Inertial and Video Methods – A Non-Invasive Approach to Measuring the Human 's Upper Limb Joints Biomechanical Parameters

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Abstract: *The correction of the biomechanics of human movements is an extremely important activity both for the civilian environment (in which we include: domestic, lucrative activities and those related to sports training) and for the military, as this allows the optimization of neuromuscular control and also the increase of the efficacy of physical and mental resources allocation, in humans. This fact leads to a reduction of the injury risks, to the correction of certain anatomical-functional deficiencies/limitations and last but not least, it allows the improvement of the individual's quality of life. The non-invasive character of certain biomechanical analyses gives them a privileged status because the degree of intrusion and discomfort endured by the human subject subjected to the analysis is minimal, a fact that allows a better interaction with him in terms of he's availability of physical and mental involvement. From the category of these non-invasive systems for biomechanical analysis of motion, as well as of posture, the most used (due to their facilities) are video and inertial ones. They allow qualitative/quantitative evaluations of posture (static determinations) and/or human motion (dynamic determinations).*

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

1. Introduction

The non-contact analysis of human movements using video systems and dedicated software applications involves locating in the video images some landmarks intrinsic to the anatomy of the human body, such as the wrists (shoulder, hip, thigh, knee, etc.). These anatomical landmarks allow the identification of body segments and subsequently, through software analysis, the necessary measurements and validations involved in postural analysis. One such video analysis system of human movements is the MediaPipe Pose Landmarker which uses machine learning (ML) models and provides body landmarks in image coordinates and 3D world coordinates [1].
In the field of human biomechanics analysis, inertial systems have stood out in particular due to the accurate representation of human joints, from the point of view of their degrees of freedom, through the possibility of recording the movements of body segments without the risk of obstruction (such as it is found in the case of video analyses) and last but not least by their level of portability. However, the quality of the results offered by the inertial systems is particularly influenced by the quality of their calibration, which is dependent on the accuracy of the estimation of the sizes of the various anatomical segments.
Motion analyses that can be carried out by non-invasive video or inertial methods can be classified into two categories, namely:

- analyses in which attention is directed at the quality of human movements. This category includes postural analysis, gait analysis [2], range of motion determination, etc.;
- analyses in which attention is directed at the amount of movement achieved. As an example, in this regard, we can mention the analyses that follow the realization of a certain number of movements made in total or in a certain unit of time.

2. Previous and related works

In the paper [3] an introduction is made in 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.
In the paper [4] there are presented 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.
In the paper [5] there are presented the most important elements that Xsens MVN inertial motion analysis system uses in order to be able to generate results that reflect as precisely as possible the real situation analysed. This article presents the results of the motion analyses that which aimed to highlight the facilities and limitations arising from the use of 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) and also the graphic elements used by the dedicated software - MVN Analyze, as landmarks for the inertial analyses carried out;

3. Material and method

The analyses carried out in this study were based on the following physical elements/systems: an inertial motion analysis system, a stereo vision type camera, a laptop, a digital protractor, an angle gauge, a roulette, a ruler, a 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.
From the software point of view, the analyses mentioned in this work were carried out using MediaPipe and OpenCV for video analysis and MVN Analyze for inertial analysis.

3.1 Hardware and software used in the video analysis

The hardware and software architectures used in this study contained the following distinct elements:

- From the hardware point of view:
  - 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.
- From the software point of view:
  - UBUNTU operating system version 18.04.6 LTS;
  - OpenCV software package version 4.7.0;
  - The MediaPipe software package;
  - Python version 3.10.5.

