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Research Article

MOTION CAPTURE AS A MODERN TECHNOLOGY FOR ANALYSING ERGOMETER ROWING

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ABSTRACT
The paper presents a purpose-built laboratory stand consisting of a Vicon motion capture system with reference video cameras, wireless EMG system, Concept 2 Indoor Rower ergometer, wireless heart rate monitor and the Nexus software. A pilot study of people who exercise on the ergometer helped to create a proper configuration of all the components of the laboratory. Moreover, a procedure for carrying out research was developed, which consists of several steps divided into 4 stages: preparation of the motion acquisition system; preparation of the participant; familiarising participants with the technique of rowing, recording their movements and acquiring other measurement signals. Preliminary analysis of the results obtained from heterogeneous signals from various devices showed that all the components of the research stand are mutually compatible and the received signals do not interfere with one another.

Keywords: motion capture, ergometer rowing, biomechanical body parameters.

INTRODUCTION

Information technology in the form of specialised hardware and software is becoming a common procedure in the study of individual athletes and groups of players practising a chosen discipline. Another important issue is the development of effective methods for the registration of three-dimensional movement of the whole athlete, his/her individual limbs or other parts of the body (back, head) and their relative positions, which could be saved in a format allowing for further standard or authored processing. Having a digital record of a person's three-dimensional motion or its selected parts allows to carry out further comparative analyses through proper filtration of the recorded data. Thus one can plot standard motion trajectories, compare the trajectories of individual players with the generated pattern, pick their technical faults invisible during normal observation or subject the obtained results to the appropriate statistical processing.

In order to carry out research involving the registration of an athlete's three-dimensional movement, this study uses the optical motion capture system (MC) by Vicon. For the measurement of muscular activity a wireless electromyography (EMG) system was used. These facilities are available in the recently opened Laboratory of Motion Analysis and Interface Ergonomics of the Institute of Computer Science at the Lublin University of Technology. In addition, the research process uses a heart rate monitor to record a sportsman's heart rate during the exercise, and an ergometer, on which the exercise is carried out. Registration of multiple heterogeneous signals from different parts/organs of an athlete's body (external – e.g. the muscles and limbs; internal – the heart) allows to make complex analyses and corresponding comparisons. This in turn allows the researchers to search for correlations between the biomechanical properties of individual subjects, their level of training, technical skills, individual effort and permissible training load. The end result of such activities is the opportunity to prepare individualised training plans that lead to getting ever better sports performance.

The paper presents a method of using MC for mapping the spatial movement of the athlete practising on the ergometer, including analysis of the heart rate. The ergometer is used to simulate the movements made while rowing on the water. It can be used both by professional athletes and beginners in order to improve their overall efficiency. According to the Concept 2 ergometer guide, the device is a safe and beneficial form of exercise [11], which can also be used at home, provided that the principles are observed, i.e. equipment and health status check before the exercise and sensible training.

The authors set themselves the achievement of two research purposes. The first goal of this pilot study was to develop their own research methodology allowing for efficient mapping of an athlete's movements on an ergometer by using the MC optical system, the wireless EMG system and heart rate monitor. The developed methodology should adopt some of the skills obtained by authors in the Multimedia Laboratory at the University of Alicante, Spain, but adapt them to the actual equipment of the laboratory test stand. The second objective was to verify the compatibility of devices making up the laboratory stand. In this case the idea was to examine whether individual recorded signals do not interfere with each other and the way they are recorded is correct and sufficient for further analysis.

In many sports athletes' movements are recorded by digital cameras, infrared cameras and other motion capture systems, for example inertial ones. Their analysis and comparison with the reference model provides the opportunity for error correction, movement synchronisation, muscle conditioning or adaptation of the training to a particular player's psychophysical condition. In the case of sport, the use of a number of digital tools and equipment made it possible to adjust the sporting, medical or training requirements. One should underline that research supported by computational technology must consider ethics, especially in relation to subjects, an issue seriously addressed by Harriss [15] and Guillemin [14].

