Manipulative robot for knee rehabilitation of patients with Ilizarov apparatus mounted on the thigh

Artykuł recenzowany

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Abstract

We present a new manipulative robotic system with 1 degree of freedom designed for increasing of the knee rehabilitation efficiency in case of patients with the femur distraction osteogenesis with use of Ilizarov apparatus. Based on the conducted analysis of the knee's anatomy, biomechanical functionality of knee-joint and characteristics of considered medical treatment, overall assumptions concerning robotic assistance in knee rehabilitation process are formulated. Then we propose a simplified kinematic structure based on one rotational fixed axis taking into account-guidelines resulting from specificity of complications following a femur distraction osteogenesis with use of Ilizarov apparatus. The paper presents description of mechanical and measurement system for a considered manipulative robot. The issues regarding patient's safety while realization of robotic rehabilitation are also discussed. Additionally, motion control and force control design issues are considered and some preliminary experimental results are presented.

INTRODUCTION

The main aim of the presented research concerning design of robotic manipulator for rehabilitation is evaluation of a prototype compact portable knee rehabilitation manipulator. The research concerns a specific kind of the knee rehabilitation process – the rehabilitation of the patients who undergo a distraction osteogenesis of a femur with use of Ilizarov apparatus. Distraction osteogenesis of lower limbs is a surgical process aiming to lengthen the long bones and reconstruct deformities. The procedure is necessary due to abnormal bone growth or post injury complications, causing e.g. length discrepancy, short stature, angular defects. The Ilizarov apparatus is commonly exploited as an external fixator, allowing the consolidation of the fractured bone to be accomplished properly. One of the most common problems associated with lengthening process of the thigh using the Ilizarov method is reduced mobility of the knee [1, 2, 3]. Another known problem appearing after the femoral lengthening procedure concerns the extension contracture of the knee (knee stiffness) resulting from knee joint motion limitation. Then the mobility of the knee can be reduced even to 50 deg. A next complication is an occurrence of posterior subluxation of the knee, which is manifested as a displacement of one or two lower leg bones – the tibia and the fibula. Those complications can be partially avoided through almost immediate start of the rehabilitation process after performing of the surgery operation. Naturally it will increase a cost of the whole healing process, especially because this kind of rehabilitation requires whole time assistance of specialized physiotherapist. Hence, the aspect of contribution to the rehabilitation process and improvement of its effectiveness through usage of robots is so attractive area of research. The robot can be considered here as individual physiotherapists, and its performance can outbalance the properties of traditional rehabilitation by means of repeatability, intensity, security, reaction time to abnormal situations and prevention of possible complications.

The paper is organised as follows. First we discuss realized preliminary research, which in turn allowed to provide a specification for rehabilitation manipulator design. Then we present the details concerning the design of rehabilitation robot's mechanical construction, its hardware control system and a proposition of control algorithm which takes to account the dynamic model of a robot and the specification of considered medical treatment. At the end preliminary experiments are shown.

PRELIMINARY RESEARCH

In this section we will only recall some conclusions resulting from realised research surveys and for the details the reader is referred to appropriate literature. The main preliminary research was done with the participation of 16 years old patients with Ilizarov apparatus mounted on the thigh. At first, isometric and isotonic tests were carried out. Next, the kinematics of the knee was assessed on the basis of X-ray images.

Performed isometric and isotonic studies [3] were carried out with use of Biodex system [4]. According to this research, it was stated that the equipment used for dynamic knee joint properties analysis is not well suited for a patient with Ilizarov apparatus mounted on the thigh. The seat of used rehabilitation system does not allow to assure an appropriate position of the patient while seating. Through modification of rehabilitation chair seat, the Biodex system permitted to define a strength deficit of the injured leg in comparison with another healthy patients' legs. These results permitted to define torque, angular position, velocity and acceleration needs for design of prototyped rehabilitation manipulative robot.

Another subject concerned in the research constituting a prelude for our rehabilitation robot design dealt with the determination of the ICR (instantaneous center of rotation) of knee joint [3, 5]. It was realized with use of series of X-ray images of the knee while it was bending. Also a partially automatic algorithm evaluating a knee joint kinematics was presented [5]. Performed research shew, that in the range of knee deflection from straight position marked as 0 deg, to the deflection of 45 deg, the ICR positon can be properly approximated by fixed point. This result was a crucial issue in prescribing of the proposed rehabilitation manipulator mechanical structure.

