POLYTECHNIC UNIVERSITY OF BUCHAREST

Faculty of Mechanical and Mechatronics Engineering
Department of Mechatronics and Precision Mechanics

PhD THESIS SUMMARY

Cercetări privind sistemele mecatronice inteligente utilizate în antrenamentul de performanță la Arte Marțiale, pentru corectarea biomecanicii mișcărilor și reducerea riscului de accidentare în cadrul antrenamentelor

Research on intelligent mechatronic systems used in Martial Arts performance training, to correct the biomechanics of motion and reduce the risk of injury during training

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INTRODUCERE

The term "*mechatronics*" first appeared in Japan in 1969 as a trademark of Yaskawa Electric and is a combination of the abbreviations "mechanical" and "electronic". Nowadays "mechatronics" is a concept that refers to the interdependence and cohesion of mechanics, electronics and computer science, necessary for the realization of mixed systems, which contain both mechanical elements and electrical elements interconnected through software.

Intelligent mechatronic systems represent mechano-electronic structures that can react and interact with the environment independent of the human operator, based on a predetermined decision algorithm through software.

Regarding the intelligent mechatronic systems used in performance training in Martial Arts, their history is relatively recent, being related to performance sports in general and adapted to their specifics.

With the growing interest in achieving top sports performance in the shortest possible time, with increased efficiency and the involvement of minimal health risks has resulted in a huge development of scientific research in the field of performance sports.

Martial Arts is currently a conglomeration of systems of physical and mental development, oriented or not to the competitive side and having its own rules and precepts. The name "Martial Arts" is supposed to come from the Latin language, meaning "the arts of Mars", where Mars was considered the Roman god of war [1] [2] [3] [4] [5] [6] [7].

Although martial arts have a millennial existence, the techniques used in them have been developed and optimized, most of the time, based on the personal experiences of the various masters involved, based on their observations, but without a scientifically proven biomechanical foundation.

With the acceptance of the organization of the World Championships, in different styles of Martial Arts, there is an increasing need to analyse the fighting techniques used, both to increase efficiency in combat and to protect the athletes involved. From the sports that have elements in common with the Martial Arts and adapted, those elements common with the martial arts were taken over, namely: the ways of developing the motor qualities, as well as the methods of optimizing the techniques of punching and lifting and throwing the opponent.

The elements that have a special impact on sports performance are the following:

- the correctness of the act of learning the movements that compose the techniques used in competitions and not only, as well as the quality of the execution of the specific techniques;
- the level of development of the motor qualities (speed, strength, skill and mobility) and motor skills (coordination, precision, fluency, ease), motor skills (elements in which each individual excels natively) of the athlete;
- the correct choice of methods, means, moments (periods) and length of time necessary for the post-effort recovery of the athlete involved. This is all the more important in the case of athletes participating in combat sports, such as those in Martial Arts [21] [22] [23] [24] [25], wrestling and boxing [26], as they do not face only the problems related to exceeding one's own limits, but also with those due to direct interaction with an opponent.

Based on the above, it is necessary to develop and implement methods and means to allow an objective assessment of the quality of the basic movements that make up the specific techniques and the ability to perform them in a correct manner from a biomechanical point of view, early correction of these basic movements, both during training and as far as possible outside them, the development of the qualities, skills and motor skills of the athlete concerned, in order to achieve sports performance without having a negative impact on health his.

SYNTHESIS OF THE CONTENT OF THE DOCTORAL THESIS

The doctoral thesis begins with a preface, followed by an introduction to the field of research addressed in it and is structured in six chapters, as presented in the table of contents. At the end of them, the conclusions of the research undertaken, the bibliography and the annexes are presented. The thesis has a total of 311 pages and contains 189 bibliographical references. Some of the research developed in the thesis were disseminated through the publication of scientific articles, containing research results, in specialized journals, by participating in scientific events, as well as through a number of patent applications.

Chapter 1, entitled "Mechatronic systems used in performance training in Martial Arts", presents the main concerns related to the training of performance athletes in Martial Arts and also the main categories of mechatronic systems used in performance training, the advantages and their disadvantages. Regarding the mechatronic systems mentioned, the emphasis is on the presentation of motion analysis systems, both in chronological order and in order of importance from the point of view of the subject addressed in the current paper, namely: optical motion analysis systems based on the use of high-speed video cameras [28], mechano-electronic systems [34], magnetic systems [35], acoustic systems and inertial systems (see fig.1.11).

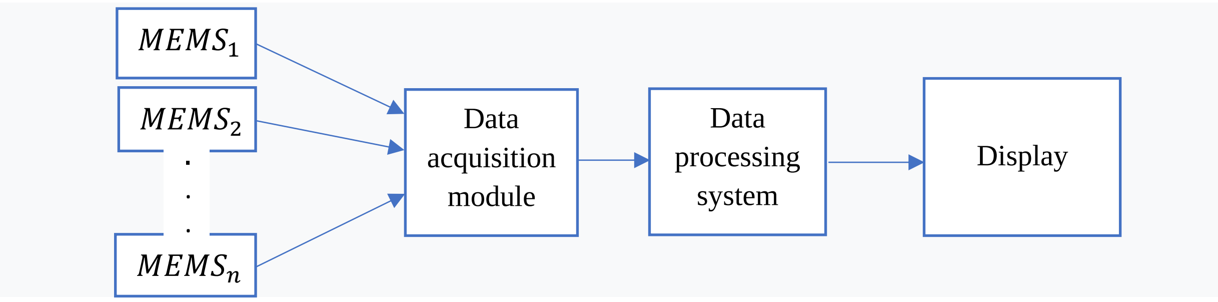


Fig.1.11. Block diagram of an inertial mechatronic motion analysis system using MEMS

Chapter 2, entitled "**Experimental research on inertial motion analysis systems**", presents the analyses performed using the Xsens MVN inertial system [37], in order to test the facilities and limitations of this system, so that, starting from the practical findings, designing of a high-performance system, which will allow not only the analysis of motion, but also the correction, as much as possible in real time, of them, will be possible.

The analysis performed were of a qualitative nature and were divided into two categories, depending on the type of information obtained:

➢ The first category is that of biomechanical analyses that provided information on the correctness of the movements, the level of static and dynamic balance, as well as the level of symmetry / asymmetry of neuromuscular control, including where appropriate and postural correctness. This information has been called direct, as it is the main result of an analysis of movements.

In this sense, in order to obtain the clearest and accurate information, it was decided to perform the analyses on simple exercises, which are the basis of complex techniques in Martial Arts performance training.

Thus, the analyses within this category were outlined around the following types of exercises / positions:

a) Exercises / positions, in which the attention was directed on the correctness of their realization (see fig.2.1). The correctness was judged, depending on the specificity of each exercise, based on the symmetry of the positions / angles of the segments / joints that make up the two upper / lower limbs in relation to the sagittal plane of the human subject under analysis.

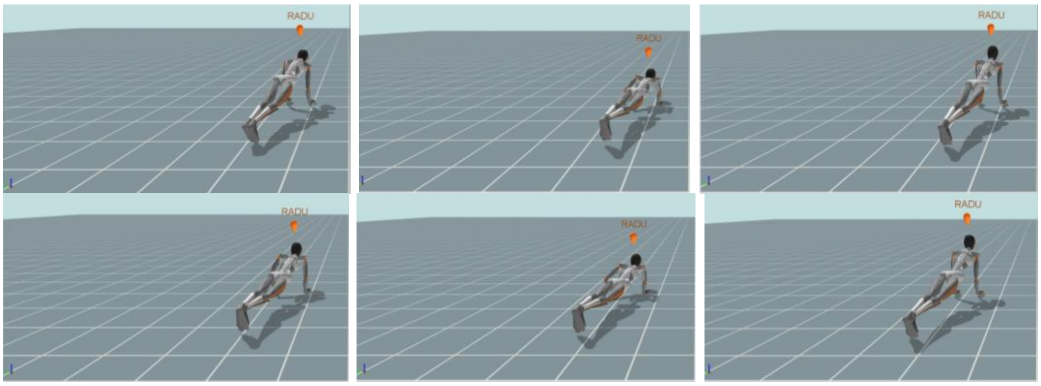


Fig.2.1. Image containing representative motion frames for the analysis session of the "*Push Up*" exercise

b) Exercises / postures, in which the attention was focused on the static balance during their performance (see fig.2.28), as well as on the symmetry of the neuromuscular control, by comparing the way they are performed by the right side of the body, with how they are performed by the left side of the body.

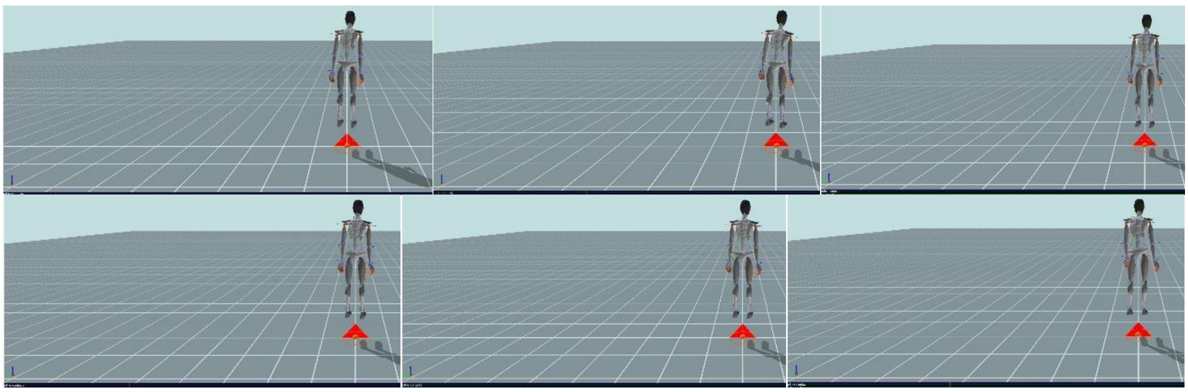


Fig.2.28. Image containing representative motion frames for the analysis session of the " *Orthostatism on the balance disc*" exercise

c) Exercises / postures, in which the attention was focused on the dynamic balance during their realization (see fig.2.32), as well as on the symmetry of the neuromuscular control, by comparing the way they are performed by the right side of the body, with how they are performed by the left side of the body.

