DESIGN AND IMPLEMENTATION OF A MECHATRONIC SYSTEM FOR LOWER LIMB MEDICAL REHABILITATION

Ana-Maria Amancea [1, 2], Ioan Doroftei [1], Alexandru Barnea [1], Florentina Adăscăliței [1]

[1]"Gheorghe Asachi" Technical University of Iasi-Romania, Faculty of Mechanical Engineering, Department of Mechanical Engineering, Mechatronics and Robotics
Blvd. D. Mangeron, 61-63, 700050 Iasi, Romania
[2] Université de Lyon, CNRS INSA-Lyon, LaMCoS, UMR5259, F-69621, France

Corresponding author: Ana-Maria Amancea, ana.amancea@gmail.com

Abstract: The design and implementation of a new mechatronic system for lower limb rehabilitation is presented in this paper. The medical rehabilitation of the knee joint will be focused in this paper, because their injuries are characterized by a high degree of importance. The system applies a closed loop rehabilitation protocol, diagnosis - treatment - feedback from the patient, and allows a real time recuperative progress recording for the patient, using a database that stores the patient's evolution. The mechatronic system evaluates the patient's recovery based on the joint angular positions variation and also based on normal and tangential forces developed during the interaction between the human foot and the rehabilitation system. The normal and tangential forces can highlight the disease's gravity and also the rehabilitation progress. The results obtained from the experimental testes performed on a healthy subject and patient provides valuable information concerning the main parameters (angle, forces) involved in rehabilitation process appreciation and also, demonstrate the system's efficiency.
Key words: mechatronics, lower limb, rehabilitation.

1. INTRODUCTION

The lower limb is an anatomic segment which has a significant role in providing locomotion, balance and stability in standing position.
Medical statistics and information received from departments of orthopedics and traumatology show that many injuries occur annually at the lower limb and also that the number of diseases is growing, especially in the winter. Regardless of their type (mild, severe or chronic), after the medically treatment, the physical rehabilitation of the leg is imperative. In general, its medical recovery is a long and continuous process that can take up to 6 months. The physical therapy sessions are conducted either physiotherapists or some commercial systems, which are specifically developed for the lower limb recovery.
Mechatronic systems may be applicable in any medical field and some of them are widely used in physical rehabilitation of various pathologies, especially of the knee joint, because of their multiple benefits.
According to (Amancea et. al. 2012), in recent years, several researchers have proposed some rehabilitation devices (Emken et. al. 2006), (Buerger et.al. 2004), (Popescu et.al. 2000), (Nikitczuk et. al. 2005, 2009), (Acosta-Marquez et.al. 2006), (Wang et.al. 2009) and the research in this field is in a considerable ascending (Lee et. al., 2005). Although the literature notes a variety of mechatronic systems for the knee rehabilitation, these kinds of systems still have many technical problems and deficiencies. We can say that, currently there is no one device which is able to fully satisfy the need of patient's recovery.
It can be mentioned some of the most important technical issues which are related in the literature, such as:
-Issues generated due to the interaction between the patient and recovery system (it is known that during therapy, the patient is connected directly to the rehabilitation device);
-The absence of some additional control techniques in order to ensure patient's safety conditions during the recovery session;
-Some devices are unable to realize the movements according to the patient's physiological limits of motion;
-The lack of some communication protocols and real-time display of the patient response during the recovery technique applied and also for monitoring its recuperative progress;
-The individualization of the systems for a single pathology, or for one leg;
-Some devices have a weak control force and the direct consequence is reflected on the patient (for example, if the system applies an excessive force and it is unable to adjust the force in real time, this situation can force the leg into a hyperextension position);
-Their inability to manage some critical situations occurring during therapy (technical) or changes related to functional status of the patient. It is known

that during the recovery process, sometimes patients have a tendency to suddenly move his legs as a result of spontaneous reflexes. Such a reflex occurred during rehabilitation session with the system can force the leg to move more than his maximum range of the motion, generating an additional damage to the other elements of the joint structure (ligaments, tendons, muscle stretching);

-Complicated interfaces for operation/control;

-Constructive aspects such as: inadequate materials used in their construction, shape and dimensions.

