Assistive Control of Motion Therapy Devices based on Pneumatic Soft-Actuators with Rotary Elastic Chambers

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Abstract—**Robot assisted motion therapy attains increasingly importance and acceptance especially in neurorehabilitation after stroke or spinal injury, but also in orthopedic rehabilitation and surgical interventions. Several studies have shown that a patient-cooperative (assistive) motion therapy, which activates remaining muscle strength and so optimizes recovery, will cause a much higher effectiveness compared to commonly used continuous passive motion (CPM) machines with pre-programmed trajectories (motion profiles). This article describes an assistive control concept developed for orthopedic rehabilitation based on inherent compliant (soft) actuators. Control concept takes into acccount specific properties of physiotherapists behavior during treatment. The patient will be supported and at the same time encouraged to generate own muscular strength to perform desired movement. Concept has been implemented for two prototypes of motion therapy devices (MTD) for knee and shoulder motion therapy. The first prototype (Knee-MTD) has been extensively tested with healthy persons and now is being tested in the Clinic for Orthopaedics and Trauma Surgery of Klinikum Stuttgart to prove concept in real-life conditions.**

Assistive control; motion therapy; orthopedics; rehabilitation robotics; soft pneumatic actuator.

I. INTRODUCTION

Recent studies confirm the effectiveness of robot assisted therapy in neurorehabilitation after stroke or surgical intervention [1], [2]. Already the poor position controlled gait-machines (like GaitTrainer GT1 and LokoHelp) or passive exoskeletons for upper extremities (like WREX and Armor) allow neurological patients to intensify repetitive task specific training and to improve motor functions. It is assumed that patient-cooperative (assistive) control strategies, taking into account the own patient's effort, can maximize the therapeutic outcome, reduce the treatment period and in the end decrease the medical costs. Furthermore it is assumed, that this should be valid in orthopedic rehabilitation too, where mainly the position controlled CPM-machines are now in use.

The realization of assistive (patient-cooperative) behavior premises compliancy or back-drivability of robot mechanism, allowing deviations from desired trajectory. In assistive MTD based on conventional electrical drives [3]–[6], the required compliancy has been achieved using precise (and mostly expensive) force/torque sensors as well as different variations of impedance control concepts to regularize interaction force and position simultaneously [7]. Demonstrating well performance, such MTD are mostly voluminous and really expensive.

An alternative approach offers the robotic system Pneu-WREX [8], which is based on pneumatic cylinders. Instead of force/torque sensors, pressure and acceleration sensors are used. The prototype has been developed to allow assistive activities of daily living (ADL) training in neurorehabilitation. Control law relies on a neuronal network combined with an error based adaptive law to estimate model of human-robot. Thereby the systematically reduction of supporting guidance of robot, when position errors are small, has been described as AaN (Assist-as-Needed) force decay. Thus, patients get the opportunity to generate own muscular strength in case of small position errors.

Soft actuators like linear pneumatic muscles possess inherent compliancy and therefore, they are well suitable to achieve the interactive behavior between patient and MTD even using simple open-loop control concepts [9], [10]. This kind of actuators allows light-weight construction of MTD, however the realization of revolute joints requires more or less complex transmissions.

The novel soft fluidic actuators with Rotary Elastic Chambers (REC-actuators) enable compact modular design of motion therapy devices, interacting with patients [11], [12].

This article describes the concept and realization of assistive control for motion therapy devices with pneumatic REC-actuators. In case of orthopedics in comparison to neurology, patients are able to set motion more precisely and therefore the developed assistive control concept allows patients to move into therapeutic requested direction without generating of counteraction. However they are supported by therapy device at any position to compensate gravity. Currently a first prototype for assistive knee MTD has been developed and was successfully tested with healthy persons. Experimental results show the effectiveness of the assistive controller. Prototype is being tested in the Clinic for Orthopaedics and

Trauma Surgery of Klinikum Stuttgart to prove concept in real-life conditions. Furthermore the same control low is implemented for a 2 DOF shoulder MTD.

II. PNEUMATIC ROTARY SOFT-ACTUATORS

To realize compliant robots, one approach is to use well-known pneumatic artificial muscles (PAM) [13], which are naturally compliant in general, instead of using conventional rigid electromechanical drives with complex and expensive force/torque feedback solution. This inherent compliancy is one of the main advantages and yields to much more safety in human robot interaction applications. But due to a relative small contraction ratios (about 25% - 30%) and one-axis linear motion realization of bidirectional revolute joints is quite complex and often results in non-compact and voluminous devices.