Motion capture technology allows to capture every movement, regardless of its speed and complexity, obviously taking into account the maximum frequency of NIR cameras and video. Combining it with an indoor rowing ergometer, it is possible to obtain data whose thorough analysis enables the researchers to spot connections, differences, movement sequences or errors imperceptible to the naked eye. The combination of motion capture with an ergometer is a positive aspect, mainly for trainers. The visual process of reading data, saving many parameters together with an indication of their interrelations and other information contained in the research team's reports provide the coach with a valuable source of knowledge that can be used during training. Graphs, comparisons, ratios – all this facilitates the process of shaping an athlete's silhouette and assisting his/her achievement of ever better results.

OVERVIEW OF ROWER RESEARCH BY MC TECHNOLOGY

In the early period motion capture (MC) technology was used primarily in the creation of motion pictures production utilising the mapping of the movement of real people to substitute them for animated characters through the use of rotoscoping [6, 16, 19]. The first research on the use of MC concern the techniques, methods, systems and algorithms that describe motion capture [5, 10, 12, 20, 21, 27, 29]. In many works the authors portrayed different MC systems: optical [17, 18], inertial [25] magnetic [28] or mechanical [28], describing their advantages and disadvantages, and then matching the capabilities of these systems to the problems of their research. These actions led to the use of MC technology in studies of athletes from various disciplines (such as tennis, golf, martial arts, volleyball, soccer or rowing), medicine (particularly in the rehabilitation of people after injuries and surgeries, but also in the overall analysis of biomechanical movement in various medical conditions) and in entertainment.

In the area of broadly conceived sport, Brodie et al. [7] using inertial MC system compared a competitor's biomechanical parameters during cross-country skiing to get information that would support the creation of individual training plans. In the available literature several works can be found in which various authors used motion capture to study people exercising on a rowing ergometer. Cerne et al. [9] used the optical MC system of the Optotrak Certus company to study the biomechanical parameters associated with the technique of ergometer rowing (according to Concept 2). They took measurements of the ergometer's rod trajectory as well as the body position: tilt of the athlete's torso, speed and accuracy of rowing. In addition, they measured the body load, particularly the knees and the length of the lumbar-sacral segment, the length of the stroke (pull), and its strength, and the force exerted by the player on the ergometer's footrests. The subjects consisted of three groups: experienced paddlers, beginners and first-timers. To measure the movement of the players only 14 markers were affixed to their ankles, knees, hips, lumbar-sacral segment and shoulders. The research program included the measurement of rowing during three intervals: 60 seconds at the rate of 20 strokes/minute, 30 seconds at the rate of 26 strokes/minute and 30 seconds at the rate of 34 strokes/minute. The authors found that the movement of the rod and the angle of the rower's trunk at the beginning of the ramp-up phase of experienced and novice rowers are constant and independent of the speed of rowing. In addition, the study showed that the rowing technique of both experienced and novice oarsmen is constant, and of amateurs – variable in different strokes and rowing periods.

Sforza et al. [26] made a three-dimensional quantitative analysis of movements (just as Panjkota [22]) and examined the links between anthropometry and rowing kinematics. Using an optoelectronic system (21 markers affixed to the body of the players), they recorded the movements of 18 professional rowers rowing at the rate of 28 strokes/minute. The results of the study showed that the average slope of the chest was 68° and the angular range of motion of the lumbar-sacral segment reached 59° and was lower in heavier riders. The symmetry of the movement of the upper limbs was confirmed, as was the almost vertical position of the plane formed by the bent legs to the ground surface.

The test results of the biomechanical parameters and motor efficiency and productivity of the rowers' legs and hands were presented in [1, 2, 3, 4, 8, 18, 23]. These studies were carried out to improve athletic performance, create training plans and to minimise the risk of injury. Fothergill [13] proposed the concept of using the data obtained as a feedback to verify the movement of rowers and overcome their mistakes and motivate them for further work.

The authors presented investigations which were some sort of case studies. In the above-cited works the study population was not large enough to enable a statistical analysis of the results.

In this paper, the authors describe the laboratory stand which significantly increases the ability to measure various parameters of an athlete, including the strain of selected muscles, e.g. of the legs and arms or the heart rate at different times. Moreover, in measuring the movement of athletes a more complex biomechanical model was used, which required as many as 39 markers (against the 14 in [9] and 21 in [22]).

