Rehabilitation device supporting active and passive upper limb exercises

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This article presents a mechatronic solution for rehabilitation devices supporting active and passive exercises in persons with motor dysfunctions of the upper limbs in the area of the elbow and shoulder joints. A planar positioner integrated with original software and a control system, served as the basis for creating the present solution. Bellman's programming method was applied to optimize the motion trajectory of the planar positioner along with the upper limb undergoing rehabilitation. The design of the planar coordinate positioner and the components of the system for supporting a therapy conducted by a rehabilitation specialist are presented.

Keywords: Mechatronics, positioner, rehabilitation, upper limb.

PROLONGATION of the average human lifespan, late retirement and propagation of active lifestyle have forced modern medicine to face new challenges.

Many rehabilitation techniques that are applied include solutions supporting general and topical kinesiotherapy. The primary objective of the actions undertaken by the patient and rehabilitation specialist is the restoration of all primary functions or maximization of motor functions in an already difficult or irreversible stage of illness.

Upper limb rehabilitation may involve work on muscles and joints, starting from shoulder girdle, through elbow and wrist, and ending with fingers of the hand. Depending on the type of dysfunction and the cause of its occurrence, various technical measures and types of exercises are in use. They are: (i) passive, isometric – changing muscle tension, but not length; (ii) active-assisted: supported by a therapist, but involving force exerted by the patient; (iii) self-assisted – during which the patient supports the impaired limb with the muscle strength of the healthy limb and (iv) active with reduced load or active with loading[1]. The presence of a physician-physical medicine and rehabilitation specialist, who supervises the correctness and scope of the performed exercises is advisable while exercising, particularly during initial stages. The application of devices supporting rehabilitation enables reducing the time devoted to a single patient and improve the effectiveness of rehabilitation[2]. Various devices supporting passive and active exercises can be found in the market. The simplest ones, supporting therapeutic gymnastics, are, among others: hand gripping devices (grips, balls, etc.), nets and bands for stretching, ladders and bars for pull-ups, weights, etc.[3].

Another group is made up of mechanical devices for stretching, bending, abduction of a limb, as well as simple devices providing support for a limb and its mobility in a specific joint – most often the elbow or shoulder joint. Some specific examples are presented[4–6]. This group is supplemented by Continuous Passive Motion (CPM) rails, which are intended for continuous, passive mobilization of joints and muscles in patients with flaccid or spastic paralysis or with a significant degree of paresis[7–9]. The third group, typical resistance systems, is the bridge between passive and active systems.

These devices consist of tension members with additional loads. During exercises, a patient actively stimulates the work of a limb through a system of levers, loads and range of motions selected by a rehabilitation specialist, thus successively strengthening the limb's muscles and its Range of Motion (ROM)[10]. The last group – technically advanced bionic devices, i.e. exoskeletons – supports lost nerve-muscle functions of the upper and lower limbs[11,12].

The most common clinical conditions that later require upper limb rehabilitation include stroke, conditions after orthopedic surgical operations like carpal tunnel release, acromyoplasty, anterior capsular reconstruction, rotator cuff repair, after bone fractures or other injuries. In order to achieve optimal effects after rehabilitation process in these clinical conditions the devices supporting rehabilitation should be characterized by the possibility of implementing active, passive and isometric exercises with smooth movement of the limb, the possibility for accurate reconstruction of movement trajectory designed by a physiotherapist, the possibility of precisely added or reduced weight or load during exercise[10].

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Only a few of the above-mentioned analysed devices seem to meet these requirements. Many are very expensive in terms of money, preparation time for exercise and ease of use[13]. This was the motivation for the present study. An original rehabilitation device for persons with dysfunctions of the upper limb in elbow and shoulder joints is presented in this paper. The proposed device is programmable and enables execution of individual therapeutic passive, active and resistance exercises while maintaining a constant hardware configuration. A mechatronic planar positioner with aerostatic bearing, integrated with original software and a control system, served as the basis for creating the present solution. The application of compressed air as a lubricant, practically eliminates frictional resistance (friction co-efficient $\mu = 10^{-4} \div 10^{-5}$), which is the primary cause of relaxation oscillations (stick–slip phenomenon). Additionally, it makes the system self-levelling. The dynamic programming method applied to optimize the motion trajectory of the planar positioner ensures precise control of the device during exercises. The original software, which is rehabilitator friendly, allows programming and realization of rehabilitation exercises.

