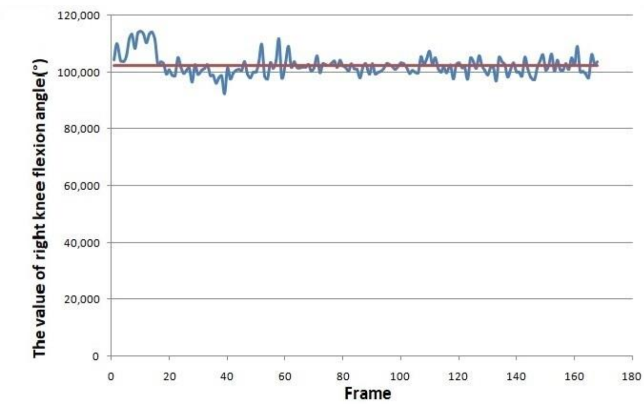

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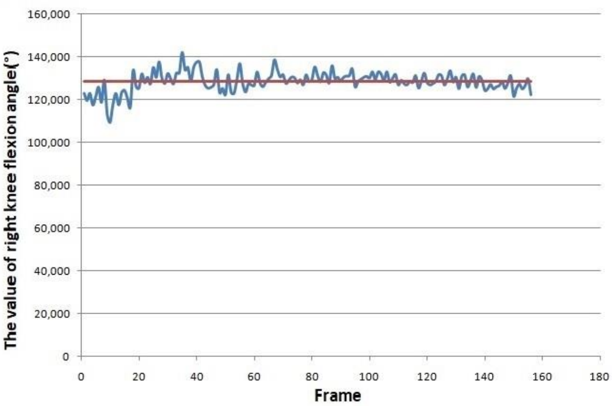

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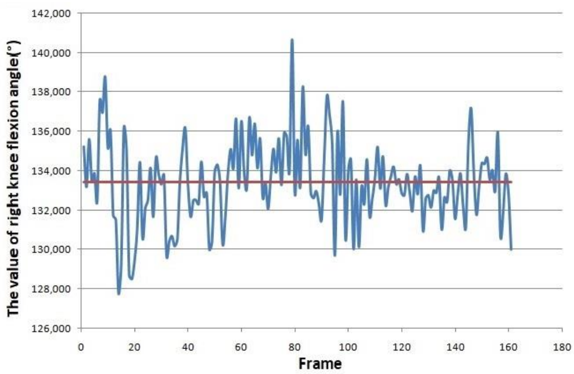


e.

Fig. 8. The comparative results obtained after processing the video frames for the angles of the right knee joint, having the angle gauge mounted on its inner face

Table 4 shows the data processing situation for the angular position in static conditions of the right knee joint, as it was monitored by the video application.

Table 4: The data acquired and processed by the video application for the static flexion position of the right knee joint

The position of the body relative to the fixed reference on the floor	Number of frames having detected Landmarks	Average value of flexion angle (°)
Rotation: 0°	202	103.77
Rotation: 15°	215	98.43
Rotation: 30°	168	102.40
Rotation: 45°	156	128.47
Rotation: 60°	161	133.42

4.5 Static analysis sessions using *Xsens MVN* inertial motion analysis system

a. Static analysis section - within these analyses the human subject had to maintain, with or without external help, certain positions corresponding to certain joint angles (at the level of the elbow and knee joints) determined with the help of the electronic protractor and/or the 90° angle gauge.
In order to be able to determine the correctness of the estimation of joint angles and of joint's range of motion, with the help of the Xsens MVN inertial motion analysis system, the values provided by the system in question were compared with those recorded on the digital protractor, as well as with the angle determined by positioning the angle gauge inside the joints in question. This digital protractor was chosen because it is commonly used in anthropometric measurements, being known as a goniometer.
Thus, the comparative analyses were focused both on the determination of a relationship of proportionality between the values indicated on the digital protractor and those provided by the Xsens MVN inertial system, as well as on the verification of the accuracy of the latter. Fig.10 shows the results obtained in the case of the previously mentioned analysis. For this analysis, the human subject had to keep his forearm in three consecutive different positions, corresponding to the following flexion/extension angles indicated on the digital protractor: -8.8°, 65.2° and 98° respectively.