THE RESEARCH STAND AND CONDUCTING TESTS

The research stand

In order to study athletes exercising on an ergometer a stand was built consisting of devices in the Laboratory of Motion Analysis and Interface Ergonomics, and additional components typical of conducting training classes. The stand was placed in a shaded room (without windows) of the said laboratory, which was already equipped in a passive motion capture system. Other elements of the laboratory include: cameras recording video images, EMG system, ergometer (with a system registering the device's parameters) and heart rate monitor.

The Vicon motion capture system consisted of eight T40S cameras operating in the near infrared and two Bonita reference video cameras, a Giganet hub collecting data and a desktop computer. The system records the movement of the markers placed on the body of a subject (each marker must be seen by at least two cameras). Two reference cameras record video, which is used both for data processing and to generate video files containing integrated video and a biomechanical model of man. The myon wireless 16-channel EMG system allows to record real-time activity of an exercising athlete's selected muscles. One can record simultaneous work of up to 16 different muscles. Each transmitter has two electrodes attached to a single muscle. A great advantage of the presented system is the temporal integration of all the recorded data, both analogue and three-dimensional. The equipment is supplied with Vicon's Nexus software, used to calibrate the system, record data and data processing. In this study version 2.0 of 2014 was used. A fragment of motion capture test stand, together with the ergometer placed on a non-slip mat is shown in Figure 1.

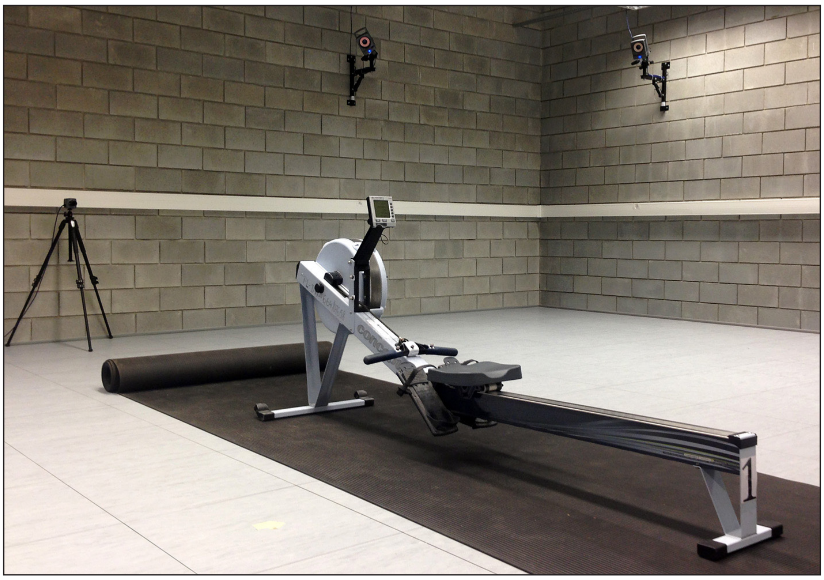

Fig. 1. The motion capture stand with an ergometer in the LARiEI room

Ergometer

The studies used a Concept 2 Indoor Rower ergometer. This construction is considered one of the best rowing ergometers in the world. It allows to control the effects of rowing in real-time with a built-in microprocessor and performance monitor (PM). The monitor registers data from the beginning of the exercise. The information includes (1) elapsed time, (2) stroke rate, (3) data from the last stroke (time/500 m, calories/hour or power in watts), (4) final score – average time, distance in meters, burned calories and power (watts), (5) the heart rate (beats per second) if it has such functionality.

The obtained values are directly displayed on an electronic monitor, which can be observed by the athlete. In the used ergometer the air resistance can be adjusted, hence the design is suitable for use by athletes of different gender, age, weight and level of fitness.

Heart rate monitor

Subject's pulse is measured using the Suunto Dual Comfort heart rate belt. The resulting measurements are transmitted wirelessly to the Suunto Quest watch placed on the subject's hand. During real-time training the display of the watch shows additional information (e.g. workout intensity, tips on the speed, information related to the selected training programme, heart rate). The data recorded during training are also sent to the Movescount site, which allows for their appropriate processing.