2. GENERAL ARCHITECTURE OF THE MECHATRONIC REHABILITATION SYSTEM

According to Fig. 1, our mechatronic rehabilitation system contains a hardware and software component, and the communication protocols with the computer.
The hardware structure of the system includes the following components: mechanical structure, microcontroller, sensory systems, actuators, electrical and microelectronic components, and various communication protocols with the software structure.
The mechanical part, presented in figure 2, consists of a structure that integrates, in a single and compact structure, two systems operating simultaneously: a central body (1) on which is mounted an assembly based on a ball screw-nut transmission (2), (3), one DC gear motor that transmits the movement through two toothed pulleys (4), a leg support system (7) that is attached to the nut body (2),a positioning support for the pressure sensors (6), elastic elements with strain gauges (5), guidance mechanisms (8) and an orthotic structure with their elements, which are attached to the leg: foot (9), shank (10), thigh (11), trunk (12). The orthotic device is operated by turning the screw, which will move forward/backward the nut, thereby generating flexion-extension movement of the lower limb. On the mechanical structure of the

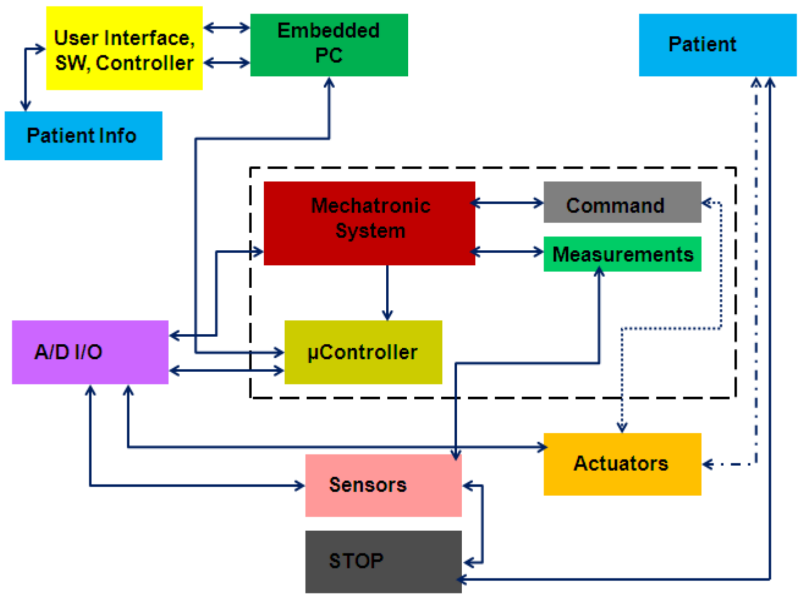

Fig. 1. General architecture of the rehabilitation device

ball screw-nut assembly are implemented two limit switches, which have a dual role: to avoid the mechanism damaging (in case of an excessive movement of the nut) and for ensure the patient's safety (when the leg reaches the end position). The maximum stroke of the nut is around 350mm. A DC gear-motor manufactured by Maxon was used, that is able to develop the necessary torque for the knee flexion-extension movement. The patient position is sitting on a chair (16) in order to form a 90º between shank and thigh.
The electronics consists of a sensory system for real-time monitoring and recording of angular changes of the foot joints, and normal and tangential forces developed at the interaction between the human foot and mechatronic recovery system, and a control module with a DC gear motor driver control, a microcontroller development kit and a control panel.
The sensory system contains the following types of sensors: pressure sensors, electro resistive transducers, potentiometers. Pressure sensors have been used to monitor normal forces developed primarily by the weight of the tibia, being placed on human foot supporting platform, and the mechatronic system. Four such sensors have been used, being called generic: front sensor, heel sensor, right sensor, left sensor. The electroressistive transducers were placed at the extreme ends of the mounting leg in order to provide information about the developed tangential forces. Potentiometers (13), (14), (15)

attached to the orthotic structure have been used to control joints angular position.

