ISSN: 0974-5823 Vol. 7 No. 6 June, 2022

International Journal of Mechanical Engineering

A New Approach to the Actuation of Physical Therapy Exercise Devices

Andrea Deaconescu [1]

[1] Dept. of Industrial Engineering and Management, Transilvania University, Brasov, Romania.

Tudor Deaconescu [2]

[2] Dept. of Industrial Engineering and Management, Transilvania University, Brasov, Romania.

Abstract - The paper presents a device conceived for the physical therapy of the main weight-supporting articulations of the human body by applying recovery-specific continuous passive motions (CPM). The authors put forward the innovative concept of deploying pneumatic muscles for the actuation of the device.

The paper discusses the construction of the machine, its pneumatic drive, and dynamic performance. The time-related evolution of angular velocities and accelerations of the actuated joints are illustrated for modifications of pressure and flow rate of the compressed air supplied to the pneumatic muscle, with the aim of obtaining working parameters adjustable to various degrees of handicap.

Index Terms : *physical therapy exercise device, pneumatic muscle, isokinetics, continuous passive motion.*

INTRODUCTION

The utilization of isokinetics as a means of rehabilitation has been the subject of numerous explorations worldwide. Emerged about 1970 isokinetics addressed mainly orthopedic rehabilitation and function assessment. Isokinetic testing was originally a tool used mainly in exercise science and the only isokinetic movements available were concentric (with no thought given to isotonics, isometrics, continuous passive motion (CPM) or range of motion expansion). In terms of orthopedic rehabilitation, existing studies focus primarily on the knee, followed by ankle and shoulder.

Beyond its statistical significance, the relevant scientific publishing also highlights the current state of development of the isokinetic method, as well as its specific role in the field of rehabilitation robotics, confirmed by the fact that most insurance companies cover the cost of isokinetic testing.

The specific objectives of recovery medicine include maintenance and recovery of body functions, as well as prevention of dysfunctions, employing kinetic and orthotic techniques together with various adaptive accessories. Currently a number of methods are employed to alleviate the dysfunctions of limb joints, like for example passive exercising for joint mobilization, exercises devised to improve the contractions and thus the force developed by the muscles, utilization of adaptive equipment for promoting functioning (limb prostheses, ortheses, walking aids).

Fig. 1 Weight-supporting articulations of the upper and lower leg and foot (hip, knee, ankle)

The mobility of weight-supporting articulations (Fig. 1) that are affected consequently to various traumas can be recovered by passive exercising, known as continuous passive motion.

CONTINUOUS PASSIVE MOTION

Continuous Passive Motion (CPM) is a method of postsurgical rehabilitation applied to the operated bearing joints of the lower limbs. Upon surgery the tissue surrounding the wound becomes rigid, thus significantly diminishing joint mobility. Natural recovery of the joint could last, in certain cases, up to several months.

Passive exercising is beneficial to several systems of the human body [1]:

- locomotor system:
- – preserves the standard range of mobility and structure of the articulations affected by segmental paralysis;
- – enhances the current range of mobility of the joint by slimming the ligaments that thicken the joint capsules and by stretching the muscle-tendon junction;
- – maintains or even increase muscle excitability;
- – increases the stretch reflex by passive extension motions of the muscle, that determine muscle contraction;
- – preserves the motion awareness of the articulation by providing information on the movement and position of the own body signaled by the receptors;
- – prevents or eliminates immobilization related oedema.
- nervous system and psychic well-being:
- – counteracts the damaging psychological effect of physical trauma or impairment.
- circulatory system:
- – mechanically stimulates blood pumping in the small vessels of the concerned muscles, as well as circulation in veins and lymphatic vessels.
- further:
- – helps ensure the nutrition of the affected tissue (skin, muscle, tendons and ligaments);
- – stimulates lung and tissue respiration:
- – accelerates GI passage and aids urine release.

Therapeutic efficiency is achieved by customizing passive exercising according to the specific pathology and severeness of the addressed condition resulting from a medical assessment of the dysfunctional joints and muscles.