DESIGN OF REHABILITATION MANIPULATOR

Performed preliminary research, review of the literature which describes structures of rehabilitation manipulators [6, 7, 8, 9] and evaluation of consultations with orthopedists and physiotherapists, facilitated to define following assumptions for design of a rehabilitation manipulator:

a) it must have a rotational joint allowing to move the shin while the patient is sitting,

b) in case of the manipulator with a variable position of a rotational joint axis a rigid mounting to the leg should be provided: a precise and rigid fixation to the Ilizarov apparatus and the patient's shin,

c) in case of the manipulator with a fixed rotational axis it should have some elasticity in fixation of a leg; this elasticity can be ensured in a point of a Ilizarov apparatus montage or in a point of shin fixation,

d) the system must be equipped with a suitable sensing system that provides control of joint movement with the ability to measure forces and torques acting between a patient and the robot,

e) manipulator must have a possibility of exerting a force which protects the patient from the back knee dislocation,

f) manipulator must be equipped with actuators with flexibility and it should guarantee a continuous movement of a limb in a passive and repetitive manner,

g) mechanical structure of the device should be optimized for using it for rehabilitation of children patients.

The fundamental requirements for a proper knee rehabilitation presented above became a starting point for consideration of a possibility of using a specialized manipulative robot to support the rehabilitation process. Referring to those assumptions, we selected the most critical ones which should be satisfied first. That allowed to simplify the mechanical structure of a rehabilitation manipulator and it also allowed to loosen some of the restrictions for a control algorithm. In the proposed design of rehabilitation manipulator we decided to fulfil the assumptions described in points a), c), d), and g). The most important guideline for design of considered rehabilitation robot concerned the assumption about usage of the fixed rotational axis, what means that it is one degree of freedom robot with rotational joint. As it is pointed out in [3] with use of that kinematic structure it is not possible to project the position changes of rotational axis, as observed in normal knees, but for limited range of motion, e.g. 0-45 deg (which is the maximum range of the knee after distraction therapy) this kind of structural simplification is sufficient for considered rehabilitation process. On the basis of research and consultations conducted with doctors of medicine and physiotherapists it is assumed that the rehabilitation manipulator should be able to change knee angle from 0 deg to approximately 30 deg and to exert a continuous torque up to M_{max} = 55 Nm, with feasible angular velocity up to ω_{max} = 1 rad/s.

Further we describe the main elements of the rehabilitation manipulator design: the driving unit, the fastening of the shine and Ilizarov apparatus, the rehabilitation stand and the hardware control system. Finally we present the structure of adopted control algorithm.

DRIVING UNIT

The proposed construction of the manipulator driving element (Fig. 1) is a rotational joint with fixed axis. The drive is equipped with a flat BLDC motor M serially connected with a torsional spring k, further with a harmonic gear HG which will ensure backlash-free motion (Fig. 1b). The spring gives possibility to measure a torque transmitted from the engine to the gear through measuring of its deflection. A set of incremental encoders are used to measure angles ϕ_1, ϕ_2, ϕ_3. The spring k is serially connected with a mechanical clutch – a torque limit unit TL responsible for limitation of the torque transferred to patient's shin. This is an element which increases work safety and constitutes additional protection in case of torque software controller failure. Additionally, because of the safety reasons, the driving unit is equipped with physical limit switches which limits acceptable configuration angles.