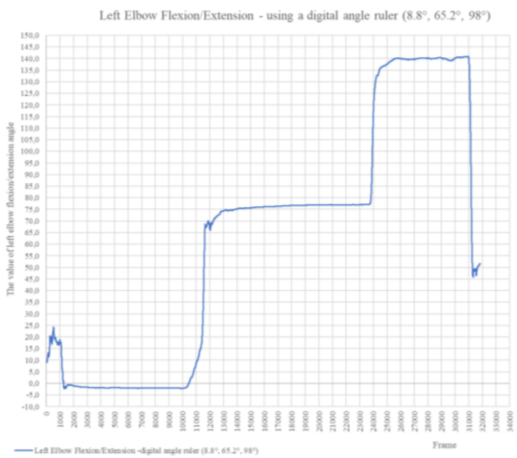


Fig. 9. The results obtained using Xsens MVN inertial analysis system, in the case of maintaining the flexion/extension angles at the level of the left elbow joint, for three different angular positions

Analysing the graph in Fig.9, one can see the three levels corresponding to the previously mentioned flexion/extension angles. Following an elementary calculation, it can be established that the angle of -8.8° indicated on the digital protractor corresponds to an extension angle of -1.98° in the inertial system. If there was a proportionality between these two measurements, it would mean that for the flexion angle of 65.2° indicated on the electronic protractor, the inertial system should indicate an angle of approximately 14.67°, respectively for the flexion angle of 98° indicated on the electronic protractor, the inertial system should indicate an angle of approximately 22.05°. However, the graph shows an angle of approximately 76.64° and 139.94°, respectively. The situation is repeated if the other two angles indicated by the digital protractor are taken as a reference. It thus emerges the fact that a proportionality between the two measurements cannot be determined, this fact could be due to one of the following phenomena: the occurrence of a gross error of the inertial system, or the change in the position of the digital protractor in relation to the initial position.

Due to the fact that the digital protractor was placed and fixed on the external face of the arm and the forearm respectively, the conducted experiments highlighted the following aspects:

- the maximum and minimum values of the joint's range of motion recorded with the help of the digital protractor differed not only from one session to another (each session presupposing a repositioning of the digital protractor on the arm of the human subject under analysis), but also from one movement to another. The differences were created, as expected, by the location of the joint of the digital protractor in relation to the studied joint, by the muscular reaction at the stroke ends of the movement, a phenomenon that produced the displacement of the measuring instrument used, in relation to his initial position. More precisely, this change in the position of the digital protractor during movement was due to the impossibility of fixing in place the measuring instrument in question, directly on the bone surfaces (which has the advantage of not changing its three-dimensional shape in relation to the joint angle) and the lack of fixed physical landmarks having a well-defined shape, which allows precise and repeatable successive repositioning;
- even if the forearm was kept in supination throughout the execution of the flexion/extension movements at the elbow joint, a displacement of the digital protractors position still occurred in relation to its initial position. As expected, another thing happened in this situation, namely the decrease of the maximum amplitude of the studied joint, by decrementing the value of the upper limit of the flexion angle, due to the biceps muscle contraction necessary to maintain the supination of the forearm.

This latter phenomenon was also observed in the case of the analyses performed with the angle gauge positioned on the inner face of the elbow joint. In the case of these analyses, the attention was focused on the ability of the inertial system to provide values that indicate that the movement at the level of the elbow joint it is blocked, due to the placement of the mentioned instrument inside the elbow joint and to its fastening on the arm and forearm.

Analysing the graph in Fig.10, it can be seen that the Xsens MVN inertial system correctly indicates the fact that the flexion angle at the level of the right elbow joint is properly maintained within certain limits.

Fig. 10. The amplitude of the variation of the flexion/extension angle at the level of the right elbow joint, blocked due to the positioning of the angle gauge inside it

The variation of the flexion angle, graphically indicated in Fig.10, it is relatively small (approximately 0.4°) and is most likely due to the attempt of the human subject under analysis to maintain the imposed angular position. Thus, it can be observed that, even in the case of physical blocking of the joint movement, there is still an angular variation due to the modification of the shape of the muscles with which the angle gauge is in contact, this amplitude being able to decrease once the biceps muscle gets in a relaxed state. It should be mentioned, in the case of this analysis, the fact that the digital protractor did not register changes in the angle value. This clearly denotes the fact that this last-mentioned instrument cannot be mounted so well as to be able to record even the smallest possible variations and also clearly highlights the involvement of the bicep's contraction in the angular variations that occur, as well as a compression of the soft body segments in contact with the angle gauge. An extremely important element in this analysis is that the value of the flexion angle is different from the value of the angle gauge, due to the fact that the latter is in contact with the muscles and not with the bones, the joint angles being determined according to the specialized literature by reference to bone structures. It should be mentioned that the flexion/extension angle within the Xsens MVN it is represented by the angle between the forearm in the "0" position of the calibration of the system in question and the position of the forearm at a certain moment in time. More precisely, the flexion angle does not represent the angle between the arm and the forearm. Xsens MVN thus assigns positive angle values to the flexion movement and negative values to the extension movement, regardless of whether it is the upper or lower limb.