Preparation of test persons

The subject tested with the MC must be properly prepared for experiment. An athlete's movement acquisition session involves placing retroreflective markers directly on the skin with a hypoallergenic double-sided tape. A schematic layout of the markers used during the tests is shown in Figure 2. The markers were placed in accordance with the biomechanical Plug-in Gait model [24]. Correctly applied, this model can calculate angles, torques and forces in the joints of a subject. According to this model 39 markers are placed on the body of a patient. It should be pointed out that many markers are glued to specific bone protrusions, the position of which may be slightly different in different people. Properly locating them is critical and requires a lot of experience of the research team.

The next preparatory step is the measurement of a subject. Nexus Software is necessary to introduce data such as height, weight, leg length, arm offset, knee, ankle, elbow and both hands' thickness. This data is necessary for the proper execution of scaling the created model. Only later is the model's calibration performed.

Due to the subject's dynamic movement and the appearance of sweat on his/her skin surface, markers tend to get unstuck and fall off. This was demonstrated by the first attempts of rowing on the ergometer. To counteract this, the glued markers are additionally protected against falling off by special-purpose dressing grid, as shown in Figure 3a.

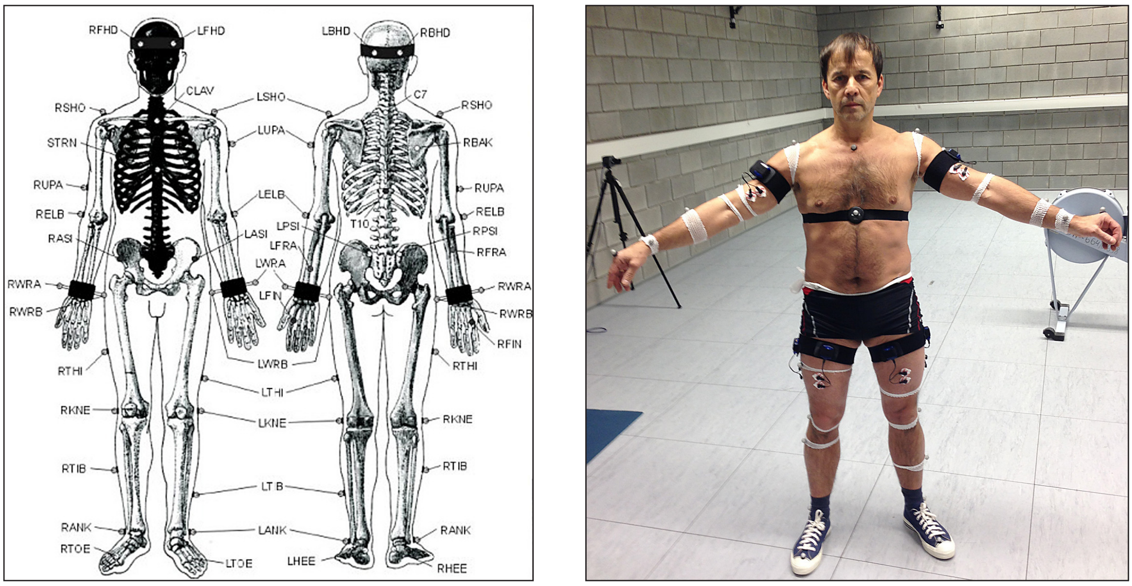

Fig. 2. Marker placement in accordance with Plug-in Gait model details [24] (a); Subject (one of the authors) with markers and EMG transmitters (b)

On the subject's body there were also placed electrical muscle activity sensors (EMG). Preliminary studies on the ergometer showed that subjects felt the most fatigue on the outer muscles of the thighs and the biceps muscle of their hands. Ultimately, six transmitters were used, one each on the biceps muscle of both arms, one each on the straight muscle of both thighs and one on the large side muscle of both thighs. The method of sticking electrodes (two electrodes connected to a single transmitter) is shown in Figure 3b.