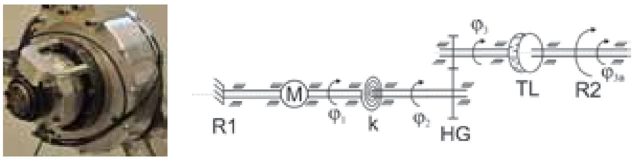
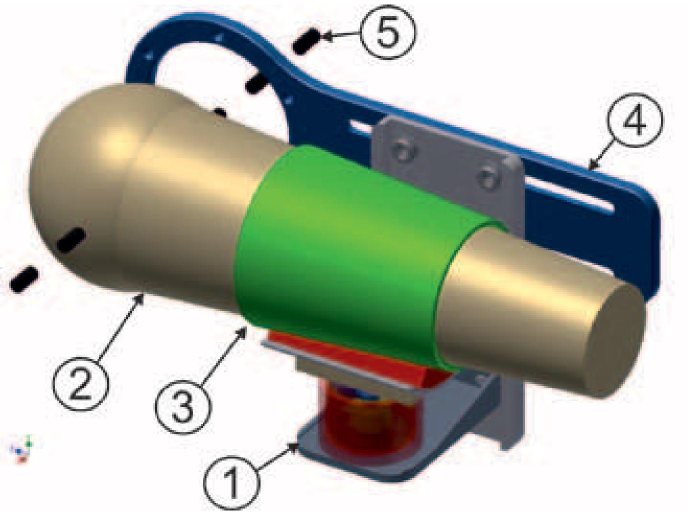


Figure 1. Driving unit: a) picture of manipulator's driving unit; b) schematic diagram of driving unit mechanical elements: R1 – basis of manipulator, M – motor engine, k – torsional spring, HG – harmonic gear, TL – torque limit unit, R2 – torque output, ϕ_1, ϕ_2, ϕ_3 configuration variables.

FASTENING OF SHINE AND ILIZAROV APPARATUS

In order to measure a torque exerted by a manipulator's arm on the patient's shin, we designed the grip handle for a patient's shin with integrated strain gauge force sensor (Fig. 2). This torque measurement unit is used in control feedback loop, and allows to provide a software torque limitation for safety purposes. Mounting of the patient's shine to a fastening unit (element 1 in Fig. 2a) is realized through elastic bends which allow to adapt fixation of the leg to the manipulator arm. Additionally, the position of the fastening unit can be changed along the manipulator's arm (element 2 in Fig. 2a).

Fig. 3 presents the Ilizarov apparatus with elements ensuring it rigid fixation with the manipulator. The patient with the Ilizarov apparatus (mounted to patient's thigh) has to sit on the rehabilitation chair and his or her maneuvers are restricted with use of the safety belts. The adaptive fixing system mounted on the Ilizarov apparatus (elements 2 and 3 in Fig. 3a) allows to adjust position of the Ilizarov apparatus relatively to position of the manipulator. Proposed Ilizarov rings fixing system also allows easy connection and disconnection of those elements.



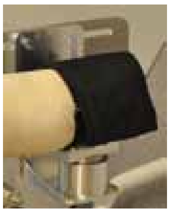


Figure 2. Shine fastening unit: a) CAD model: 1 – shine fastening with force measurement unit, 2 – shine model, 3 – fixing band, 4 – manipulator's arm, 5 – manipulator's rotational axis; b) picture of shine fastening unit with lower limb medical model.

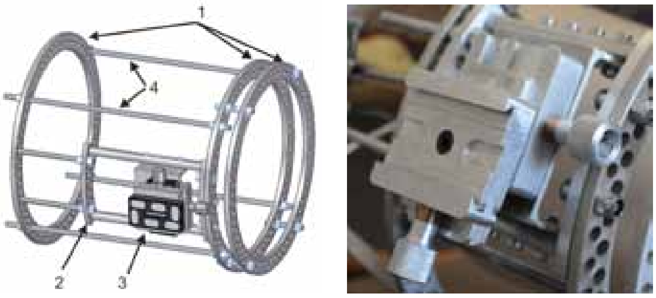


Figure 3. Ilizarov apparatus with fixing system: a) CAD model: 1 – Ilizarov rings, 2 – adaptive guides of fixing system, 3 –coupling unit of fixing system, 4 – Ilizarov ring's rods; b) picture of coupling unit of the fixing system.

Rehabilitation stand

The proposition of the manipulator is presented in Fig. 4. It is shown with the tripod which allows to adjust a position and orientation of the manipulator to a location of a patient. The tripod constitutes the support basis for the manipulator.

Figure 4. Rehabilitation stand consisting of rehabilitation manipulator stand, rehabilitation manipulator with mounted lower limb medical model with Ilizarov apparatus; a) lateral view, b) front view.