Pneumatic soft REC-actuators, which generate a rotary motion directly, have been developed to permit modular design of robotic devices [14], [15]. The new generation of REC-actuators with buckled elastic chambers, the bREC-actuator (Fig. 1a), has chambers consisting of buckled fire flat hose. Compared to the formerly used pleated elastic chambers (pREC), special produced from polyurethane film, the main advantages are slim design as well as reduction of costs [11]. The basic construction of bREC-actuator consists of two parts, one fixed and one moving part, connected in the middle through rotary axis. By pressure variations the buckled working chambers expand crosswise and direct rotary movements have been achieved. The working range is about 110° with maximum torque of about 40 Nm at a standard pressure of 6 bar. Note that experimental determined torque characteristic, shown in Fig. 1b, is a non-linear function of working pressure and angle. The effectively usage of slim designed bREC-actuators allows realization of very compact light-weight MTD with soft and gentle interaction between humans, which will be demonstrated in next sections.

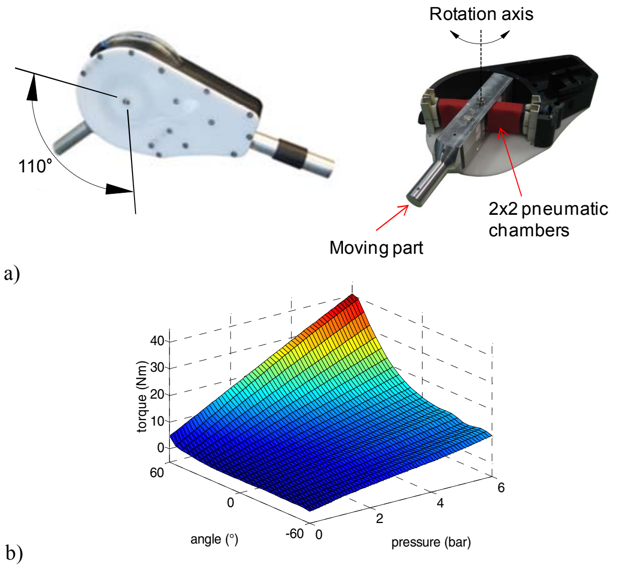

Figure 1. Last generation of soft REC-actuator, a) working principle, b) torque characteristic

III. SOFT MOTION THERAPY DEVICES

Current state of the art of orthopedic MTD in rehabilitation facilities are continuous passive motion (CPM) machines, which are used for more than thirty years, because time for medical treatment by physiotherapists is limited and expensive. To develop assistive and soft motion therapy devices, key idea was replacement of electromechanical drives by pneumatic soft actuators to achieve inherent compliancy [12].

The design of knee motion therapy prototype (Fig. 2a) is based on exoskeleton-like mechanics of a common CPM-machine. Equipped with two parallel working slim bREC-actuators in knee joints and additional bRECs in hip joint, the prototype provides a strong but soft behavior. Design of shoulder MTD is also based on common CPM devices. Combinations of abduction/adduction and anteversion/retroversion movement patterns allow circular movements of human shoulder. First prototype is presented in Fig. 2b.

To ensure silent operation, low noise servo valves (FESTO MPYE-5-1/8LF-010-B) are used and integrated in the housing. Due to basically back-drivability of bREC-actuators interaction between patient and therapy device can be estimated using position and pressure sensors only. To ensure safety, a number of redundant sensors for pressure and position control have been integrated. Thus, no expensive force/torque sensors are needed to measure interaction. A touch-screen interface with intuitive handling (Fig. 2c) assures a simplified usage for therapists as well as for patients. A visual on-screen feedback shows human machine interaction and shall motivate patients to maximize their effort which should optimize the healing process. Furthermore, new technologies demand high attention to safety requirements, especially for interaction between humans and machines in rehabilitation applications. Developed safety concept is merged with control algorithms to provide sufficient safety and catch any possible system errors as well as sudden emergency situations. Due to this various safety features, which are integrated in addition to principally softness of actuators, a safe and gentle treatment is assured.

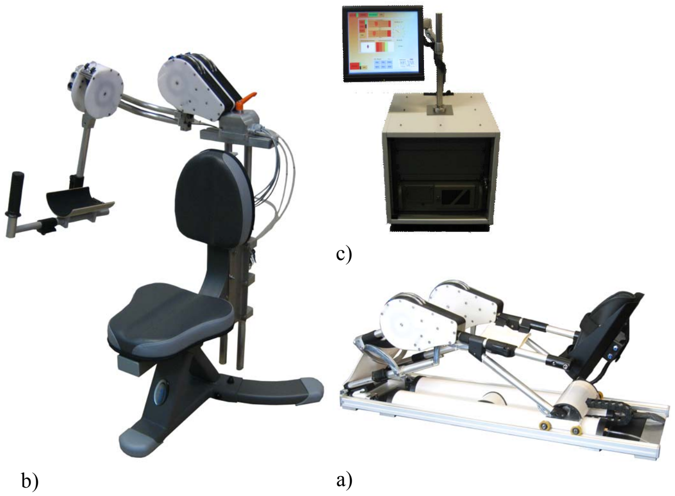

Figure 2. Prototypes for motion therapy for a) knee and b) shoulder, c) control unit