3.2 Inertial motion analysis system

In regards to the Xsens MVN inertial motion analysis system, the carried-out tests were aimed on testing the advantages and disadvantages of such the system, as well as on the comparison between the this and a video analysis system. On the motion analyses field, Xsens MVN represents one of the best performing inertial systems [6][7]. Xsens MVN is 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 obtained data is 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:

- 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].
- the communication between the inertial system and the computer is wireless. 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;
- 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);

3.3 Types of biomechanical analyses performed and their specific requirements

For each of the systems used (video and inertial), the biomechanical analyses were structured in two sections, as follows:

➢ The static analysis section – dedicated to the calibration of the two analysis systems used. The focus on this section was put on the capacity of the two motion analysis systems to determine, in static conditions, the joint angles at the level of the elbows of the human subject (alternating biceps-triceps contractions, see Fig.1);

Fig. 1. Successive positions of the human subject carried out for the static determination of the flexion angle of the right elbow joint

➢ The dynamic analysis section – dedicated to the ability of the two motion analysis systems to determine, in dynamic conditions, the correct joint’s range of motion for the elbow joint. 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 having different amplitudes.

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

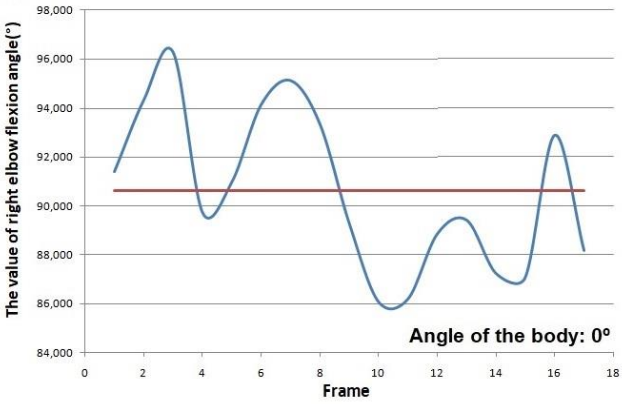
In order to fulfil the proposed objective, certain conditions were imposed and respected, as follows:
- to ensure that the human subject can obtain and maintain the joint angles as correctly as possible (necessary for the static analysis), a specially designed angle gauge was used so that it could be placed and maintained between the arm and forearm, having the angle of interest of 90°;
- an electronic protractor with a resolution of 0.1° was used and mounted at the level of the studied joint, distally, on its lateral face, in order to ensure a standardized measurement of the angles and the of joint's range of motion;
- during the motion analysis sessions, the human subject was equipped with the sensory suit of the Xsens MVN inertial motion analysis system;
- in regard to the elbow joint, the analysis sessions carried out 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;
- in order to ensure a proper procedure, 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;
- in accordance with the previously mentioned objective, 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° (see Fig.1);
- in the case of video analyses, a software application was written in order to create twenty *.avi* files during the flexion-extension exercise of the right elbow 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) 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 and 2 (presented above) show the static and dynamic video analysis sessions of the elbow joint of the human subject.

4. Results

Both in the case of video analysis and in the case of the inertial one 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 of the human subject under analysis. As mentioned before, the first section for each of the two types of motion analysis is dedicated to static conditions, and the second one to dynamic conditions.

4.1 Video monitoring - the right arm in a fixed position regarding the flexion angle of the elbow

The graphs in Fig.3 shows the measurement data of the 90° flexion angle of the right elbow joint depending on the processed video frame.



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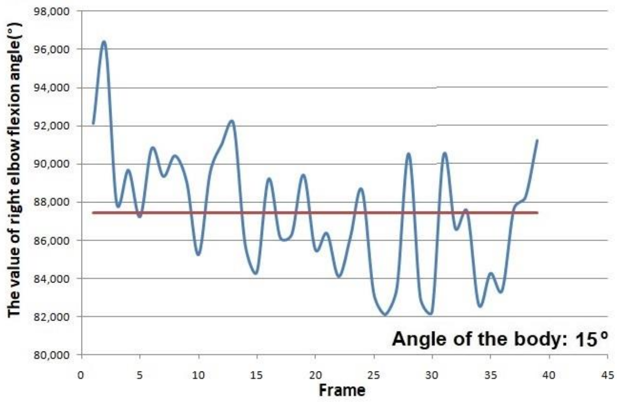