Through susceptible bands the arm of the manipulator is affixed to the shin of the lower limb medical model which imitates a real human lower limb. The elastic bands have necessary degrees of freedom to avoid a drive torque transfer in undesirable directions. The lower limb medical model has the Ilizarov rings set mounted on the thigh. It should be emphasized that the lower limb model is equipped with the models of lower limb bones and it imitates behaviour of the human lower limb with very high precision.

Hardware control system

The main parts of the hardware controller of the manipulator (presented in Fig. 5) are: a commercial programmable power end for a BLDC motor, the peripheries expander, the energy management unit and a DSP (digital signal processor) controller. The peripheries expander ensures electrical and logical compatibility of used modules. The energy management unit provides electrical power to all used systems and also provides electrical safety in the rehabilitation stand. The DSP controller is a unit mainly responsible for realization of mathematical calculations needed by a control algorithm and it acts as a low-level embedded system. The control signal for a DSP unit is provided by a PC unit with use of the software application designed specially for a rehabilitant or an end user of the system.

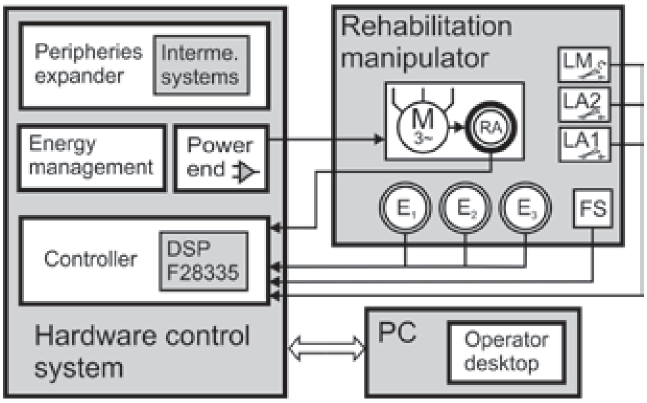


Figure 5. Schematic diagram of hardware control system.

Control algorithm

The fundamental part of the control algorithm designed for the manipulator is a motion controller. It is used to establish tracking of a reference trajectory with an acceptable precision for the given rehabilitation task. Although this problem can be seen as a well-known classic task in robotics, its particular solution can be relatively challenging. This is due to a quite complicated dynamics of the manipulator joint consisting of elastic elements and hard nonlinear friction phenomena. Moreover, during the rehabilitation treatment significant time-varying external forces are generated by a patient's leg. Motivated by these issues we propose an adaptive-like control approach taking advantage of disturbance observers. Basically, these observers are used to estimate resultant additive disturbances based on assumed reference dynamics defined on input side of the transmission spring and output side of the gear.

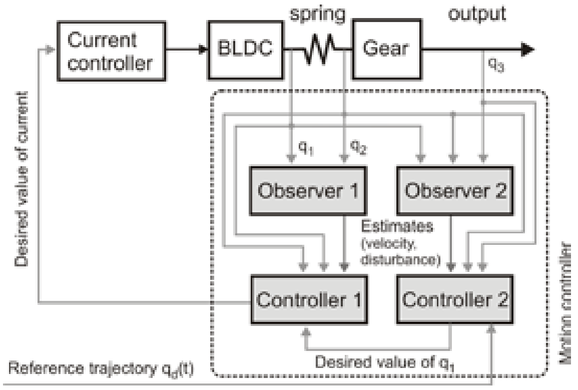


Figure 6. Basic structure of the motion controller.

To cope with compliant elements, the controller is based on backstepping design which improves stability of the closed loop system and allows one to formulate clear tuning rules. The estimated disturbance terms are added to control inputs which give possibility to partially remove their negative effects on the controller performance [10]. As a result, robustness of the control solution to some class of disturbances is increased which can lead to better tracking accuracy.

The cascade structure of the controller responsible for motion control is presented in Fig. 6. Basically, two control loops can be distinguished. The first one is used to control the motor while the second one is designed for motion control of the manipulator link. These two control sub-tasks are realized by controller 1 and 2 supported with use of two extended state observers. It is assumed that every coordinate variable is measured directly. Hence, it is possible to quantify dynamics properties of the spring and the gear which is used for compensation of unmodelled dynamics and other input disturbances.