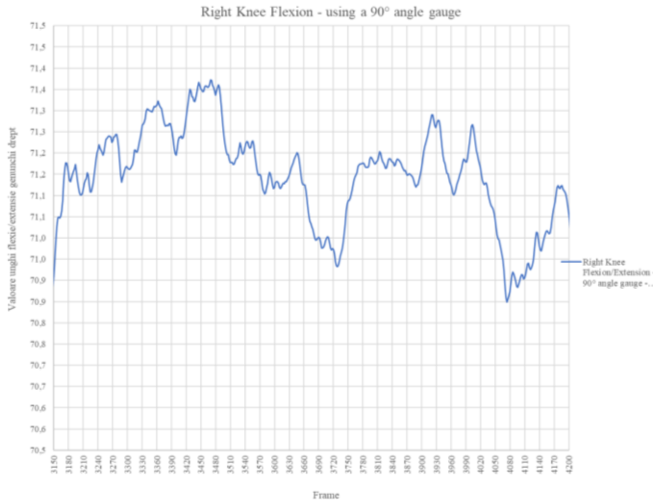
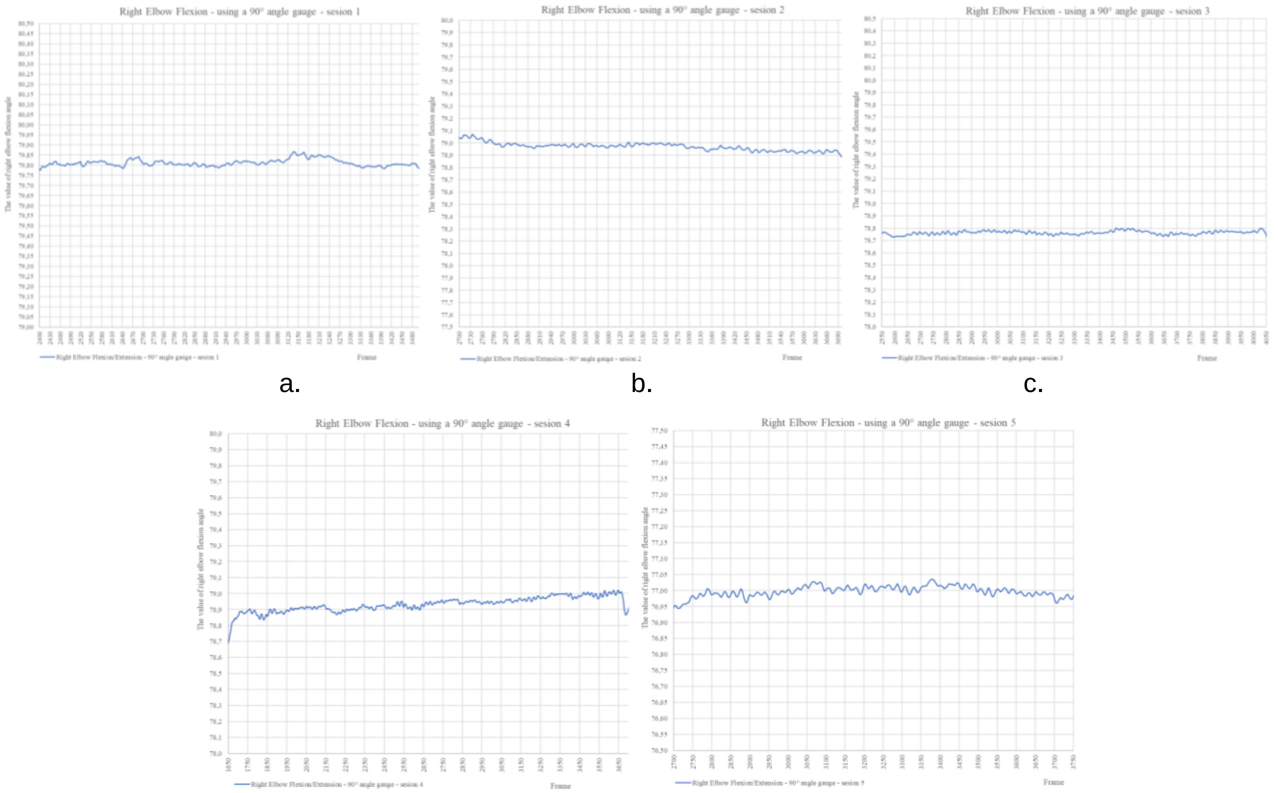