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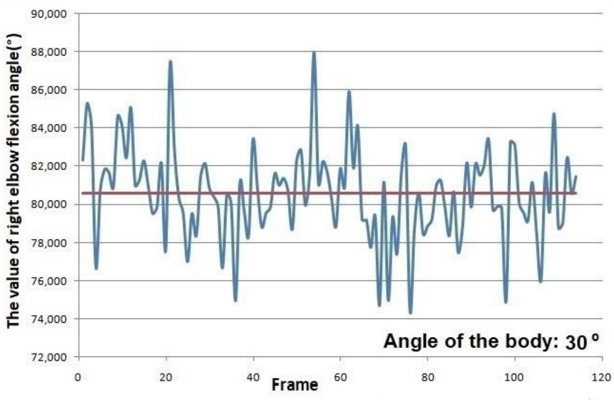

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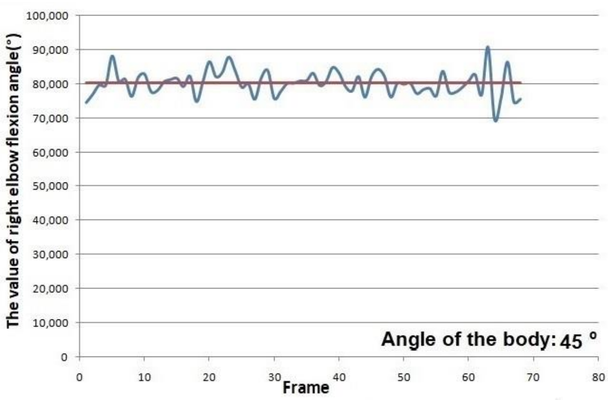

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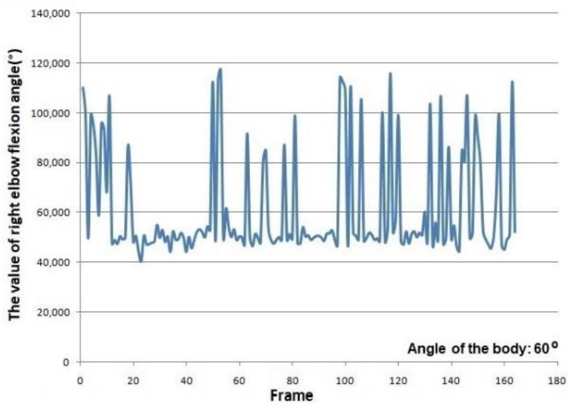

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Fig. 3. The data extracted from the video frames regarding the angles of the right elbow joint, having the angle gauge mounted on its inner face - comparative results obtained after post-processing

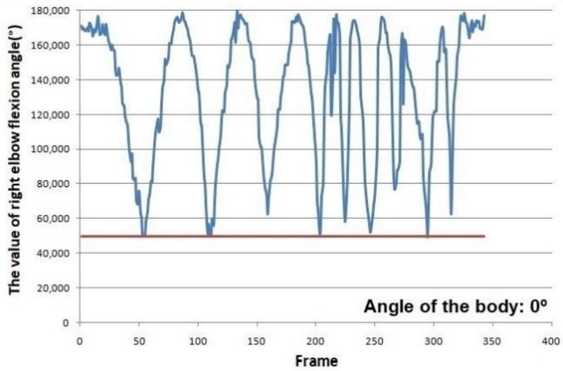
In this analysis there were image frames in which human body landmarks could be detected by software and therefore the flexion angle was not represented on the graphs. Table 1 shows the data processing situation for the angular position in static conditions of the right elbow joint, as it was monitored by the video application.

Table 1: 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

4.2 Video monitoring - the right elbow flexion/extension

The graphs in Fig.4 shows the variation of the flexion/extension angles value of the right elbow as it is extracted from the processed frames.