In order to improve time response of the closed loop system during transient states, it is assumed that initial tracking error should be limited. This is an important issue necessary to guarantee a safe motion during the rehabilitation treatment. This problem is solved through an auxiliary trajectory initially coinciding with current configuration of the joint. This trajectory is calculated as a solution of a linear differential equation and gradually tends to the original reference trajectory. This idea is illustrated in Fig. 7.

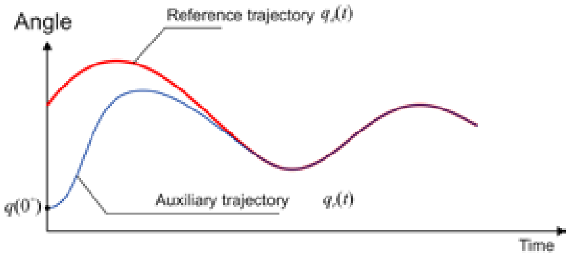


Figure 7. Generation of auxiliary trajectory for the motion controller.

Another control problem met in rehabilitation exercise is strictly related to force/torque control. Since the mechanical structure of the manipulator and position of a force sensor are known, the force exerted by the manipulator or the leg can be relatively easily transformed to the torque value which is typically used in the rehabilitation of the knee. In the considered manipulator the force control algorithm is realized indirectly taking advantage of the motion controller – cf. Fig. 8. It is assumed that the force controller generates a position reference trajectory based on the desired and the current value of force measured by a sensor. In the simple case, calculation of this trajectory can be made using PI controller. Taking into account that during the rehabilitation exercises a feasible range of force is required, one can introduce a dead zone rule to quantify required lower and upper force limits.

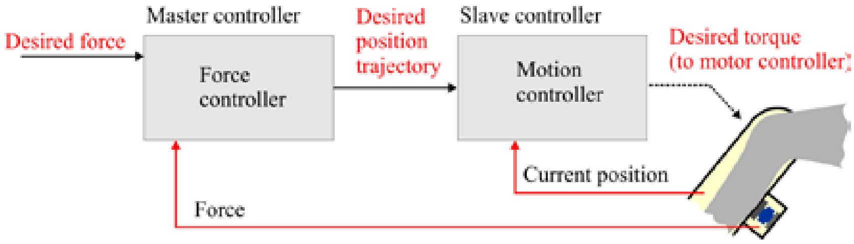


Figure 8. Basic structure of the force controller.

It is worth noticing that pure force control in the rehabilitation treatment is not used extensively. In some cases the direction of the force and the velocity is crucial. Hence, one can consider more complicated control schemes referring to feasible conditions combing force, position and velocities. However, the designed control structure of the manipulator is open and it seems to be well prepared for realization of more advanced rehabilitation tasks.

EXPERIMENTS

To make a preliminary verification of the controller performance, basic laboratory tests were conducted. To simulate an external disturbance, supposedly generated by a leg, the manipulator link was connected with a human arm. The external torque M_R was calculated based on the current value of force F_R exerted by the human arm at a constant point of the manipulator's arm.

First experiment evaluates tracking accuracy properties of a known reference trajectory $q_d(t)$ in the presence of the external disturbances. The purpose of this verification is to check the closed-loop control system stability and its ability to maintain the tracking error in some bounds in spite of various disturbances. The desired angular trajectory of the manipulator joint is selected as a sinusoidal time-varying function. In Fig. 9 time plots of tracking error and external torque are presented for the chosen experimental test. It can be observed that impact of a slow-time varying load torque M_R is well attenuated – cf. Fig. 9a. The tracking error increases considerably at 10 s when the direction of the joint rotation changes. This is a result of the internal spring dynamics combined with the static friction which cannot be compensated instantaneously. Comparing the result with loaded and unloaded manipulator one can conclude that a gradually increase of the external load does not deteriorate the tracking precision. However, when dynamics of the external disturbances becomes significant, it may lead to worse tracking performance. It is illustrated in Fig. 9b – one can observe oscillatory response of the control system to a rapid external disturbance. This property can be quite easily understood taking into account the presence of internal spring with low stiffness and limited bandwidth of the controller. In spite of this limitation, it seems that accuracy of tracking is satisfactory for the rehabilitation purpose.