The input quantities of the patient-machine system include the force exerted upon the mobilized joint, the characteristics of the induced motion like length, speed and acceleration of the stroke, as well as the number of stokes performed in a set time interval. The set-points of such parameters while accommodating the patient's specific condition have to ensure the desired regaining of mobility. Consequently, the parameters identified above need be adjustable within certain ranges on the physical therapy (PT) device.

The impaired muscle's condition is further impacted by the rate of the motion. If the PT program is aimed at improving muscle tone, a heightened tact of exercising will be required.

Typical physical therapy schemes include single, repeated bidirectional motions carried out in about 1-2 seconds or motions conducted in a 2 or 4-cycle. In each case the straining of the joint is held for about 5 to 15 seconds before the return motion is initiated. Thus, at one time PT does not exceed 10 minutes, depending on the strain tolerated by the human subject. For a speedy recovery, PT is to be conducted at least twice daily [1].

The utilization of CPM procedures involves the mechanized driving of the joint that has undergone surgery, without however requiring any effort from the patient. For this purpose, dedicated devices are called for that ensure the best possible mobilization of the articulation.

Research confirmed that recovery is indeed accelerated by deploying such devices and consequently the patients require less analgetic medication. Thus, a speedy and healthier recovery at lower costs is achieved.

The utilization of such equipment, however, entails a number of cautions. Besides general cautions related to the fact that isokinetic exercising requires added breathing effort and intensifies the straining of the heart, such PT is not recommended immediately following the traumatic event, or if the patient suffers from burns or inflammation, in cases of non-consolidated broken bones or incomplete surgical ligament repair. Isokinetic exercising is applicable provided it is pain-free. Based on their experience and expertise the PT specialist will be able to tune the device in order to eliminate any risks for the patient and conduct well-tolerated mobilization exercises.

The most frequent and serious complication is the occurrence of tendonitis. Tendonitis can be prevented by warming-up and stretching exercises prior to an isokinetic session, but mainly by a progressive application of this method, in order to avoid over-straining during the first cycles of exercising. In addition, manual therapy is recommended subsequently to particularly straining exercises.

EQUIPMENT FOR CONTINUOUS PASSIVE MOTION

Isokinetic exercises were first introduced by Hislop and Perrine in 1967, and have been since often used in rehabilitation. As opposed to isometric and isotonic contractions, the isokinetic ones achieve muscle training by the programming of the motion path of the joint, the contraction being assumed as having a constant velocity.

Devices conceived for isokinetic rehabilitation are also able to evaluate the muscles that they mobilize. True to their name, however, they work from the premise of isokinetic motion, meaning that the muscle angular rate is constant. This is not entirely accurate, as the driving velocity of the disabled joint varies within the limits of a certain interval, around the so-called pre-set angular velocity (PAV) (Fig. 2) [2].

At the beginning of the recovery exercise, depending on the state and shape of the patient, the rehabilitation equipment is set to a certain value of the angular velocity (PAV). It is not possible, however, to maintain this velocity constant in time, as the resisting force generated by the patient is variable in different points of the motion path. Thus, when the patient opposes a higher force to the motion, the velocity decreases in relation to PAV, and conversely, for a smaller patient resistance to motion the velocity will increase. The angular velocity can be preset between certain limits, this range being a fixed device specification.

The continuous passive motion (CPM) devices presented in literature are either dedicated to the rehabilitation of a single specific joint or can be deployed with the help of auxiliary components for exercising a number of different articulations. Thus, literature distinguishes between mono-articular and pluri-articular rehabilitation equipment. Fig. 3 [3, 4] shows equipment conceived for mobilizing knee and ankle.

Devices conducting continuous passive motion are connected to and controlled by a computer. Thus, the operation of the muscle can be monitored and the measured data transposed into graphs that show the evolution of muscle inflation over the active stroke. Thus, patients are able to follow their progress and the assisting medical professional is provided with the necessary information and data to formulate a live evaluation of the ongoing PT.