In addition, the subject is equipped with a heart rate monitor. Due to the fact that the monitor is positioned exactly at the point where two markers should be located, they were attached to the heart rate sensor and the fastening tape.

Preparing the player for the experiment is very labour-intensive and takes a trained person at least 30 minutes. It should be noted that the laboratory room must be sufficiently warm. Bathroom-type comfort is required (temperature about 25 °C) because the subject is only dressed in a minimum of clothes allowing the correct placement of markers (e.g. swimming trunks or swimsuit), and staying undressed for at least 45 minutes.

Record motion

Registration of movement was carried out with the T40S camera's resolution set to 100 Hz. The proper connection of all the components of the system was ensured by the use of Nexus software. The series of proper tests was preceded by calibrating the system and setting the data management hierarchy. Movement acquisition is carried out automatically by the system and consists in recording the subject's motion from start to finish (the moment of starting the recording depends on the operator). All the obtained recordings are linked to a specific person (subject).

Fig. 3. Securing the glued markers with dressing mesh (a); EMG sensors with electrodes on the thigh (b)

An important factor influencing the quality of the recording is the elimination of all reflective elements from the cameras' sight. Accidental glare resulting from elements of the subject's or the experimenter's outfit can introduce additional artefacts in the recordings and make subsequent processing more difficult.

Data processing

Four stages can be distinguished in processing the recorded data:

- Labelling all the markers. Each marker has a name assigned by the system. If the system does not automatically assign a name, this must be done manually.
- Supplementing the gaps in the acquired marker motion trajectories by using suitable interpolation methods.
- Clearing the recording of additional unintended markers, such as instances of glare.
- Calculation of motion parameters using a biomechanical model.

It should be remembered that the biomechanical model can be calculated in each frame of the recording only when all the necessary markers are visible. Processing the recorded data is labour-intensive and a full preparation of a 90-second-long recording may take even up to several hours. Overall data processing time depends on the skill of the operator, but also the parameters set when creating a recording: recording accuracy, calibration precision and recording frequency.

A DESCRIPTION OF THE RESEARCH PROGRAMME

Participants of the ergometer study

In a pilot experiment three persons were tested. Their data are summarised in Table 1. The subjects represented different levels of motor skills and predisposition to physical effort. Often, it was their first contact with a rowing ergometer. Each participant filled a questionnaire that evaluated his level of physical activity. All participants agreed to take part in the experiment and made themselves familiar with the information prepared for them.

Table 1. The data of tested persons

Number	Age [years]	Weight [kg]	Height [cm]	Activity* [points]	BMI**
1.	57	69	169	30	40.8
2.	27	79	178	7	44.4
3.	37	78.5	185	29	42.4

* Activity was evaluated based on a survey.
** Body Mass Index.

Study procedure

The testing procedure was developed on the basis of pilot studies and previous experience. In 2014 two team members took an internship in the Multimedia Lab at the University of Alicante, during which professional rowers were tested using the Opti Track motion acquisition system consisting of eight NIR cameras attached to the rail on the wall and two NIR cameras placed on tripods. The rowers' movement was also recorded with a video camera. Despite the fact that the endurance exercises performed were different, the acquired experience helped in the development of the testing procedure.

The testing procedure consists of the following steps:

Stage 1. Development of the movement acquisition system for testing.

- Step 1. Calibration of the movement acquisition system.
- Step 2. Masking the reflections (in the Nexus software). The ergometer has a number of reflective elements disturbing the measurement.

Stage 2. Preparation of the participant for the test.

- Step 1. Outfit. Each participant had appropriate attire (swimsuits and sports shoes), which did not restrict movement, and allowed to attach the appropriate number of markers.
- Step 2. Warming up on another ergometer.
- Step 3. Attaching markers. To stick the markers on the participant (39 pieces) double-sided tape was used, additionally secured with a dressing mesh. Markers placed on the back and shoulder blade were secured with Kinesio tape. Attaching two additional markers on the spine (for future studies of participant posture).
- Step 4. Participant measurement. Measurements of weight, height, lower limb length, limb joint width and shoulder offset. Introduction of the acquired data to the Vicon Nexus software to scale the created model.
- Step 5. Placement of EMG sensors. The sensors measure the activity of selected muscles: biceps, rectus femoris and vastus lateralis.