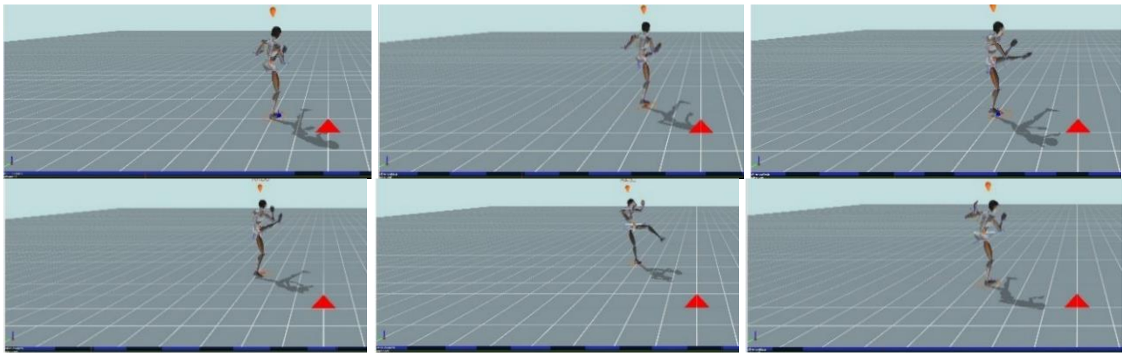


Fig.2.32. Image containing representative motion frames for the analysis session of the " *Orthostatism on the balance disc*" exercise „ *Hopping in one foot (the right one), in the direction imposed by the manipulation, by another person, of the left foot of the subject under analysis*”

The final conclusions of the analyses that provided direct information - related to the correctness of the movements performed by the human subject under analysis:

- the human subject performs the movements of the exercises and the positions, respectively, relatively wrong, tending to use the right side of the body, more than the left. It was also found that he has a strong tendency to change his position in relation to the reference. This fact indicates an asymmetry in terms of neuromuscular control between the two parts of his body and may contribute to the appearance of a postural pathology;

- the human subject presents an average level in terms of static and dynamic balance.

➢ The second category is that of biomechanical analyses (see fig.2.43), which provided information on the errors generated by the Xsens MVN system. This information has been called indirect, as it derives from a motion analysis.

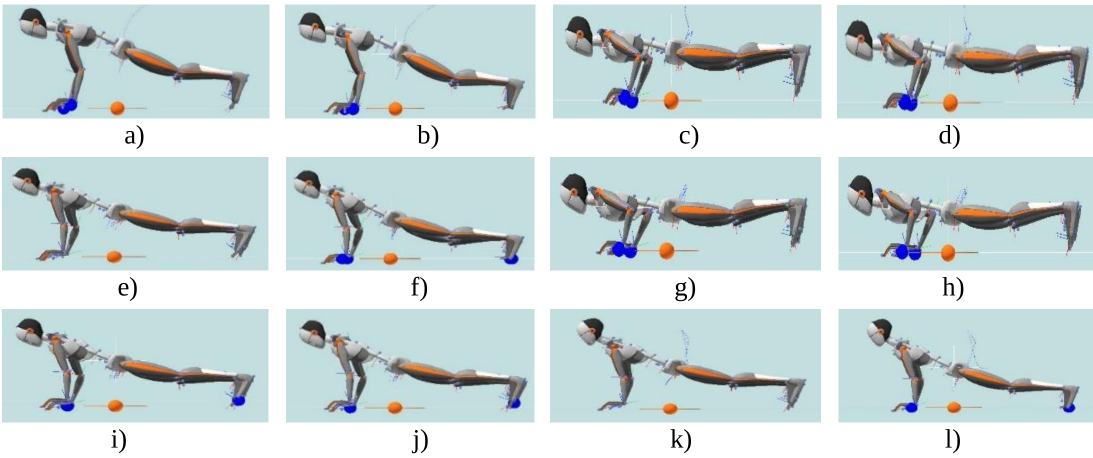


Fig.2.43. Virtual representations of the human subject under analysis, in the left sagittal plane, located at various moments in times, during the exercise "*Push Up*", having his arms stretched or flexed

In the analyses that focused on the errors generated by the Xsens MVN system, the following aspects were aimed:

- the appearance of positional "drift";

- the ability of the system, Xsens MVN, to correct any positioning errors that have occurred, by using the REPROCESS (or post-processing) function;

- the appearance of the errors generated by the interaction of the human subject, undergoing the analysis, with the environment (see fig.2.43), by using, within the analyses, the four working scenarios, provided by the MVN Analyze software.

The final conclusions of the motion analyses, which provided indirect information about the Xsens MVN inertial system, used:

- the system in question has both a global positioning error and errors in the MEMS located on the feet. You can also see the transfer of contact points, from the palms, to the toes and vice versa, throughout the exercise;

- comparatively analysing the previously presented motion frames, a “sliding” of the human subject is observed, in the horizontal plane of the image, in the positive direction of the 0Y axis and only in the direction of this axis;

- after calling the REPROCESS function, the errors decrease, but are not completely eliminated, they are reduced from cm level to mm level.

Chapter 3, entitled " **The original design of a calibration system (cs), used to obtain and maintain the position and movement, imposed during the motion analysis sessions while using inertial systems**", describes the design of a system that allows a higher-level calibration (see fig.1.1) of motion analysis systems, so that the latter can provide accurate information about the biomechanics of motion. Based on the conclusions resulting from the motion analyses performed using the Xsens MVN inertial motion analysis system [64] [65] and described in Chapter 2, it was decided to develop a mechatronic system that can accurately perform the calibration required and also that can enable a good repeatability of this action. Together with the Xsens MVN system, CS will form an assembly that is easy to use and presents a good portability.

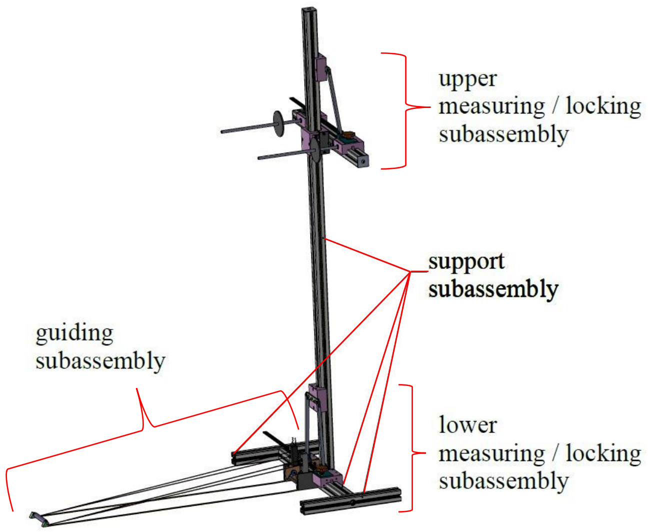


Fig.3.1. Perspective view of the *calibration system*, designed to facilitate the achievement and maintenance of the posture and the movement, imposed during the motion analysis sessions, performed using inertial mechatronic systems

The system in question, presented in fig.3.1, represents a set of elements that contribute to the achievement and maintenance of a certain posture, predefined, imposed, as well as to the achievement and maintenance of the correct displacement in terms of the rectilinearity of its trajectory and also from the point of view of the perpendicularity of the direction of movement on the sagittal plane of the subject under analysis (see fig.3.9).

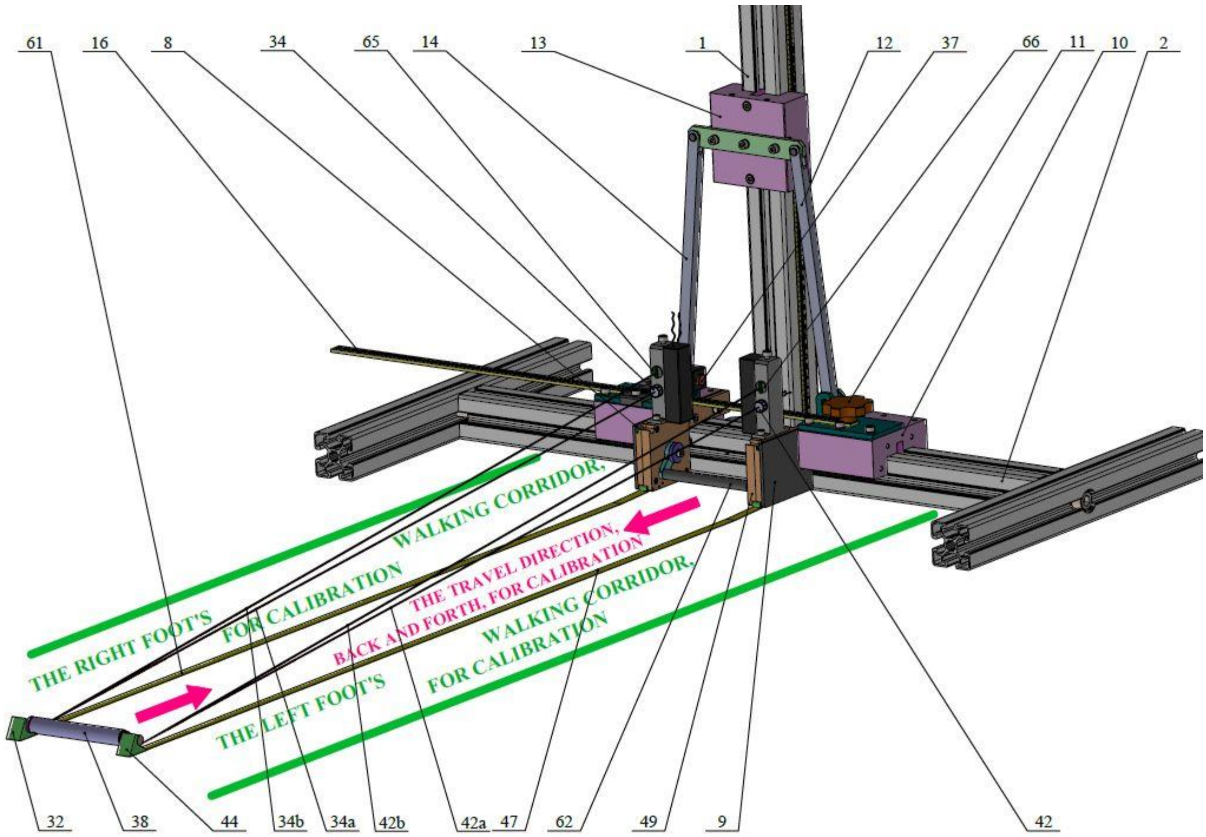
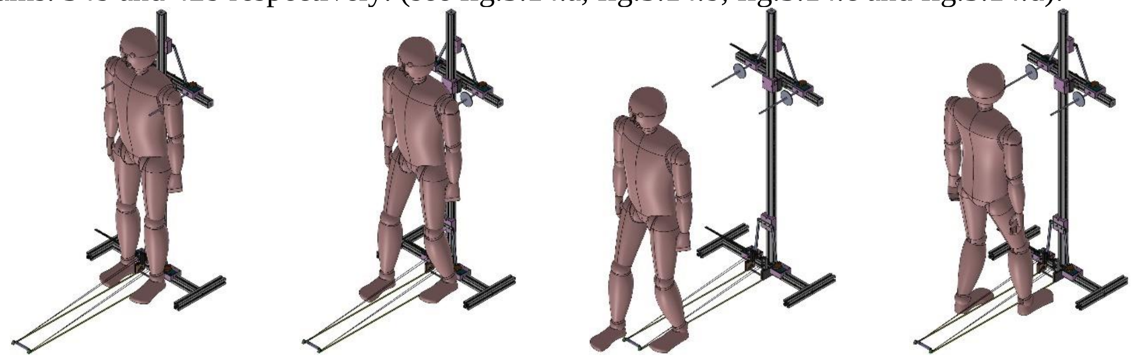


Fig.3.9. Perspective view of the *guiding subassembly*

According to the calibration requirements, the athlete will have to move on the corridor indicated by the two lanes, right 61 and left 47, respectively, any deviation from this path, causing the interruption of incident light beams 34a and 42a and therefore of reflected light beams. 34b and 42b respectively. (see fig.3.14.a, fig.3.14.b, fig.3.14.c and fig.3.14.d).



a) b) c) d)

Fig.3.14. Perspective view of the calibration system, with the user on the necessary path for the calibration, corresponding to steps P9-P10, as follows: a) the user in the starting position; b) the user on the move; c) the user at the end of the path; d) the user moving towards the *calibration system*

Walking inside the corridor placed on the ground, will cause the laser beam, corresponding to the faulty foot, to be interrupted. This interruption will cause the sensitive modules, right 65 and left 66, respectively, to emit some audible warning signals, which have the role of determining the athlete in question, to return to the indicated path. From the operator's point of view, depending on the severity of the deviation from the established path, he may decide whether or not to resume the calibration process.