The proposed original solution does not end our interest in this topic. In the summary section the directions of future research are outlined.

Materials and methods

Description of the precise co-ordinate positioning system

The precise coordinate positioning system (planar stepping motor) consists of the inductor (forcer) with gas-film lubrication (aerostatic lubrication) – relative base and the stator – absolute base[14,15] (Figure 1).

The basic elements of the inductor are shown in Figure 2 (ref. 14). The inductor consists of the following elements: aluminum frame; electromagnetic modules: I, II;
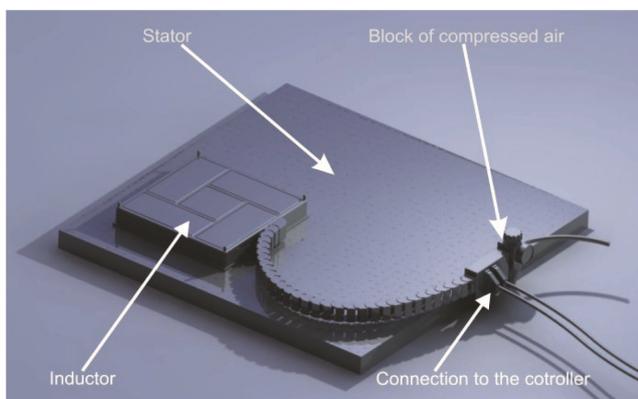
pneumatic system: supply conduit, built-in pneumatic system and bearing chambers. The principal element of the pneumatic system is the built-in pneumatic system with nozzles and bearing chambers, which provide the air into the air-gap between the stator and the inductor. The air cushion acting as an air layer, whose pressure is greater than atmospheric pressure, produces aerodynamic lift F_n. By means of the aerodynamic lift, the inductor is suspended at height h above the stator. The use of air-gap completely eliminates the physical contact of the working surfaces, and the application of aerostatic lubrication reduces friction and wear of the sliding surfaces.

The working surface of the inductor contains two groups of orthogonal electromagnetic modules. The electromagnetic module (I) is responsible for movement of the inductor along the X-axis, and the module (II) is responsible for movement of the inductor along the Y-axis.

The planar stepping motor converts control pulse signals directly into a sequence of linear shifts. The direction of shifts made by the forcer is related to the sequence of passing impulses and the speed of the forcer depends on the frequency of the current. The value of the shift of the forcer with regards to the stator depends on the current pulses. The planar stepping motor cannot be operated without an appropriate control system which ensures the desirable performance of the step motor.

Figure 3 shows the forces of the precise coordinate positioning system. The aerodynamic lift F_n (reactive force of air cushion) counterbalances the loads resulting from gravity (weight of the inductor P_p + weight of the object mounted on inductor – payload P_r) and magnetic attraction forces F_p. The attraction force of the inductor towards the ferromagnetic stator is caused by permanent magnets, which are part of the electromagnetic modules[15].

The force equilibrium conditions in the relative base-air gap-absolute base system, has the form

$$F_n = P_p + P_r + F_p. \tag{1}$$

Figure 1. Basic elements of precise coordinate positioning system.
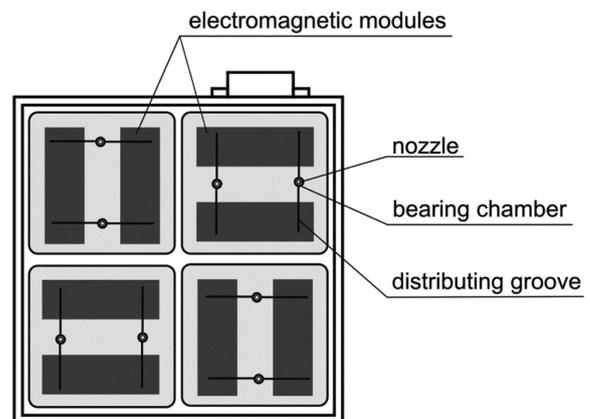
Figure 2. Basic components of the inductor.

Implementation of dynamic programming method for practical execution of programmed movements of the mechatronic planar positioner

The control task of planar positioner displacement in accordance with trajectories of movements performed in subsequent active and passive rehabilitation exercises is complex and ambiguous. It must therefore be considered as an optimization problem. The dynamic programming method, developed by Bellman[16], is an algorithm design technique that is applied to solve optimization problems. The extended method described by Karpovich et al.[14] was applied with respect to the planar positioner utilized in the original rehabilitation device.