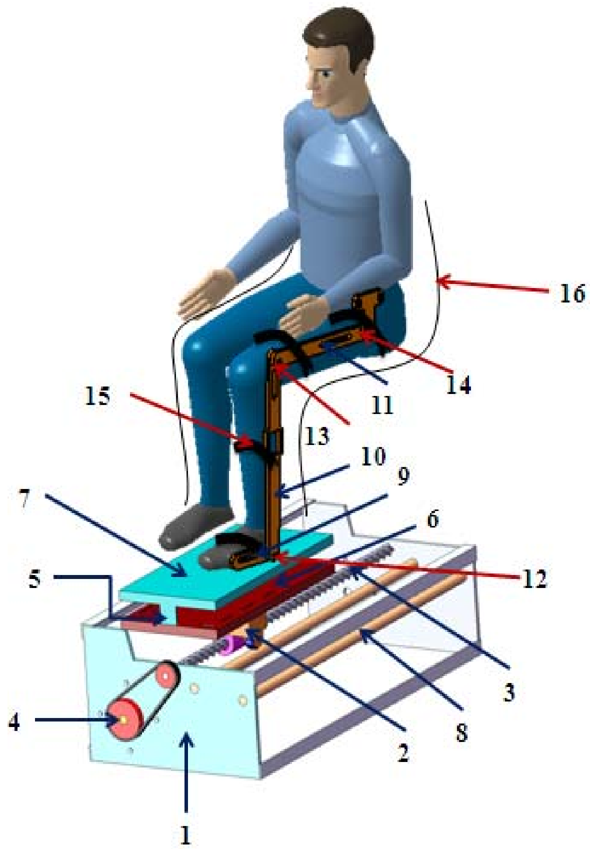

Fig. 2. A 3D model of the mechatronic rehabilitation device

In the software component are integrated: the communication modules with microcontroller, voltage scaling part for the used sensors, logic control, real time recording of all values from microcontroller and storing them in an own database, real-time display of obtained values, defining the parameters and their functional limits, manual control options and analysis, view recorded data, and also patient safety criteria.

Graphical user interface is presented as a display containing some of the basic information of the patient: anthropometric data (sex, age, height and weight), the range movement customized for each patient, biomechanical consideration, enabling and displaying information about the condition of the patient. This database will also be found in the computer used for data storage and processing. The information about the patient is transmitted to the computer and then to the mechatronic system by using communication protocols.

The safety condition was one of the most important design criteria, because the patient should be protected while using the device. The mechatronic rehabilitation apparatus has included a safety device, according to the ISO regulations. The safety device is able to react both automatically and manually, and also by user interaction. All the actions undertaken by the safety device have as a first priority the patient safety and the system can react due to mechanical or electrical failure and also different types of malfunction, due to the user interaction. For ensure the safety condition it was necessary to establish, from the designing phase, different safety limitations both hardware and software for the involved motions (rotation, translation or combined motions). The imposed limitation refers to the construction of the mechatronic rehabilitation device, which is directly supervised by the safety device that receives information from the mechanical and electrical sensors mounted in the structure of the system. The emergency actions are triggered automatically by a safety event. Each motion is limited also by the software safety limits, included in the software design. In the monitoring software, a set of variables and constants were defined, such as: motion variables, the range of motion, anthropometric parameters, biomechanical considerations, the technical parameters of the system and the motor control algorithm. The software is also able to trigger safety events, received by the safety device in real time (Amancea et al., 2011).

3. CLOSED LOOP REHABILITATION PROTOCOL

The mechatronic system allows a differentiated and customized rehabilitation protocol for each patient and applies a closed loop method: Diagnosis - Treatment - Feedback from the patient (patient's recuperative progress assessment), based on angular position variations reached in the of lower limb joints and also based on normal and tangential forces developed due to the interaction between the human foot and the recovery system. In figure 3, it is shown the operation of the rehabilitation mechatronic system, which applies a closed loop therapy: diagnosis - applied treatment - feedback from the patient, as follows:

-before starting the therapy, the anthropometric characteristics of the subject under test are recorded in a database, its general information and previous medical history, if they existed;

-based on the medical diagnosis received, the recovery criterion is developed, which is customized to each patient based on various types of exercises (gymnastics rehabilitation);

-after some intensive and repetitive exercises is evaluated in real time the patient rehabilitation progress (based on knee angle, normal and tangential forces). A doctor will observe the patient’s recuperative process, will offer a new diagnostic, a new rehabilitation protocol, a new reevaluation of the patient, and so on, in a closed loop method.