Fig. 11. The amplitude of the variation of the flexion/extension angle at the level of the right knee joint, blocked due to the positioning of the angle gauge inside it

The analysis performed with the angle gauge positioned at the level of the elbow joint was also applied at the level of the knee joint (see Fig.11). And in this situation, the phenomena observed in the previous case appear. Thus, analysing the graph in Fig.11, it can be seen that the Xsens MVN inertial system correctly indicates a relative blockage at the level of the knee joint. The variation of the flexion angle, found graphically, is, as in the case of the knee joint, relatively small (approximately 0.5°) and is most likely due to the attempt of the human subject under analysis to maintain the imposed angular position, as well as due to the compression of the soft body's segments in contact with the angle gauge.
In order to confirm or deny this assumption, a new analysis was carried out, composed of five sessions, which assumed the repetition of the restriction of the elbow and knee joints movement, respectively. In this case, the human subject has had the task of maintaining the same muscle tension in the analysed joint, on the inner side of which the angle gauge was placed. Analysing the data provided by the Xsens MVN inertial system, it can be seen that it correctly indicates the blockage at the level of the elbow joint (see Fig.12) and respectively the knee (see Fig.13), in all five dedicated sessions.

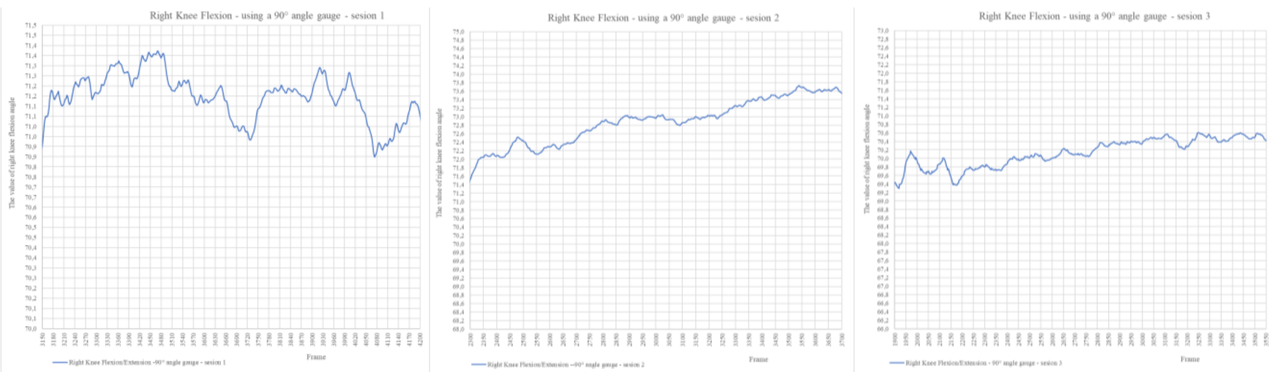


a. b. c.

d. e.

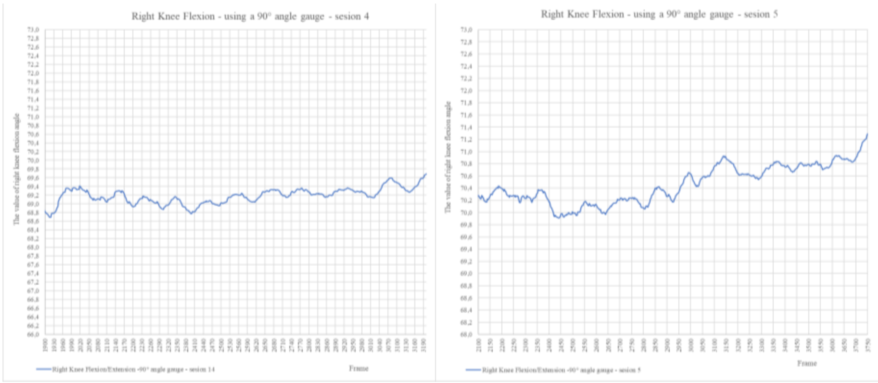
Fig. 12. The results obtained in the five motion analysis sessions carried out using Xsens MVN, regarding the amplitude of the variation of the flexion/extension angle at the level of the right elbow joint, blocked due to the positioning of the angle gauge inside it