IV. ASSISTIVE CONTROL CONCEPT

To provide a basis for specific control concepts of assistive MTD, definition of requested behavior is essential. The intention was to imitate treatment techniques which are used by physiotherapists and therefore the approach was to concentrate on the specific properties and behaviors of therapists. In general, therapists ensure discharge of extremity weight, guidance of motion and assistance relative to muscular strength of patients. Developed assistive control concept is based on these requirements and illustrated as block diagram in Fig. 3. Because control concept is developted for orthodedic rehabilitation, concept provides the opportunity for patients to move into requested direction of motion without generation of counteraction, in each position supported by therapy device. Thus, patient's get the opportunity to generate own muscular strength to perform desired movements, which shall activate remaining muscle energy.

The presented assistive joint-based control concept is basically applieable for multi-DOF robots. It has been implemented for fully functional 1-DOF knee MTD and will be realized for 2-DOF shoulder MTD afterwards. This section describes control concept in general. The innermost loop of cascade structured control concept is a pressure control loop. To allow dynamic and precise pressure control using servo valves and REC-actuators, a model-based non-linear pressure controller based on the feedback linearization approach has been developed [16]. The $n \times 1$ desired pressure vector $\mathbf{p}_{des}$ consists of n desired pressures values p_{des_i} provided for each joint, calculated by inverted model of torque characteristic, which has been determined in experimental manner.

$$p_{des_i} = f^{-1}\left(\tau_{des_i}, q_i, \Delta p_i\right) \tag{1}$$

Note that pressure is a non-linear function of desired actuator torque τ_{des_i} and angle q_i of joint i. Actuator torque is calculated as difference of torque developed by lower $\tau_{Li}\left(q_i, p_{Li}\right)$ and upper $\tau_{Ui}\left(q_i, p_{Ui}\right)$ chamber of actuator.

$$\tau_i = \tau_{Li}\left(q_i, p_{Li}\right) - \tau_{Ui}\left(q_i, p_{Ui}\right) \tag{2}$$

Torque and stiffness is independently controllable; stiffness can be defined by changing the basic pressure Δp_i of actuator chambers. The desired torque $\boldsymbol{\tau}_{des}$ provided by MTD during treatment is a $n \times 1$ vector in joint space, depends on patient's behavior and is defined as combination of gravity torque $\boldsymbol{\tau}_{grav}$, a patient specific optimization torque $\boldsymbol{\tau}_{opt}$ and an assistive torque $\boldsymbol{\tau}_{ass}$, which are defined as $n \times 1$ vectors, whereby n describes the number of DOF.

$$\boldsymbol{\tau}_{des} = \boldsymbol{\tau}_{grav} + \boldsymbol{\tau}_{opt} + \boldsymbol{\tau}_{ass} \tag{3}$$

To ensure discharge of mechanics weight and extremity weight, gravity compensation can be used. Currently widely used are passive solutions like elastic bands or springs, whereby one example is the famous neurologic rehabilitation device Armeo®Spring provided by Hocoma.