In Chapter 4, entitled "**The original design of an intelligent mechatronic system used for performance training in martial arts, to develop neuromuscular control / dynamic and static balance, strength and endurance of legs and coxo-femoral joints mobility, of**

athletes", is described the design of a mechatronic system that can replace a human partner in performing certain exercises specific to Martial Arts training (see fig.4.1).

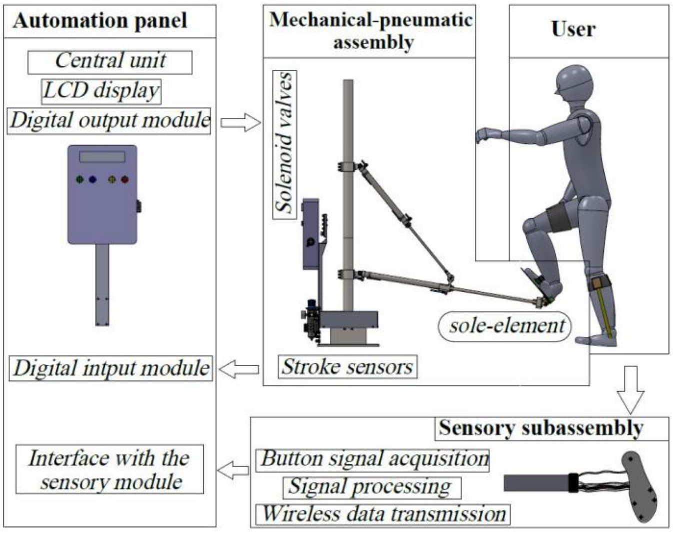


Fig.4.1. Schematic representation of the architecture of the *manipulating system*

In the preparation for performance in Martial Arts, due to the competition specifics, in addition to the development of motor skills (speed, strength and endurance), a very important aspect is the development of motor skills: balance and coordination. The development of these two elements involves in fact the execution of physical exercises aimed at increasing the neuromuscular control of the athlete. Whereas much of the technical procedures used in Martial Arts competitions involve unbalancing the opponent, followed by throwing him to the ground (a technical action called *throwing the opponent to the ground*), it is necessary to increase the efficiency of athletes and reduce the risk of injury, that the exercises intended for the development of neuromuscular control take precedence in the beginning phase of sports training, to be continued throughout the training for competition and most importantly to be very carefully structured. Designed ***MS***, it replaces the actions that must be performed, usually by a partner / coach, to help train an athlete (called in this case *user*). The manipulating system will allow the user to perform in the best conditions training for the development of neuromuscular control / dynamic and static balance, strength and endurance of his lower limbs, allowing him to perform exercises such as those that form the basis of counter-procedures used against techniques of throwing of the opponent on the ground.

One of the most complete exercises, which allows the development of neuromuscular control / dynamic and static balance, strength and endurance of the lower limbs of the athlete, is to move one leg of the latter, in the direction and speed imposed by a human partner. [75]. The role of the human partner is to keep the athlete in a continuous state of imbalance, constantly changing the direction of travel, and the role of the athlete is to adapt to the demands imposed, trying to move and even intuit the direction of movement. movement, in order to maintain balance.

Starting from the requirements that are to be fulfilled by the designed handling system, the main elements / subassemblies that are part of it, are:

a) A mechanical-pneumatic assembly consisting of:

a.1) The *lower subassembly*, used to perform the horizontal rotational movements of the assembly, these having the role of causing the user to move to the left or to the right, thus taking over the actions imposed on the athlete by a partner / coach, in accordance with the requirements of the exercise in question (see fig.4.3).

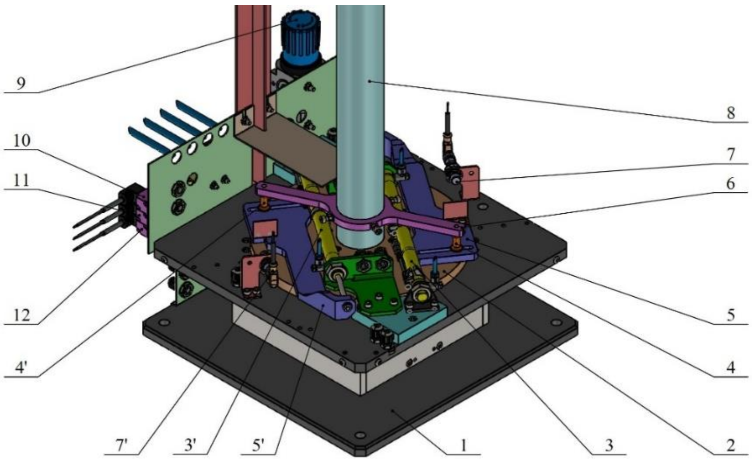


Fig.4.3. Perspective view of the ***manipulating system***, highlighting the elements of the *lower subassembly*

a.2) The *upper subassembly*, used to perform the vertical displacement movements of the device, these having the role of causing the user to move forward or backward, thus supplementing the actions of forced movement in one of the aforementioned directions, imposed to the athlete by a partner / coach, in accordance with the requirements of the exercise in question (see fig.4.7).

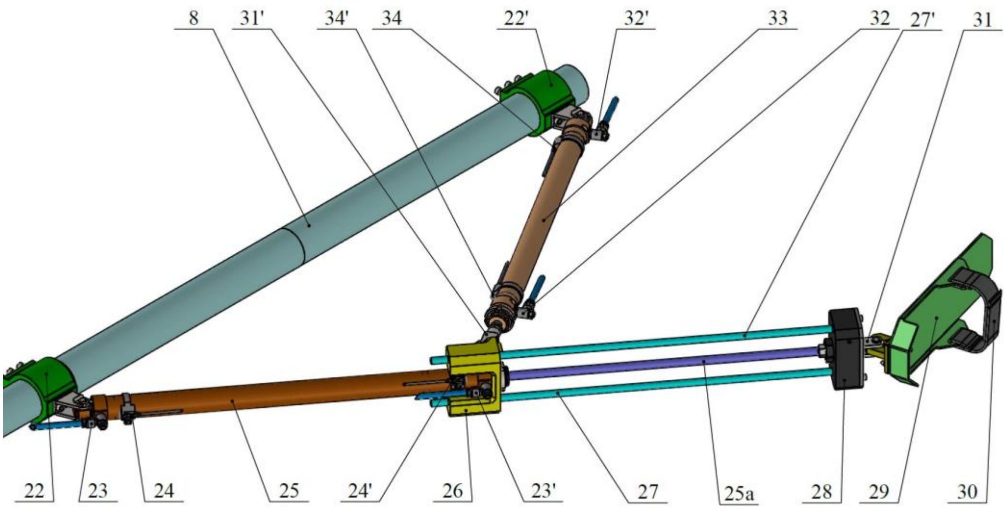


Fig.4.7. Perspective view of the ***manipulating system***, highlighting the elements of the *upper subassembly*

b) A *sensory subassembly*, which contains a *portable electronic module* and a *sensitive module* containing a set of five micro push buttons, located on a shoe insole. The *sensitive module* is used to determine the position of the support, at the user's supporting foot level (see fig.4.32).

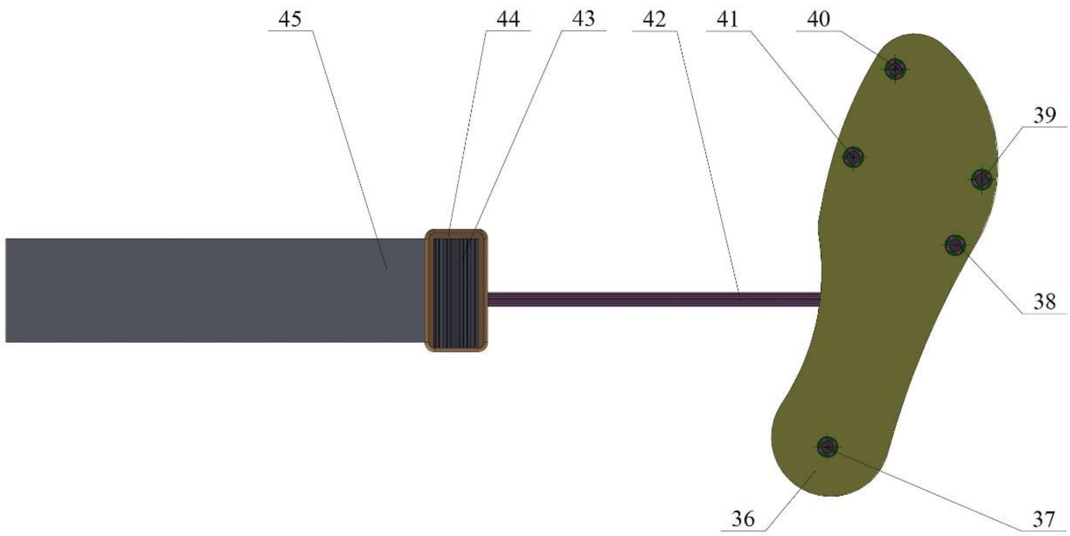


Fig.4.32. Top view of the *sensory subassembly*

The *sensory subassembly* (see fig.4.32) is composed of:

- *the sensitive module* - used to determine the position of the support, at the level of the user's supporting leg;

- *the portable electronic module* (see fig.4.34) - responsible for the acquisition and processing of data from the *sensitive module* and their transmission to the automation panel**.**