In the case of the elbow joint, the amplitude of variation of the flexion angle is the same in all five sessions (approximately 0.4° - see Fig.12), differing only in the average value of the angle in question. This variation is clearly due to a combination of factors, namely: the different muscle tension from one session to another, the impossibility of identical placement of the angle gauge from one session to another and the compressibility of soft anatomical elements (skin and muscles).



a. b. c.

Fig. 13. The results obtained in the five motion analysis sessions carried out using Xsens MVN, regarding the amplitude of the variation of the flexion/extension angle at the level of the right knee joint, blocked due to the positioning of the angle gauge inside it



d. e.

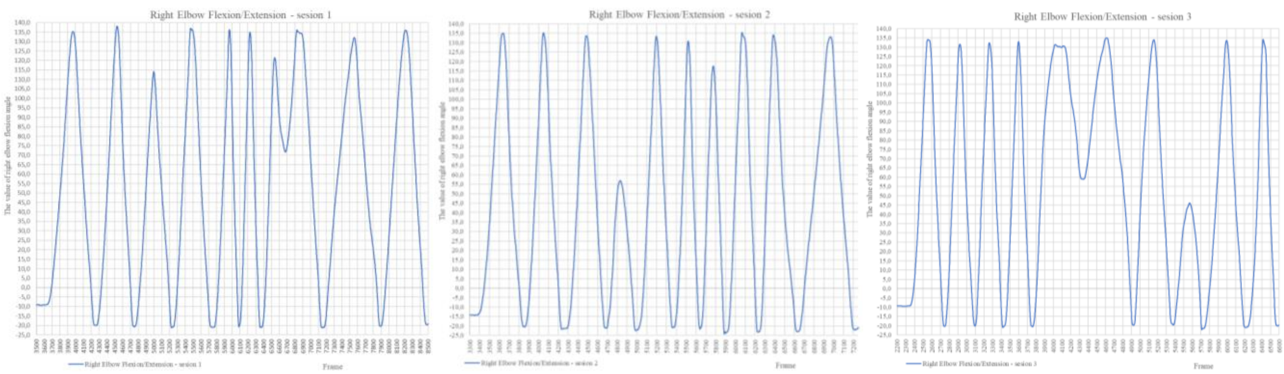
Fig. 13. The results obtained in the five motion analysis sessions carried out using Xsens MVN, regarding the amplitude of the variation of the flexion/extension angle at the level of the right knee joint, blocked due to the positioning of the angle gauge inside it

Analysing the graph of the variation of the amplitude of the flexion angle at the level of the knee (see Fig.13), with the angle gauge mounted on its internal face, it can be considered that the phenomenon appeared in the case of the elbow joint and manifests in the same way in this case as well, the differences being given by : a different neuromuscular control between the lower and upper limbs (neuromuscular control at the level of the upper limbs being clearly higher due, mainly, to the fact that they are trained throughout life to perform precision movements) and the pressure exerted on the lower limbs due to the vertical position of the body during the sessions dedicated to knee analysis.

Therefore, it can be said that the hypothesis of the appearance of an angular variation due to the human subject's attempt to maintain the position even in the case of a physical blockage applied to the joint in question, in contact with the angle gauge, is confirmed.

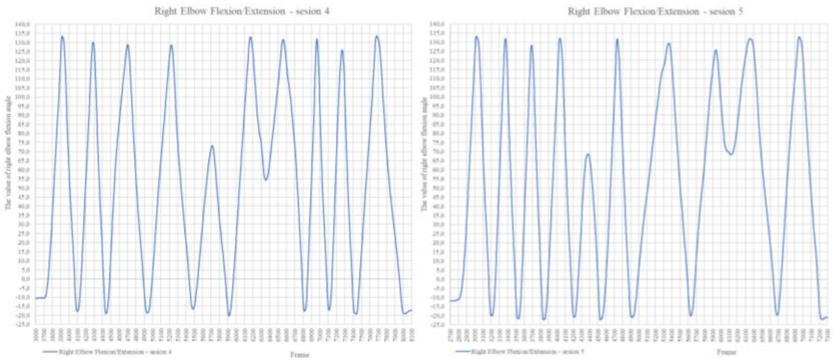
4.6 Dynamic analysis sessions using *Xsens MVN* inertial motion analysis system

In these analyses, the human subject had to perform ten flexions/extensions at the level of the elbow and/or knee joints, the movements being limited or not in a certain direction with the help of props whose shape and position in space cannot be modified. The purpose of these analyses is to determine the ability of the Xsens MVN inertial system to properly determine the flexion/extension angle and respectively the joint's range of motion. In this situation, the role of the prop was to ensure the necessary framework for the execution of joint movements with a predetermined range of motion, limited by the contact at the end of the stroke between the moving body segments and it.



a. b. c.