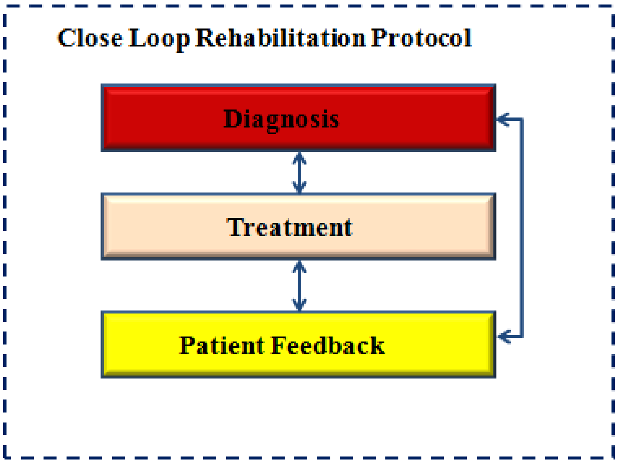

Fig. 3. Closed loop rehabilitation protocol applied by the mechatronic rehabilitation system

Normal and tangential forces represent an important criterion for assessing the patient's recovery and led to the following conclusions:
-a greater normal and tangential force indicates functional knee joint failure; their decreasing values after rehabilitation sessions highlight the capability of patient to realize the movement, in practice - the degree of rehabilitation;
-based on their values it can be inferred severity of the condition, being the necessary information to establish physical therapy sessions;
-normal force may reveal the knee instability (immediately after local injury). Instability can be caused by partial or total atrophy of the muscles (for a prolonged immobilization of the foot), and resulting in the inability control of the patient to transfer the weight of the tibia, causing severe pain in the knee joint. This instability generates lateral inclinations of the foot, so the lateral sensors will record high values of the forces;
-normal force can be useful for monitoring the recovery process after some pathologies of the ankle joint or to assess postrecuperator gait phases and weight transfer on the affected member.
Analysis and monitoring of angle joints variation, using potentiometers, it was necessary for the following reasons:
-knowing the values/modifications of joints angular position is useful to monitor the patient progress during the physical therapy sessions, in terms of motion range. Basically, the flexion angle is a criterion for starting or completing the recovery. Patient recovery procedure starts from a minimum degree of flexion that can be achieved, and ends when the doctor decides that it is able to actively move the member up to a limit of flexion-extension;
-based on the knowledge of the specific angular values for each patient, it could be customized the amplitude of the movement.

4. EXPERIMENTAL TESTS AND RESULTS

The system is used to rehabilitate the flexion and extension movement. A predetermined number of full stroke displacements of the foot from forward to backward direction are performed. During the recovery process are monitored values of the normal and tangential forces and all the variations in the joint angle, which are recorded in real time, and can thus generate a complete analysis of the evolution of the patient.
The mechatronic rehabilitation system (fig. 4) ensures successive recovery for both right and left legs and the disposal of the patient with the developed system is conditioned by placing it on a pivoting chair. Initial position to start therapy requires setting the patient's foot on the platform system using braces, in order to obtain 90 degrees angle between thigh and shank (fig.8). Once the patient was properly positioned in the recovery system, the orthotic structure is attached on the inferior limb. The orthotic device was used to stabilize the foot throughout the recovery therapy and its constructive elements align perfectly to the anthropometric characteristics of the patient, allowing him to achieve the movements in physiological limits. Such a structure is fixed on the leg by using Velcro straps, which facilitates the implementation of potentiometers for each joint involved in the movement, in order to track variations in the successive angular positions of joints during therapy. Real time monitoring of angular positions is extremely important to evaluate the progress of the patient, also representing a criterion to start and finish