Let J be a functional defined as

$$J = \int_0^T F(X,U)\mathrm{d}t. \tag{2}$$

Optimization of the planar positioner's motion trajectory consists of finding such a control function $U^*(t)$ (and the optimal trajectory $X^*(t)$ corresponding to it) that satisfies:

$$S(X_0) = \min_U (J). \tag{3}$$

Optimization of the trajectory over the whole period $[0, T]$ is a difficult task. Thanks to the dynamic programming method the task can be divided into two or more sub-tasks

$$S(X_0) = \min_U \left(\sum_{i=0}^n J_i \right)$$

$$= \min_U \left(\int_0^{\tau_1} F(X,U)\,\mathrm{d}t + \sum_{i=1}^{n-1} \int_{\tau_i}^{\tau_{i+1}} F(X,U)\,\mathrm{d}t + \int_{\tau_n}^T F(X,U)\,\mathrm{d}t \right). \tag{4}$$

According to Bellman's optimality principle, if $U^*(t)$ provides a minimum for the entire functional J, then it
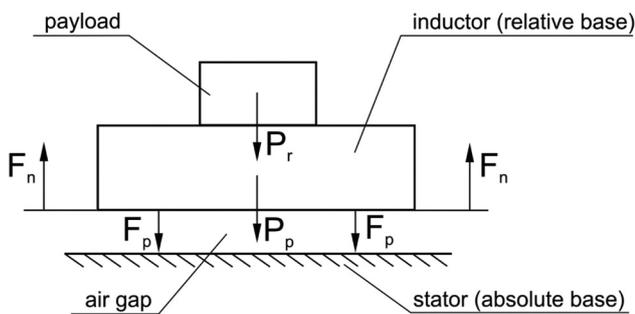
Figure 3. Forces of precise coordinate positioning system.

also provides a minimum for each single functional J_i. Thus each segment of the trajectory is optimal and can be considered as an independent trajectory.

Let us consider a simplified method of the required control optimality condition for a stationary task with closed ends, i.e. if X_0 and X_T are fixed.

Assuming that τ is of sufficiently small value, for time τ, X has an increment ΔX, f describes the system dynamics, F is the running cost and S is a value function that is explicitly dependent only on X

$$S(X_0) = \min_U \left(\int_0^\tau F(X,U)\mathrm{d}t + \int_\tau^T F(X,U)\mathrm{d}t \right)$$

$$= \min_U \left(\int_0^\tau F(X,U)\mathrm{d}t + S(X(\tau)) \right), \tag{5}$$

$$\int_0^\tau F(X,U)\mathrm{d}t \approx F(X_0,U_0)\tau, \tag{6}$$

$$S(X(\tau)) = S(X_0 + \Delta X) \approx S(X_0) + \frac{\partial S}{\partial X}\Delta X, \tag{7}$$

$$\Delta X = f(X_0, U_0)\tau, \tag{8}$$

which gives, after substitution:

$$S(X_0) = \min_U \left(F(X_0,U_0)\tau + S(X_0) + \frac{\partial S}{\partial X} f(X_0,U_0)\tau \right). \tag{9}$$

Because the function S does not depend explicitly on the U controls for which the minimization (eq. (9)) is carried out

$$S(X_0) = S(X_0) + \min_U \left(F(X_0,U_0)\tau + \frac{\partial S}{\partial X} f(X_0,U_0)\tau \right). \tag{10}$$

According to Bellman's principle of optimality, the initial values can be replaced with current values, so after substitution and simplification, eq. (10) takes the form

$$\min_U \left(F(X,U) + \frac{\partial S}{\partial X} f(X,U) \right) = 0. \tag{11}$$

Finally, the Bellman functional equation can be presented as

$$\frac{\partial F(X,U)}{\partial U} + \frac{\partial S}{\partial X} \frac{\partial f(X,U)}{\partial U} = 0. \tag{12}$$

Function S is unknown, but it was assumed that it is explicitly dependent only on X and its form must ensure the stability of the considered system. If the quality criterion is a quadratic function, then function S can be sought in the form

$$S(X) = \frac{1}{2} X^T K X, \tag{13}$$

where K is the matrix of coefficients.

In the process of solving the problem, direct substitution of function $S(X)$ is applied and because coefficients K are unknown, they are calculated along with controls U.