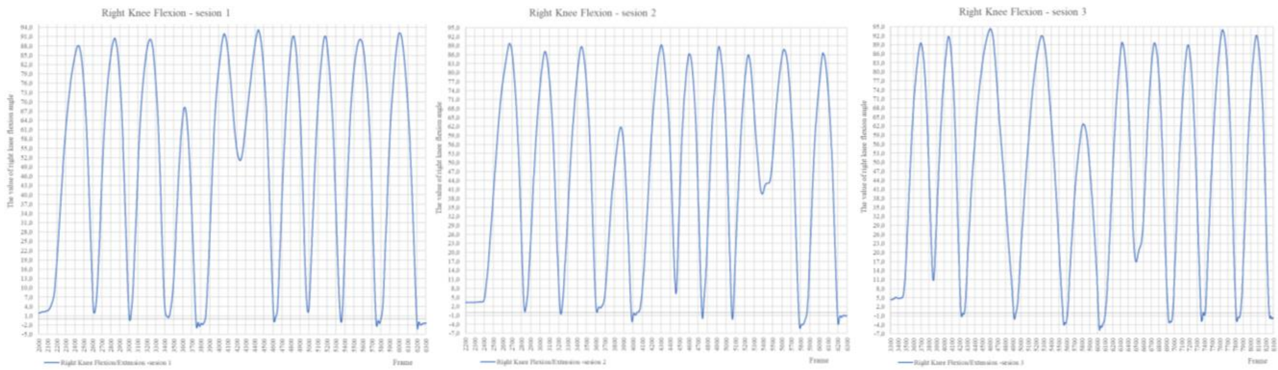
Fig. 14. The results obtained in the five motion analysis sessions carried out with the help of Xsens MVN, regarding the range of motion at the level of the right elbow joint, during an exercise performed without additional loading



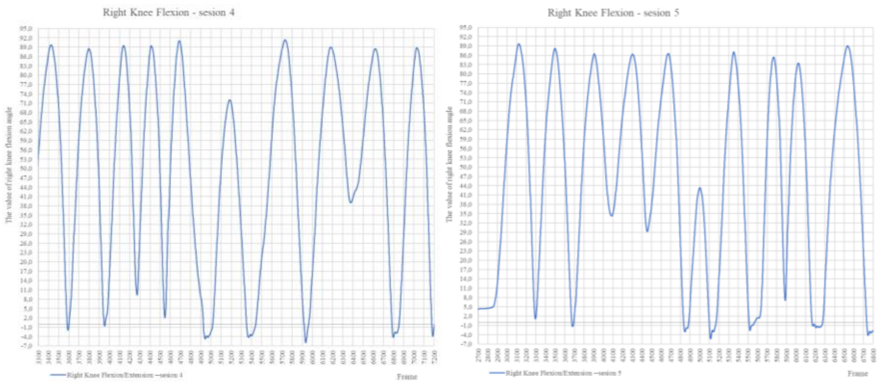
d. e.

Fig. 14. The results obtained in the five motion analysis sessions carried out with the help of Xsens MVN, regarding the range of motion at the level of the right elbow joint, during an exercise performed without additional loading

In the case of the elbow joint, the movements were mechanically limited by the contact with the outer face of the chin of the human subject undergoing analysis, with the head previously fixed in an immutable position for the entire duration of an analysis session. Intermediate flexion/extension movements were also performed, in order to clearly demonstrate the ability of the Xsens MVN inertial system to properly determine the flexion angle. As can be seen in Fig.14, the amplitude differences between the ten flexion/extension movements performed in each analysis session are clearly highlighted. It can also be observed that the average value of the range of motion is approximately the same in the five sessions, the small differences of tenths of a degree being most likely generated by the compression of the soft body segments, following the contact with the limiting elements.



a. b. c.