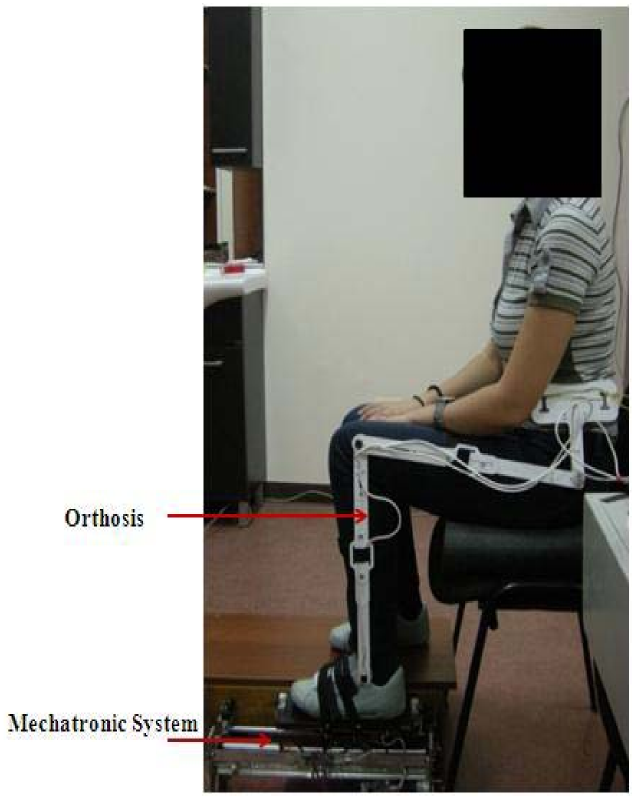

Fig. 4. Patient during the rehabilitation session

medical recovery. Before starting the therapies sessions, the patient's limit of movement is measured and the tests were performed both on healthy subjects and patients also.

In Fig. 5 is shown the range of motion for the knee joint recorded during a test with our mechatronic system, for a healthy subject and also a patient. The figure can clearly distinguish four full course of displacement, which means extension (forward motion) and flexion (backward motion). It can also be noticed the change in joint angle relative to position zero (corresponding to the initial position of 90 °) as a function of the foot movement (forward and backward). Peaks located above the zero correspond to extension movement and those located on the negative axis correspond to flexion movement. It may be noted that they have a symmetrical shape both for healthy subject and patient also, after four rehabilitation sessions.

Amplitude of motion is greater for the forward motion and lower for the backward motion. This angle difference is explained by the fact that the therapy starting position is favorable to extension movement, the subject making this movement easily,

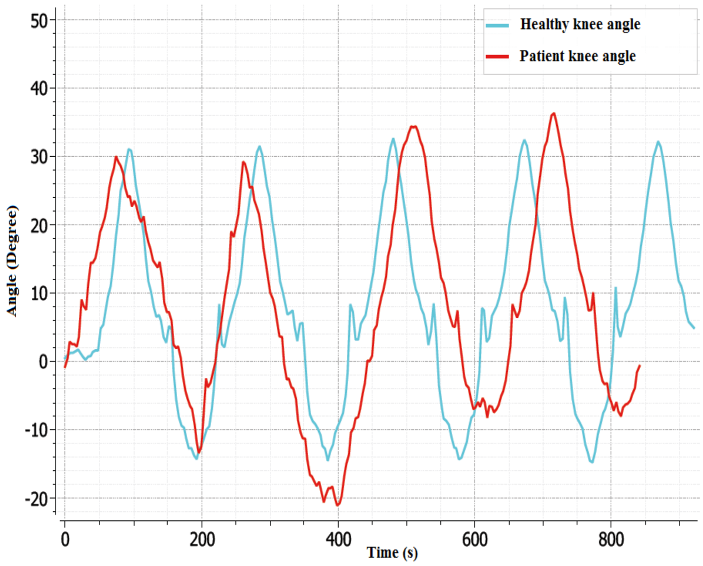

Fig. 5. Knee angle of the healthy subject and patient after rehabilitation therapy

while flexion movement is limited by the presence of the seat, the constraints caused by ligaments and muscles and because of posterior level meeting of the two segments, thigh and shank. Analyzing the curves presented in Fig. 5 it can be observed small peaks recorded above the reference position. These peaks are caused by the transition from flexion to extension movement and also because of the bones movement inside of the human joint, one against another, in this case femur is fixed and tibia slides on it.

In Fig. 6 and Fig. 7 are plotted the tangential forces developed due to the interaction of the human foot of the healthy subject and patient, with the recovery system, when leg realizes the flexion-extension movement. Analyzing the figure 6, it can be observed the same symmetry of the curves both for healthy subject and patient but with small differences of heel tangential forces values. A similar behavior and the same symmetry of the curves (healthy subject and patient) can be observed in figure7. It is visible that in figure 7, between 400 and 600 s, the curve of toes tangential force has a peak. This can be probably explained by some vibrations which appear in the mechatronic system during the operation mode, or maybe because the patient change his initial position during the rehabilitation therapy session.