Results

System components

The mechatronic rehabilitation device supporting active and passive exercises for persons with motor dysfunctions of the upper limb is presented in Figure 4. The mechatronic rehabilitation device consists of the following elements: precise coordinate-plane positioning system (1); motion control card (2); computer with rehabilitation software (3); and handgrip (4) mounted on the relative base.

The extreme 3D pro-gaming joystick from Logitech company was adopted as the handgrip. The shape of the controller (its contour), as designed by the manufacturer, is ergonomic. This translates to optimal adaptation of the device to the human hand. The grip is stable. A broader base provides support for the exercised arm during long exercises.

In its basic configuration, the system enables the performance of movements in the horizontal plane with adjustment of their proper trajectories, at set values of speed and acceleration. In the expanded configuration, thanks to the possibility of placing a planar positioner on top of a rehabilitation table that would provide the capability for changing the positioner's angle of inclination relative to the exercising person, the limb's working movement can also be performed in the sagittal (vertical) plane, which may be important in certain forms of rehabilitation.

Based on detailed guidelines of a physiotherapist, original algorithms were prepared, based on which training

Figure 4. Mechatronic rehabilitation device supporting active and passive exercises for persons with motor dysfunctions of the upper limb.

computer programs dedicated for specific upper limb exercises, performed in successive phases of rehabilitation, were developed.

The optimized motion trajectories of the planar positioner were used to create computer training programs. Control of the support, according to the desired trajectory, is realized according to the training program installed on the computer. An appropriately prepared training program enables execution of successive stages of training, while maintaining a constant hardware configuration.

Upper limb therapy using the mechatronic rehabilitation device

Enabling a patient to perform an arm movement during upper limb therapy requires elimination of load (in passive exercises), and in the case of active exercises requires controlled reduction of load on the musculoskeletal system. Movements without load required during therapy would be impossible due to the pain felt in joints or due to weakness in the muscle. The load reduction effect is achieved by means of load-bearing sliding surfaces of the support of planar coordinate positioner. The patient's arm is moved by the support over a specific trajectory according to the training control program. Owing to load reduction, motion is fluid and can be performed with required precision, which translates to effectiveness of therapy. The next step of therapy can be exercised without load reduction, and then, depending on the progress and patient's capabilities, exercises with appropriately selected resistance are selected.

The position of support during exercises without load reduction and exercises with resistance is determined by means of a Hall effect sensor installed on the support. Exercises without load reduction are based on movement of the support according to the trajectory displayed on the monitor. The patient sees the trajectory over which his or her arm is to move, as well as the actual trajectory, on the screen. In the case of exercises with resistance, the patient must also move virtual objects – obstacles. When a given virtual objects is moved, force is generated on the support, i.e. touch input device, and the patient must overcome this force. Moreover, depending on the level of involvement in therapy, the patient is stimulated by sound. This feedback information motivates the patient to perform intensive exercises as per recommendations.

Analysis of literature in physiotherapy[17–20] made it possible to elaborate stages of rehabilitating upper limb dysfunctions with elements of computer assistance using the mechatronic rehabilitation system presented in Figure 5.