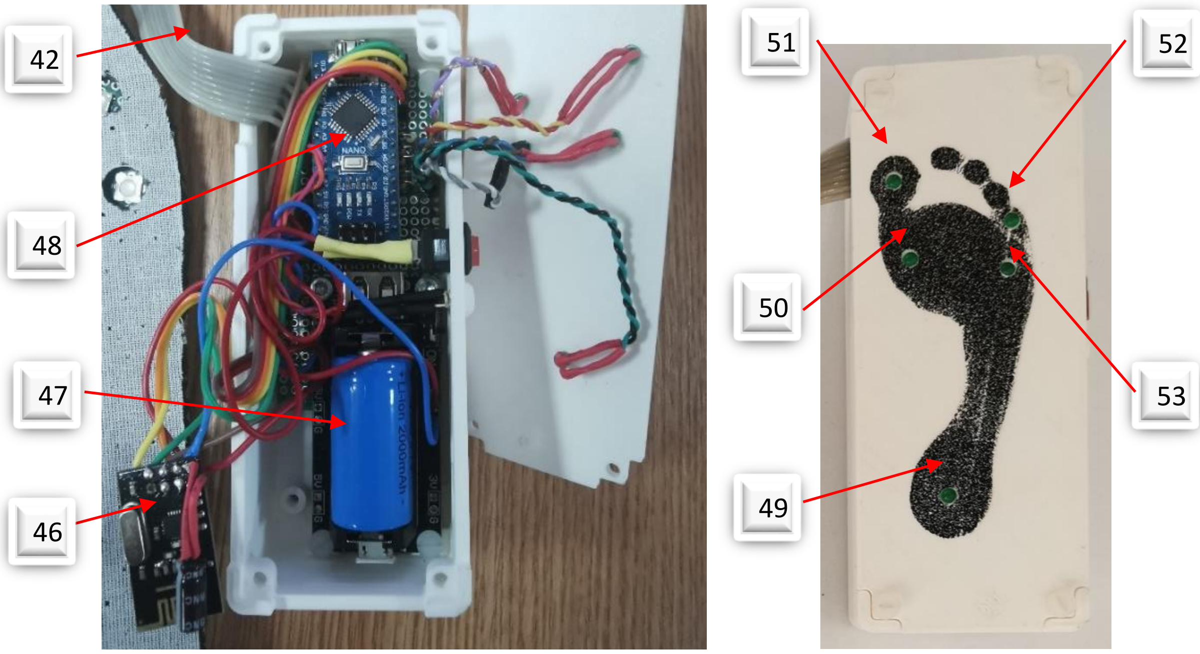
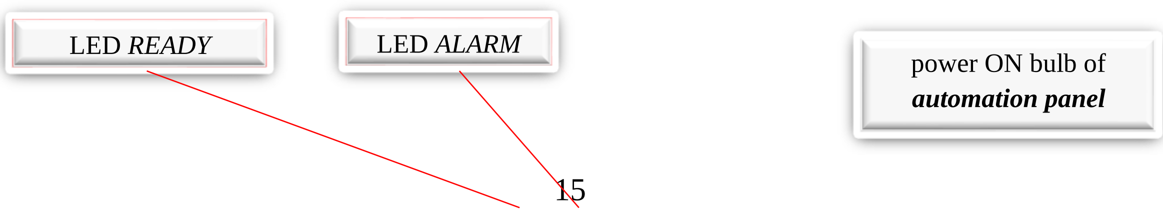


Fig.4.34. Top view of the *portable electronic module*: a) having the housing cover removed; b) having mounted the housing cover

c) A ***subassembly of the central electronic unit***, called the *automation panel* (see fig.4.36), used for the management and implementation of all the functions of the system in question, as well as their related actions, either based on a predefined cyclogram, which can be dynamically modified in such a way. so that the information provided by the sensory subassembly is also taken into account, or on the basis of orders received directly from the human user.



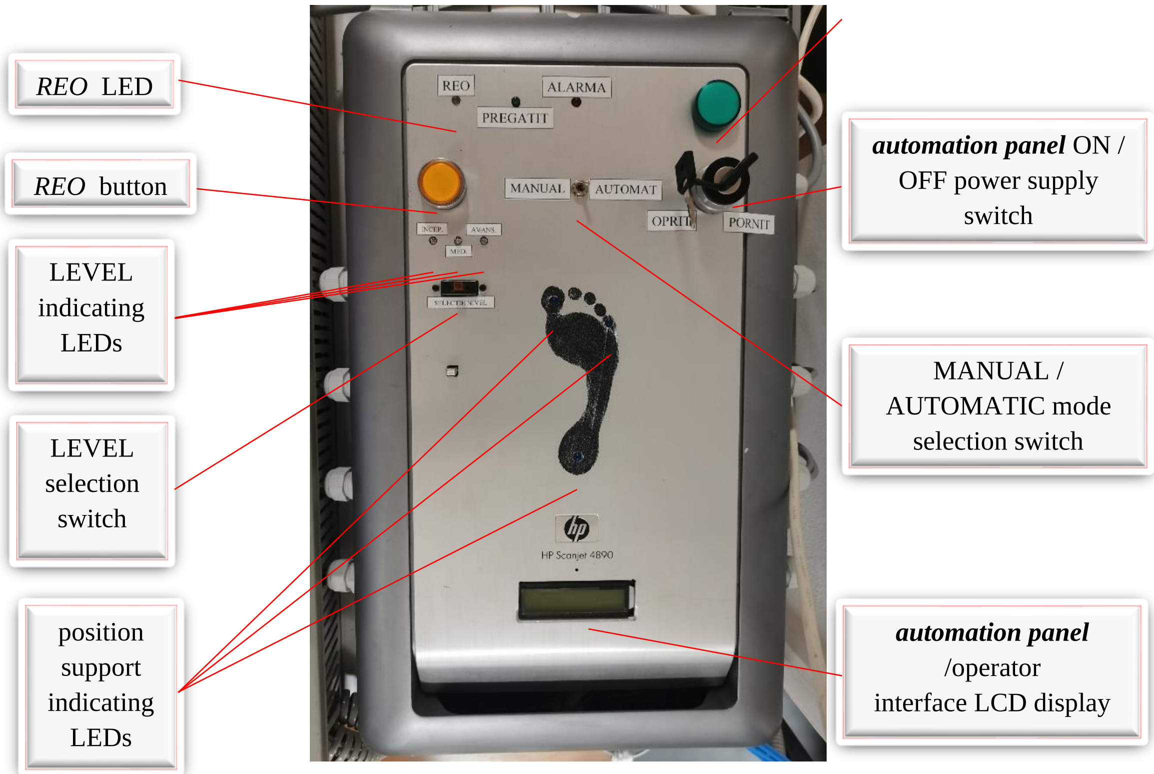


Fig.4.36. Presentation of the human-machine interface of the *automation panel* of the ***manipulating system***

Also, the ***manipulation system*** will allow the user to perform, in the best conditions, the training to maintain and / or develop the mobility of his coxo-femoral joints.

Chapter 5, entitled "**Original design of an intelligent mechatronic system used in martial arts performance training for real-time monitoring and active postural self-correction (APCS)**", presents the design of an intelligent mechatronic system that warns, in real time, the user on the changes in his posture, in relation to a predetermined posture considered standard (see fig.5.22).

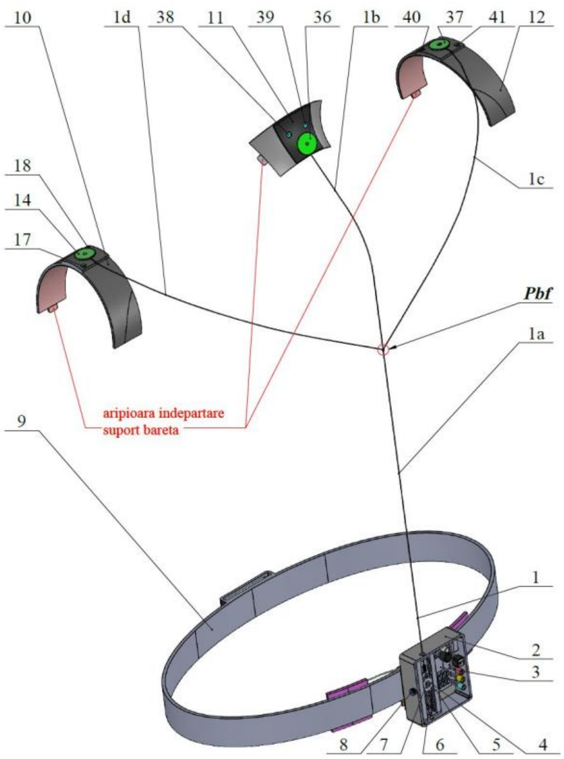


Fig.5.22. Components of **APCS**

One of the most common causes of postural deformities in performance athletes in contact sports, such as Martial Arts, boxing, or wrestling, is the posture called the "guard" (see Fig. 5.1).

a. View in the sagittal plane of the athlete   b. View in the front plane of the athlete

Fig.5.1. Representation of the "guard" used in full contact Martial Arts competitions - *Sanshou-Wushu Kung-Fu*

This allows athletes to more easily protect their vital points in their upper body. The "guard" implies certain changes (see fig.5.2.b [107] [108]) in relation to the physiological posture (normal, or ideal - see fig.5.2.a [107] [108]).

a. Physiological posture   b. Pathological posture

Fig.5.2. Representation of the physiological and pathological posture, from the point of view of the shoulders and spine, encountered in performance athletes in contact sports and due to the "guard"

APCS design requirements:

• The main requirement related to ***APCS*** is to provide athletes and not only, a means by which they can obtain, as correctly as possible, the posture that must be maintained during the execution of bending / straightening movements of the torso and lifting of some objects (weights), necessary in the physical training / physiotherapy trainings;

• The second important requirement related to the mechatronic system for real-time monitoring and active postural self-correction is to allow the user to gradually make postural corrections, taking into account his needs and pathology;

• A third requirement related to ***APCS*** is to allow the user to achieve and maintain a correct posture of the spine even in the home environment (while walking), or the lucrative one.

APCS will allow a real-time monitoring of the posture of the spine and the positions of the user's (athlete's) shoulders, signalling to him the occurrence of any change in relation to a previously established posture, considered standard.

For the ease of use of ***APCS***, it allows the setting of three levels of sensitivity (see fig.5.29), settable as follows:

- ***low sensitivity level***;
- ***medium sensitivity level***;
- ***high sensitivity level***.