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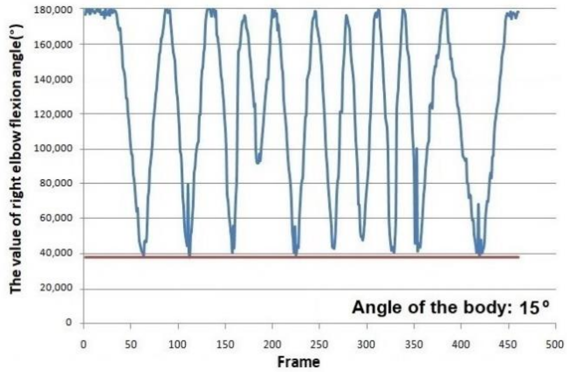

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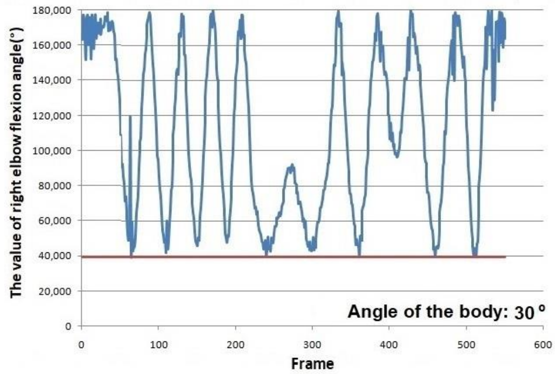

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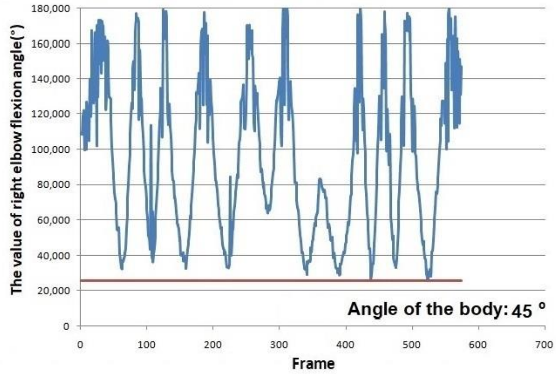

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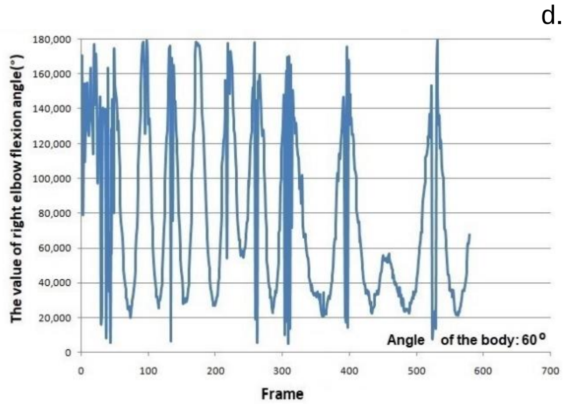


e.

Fig. 4. The results obtained after processing the video frames of flexion/extension movements at the level of the right elbow joint

As in the previous case, in this analysis sessions 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 2 shows the data processing situation for the flexion movement of the right arm, 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 elbow

The position of the body relative to the fixed reference	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

4.3 Inertial motion analysis using *Xsens MVN* system - static section

In order to create a static scenario 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 joint) determined with the help of the electronic protractor and/or the 90° angle gauge.
For the purpose of determining 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. A digital protractor was chosen because it is commonly used in anthropometric measurements, being known as a goniometer. So, this analysis sessions 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.5 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.

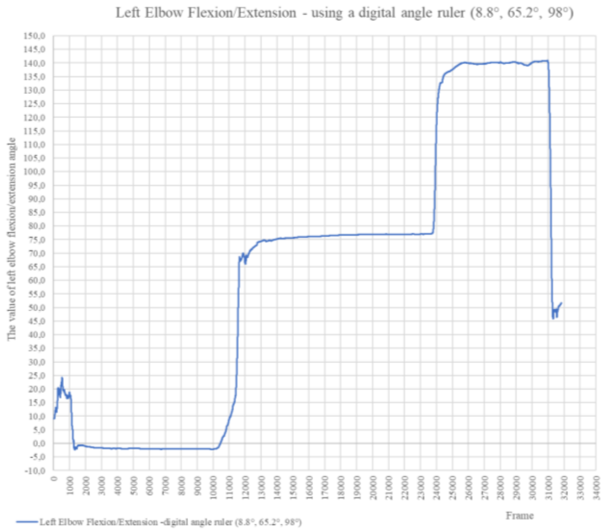


Fig. 5. The results obtained using Xsens MVN inertial analysis system, in the case of maintaining the flexion/extension angles at the level of the left elbow joint, for three different angular positions