Although the symmetry and the form of the peaks are respected, it can be notice that the curves presented in figure 6 and 7 are in opposition. This is explained by the fact that during the extension movement the toes elastic element is reached by the foot's toes and during the flexion movement the back elastic element is reached by the foot's heel.

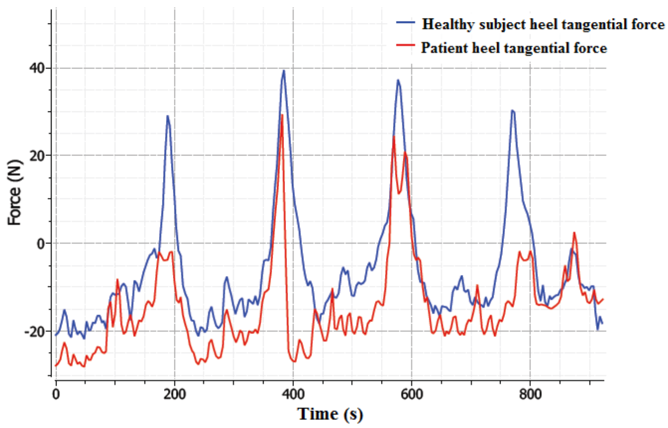

Fig. 6. Heel tangential force of the healthy subject and patient after rehabilitation therapy

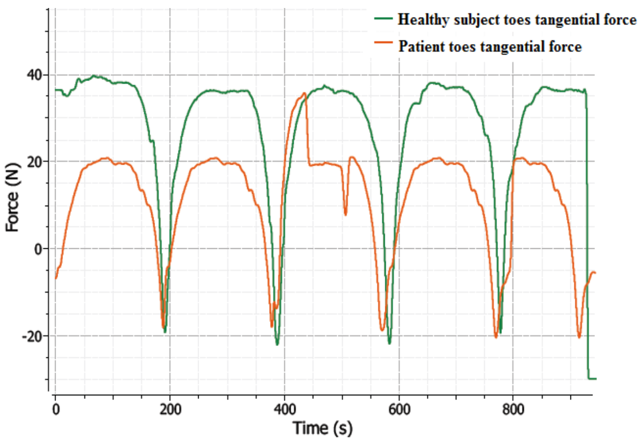

Fig. 7. Toes tangential force of the healthy subject

5. CONCLUSIONS

The design and implementation of a new mechatronic rehabilitation system, which can successively recover the both legs, is presented in this paper. The key features and the originality of the system can be highlighted by following elements: design; applications; personalized treatment to each patient; methods of command and control; communication protocols with feedback from the patient; safety requirements for the patient interaction with the mechatronic system; simplicity and portability.

This paper presents only a part of the experimental tests performed on a healthy subject with the result for the knee angle during the flexion and extension movement and the tangential forces developed to the interaction between the system and the subject's foot.

The experimental results achieved during the tests on healthy subjects and patients, show that the best results are obtained concerning the movement and knee joint recovery. During the tests, it was also visible that the mechatronic system reduces considerably the patient's medical recovery, with 40% and accelerates its healing. The results prove also the efficiency of the system which makes it to be applied successfully in any lower limb rehabilitation therapy session, for a wide range of pathologies.

Even if the device was developed for knee joint rehabilitation, it is also able to ensure a recovery therapy for the other two joints of the lower leg (hip and ankle). The next papers will contain results concerning the hip and ankle angles, and also about the normal forces of healthy subjects and patient with have different diagnosis.

In conclusion, the mechatronic system evaluates the patient's recovery based on the joint angular positions variation and also based on normal and tangential forces developed during the interaction between the human foot and the rehabilitation system. The normal and tangential forces can highlight the disease's gravity and also the rehabilitation progress. A greater normal and tangential force indicates functional knee joint failure; their decreasing values after rehabilitation sessions highlight the capability of the patient to realize the movement, in practice - the degree of rehabilitation. For the knee angle during the flexion and extension movement and the tangential forces developed to the interaction between the system and the subject's foot.

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