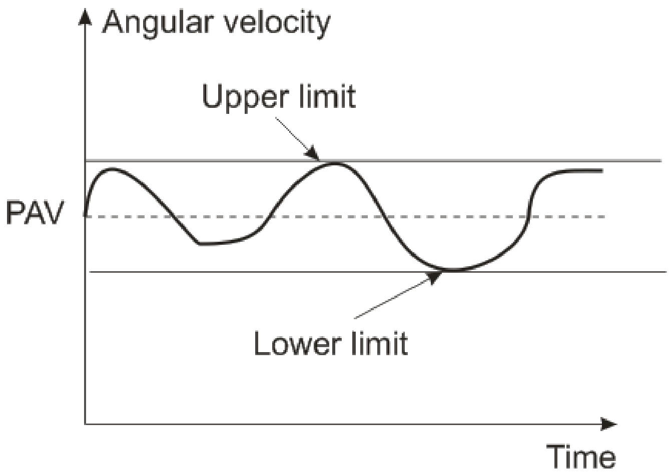

Fig. 2 Variation of the driving velocity of the disabled joint

Fig. 3 Different variants of continuous passive motion rehabilitation equipment

A significant facility offered by such CPM machines is that they can be set up and used in the homes of patients as well as in clinics providing physical therapy.

At present the actuation of the CPM devices that can be found in commercial offers is ensured by electric motors. The known rigidity of electrically actuated linkages is a disadvantage in rehabilitation equipment, due to the end-of-stroke shocks that cause pain to the patient. Furthermore, electric devices tend to be cost-intensive. Frequently they come at prices the preclude individuals from purchasing them, thus restricting their deployment to medical centers. The considerations laid out above led the authors to explore the possibility of using a different actuation system for CPM devices designed for the rehabilitation of the weight-supporting articulations. The prototype of novel isokinetic device resulted that can be manufactured at smaller costs and commercialized below the current price rates for electric equipment.

The team of researchers at Laboratory of Fluid Drives and Automation at Transilvania University of Braşov, Romania is engaged in the conception and experimental development of a CPM device for the rehabilitation of the weight-supporting articulations driven by pneumatic muscles.

Pneumatic drives benefit from less heavy structures that improve their reaction to commands, a type of behavior defined as compliance. It is the working medium of pneumatic muscles - pressurized air – that being compressible determines such compliant behavior. Consequently, air pressure can be used as the means to control compliance, a feature paramount to ensuring a soft interface between the human and the equipment and also enables soft gripping in certain robotics applications [5].

The light weight, air as a clean working medium, the operational safety and more importantly the compliant behavior of pneumatic muscles render these actuators adequate for physical therapy equipment. Fig. 4 shows the kinematic scheme and the construction of the conceived device [6].