In the graph represented in Fig.5, 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.

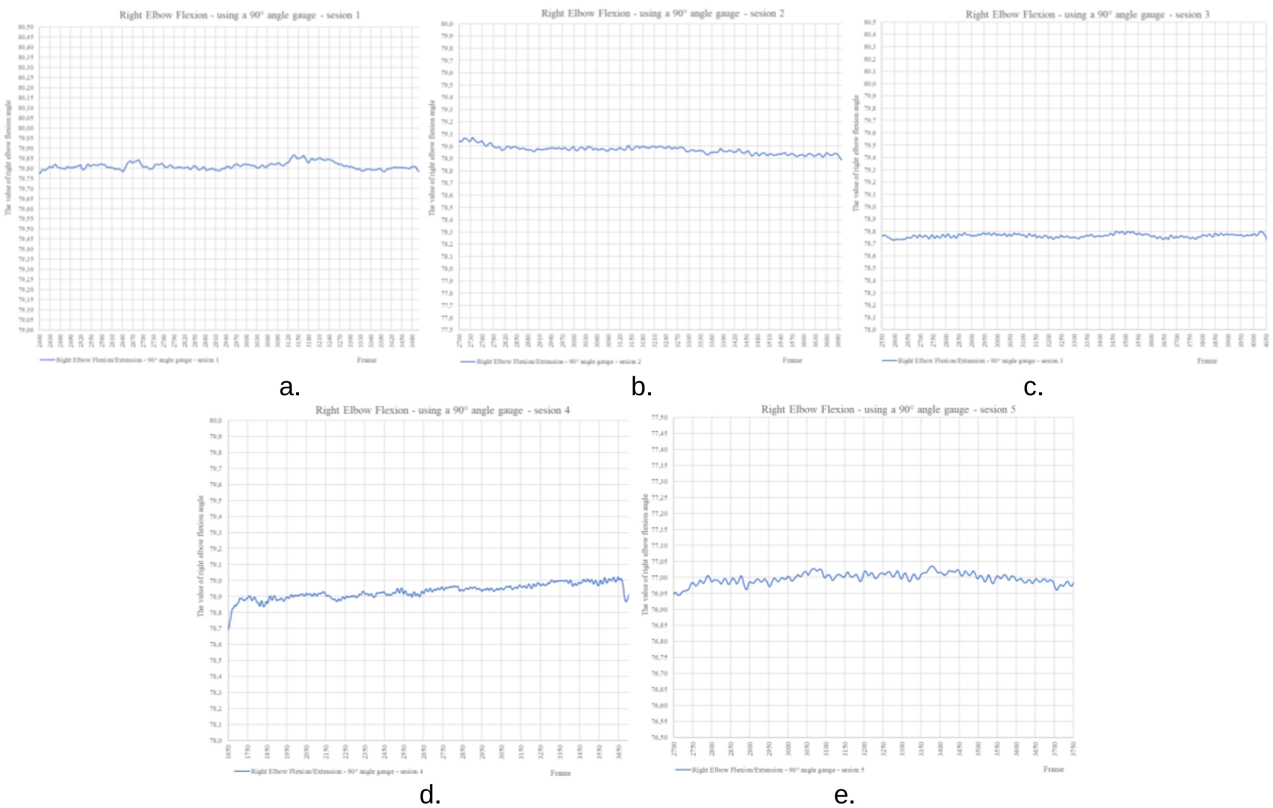
Considering the fact that the digital protractor was placed and fixed on the external face of the arm and the forearm respectively, the conducted experiments highlighted the following aspects:

- in regard to the joint’s range of motion recorded with the help of the digital protractor the maximum and minimum values 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;
- a displacement of the digital protractors positions still occurred in relation to its initial position, even if the forearm was kept in supination throughout the execution of the flexion/extension movements at the elbow joint. 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.