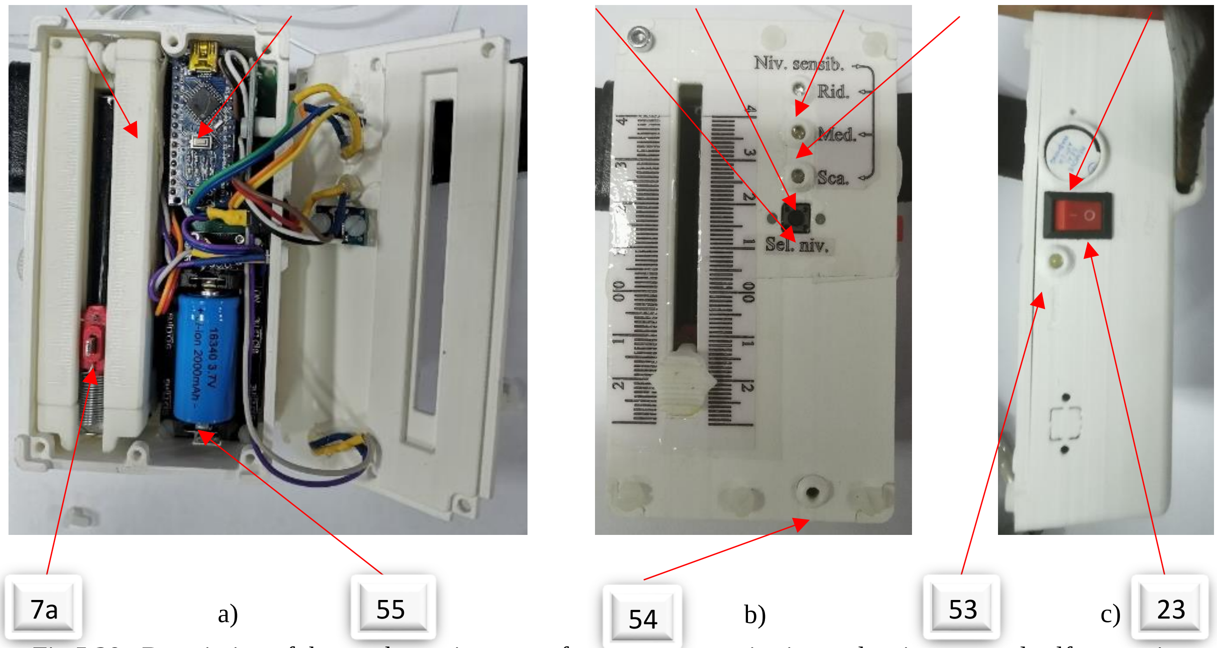


Fig.5.29. Description of the mechatronic system for real-time monitoring and active postural self-correction (***APCS***), presented in three views: a) top view of the ***APCS***, with the housing cover removed; b) front view of the ***APCS*** housing; c) right side view of the ***APCS*** housing

The sensitivity level represents an interval of postural variations, the exceeding of which, from the point of view of the lower and upper limits, respectively, produces the issuance by the ***APCS*** of a warning signal, which should determine the user to make a self-correction of the addressed posture. Thus, the lower this level of sensitivity, the narrower the range of postural variations, respectively the higher it is, the wider the range of postural variations. This allows the degree of postural correction to be adapted to the user's anatomical specificities.

In order to facilitate the precise relocation of the ***APCS***, on the user's body, without requiring the help of a third party, a *repositioning subassembly* was also designed (see fig.5.31).

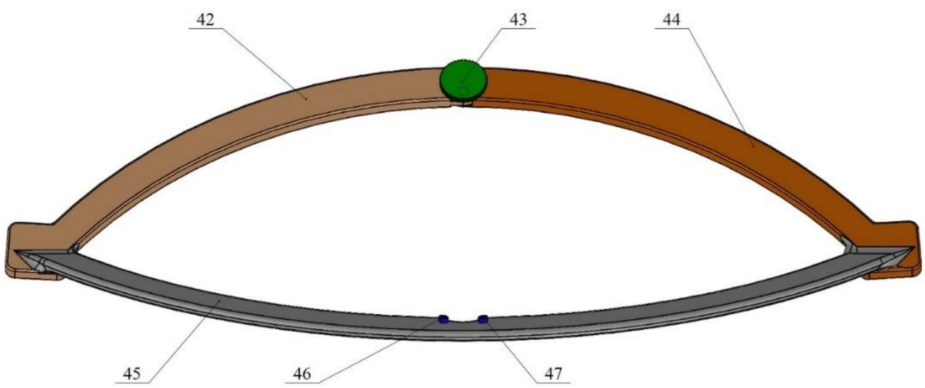


Fig.5.31. Top view, in perspective, of the *repositioning subassembly*

Chapter 6, entitled "**Results of the experimental researches regarding the functions and the modalities of use of the mechatronic systems designed and carried out**", presents the characteristics, functions and tests performed to validate the operation of designed mechatronic systems, presented in Chapters 3, 4 and 5.

The technical characteristics of the ***CS*** carried out on the basis of the project of the same name:

- overall dimensions - 800mmx400mmx1750mm;
- weight - 7kg;
- maximum accepted distance between the user's shoulders - 750mm;

- minimum accepted distance between the user's heels - 140mm;

- the maximum height allowed from the ground to the tangent of the user's armpits - 1700;

- maximum length of the indicated path - 10000mm;

- the maximum weight of the user supported by the adjusting rods of the system - 120kg.

The main functions of the calibration system performed:

- facilitates the obtaining and maintaining of the user's posture and movement, in accordance with the requirements imposed by inertial mechatronic motion analysis systems;

- allows the verification and / or correct positioning of the sensors of the inertial motion analysis system used, from the point of view of the symmetry of their positions, in relation to the sagittal plane of the user;

- is a reference against which the repeatability of the positions of the anatomical elements estimated by the inertial mechatronic motion analysis systems can be verified.

In order to verify the validity of the operation of the calibration system, designed and made, in order to obtain and maintain the posture and movement, imposed during the motion analysis sessions, performed using inertial mechatronic systems, a series of motion analyses were performed using the inertial Xsens MVN. These analyses were designed to highlight the two main functions of the calibration system, namely:

- facilitating the obtaining and maintaining a correct position of the user (see fig.6.11), corresponding to the requirements imposed in the calibration of the inertial motion analysis system used.

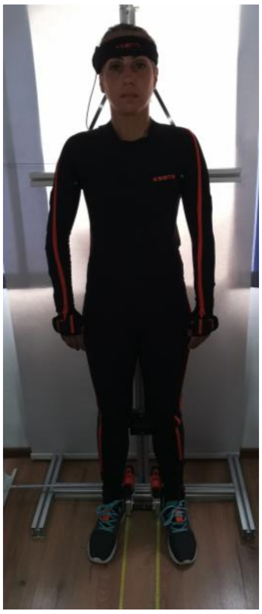


Fig.6.11. Front view with the user supported on the ***calibration system***

In order to verify the capacity of the calibration system, to create the necessary framework to meet the requirements related to the quality of the "***N***" type position, imposed during the calibration stage of the inertial mechatronic motion analysis systems, the Xsens MVN system was used, whose characteristics were presented in subchapter 2.3.

This activity consisted in the comparative analysis of the motion information, obtained during the actions taken by the user to obtain and maintain "N" type positions, imposed during the calibration stage of the Xsens MVN inertial motion analysis system, both with and without the aid of a calibration system (or another external device).

- facilitating the achievement of a correct movement of the user (see fig.6.6), corresponding to the requirements imposed in the calibration of the inertial motion analysis system used.

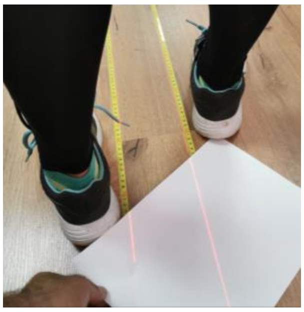


Fig.6.6. Perspective view of the directing path of the ***calibration system***, highlighting the correct way of walking, imposed on the user, the directing path strips, as well as the optical barriers materialized by means of light beams emitted by the two linear laser indicators

In order to verify the capacity of the calibration system, to create the necessary framework to achieve the requirements related to the movement quality imposed during the calibration stage of the inertial mechatronic motion analysis systems, the Xsens MVN system was used. This activity consisted in the comparative analysis of the motion information, obtained during the actions taken by the user to perform the movement, imposed during the calibration stage of the Xsens MVN inertial motion analysis system, both with and without the aid of the calibration system (or another external device).

Conclusions resulting from ***CS*** testing:

- if the required position is obtained in the calibration phase of the inertial mechatronic motion analysis system, the deviations from the shoulder positions and the position of the user's spine are reduced using the calibration system, order of tens of millimetres, as is the case of free positioning, on the order of 2-3mm;

- if the movement is carried out following the path indicated by the calibration system, deviation from the perpendicularity on the frontal plane of the calibration (Y0Z plane), the trajectory of the movement, in the useful area of the movement (starting from 0,5 m at 3.5 m from the reference), is significantly reduced compared to the situation in which the movement is free, without following a specific marked path.

Technical characteristics of the MS carried out on the basis of the project of the same name:

- overall dimensions - 1500mmx400mmx1700mm;
- supply voltage 230V;
- supply pressure 6bar;
- operating pressure 3-6bar;
- weight of the manipulating system - 30kg;
- the maximum displacement angle of the sole element of the manipulating system-30°;
- the maximum height at which the sole element of the manipulating system is raised - 1800mm;
- maximum speed, in load, movement of the sole element of the manipulating system - 0.3m / s;
- maximum length of the directing path - 10000mm;
- maximum supported weight of the user - 50kg.

The main functions of the manipulating system performed:

- allows the development of neuromuscular control / dynamic balance, strength and endurance of the lower limbs, of athletes;

- allows the development of neuromuscular control / static balance, of the lower limbs, of athletes;
- allows the development of the mobility of the coxo-femoral joints of athletes.

In the case of the function of developing neuromuscular control / dynamic balance, strength and endurance of the lower limbs, of athletes, the manipulating system has the role of imposing on the user, a motion according to a predetermined cycle, keeping him in a continuous state of imbalance (see fig.6.20).

The combination of the duration of the motion cycle and the speed of movement of the sole-element 29, determines the level of neuromuscular stress to which the user is subjected. This level must be set according to the level of training of the athlete and his specificities, respectively.