Sensors were mounted on a special myon thighband placed on the subject's limb.

- Step 6. Heart rate measurement. Heart rate is measured with a heart rate monitor.
- Step 7. Participant calibration. Sample recording of the participant in a fixed posture (i.e. the motorcycle pose) in order to calibrate the examined person. It consists in calculating the biomechanical model parameters for the test participant. Calibration allows for verification that all the necessary markers are in the right place and that readings from all the systems are correct.

Stage 3. Familiarising participants with the technique of rowing on an ergometer. Instructing them about the ongoing study.

Stage 4. Registration of movement at two distances.

- Step 1. Distance of 100 m. The participant rows at 100% of his capabilities.
- Step 2. Rest. Participant rests until his/her heart rate stabilises.
- Step 3. Distance of 500 m. The participant holds 100% of his possibilities as long as he can. Measurements of the pulse after every 100 meters of the distance.

Ergometric studies are geared at endurance so their target is centred around the analysis of biomechanical parameters. In the present study motion was recorded at the frequency of 100 Hz.

TEST RESULTS

When rowing on the ergometer, the participant was monitored with regard to: his movement by means of the motion capture system, the activity of the three muscles by the EMG system sensors, his heart rate via the heart rate monitor positioned on the bridge and the rowing parameters measured by the ergometer. This made it possible to record a number of the subject's parameters in the same time interval. The second objective of this article is to verify whether the records (three-dimensional and analog) do not interfere with each other. Figures 4 and 5 present data obtained from the Vicon Nexus 2.0 software. Figure 4 illustrates a three-dimensional object representing the examined person and the electrical activity of the biceps of the left arm while pulling the rod over the distance of 100 m. These data are synchronized in time so that the muscles can be analyzed in relation to the exercises performed.

Figure 5 shows a three-dimensional object during rowing and the spine angle (as defined by the Plug-in Gait [24]) during the exercise. This angle is shown in the form of three charts, along the X, Y and Z axes. The angle is calculated by the Vicon Nexus software, after the post-processing of the data and calculation of the values for the Plug-in Gait model [24]. Table 2 shows the data from the ergometer and the heart rate monitor for one participant for rowing over the distance of 100 m. Displayed is the passage of time, distance, pace, the number of drags, power and

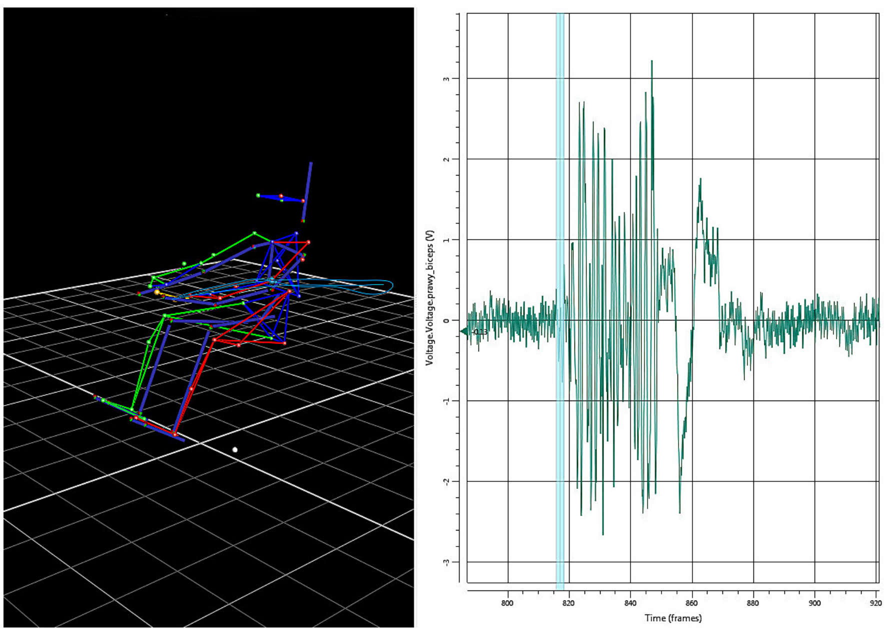

Fig. 4. 3D object and the activity of the biceps of the left arm while rowing over the distance of 100 m