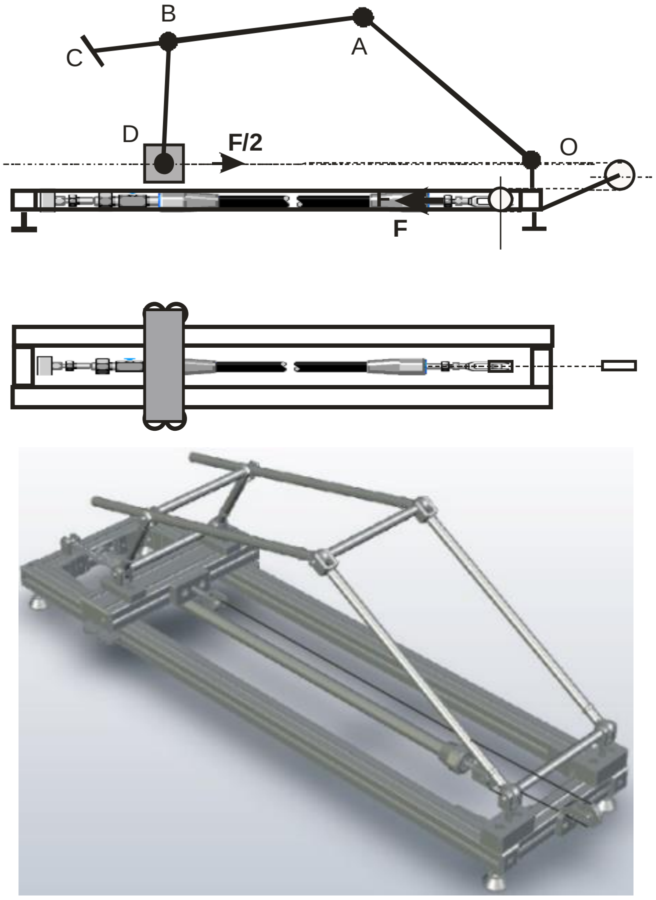

Fig. 4 Kinematic scheme and construction of the device

The considered application requires a slider that travels a length of 300 mm. The inner diameter of the muscle's rubber tube is of 20 mm, and its deflated length of 750 mm. according to the manufacturer's specification a pneumatic muscle can elongate by approximately 20% at most, amounting to a 150 mm stroke *s* in the discussed concrete application. As the application requires a 300 mm travel of the slider, the stroke provided by the muscle had to be increased to its double. For this purpose, the muscle was connected to the slider by a system of two pulleys, one mobile and one fixed (Fig. 5).