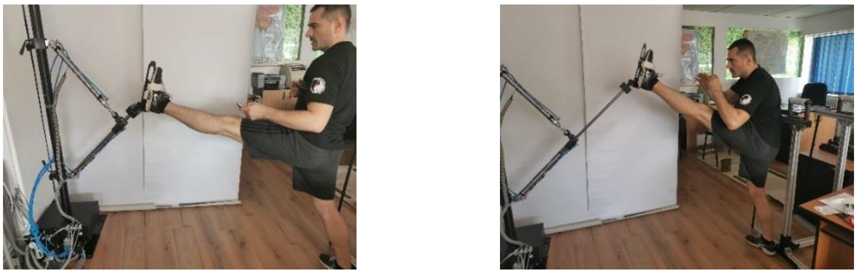
Fig.6.20. Chronological representation of the extreme positions occupied by the athlete during the use of the manipulation system, for the development of neuromuscular control / dynamic balance, strength and endurance of the lower limbs, of athletes

If one wants to use the development function of the neuromuscular control / static balance of the lower limbs, the manipulation system, the user will have to keep his foot position on the ground still. With the help of the remote control dedicated to the *MANUAL* working mode, it will be able to raise or lower, depending on the need, the manipulated leg (see fig.6.22) and also will be able to move this leg, to the left or to the right, in order to achieve the transition from one posture to another, more precisely the transition from one kicking technique to another. This adjustment, vertically and horizontally, respectively, will be made only by the user, depending on the specifics of each technique mentioned above and taking into account their own anatomical and motor specificities (level of mobility of the coxo-femoral joint area).

a) *t1* b) *t2* c) *t3*

Fig.6.22. Chronological representation (t1-t3) of several possible positions occupied by the athlete during the use of the ***manipulating system***, for the development of neuromuscular control / static balance of the lower limbs, of athletes

In the case of the ***function of developing the mobility of the coxo-femoral joints, of the athletes***, the system has the role to ensure the user, positioned with one of the feet on the sole-element 29 ', his movement and support, so that the athlete can perform the exercises known in the sports environment under the name of *front split* (see fig.6.25) and respectively the *side split* (see fig.6.26).



a) *t1* b) *t2*

Fig.6.25. Sequential representation (t1- t2) of the transition from the exercise called "split" to the so-called "string", during the use of the manipulation system, to develop the mobility of the coxo-femoral joints, athletes, in the case of the execution of the *front split*

a) *t1* b) *t2*

Fig.6.26. Sequential representation (t1- t2) of the transition from the exercise called "split" to the so-called "string", during the use of the manipulation system, to develop the mobility of the coxo-femoral joints, athletes, in the case of the execution of the *side split*

In order to determine the validity of the ***MS*** functions, a series of tests were performed which had the role of highlighting the displacement curves of the feet and the centre of gravity of the human subject under analysis (see fig.6.27).

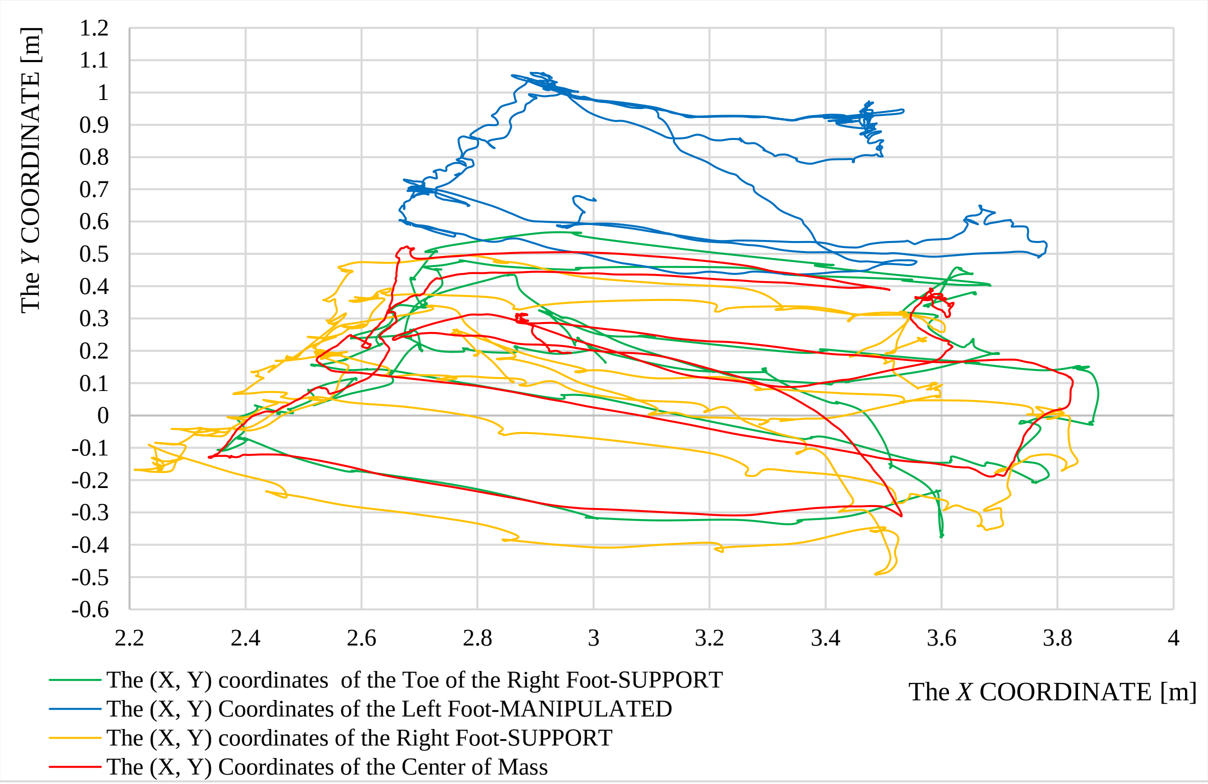


Fig.6.27. Graphical representation, in the ***X0Y*** plane, of the trajectories of the positions of the palms, toes and centre of gravity of the user, obtained during the displacement imposed by the sole-element 29, of the manipulating system, obtained with the help of the inertial motion analysis system Xsens MVN

Conclusions resulting from the testing of the prototype of the manipulating system:

-following the tests performed, it was found that the manipulation system, properly executes the required movement cyclogram;

- the tests showed that the manipulation system, adapted the movement cyclogram, according to the information provided by the sensory subassembly. Thus, MS creates the necessary framework for performing exercises whose correct execution can lead to the development of neuromuscular control / dynamic and static balance, strength and endurance of the lower limbs and mobility of coxo-femoral joints, of athletes.

The technical characteristics of ***APCS*** (see fig.6.30):

- overall dimensions - 115mmx65mmx35mm;
- powered by a rechargeable Li-Ion battery, with a nominal voltage of 4.2V and a capacity of 1000mAh;
- battery charging at 5VDC voltage, via USB port type C;
- consumption in normal operating state - approx. 100mAh;
- functional autonomy - approx. 10h;
- weight - 400g;
- maximum accepted distance between the user's shoulders - 750mm;
- uncertainty - ± 1mm;
- the pre-set minimum sensitivity - equivalent to the minimum displacement of the monitored anatomical landmark positions at which the system emits warning signals regarding the change of the user's posture in relation to the reference, is 10mm in case of frontal postural change (sagittal plane) and shoulder lift, respectively 5mm in the case of dorsal postural change (in the sagittal plane) and lowering of the shoulders;

- the maximum accepted displacement of the monitored anatomical landmark positions, in relation to the reference - 40mm in case of frontal postural change (in the sagittal plane) and shoulder lift, respectively 20mm in case of dorsal postural change (in the sagittal plane) and lowering of the shoulders.

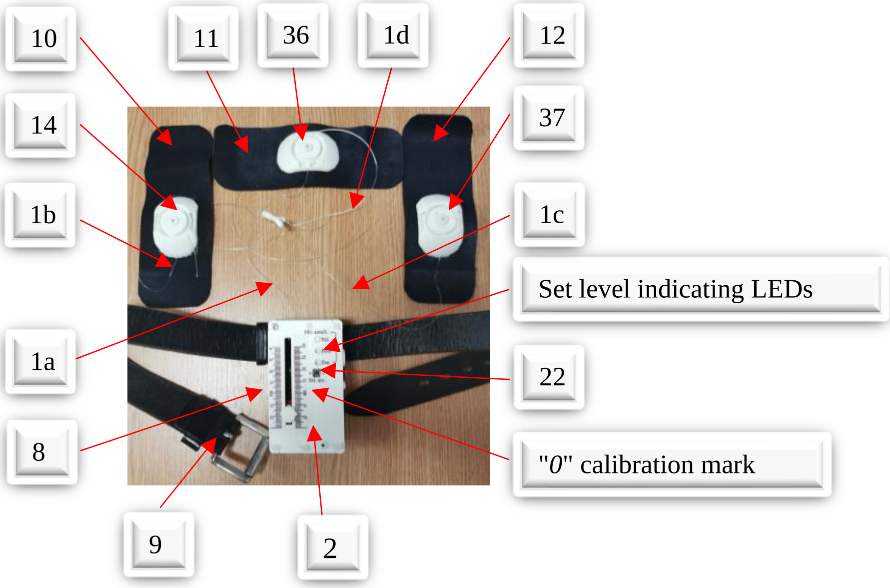


Fig.6.30. Front view of ***APCS***

The main functions of the ***APCS*** performed:

- facilitates the active and rapid self-correction of the posture of the user's torso, from the point of view of his spine and shoulders, in relation to a predetermined posture which may be the physiological posture, or a posture as close as possible to that, established according to pathological specificities of the user;

- facilitates postural correction during the bending and lifting movements of the torso, necessary during physical training / physiotherapy training or those required in various lucrative activities, as well as during normal household activities;

- facilitates the reduction of the estimated duration of the user's physical recovery, if used in combination with physiotherapy exercises;

- allows the realization in time of gradual postural corrections. By cumulating them, a major postural correction can be achieved;

- allows the re-education of the user's neuromuscular system in terms of postural control, so that, over time, he can take over and have total control over this activity.

In order to verify the degree of fulfilment of the objectives proposed for ***APCS***, a series of tests were performed with it (see fig.6.38), in which the aim was the efficiency of the system in question, in notifying the exceeding of the limits imposed by the sensitivity level setted, highlighting the user's reaction to the warnings issued by the ***APCS***, when exceeding the set sensitivity level of the system, as well as the differences between the three possible sensitivity levels to be set on it.

a) b) c)

Fig.6.38. Examples of some basic exercises performed for the purpose of ***APCS*** testing, namely: a) normal walking; b) knee flexion; c) leaning forward

In the case of testing the efficiency of the ***APCS*** to detect exceeding the limits imposed by its set sensitivity level, it was verified how the linear potentiometer 7 of the ***APCS*** reacts to postural changes corresponding to each sensitivity level of the system in question (see fig. 6.41).