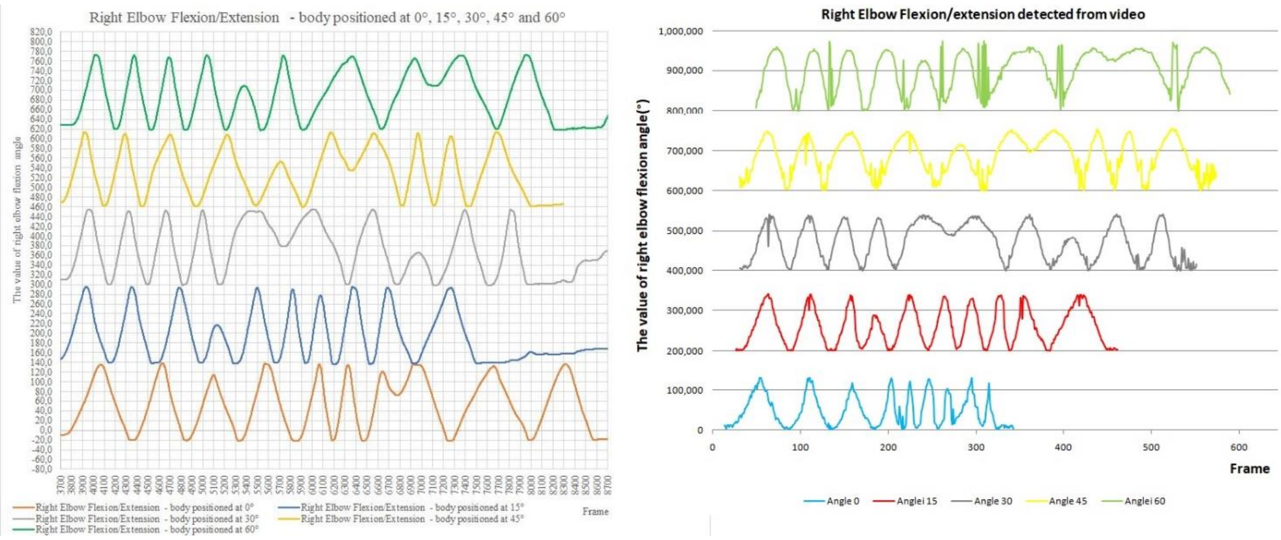
d. e.

Fig. 15. The results obtained in the five motion analysis sessions carried out with the help of Xsens MVN, regarding the range of motion at the level of the right knee joint, during an exercise performed without additional loading

Analysing the data from Fig.15, which shows the flexion/extension movements at the knee level limited lower by the contact with the fixed bars assembly having an unmodifiable spatial position, it can be clearly seen that the phenomena highlighted in the analysis of the flexion/extensions at the elbow level, manifests itself in the same way in the currently analysed joint. The difference compared to the situation of the elbow joint is given by the fact that the variation in aptitude between the movements performed are greater in this case (approximately 1° to 3°). This aspect is clearly due to the fact that the soft body elements that come into contact with the limiter in the case of flexion/extension at the level of the knee joint have a higher volume than those in the case of the elbow joint, thus allowing a higher level of compression.