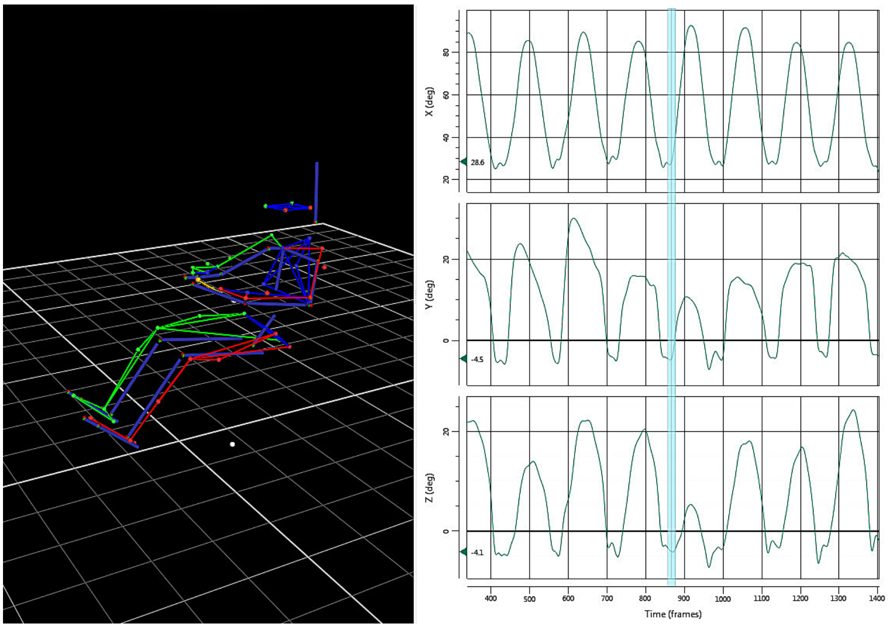

Fig. 5. 3D object and the spine angle values in three dimensions while rowing over the distance of 100 m

Table 2. Results of the ergometer and the heart rate over the distance of 100 m

Distance [m]	Time [s]	Time / 500 m [s]	Number of drags per min [spm]*	Power [W]	Heart rate range [bpm]**	Mean heart rate [bpm]	Heart rate at start [bpm]	Heart rate at end [bpm]
100	21.5	107,9	45	282	106–172	143	106	172

* Strokes per minute. ** Beats per minute.

Table 3. Results from the ergometer and heart rate monitor over the distance of 500 m

Distance [m]	Time [s]	Time / 500 m [s]	Number of drags per min [spm]	Power [W]	Heart rate range [bpm]	Mean heart rate [bpm]	Heart rate at start [bpm]	Heart rate at end [bpm]
100	21.8	109.0	41	270	114–163	136	114	163
200	20.5	102.9	41	325	165–187	178	163	187
300	21.7	108.5	39	274	187–194	192	187	194
400	23.6	118.0	41	213	192–194	193	194	192
500	25.9	129.5	37	161	191–192	192	192	191

pulse. Table 3 presents the same rower over the distance of 500 m, every 100 m.

The data presented by all the systems, are correct. Data from the ergometer and the heart rate have been verified by the coach. This allows the conclusion that the operating systems do not interfere with one another. They can therefore be used in interdisciplinary studies of rowers.

CONCLUSIONS

This article assumed two research objectives. The first involved the development of procedures for interdisciplinary research of rowers with a motion acquisition system, an EMG system, an ergometer and a heart rate monitor. This procedure was introduced after a pilot study involving three people. The second purpose of the research concerned the verification that the signals received from several devices do not interfere with one another. The results indicate that this situation does not take place, therefore the devices can be simultaneously used to conduct research on rowers. This opens the way for studies of professional rowers analysing a number of parameters of their movement, heart rate, rowing pace or the work of selected muscles.

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