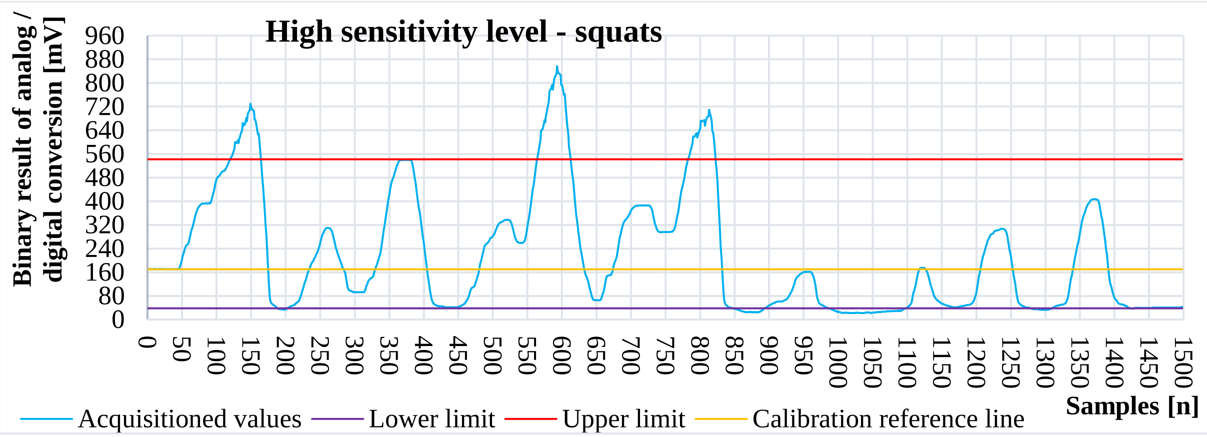
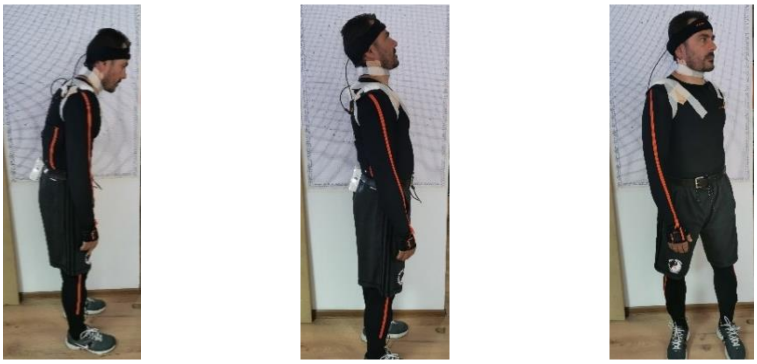


Fig.6.41. Graph of the variation of the values of the analog / digital conversion of the electric voltage, generated by the linear potentiometer 7 and determined by the movements at the spine and shoulders level, of the ***APCS*** user, appeared while he performed squats, if on the system in question was set high level of sensitivity

A second set of analyses was performed, which had the role of highlighting both the user's reaction to the warnings issued by the ***APCS***, when exceeding the set sensitivity level of the system, and the differences between the three possible sensitivity levels, that can be set on it. Also, the analyses were aimed at highlighting the ability of ***APCS***, to notice / monitor the postural changes of the user, as well as how he performs the mentioned function, which distinguishes him from other existing devices, namely:

- changes in the thoracic and lumbar curves of the user's spine, in his sagittal plane (flexion and extension), as well as in the transverse plane (twisting to the left or right of the user's torso, made without changing the positions of his feet) (see fig.6.47.a, fig.6.47.b and fig.6.47.c);



a) b) c)

Fig.6.47. Posture obtained by the user at the end of a flexion (a), extension (b) and torsion (c) movement respectively

- changes in the cervical curvature of the user's spine, in his sagittal plane (see fig.6.48 and fig.6.51).

Fig.6.48. The posture obtained by the user at the end of a flexion movement at the level of the cervical curvature

- changes in the user's shoulders (see fig.6.49.a, fig.6.49.b and fig.6.49.c). Only the analysis of the elevation movement of the user's shoulders was performed, as the protraction movement also has an elevation component.

a) b) c)

Fig.6.49. Posture obtained by the user at the end of a lifting movement of the right shoulder (a), the left shoulder (b) and both shoulders (c) respectively

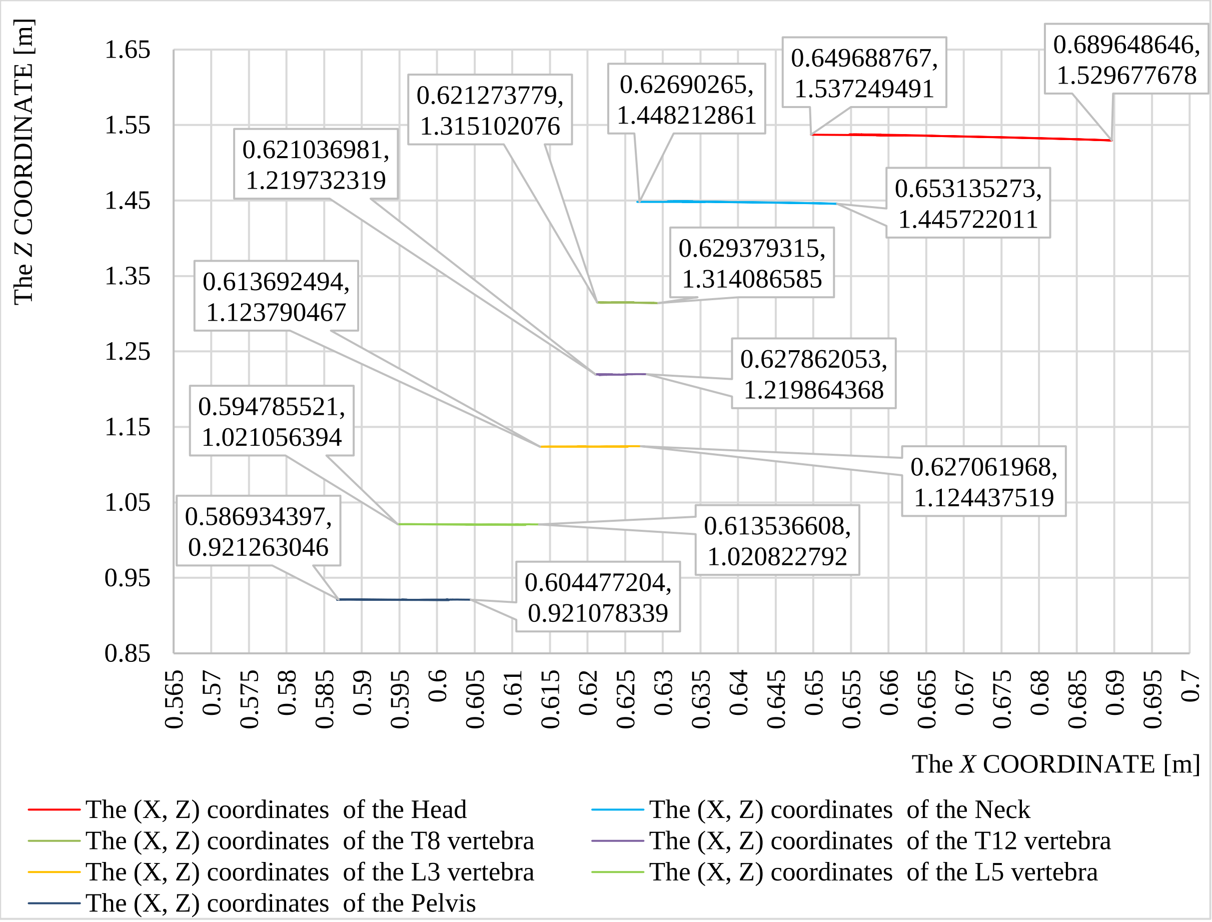


Fig.6.51. Graphical representation, in the ***X0Z*** plane (user's sagittal plane), of the trajectories of the head positions, of the vertebrae (T8, T12, L3 and L5) and of the pelvis, obtained during a flexion movement at the user's torso level and the corresponding correction in response to the alarm signal emitted by the ***APCS*** when exceeding the high sensitivity level set on it, obtained by means of the Xsens MVN inertial motion analysis system

Conclusions resulting from the APCS prototype test:

- following the tests carried out, it was found that ***APCS*** duly notices both the movements of the spine in the sagittal and frontal plane, as well as the movements of the shoulders in the sagittal and frontal plane, as well as in the transversal one;

- from the analysis of the graphs presented in this subchapter it can be seen that the positioning of the "***0***" marking line of the calibration closer to the lower limit of the postural variation interval corresponding to the back bending movements is correct due to the fact that the amplitude of the forward bending movements it is larger than that of back bending movements. This demonstrates that the choice of the limits of the variation range, corresponding to the set sensitivity level, in relation to the calibration position of the ***APCS*** ("***0***" marking line of the calibration) is correct;

- ***APCS*** allows the user to opt for maintaining / correcting posture only from the point of view of his spine, or only from the point of view of the position of his shoulders;

- ***APCS*** allows the user to meet as correctly as possible the requirements regarding the posture that must be obtained/ maintained during the execution of the bending / straightening movements of the torso, as well as lifting some objects, necessary during the physical training / physiotherapy trainings, or of those imposed in various lucrative activities, as well as during ordinary domestic activities;

- due to the possibility of setting the level of sensitivity, ***APCS*** designed, facilitates the obtaining of postural corrections, smaller or larger, depending on the needs imposed by the pathology of the person concerned;

- the use of a flexible and inextensible wire as a sensing element significantly reduces the manufacturing costs of ***APCS***, compared to alternative variants, based on the use of tilt sensors [187], bending sensors [188] [189], or of their combinations. Due to this aspect, the system presents a simple structure, has a small size and good portability;

- due to its small size and weight, the ***APCS*** thus designed can be used daily, regardless of the environment in which the user carries out his activity, without restricting the natural movements of his body, as long as they are performed correctly from a biomechanical point of view. The manufactured ***APCS*** represents a means for training / re-educating the user's nervous system, in obtaining and maintaining a posture as close as possible to the physiological one, long after the cessation of its use.

CONCLUSIONS

C.1. General conclusions of the research undertaken

The current work is the result of research conducted in the doctoral project, which aimed to conduct a detailed analysis of intelligent mechatronic systems used in Martial Arts performance training, to identify those that allow the correction of biomechanics of movements, to determine their limitations and also designing, making and testing of new intelligent mechatronic devices / systems, which will bring improvements to the existing ones and facilitate the qualitative leap pursued in sports training for performance, while reducing the risk of injuries.

▪ The designed ***CS*** corresponds to the basic requirements of the calibration action of an inertial motion analysis system:

- to allow the usage during the calibration stage without adversely interfering with this action;

- to allow the user to obtain and maintain a position as close as possible to the physiological posture, both in terms of the curves of the spine and in terms of the positions of the shoulders;

- allow the user to make a movement whose direction is perpendicular to the frontal plane of the calibration (the user's frontal plane when performing the required position) and whose trajectory must be linear, both on moving forward and on the return.

▪ The ***CS*** in question was designed in such a way that, in addition to the main functions, presented above, it also allows the verification of the positioning symmetry of the MEMS of the inertial motion analysis systems, in relation to the sagittal plane of the user. Another important feature of it is the possibility of using it as a benchmark according to which the repeatability of inertial motion analysis systems can be determined, in terms of the positions of the anatomical elements estimated by the latter.

▪ The designed ***MS*** creates the necessary framework to perform the following functions:

- simulation of an exercise that involves manipulating one of the athlete's legs in order to keep him in a continuous state of imbalance. The role of such to allow the development over time of neuromuscular control / dynamic balance, strength and endurance of the lower limbs, of athletes.

- the correct support of the athlete in order to be able to perform the exercise that allows, over time, the development of neuromuscular control / static balance of the lower limbs.