4.7 Comparative analysis between the two systems: inertial system and video system

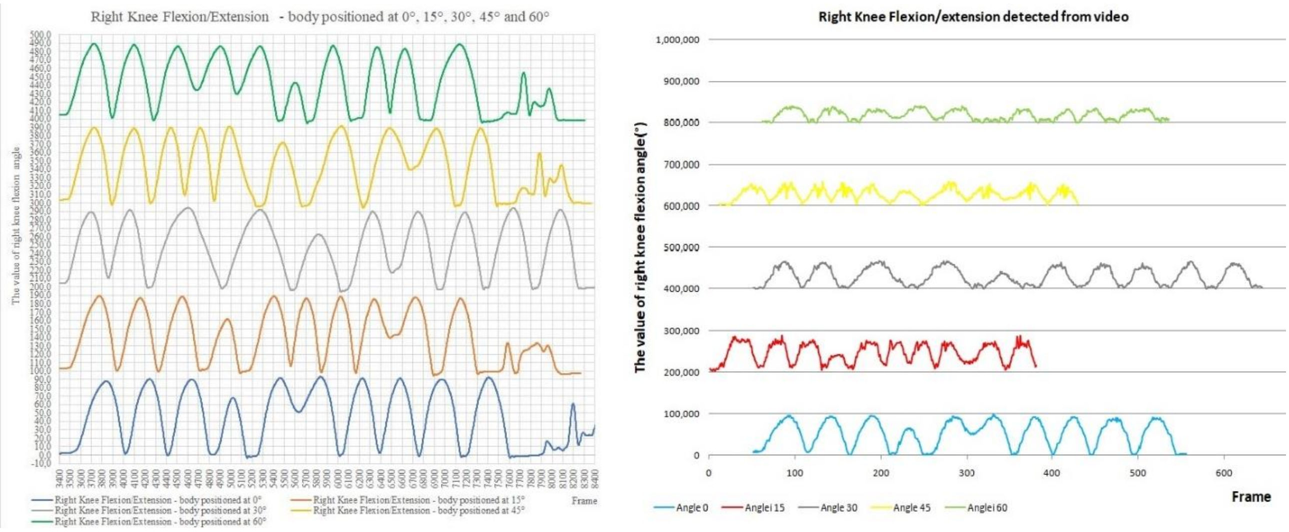
Data acquired by the inertial motion analysis system and data obtained by processing successive video frames were processed to obtain the flexion-extension angles. The graphs have local minima and maxima, which correspond to incomplete flexion-extension movements. The flexion-extension movements performed faster or slower are highlighted on the graph by the numerical value of the ascending and descending slopes associated with each movement. As expected, for all the graphs obtained with the help of the inertial system, the maximum and minimum values of the measured angles (for the full flexion movement) are not affected by the positioning of the human subject's body in relation to the video camera image plane. Instead, the minimum values of the angles measured with the help of the video application, corresponding to full flexion, are different, depending on the rotation angle of the human body compared to the fixed reference on the floor. In order to allow a comparative analysis of the quality of the graphic representations, the values of the angle supplements obtained through video analysis were represented in the graph in Fig.16.b.



a. b.

Fig. 16. The comparative results of flexion/extension movements at the right elbow joint level, obtained with: a) Xsens MVN inertial system; b) video analysis

The graphs obtained by video analysis have a different number of points because body landmarks could not be extracted from some video frames. Also, in some successive video frames from the film associated with the positioning of the human body at 60° from the camera plane, incorrect positions for the shoulder, elbow and wrist were detected, for the shoulder the calculated angle values are not acceptable. The synoptic analysis of the two graphs indicates that the allure of these graphs is the very similar.
The comparative presentation of the results for the flexion/extension movement of the right knee joint level is depicted in Fig.17.



a. b.

Fig. 17. The comparative results of flexion/extension movements at the right knee joint level, obtained with the help of: a) Xsens MVN inertial system; b) video system

5. Conclusions

Video analysis of moving images of the human body using MediaPipe software is an affordable method of calculation and quantitative evaluation of the movements made by human subjects during sports training. The experiments carried out revealed the fact that the relative position of the human subject to the room plane influences the calculated value of the flexion-extension angle. Because both the T-shirt and the pants of the sports suit, used by the human subject, are black, some image frames could not be processed. The adopted solution was to create a colour contrast between the moving arm and the rest of the body. Taking into account the previously mentioned facts, we can assert that, if the video analysis includes an initial stage of adequate calibration, this method will also allow a qualitative evaluation of the movements of human subjects. Future research will address the following aspects: augmenting the video analysis method with data delivered by acceleration, rotation, magnetic sensors and measuring the distance of the human body from the video camera plane, as well as increasing the speed of real-time detection of body landmarks, by writing software applications in the C++ language.

The Xsens MVN inertial system provides a precise method of motion analysis when the quality of the information provided by it is evaluated from a biomechanical point of view. More precisely, for the cases presented in the present paper, this means that the precision of measuring the joints angles and the joint's range of motion must be correlated with the phenomena that occur in the case of the human joint motion and not through the prism of a hinge-type mechanical joint, in which the joint elements are non-deformable. Thus, in a biomechanical analysis, the biological component can significantly modify the result of the analysis, mainly due to the high deformability of the anatomical elements involved both in making the movement and in limiting it, as well as due to the precision of making the movements, or more exactly the level of neuromuscular control of the human subject under analysis.

Although the digital protractor is used in the anthropometric measurements (goniometer), it was found during the tests described in this article, that it cannot represent a standard for the evaluation of the two analysis systems (inertial and video), mainly due to the impossibility of achieving a precise, stable and repeatable positioning of the measuring instrument, on the segments of the human body joints.

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