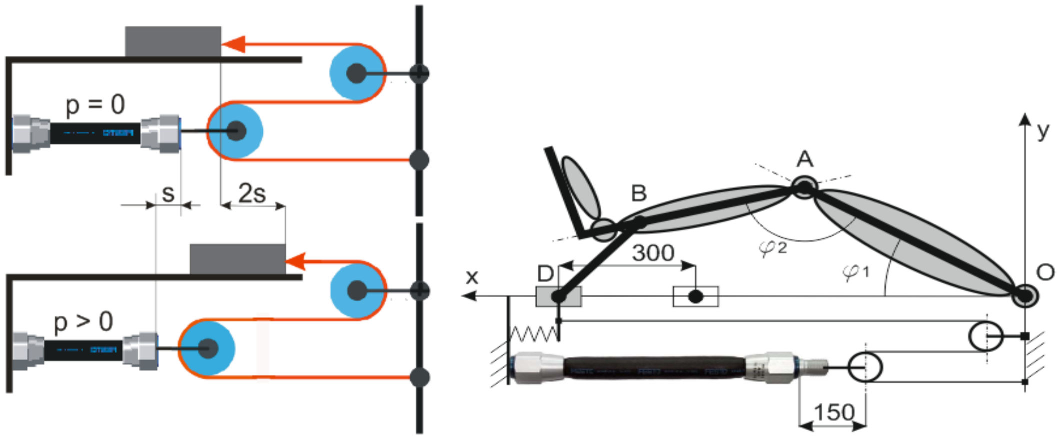

Fig. 5 Mechanical multiplier of the slider stroke

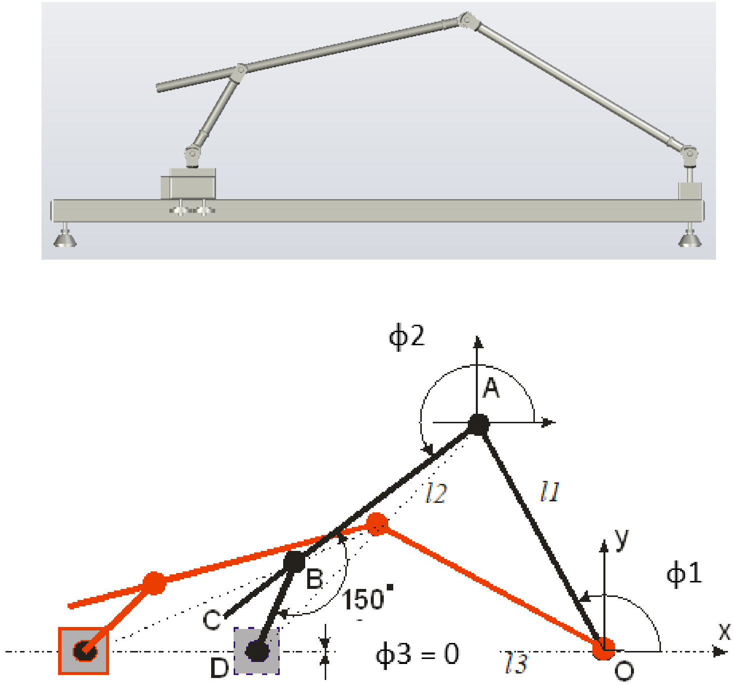

Fig. 6 Kinematics of the bar mechanism

In order to set patient knee and hip into motion, specifically rotation, the slider that moves strictly along a linear path is attached to a bar mechanism (OABD) as shown in Fig. 6.

The hip and the knee allow maximum rotations denoted by the angles $\phi 1$ and $\phi 2$, respectively. Their values can be determined based on the geometry outlined in the schematic of Fig. 6, and their variation versus the slider's stroke can be plotted. Angle calculation is based on the required 300 mm travel of the slider, *i.e.* the stroke, and on the dimensions of the bar segments, namely *l1* = 450 mm; *l3* = 600…900 mm. In triangle ABD the length of segment *l2* = AD can be calculated as being of 552 mm.

The values of $\phi 1$ and $\phi 2$ representing the angular motions of hip and knee, respectively, are determined by equations (1) and (2) below:

$$\phi 1 \quad = \quad -\arcsin\left(\frac{l2}{l1} \cdot \sin \phi\, 2\right) \qquad (1)$$

$$\phi 2 \quad = \quad \pm \arccos\left(\frac{l1^2 \; - \; l2^2 \; - \; l3^2}{2 \cdot l2 \cdot l3}\right) \qquad (2)$$

The modification of angles $\phi 1$ and $\phi 2$ versus the 300 mm stroke of the slider is represented in Fig.7. The extreme values of the angles can be read on the graphs:

hip: ϕ1 = 118.7 º….151.037 º;

knee: ϕ2 = 203,347 º….225,754 º.

The graphs in Fig. 8 present the evolution versus time of the slider's speed and of the two angular quantities, assuming a 6 second duration of a complete cycle of motion.

The diagrams in Fig. 9 illustrate the evolution versus time of the pneumatic actuator during its deflation, as simulated by means of the ProPneu v.4.2.2.18 software. Further represented is the time-related variation of travel speed, acceleration, and of the position of the muscle's free end.

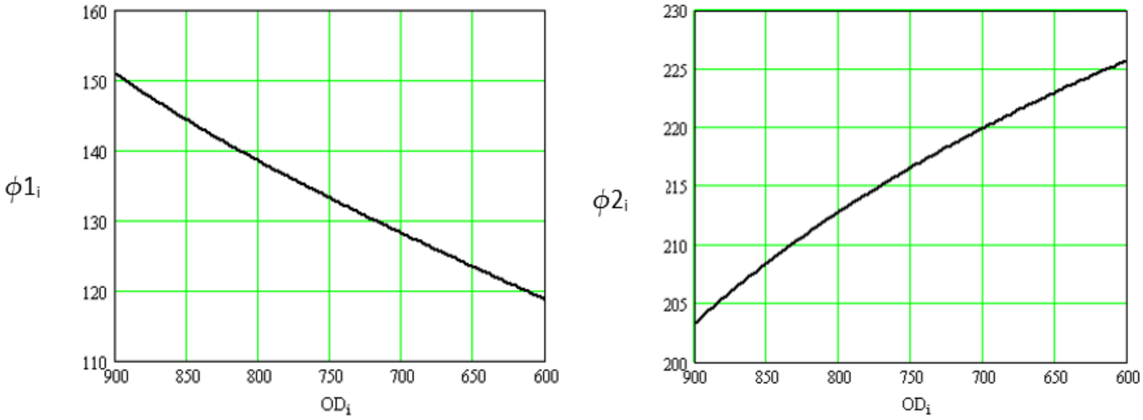

Fig. 7 Variation of angles *ϕ1* and *ϕ2* versus length of stroke

Notably the muscle's free end and the slider attached to it do not move at rigorously constant speed, given its small variations around the PAV (pre-set angular velocity). Fig. 10 presents at a magnified scale the evolution of the deflation velocity of the pneumatic muscle, within its limits of variation. Simulation of the behavior of the analyzed system has yielded a variation interval of the travel velocity of 0.101 m/s.