Discussion and directions for further research

The original mechatronic rehabilitation system for upper limb exercises described in this article is currently a
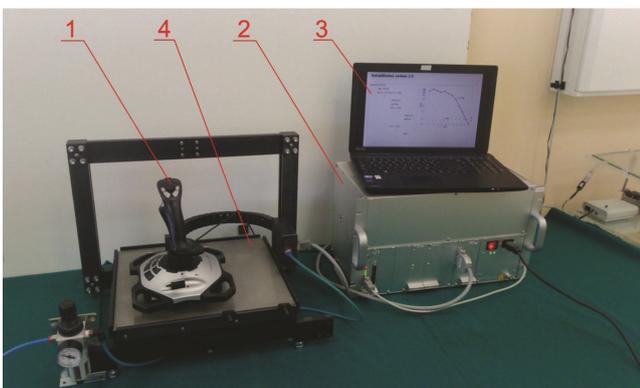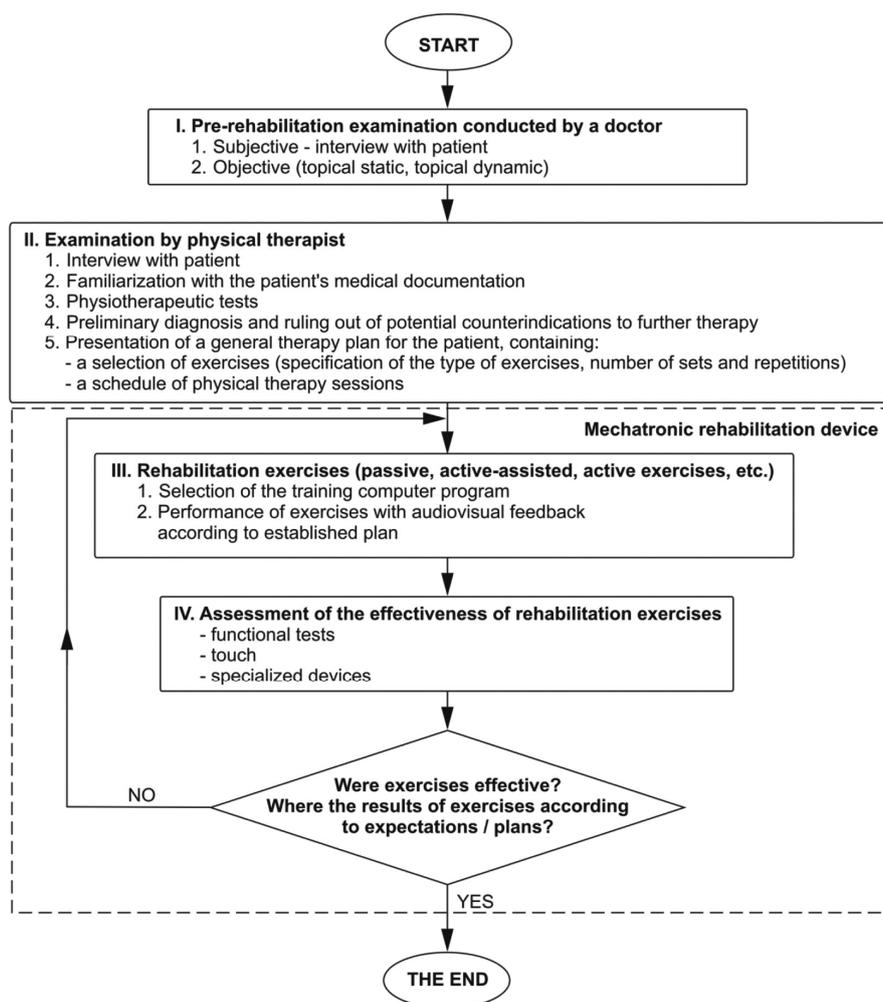
Figure 5. Stages of upper limb dysfunction rehabilitation.

prototype. A base (stator) with a greater surface will be used in the target device, due to which, its workspace will increase.

The presented solution can be successfully used in topical kinesiotherapy of the upper limb. Passive exercises are performed without the patient's active involvement by the support (inductor) of the planar coordinate positioner on which the exercised limb is found. By movement without contact over the base, the support enables safe restoration of the function of rehabilitated upper limb, gradually increasing its range of motion. While exercising, the patient gradually determines his or her pain thresholds and adjusts ranges of motion to his or her capabilities, which reduces anxiety and discomfort during the performance of exercises. The device can also be used successfully in successive phases of rehabilitation based on active exercises.

The developed system will be expanded with an additional device with force feedback, which will allow for personalization of motion performance by the physical therapist using the adopted motion controller (joystick).

By performing, for example, resistance exercises together with the patient, due to the sensation of physical resistance to the limb movement performed by him/her on his/her own motion controller (due to force feedback) and verbal communication, he/she can select the intensity and type of exercises as needed.

The solution presented will make it possible to control specific exercises or the entire patient rehabilitation process remotely or on-site. To conduct active rehabilitation remotely, so-called tele-manipulation for purposes of telemedicine, it is required to provide an appropriately fast internet link and additional audio-visual transmission in real-time. Thus, the proposed design has additional potential for development.

Conclusion

Rehabilitation is realized based on the developed computer training programs,compiled into a library to which additional training programs will be added successively.

The development of mechatronic rehabilitation system for upper limb exercises required interdisciplinary cooperation of engineers, computer scientists, orthopaedists, physical therapists, and medical rehabilitation specialists.

The next stage of work will be the implementation phase – clinical trials on specific groups of patients with dysfunctions of the upper limb as well as marketing activities. Clinical trials will aim at verifying the effectiveness and safety of the developed device.

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