- development of the mobility of the coxo-femoral joints.

▪ The ***MS*** has been designed to achieve all these objectives, with the same motion parameters, or with different parameters, to allow the attainment of a symmetry between the two lower limbs of the user.

▪ The designed ***APCS*** creates the necessary framework for postural monitoring of the user, as well as his real time warning, on changes that exceed a certain pre-set level.

▪ Following the tests performed, the resulting conclusions led to the validation of the functions assigned in the design stage of each proposed system.

C.2. Original contributions

The results presented in the thesis constitute in an overwhelming majority the original contributions of the author, confirmed in scientific publications, presented at scientific conferences, through patents, as well as through physically made mechatronic systems (see chapters C.3, C .4 and C.5). These original contributions will be briefly presented in the current subchapter.

- Rationale for the importance of the chosen topic:
  - Description of the current framework and performance training requirements in Martial Arts
  - Syntheses from the literature related to:
    - Optical systems used in the process of motion analysis
    - Mechanical-electrical systems used in the process of motion analysis
    - Magnetic systems used in the process of motion analysis
    - Acoustic systems used in the process of motion analysis
    - Inertial systems used in the process of motion analysis
- Testing the functions of the inertial mechatronic Xsens MVN motion analysis system and highlighting its limitations
- Design and physical realization of a calibration system, used to obtain and maintain the posture and the movement, imposed during the motion analysis sessions, performed using inertial mechatronic systems. The idea of this mechatronic system started from the need to perform a higher-level calibration of inertial mechatronic motion analysis systems. It was designed to meet the basic requirements of posture and movement, imposed during the calibration phase of inertial motion analysis systems. Also, due to the way it was designed, in addition to the basic functions, the system in question will also allow the verification of the positioning symmetry of the MEMS of inertial motion analysis systems, in relation to the user's sagittal plane and also it could be used to verify the repeatability of inertial motion analysis systems.
- Design and physical realization of an intelligent mechatronic system used in martial arts performance training, for the development of neuromuscular control / dynamic and static balance, strength and endurance of the lower limbs and mobility of coxo-femoral joints, of athletes. Its design was based on the need to replace a human partner in carrying out exercises designed to train athletes, so that all their specific requirements can be met, which will lead to the qualitative leap required by performance sports training, such as and to reduce the risk of injury to the athlete concerned.
- Design and physical realization of an intelligent mechatronic system used in performance training in Martial Arts, for real-time monitoring and active postural self-correction. The design of this mechatronic system was based on the need to achieve a proper physical and mental recovery, not only during specific training, but also outside it, thus increasing the speed of physical recovery of the user. The use in the civil environment of the system in question also allows the redirection of a portion of the time allocated to recovery, within the sports training plan, to the actual training activity. This mechatronic system will allow a re-education of the neuromuscular system of the athlete involved, so that, at the end of its use, the action of postural correction becomes a reflex gesture.
- Testing the operation of the systems designed and made physically, mentioned above. Within this activity were developed the methods and procedures necessary to achieve an objective assessment of the functionality of physically made systems, whose purpose is to improve the process of motion analysis, development of motor parameters of athletes, and their postural monitoring and correction.

C.3. Perspectives for the development of research on intelligent mechatronic systems used in performance training in Martial Arts, to correct the biomechanics of motion and reduce the risk of injury in training

Following the analysis of the results obtained in the research undertaken and presented in this doctoral thesis, a series of conclusions were drawn that allowed to outline some possible directions and perspectives regarding the intelligent mechatronic systems used in performance training in Martial Arts, to correct the biomechanics of motion and reduce the risk of injury during training. Of these directions and perspectives, the most obvious are the following:

- developing the researches on how intelligent mechatronic systems can be integrated into training, both to reduce the risk of injury and to optimize the process of sports training for high performance;
- continue the researches on the sources of accidents in Martial Arts training and identify methods and ways to eliminate them;
- conducting additional research on the integration of virtual reality and augmented reality systems in Martial Arts training;
- from the point of view of the biomechanics of motion, it is desired to carry out the research in order to determine a complete, standardizable set of tests that can accurately determine not only the problems related to the biomechanics of motion, but also their sources.
- from the point of view of the calibration system, intended for use in the calibration phase of inertial mechatronic motion analysis systems, to obtain and maintain posture and movement, required, it is desired to continue research to optimize the system in question, in order to obtain a higher level of portability and increased the ease of use;
- from the point of view of the intelligent mechatronic system used in performance training in Martial Arts, for the development of neuromuscular control / dynamic and static balance, strength and endurance of the lower limbs and mobility of coxo-femoral joints, of athletes, it is desired to continue the research to optimize the system in question, in order to achieve a superior product in terms of quality, which would allow a certain level of energy independence / autonomy and a low-cost price;
- from the point of view of the intelligent mechatronic system used for real-time monitoring and active postural self-correction, it is desired to continue research to optimize the system in question, in order to achieve a qualitatively superior product with a significantly reduced size, allowing it to be included in the category of systems that can be perfectly integrated in the sports environment, but also in the domestic and lucrative environment.

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ANNEXES

A.1. List of published works

During the doctoral studies, the results of the research undertaken were disseminated by publishing several articles, in specialized journals indexed BDI and other databases, as well as by participating in various international conferences in the field. In the following is presented the list of scientific publications made as first author and co-author and associated with the topic of the doctoral thesis.

1. *Mugur Spirescu, Sergiu Dumitru, Alexandru Constantinesu, Cristian Radu Badea,* Human – robots safe cooperation in an integrated approach, International Journal of Mechatronics and Applied Mechanics, Issue 2 January 2017.
2. *Cristian Radu Badea,* Researches on inertial mechatronic motion analysis systems, based on mems", The Scientific Bulletin of VALAHIA University, MATERIALS and MECHANICS, Volume 16, Issue 15, pp. 44–50, Targoviste 2018, ISSN 1844-1076.
3. *Cristian Radu Badea*, *Sorin Ionut Badea*, The positioning errors generated by Xsens MVN inertial system during the analysis of „push-ups" exercise, using the „single level" scenario, before and after the calling of „reprocess" function, International Journal of Mechatronics and Applied Mechanics, Issue 4, 2018.
4. *Cristian Radu Badea*, Study on the influence of contact points, scenarios and graphical reference elements on the motion analysis process, carried out using the inertial mechatronic system MVN Analyze, International Journal of Mechatronics and Applied Mechanics, Volume 2, Issue 6, pp. 74-81, 2019.
5. *Cristian Radu Badea, Paul-Nicolae Ancuţa, Sergiu Dumitru, Anghel Constantin, Nicuşor Nicolae*, Conceptual Model and Proof of Concept for a Complex Mechatronic System Used in Neuromuscular Control Training, Proceedings of the International Conference of Mechatronics and Cyber- MixMechatronics, pp. 90-99, 18 July 2020
6. *Cristian Radu BADEA, Octavian DONŢU, Gheorghe I. GHEORGHE*, Using the method of determining the variation of the length of the stretched chord, as a means of monitoring the postural changes of the athletes spine, U.P.B. Scientific Bulletin, Series D, Vol. 83, Iss. 3, 2021, ISSN 1454-2358.

A.2. List of patent applications filed and scientific reports

In addition to the published scientific papers, during the doctoral studies a number of patent applications were filed, a series of scientific reports were prepared and the foundations of a new laboratory were laid which aims to expand the fields of expertise of INCDMTM-Bucharest. The following is the list of patent applications filed and the list of scientific reports, associated with the topic of the doctoral thesis.

- **Patent applications**

1. *Cristian Radu Badea*, Device used for maintaining and / or improving the mobility of coxo-femoral joints, Patent number RO 125003 B1, published on 30/08/2012.
2. *Iulian Vasile, Cristian Radu Badea,* Tightness system, Patents application number A /2015 00775/29.10.2015, published on BOPI no. 4/ 28.04.2017.
3. *Iulian Vasile, Cristian Radu Badea,* Translation unit, Patents application number A/00372/25.05.2018, published on BOPI no. 4/ 28.04.2017.
4. *Cristian Radu Badea*, Device for the correct realization and support, by a human user, of the posture and displacement necessary for the calibration of inertial motion analysis systems, Patents application number A/00107/19.02.2019, published on BOPI no. 8/ 28.08.2020.

5. *Cristian Radu Badea*, Device for the development of neuromuscular control / dynamic and static balance, of the strength and endurance of the lower limbs and of the mobility of the coxo-femoral joints, of the athletes, Patents application number A / 00889/31.10.2017, published on RO-BOPI 4/2019 - 30.04.2019.
6. *Cristian Radu Badea*, Device for real-time monitoring and active postural autocorrection, Patents application number A/2019 00398/01.07.2019, published on BOPI no. 8/ 28.08.2020 and European Patent Application EP 3 760 170 A1, January 6, 2021, published on 06.01.2021 - Bulletin 2021/01.

- **Rapoarte științifice**

1. *Cristian Radu Badea,* Technical documentation study on the principles and methods used for the analysis and monitoring of human body movements, Research on the application of complex mechatronic systems in the monitoring and analysis of human body movements, Nucleus-Program entitled: Intelligent mechatronics engineering and cyber-mechatronic systems/imisc-m, 2018-2020
2. *Cristian Radu Badea,* Technical study of analysis of application areas for complex mechatronic systems for monitoring and analysis of human body movements, Research on the application of complex mechatronic systems in monitoring and analysis of human body movements, Nucleus-Program entitled: Intelligent mechatronics engineering and cyber-mechatronic systems/imisc-m, 2018-2020
3. *Cristian Radu Badea,* Experimental study on constructive architectures used in complex mechatronic systems for monitoring and analysis of human body movements, Research on the application of complex mechatronic systems in monitoring and analysis of human body movements, Nucleus-Program entitled: Intelligent mechatronics engineering and cyber-mechatronic systems/imisc-m, 2018-2020
4. *Cristian Radu Badea,* Design of an experimental model of complex mechatronic system for monitoring and analysis of human body movements, Research on the application of complex mechatronic systems in monitoring and analysis of human body movements, Nucleus-Program entitled: Intelligent mechatronics engineering and cyber-mechatronic systems/imisc-m, 2018-2020
5. *Cristian Radu Badea,* Realization of experimental model of complex mechatronic system for monitoring and analysis of human body movements, Research on the application of complex mechatronic systems in monitoring and analysis of human body movements, Nucleus-Program entitled: Intelligent mechatronics engineering and cyber-mechatronic systems/imisc-m, 2018-2020

- **Other mentions**

Setting up the Laboratory of functional, dynamic, non-invasive measurements and explorations, using intelligent, biointegrable, advanced sensory technologies -L3-MEF within PNCDI3 / Program 1. Development of the national research-development system, Subprogram 1.2. Institutional performance, Project - "Institutional development of INCDMTM to increase capacity and performance in order to support excellence in research - development - innovation in the short and medium term" - Acronym: EXCEL-MECATRON, 2018-2021.