Second experiment was conducted to quantify the performance of the torque controller. In the same way as in previous case, the manipulator link was connected with a human arm. Fig. 10 presents the results of the experiment for which the feasible range of force is assumed between -50 and +50 N. It can be concluded that the manipulator link changes its orientation when the force value exceeds the desired range. Consequently, the force is stabilized within the assumed bound quite accurately.

SUMMARY

This paper presents a prototype of the manipulative robot for the knee rehabilitation purposes for patients with the Ilizarov apparatus. The require-

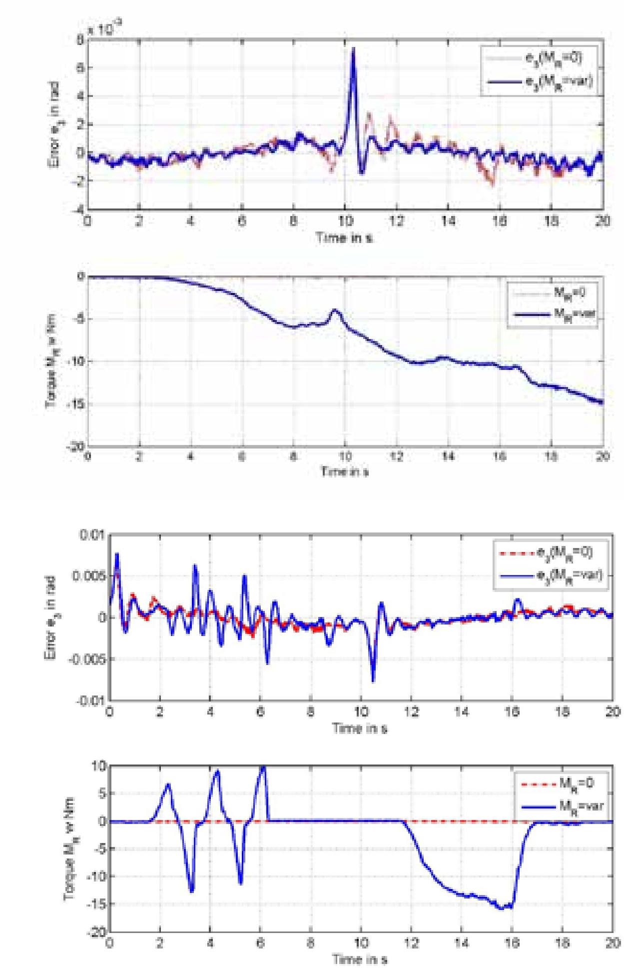


Figure 9. Results of trajectory tracking (blue lines – non zero load torque, red dots – no external load):a) slow time-varying external disturbance, b) fasttime-varying external disturbance.

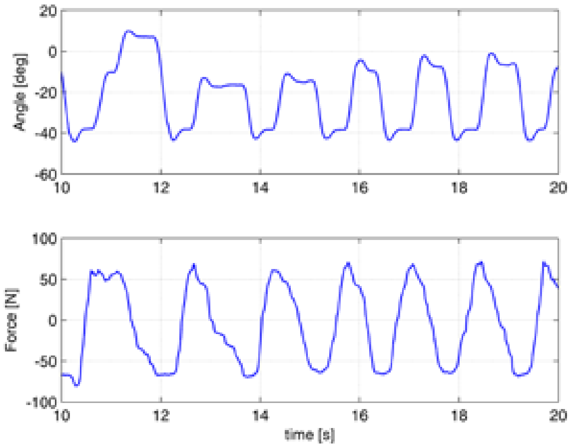


Fig. 10. Results of force control for F_d = 50 N.

ments for a rehabilitation manipulator devoted to the specific rehabilitation task were formulated. Further, a construction of the new rehabilitation manipulator prototype is described. An adapted control algorithm for the motion control and force/torque control is considered as well and its performance was examined in laboratory conditions. Experimental tests were made with use of medical lower limb model with Ilizarov apparatus mounted on it. The experimental results shew that designed rehabilitation manipulator assures a proper performance during the considered rehabilitation exercises what allows to believe that in the future this manipulator can be successfully used for treatment of the considered target patients.

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