The phenomenon described above 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. The graph in Fig.6, clearly shows that 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. 6. The graphical representation of 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 graph in fig.6 shows that the variation of the flexion angle 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.
A new analysis was carried out, in order to confirm or deny this assumption, that contained five sessions, which assumed the repetition of the restriction of the elbow joint movement. 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.7), in all five dedicated sessions.



a. b. c.

d. e.

Fig. 7. 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

The amplitude of variation of the flexion angle (in the case of the elbow joint) is the same in all five sessions (approximately 0.4° - see Fig.7), differing only in the average value of the angle in

question. The observed 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).
Consequently, 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.

4.4 Inertial motion analysis using *Xsens MVN* system - dynamic section

During these motion analyses, the human subject had to perform ten flexions/extensions at the level of the elbow joint, the movements being limited or not in a certain direction with the help of props whose shape and position in space cannot be modified. In these analyses the purpose was 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.

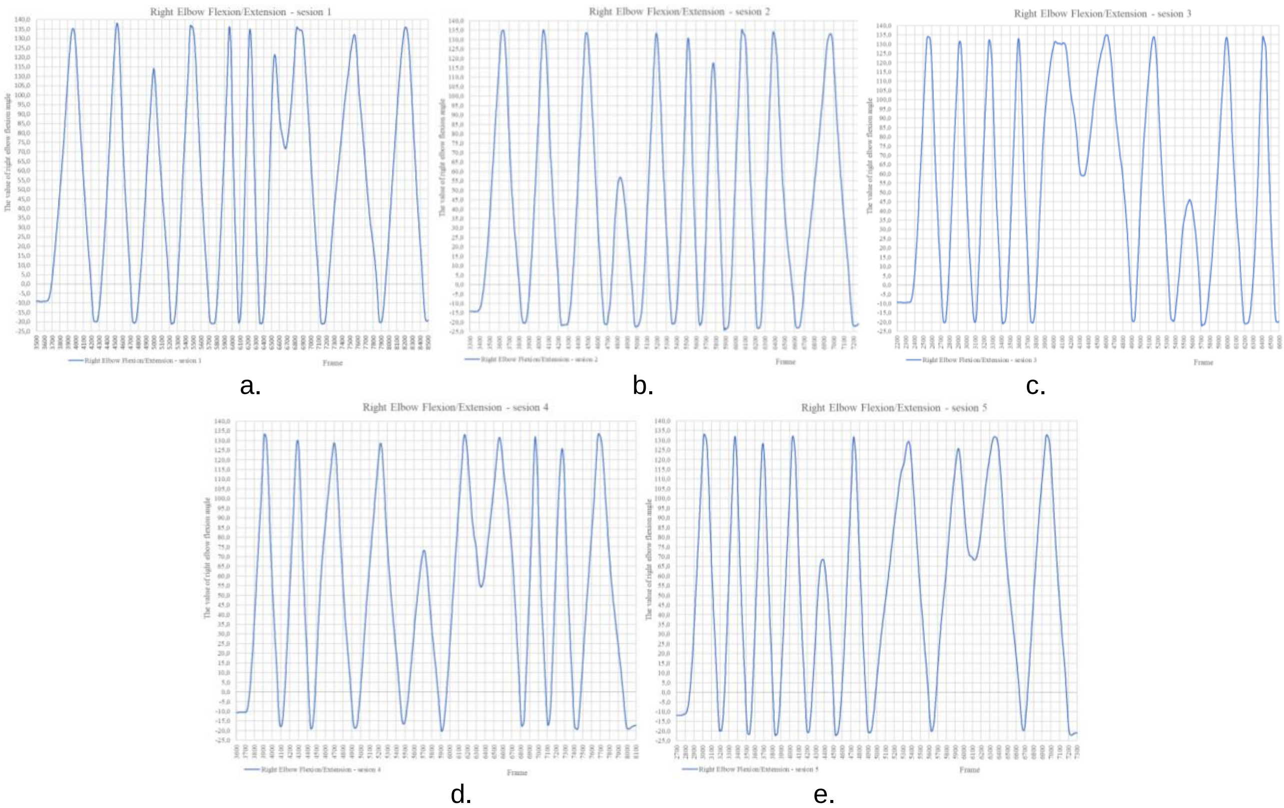