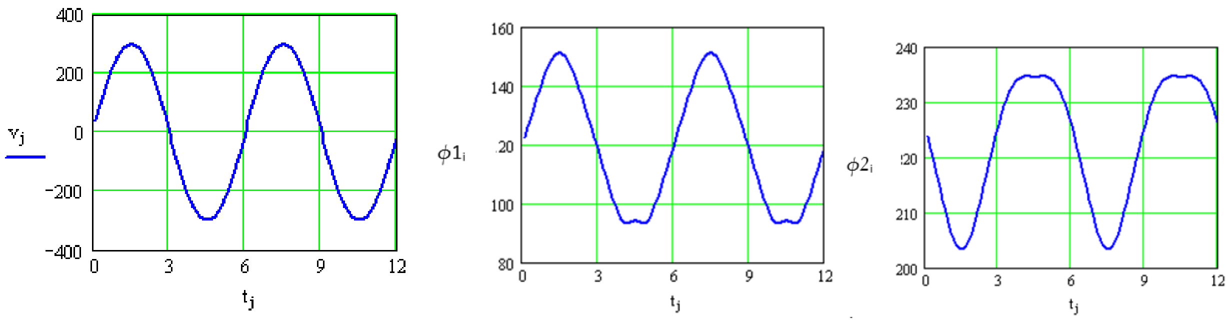

Fig. 8 Slider speed and angular displacements *ϕ1* and *ϕ2* versus time

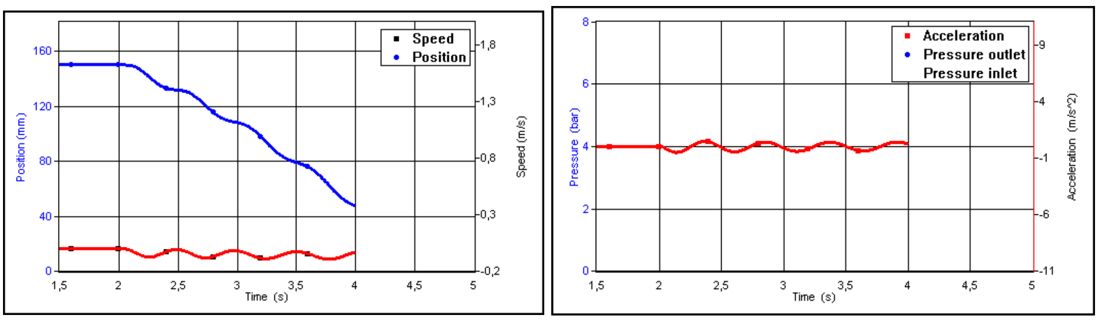

Fig. 9 Position, speed and acceleration of the muscle's mobile end versus time

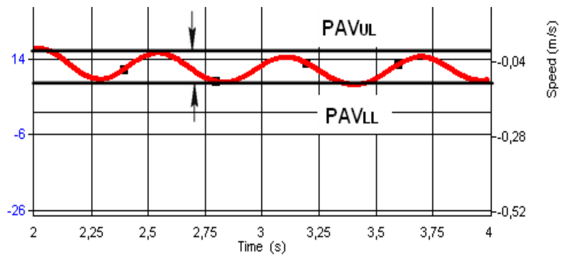

Fig. 10 Speed of the muscle's mobile end versus time

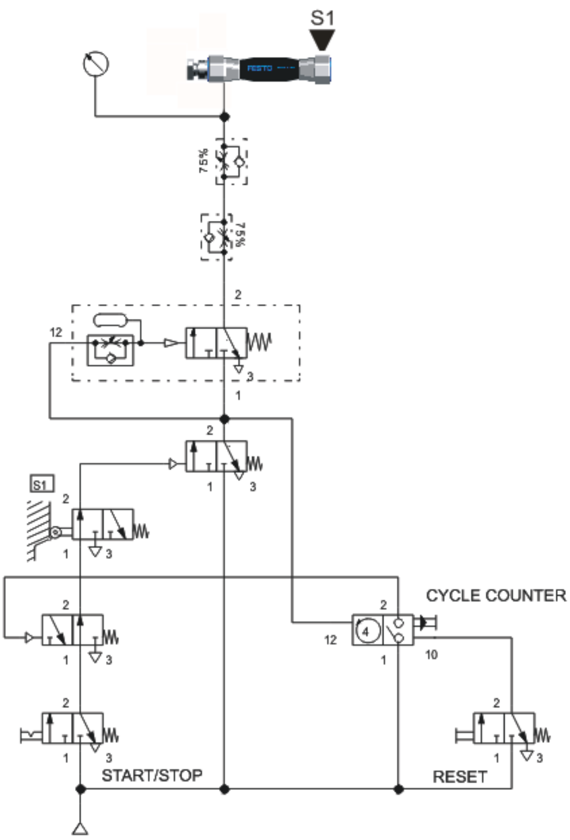

Fig. 11 Schematic diagram of the device's pneumatic actuation

A throttle valve was inserted into the pneumatic circuit in order to keep the variation interval of speed as small as possible.

A CPM exercising scheme customized for the rehabilitation needs of a specific patient is devised by programming - via the pneumatic control system of the physical therapy device - the distance travelled by the slider, its speed, the needed number of cycles and the holding times of the limb before initiating the return stroke. Fig. 11 shows the schematic diagram of the pneumatic actuation.

The speed of the muscle's mobile end can be set via the pneumatic actuation system for both the direct and the return stroke. This facilitates adapting PT to the respective phase of the rehabilitation process. In order to allow the patient to rest short halts can be set by pneumatic control once the stroke has been completed and the leg is relaxed.

An efficient rehabilitation scheme addressing an affection of a certain severity can require one or more exercising cycles to be performed during a PT session. The number of cycles can also be set by pneumatic control.

CPM entails mobilizing exerting a certain force on the joints in order to mobilize them. This force can be adjusted by setting the value of the air pressure (from 3 to 8 bar) fed to the muscle.