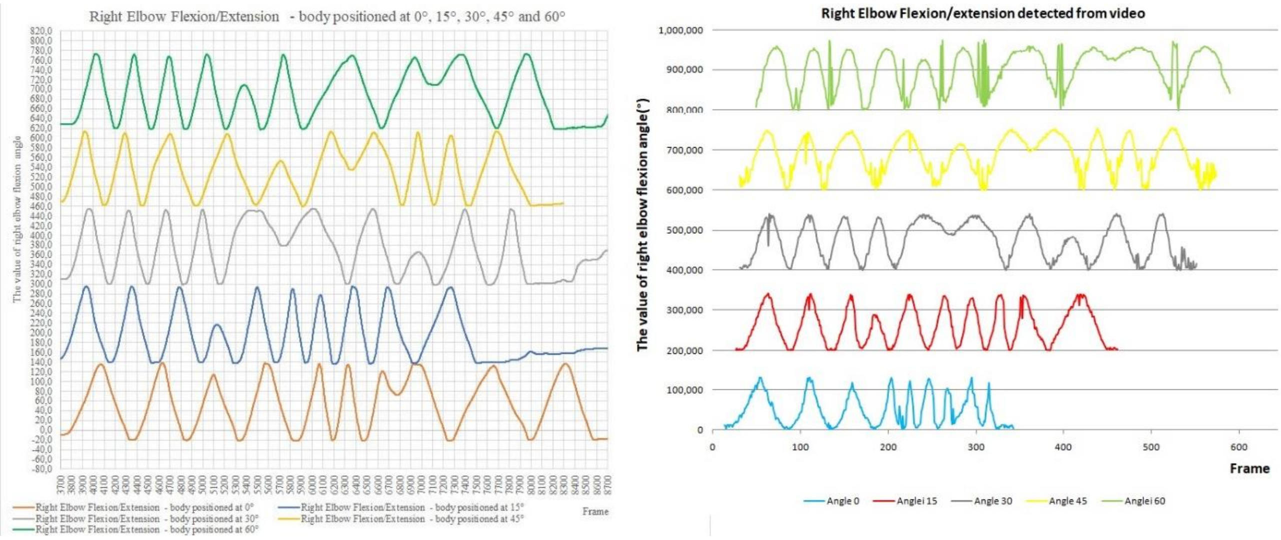


Fig. 8. The data obtained in the five motion analysis sessions carried out with the help of Xsens MVN, regarding the range of motion at the level of the right elbow joint

The movements in the case of the elbow joint were mechanically limited by the contact with the outer face of the chin of the human subject undergoing analysis (having his 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.8, 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.

4.5 Video analysis method versus inertial method – a comparative approach

The results generated 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.9.b.



a. b.

Fig. 9. The comparative results of flexion/extension movements at the right elbow joint level, obtained with: a) Xsens MVN inertial system; b) video analysis

Analysing the graph in fig.9, one can clearly see that the data extracted using video analysis has a different number of points because body landmarks could not be extracted from some video frames. 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.

5. Conclusions

Using MediaPipe software for video analysis of moving images of the human body is an affordable method of calculation and quantitative evaluation of the movements made by human subjects during sports training. The carried-out sessions 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. So, the optimum 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.
Using 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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