As the CPM device is conceived also for home us, it is designed for easy operation. The patient initiates the PT exercising session by setting the number of cycles from a counter (a cycle corresponds to a double strokes of the muscle) and flips the start switch.

CONCLUSION

The paper puts forward a novel approach to the actuation of physical therapy exercise devices. The conceived equipment is manufactured at a low cost, its structure is light and straightforward and it can be used by patients themselves.

The equipment also provides clean, environment-friendly and shock-free operation due to its working medium, namely air. This recommends pneumatically actuated rehabilitation devices over those endowed with electric motors that transfer end-of-stroke shocks to the patient's joint.

REFERENCES

[1] C. Albu, T.L. Vlad., A. Albu, Passive physical therapy, Polirom Publishing House , Iaşi, Romania, 2004 (in romanian).

[2] P. Spencer, "Isokinetics Explained", Available online: https://isokinetics.net/index.php/2016-04-05-17-04-58/the-author

[3] Kinetec. Performa CPM Machine. Available online: https://www.kinetecuk.com/shop/cpm-active/knee-cpms/kinetec-performa-with-washable-pads/

[4] McKelor Furniss DC Knee CPM Machine Model DC2480. Available online: https://www.ardusmedical.com/mckelor-furniss-dc-knee-cpm-machine-model-dc2480/

[5] S. Hesse, The Fluidic Muscle in Application. Blue Digest on Automation, Esslingen, 2003.

[6] A. Deaconescu, T. Deaconescu, "Pneumatic Equipment for Ankle Rehabilitation by Continuous Passive Motion," In: Zeghloul S., Laribi M., Sandoval Arevalo J. (eds) Advances in Service and Industrial Robotics. RAAD 2020. Mechanisms and Machine Science, vol 84. Springer, Cham, pag. 13-21.