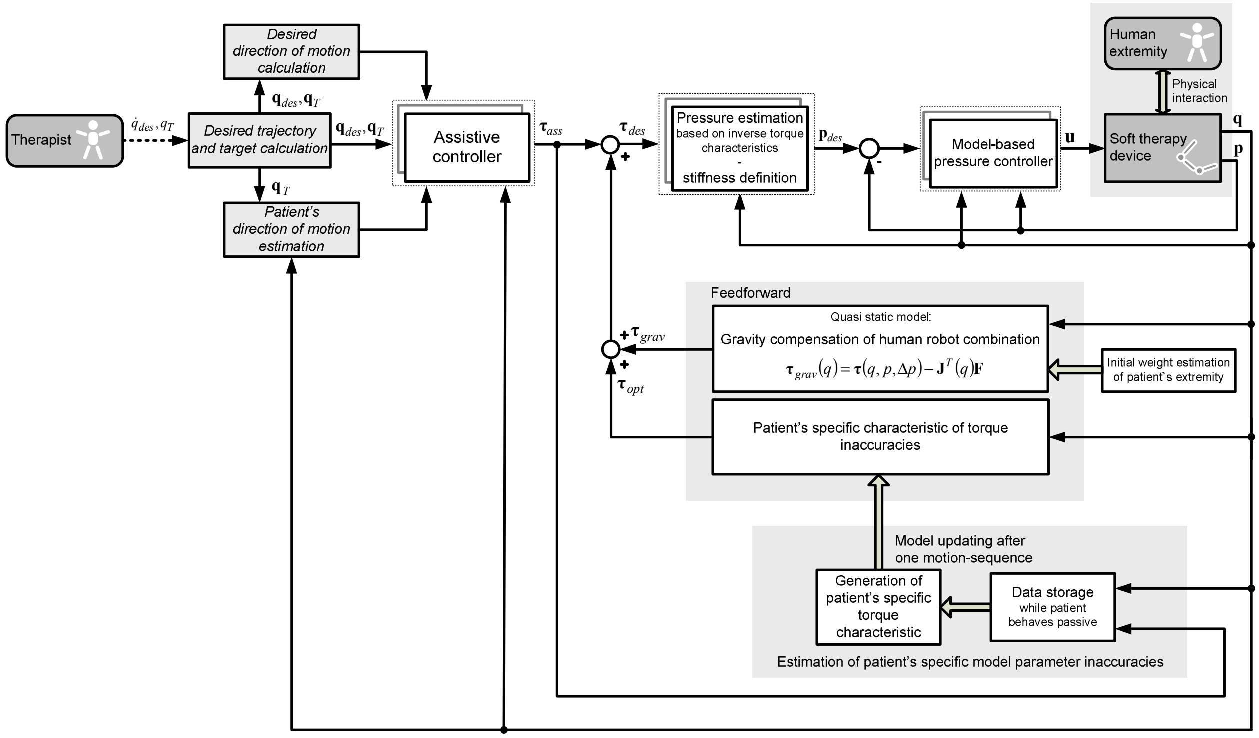

Figure 3. Assistive control concept with pressure controller and gravity compensation in inner loop and assistive controller in outer loop

Due to low stiffness and weight of bREC-actuators and because of low velocity and acceleration during motion therapy an active model-based gravity compensation of human robot combination has been developed. Whereby the quasi static model of human robot combination is defined as:

$$\boldsymbol{\tau}_{grav}(\mathbf{q}) = \boldsymbol{\tau}(\mathbf{q}, \mathbf{p}, \Delta\mathbf{p}) - \mathbf{J}^T(\mathbf{q})\mathbf{F} \tag{4}$$

The Jacobian matrix $\mathbf{J}^T(q)$ is used to convert forces $\mathbf{F}$ which are acting on the end-effector to the actuator torques.

The vector $\boldsymbol{\tau}$ is a non-linear function of pressure and position, which is described as experimental determined characteristic of actuator torque. To calculate necessary gravity torque, knowledge of mass and mass distribution of each link and patient's extremity is needed.

Because of complex mass distribution, body link parts of MTD and patient's extremity are summarized to segments, actuator masses are included. To estimate individually weight of patient's extremity two different successive methods are used. Initial estimation of extremity weight is realized by measuring pressure variations using customized air pad sensor at starting position of therapy device [17], whereby clinical studies have determined mass distribution of human extremities [18]. Thus, combination of mass distribution of MTD and patient's extremities can be calculated. Computation of gravity torque is defined as:

$$\boldsymbol{\tau}_{grav}(q) = -\sum_{j=1}^{n}\left(m_{lj}\mathbf{g}_0^T \mathbf{j}_{P_i}^{l_j}(q) \right) \tag{5}$$

The term m_{l_j} describes the mass weight of respective segment, $\mathbf{g}_0^T$ is the transposed vector of gravity acceleration and $\mathbf{j}_{P_i}^{l_j}(q)$ is part of corresponding well-known geometrical Jacobian [19], used to describe mass distribution. Nevertheless, during motion inaccuracies can occur due to unknown influence of patients. Initial estimation of patient's extremity weight provides the possibility to calculate the quasi static model of human robot combination. But because every patient has different mass distribution this can only be done with unknown model parameter inaccuracies. Hence, the calculated model is only used as basis model. To optimize model parameters, an optimization method has been developed and implemented, that automatically adjusts individual parameter inaccuracies and adapts model parameters online during treatment for every specific patient. Calculated optimization torque $\boldsymbol{\tau}_{opt}$ is defined as non-linear patient's specific function of respective angle and desired toque if patient behaves passive $\boldsymbol{\tau}_{despas}$ minus gravity torque $\boldsymbol{\tau}_{grav}$ of human robot combination, which are defined as $n \times 1$ vectors.

$$\boldsymbol{\tau}_{opt} = f\left(\mathbf{q}, \boldsymbol{\tau}_{despass} - \boldsymbol{\tau}_{grav}\right) \tag{6}$$

To ensure guidance of motion and assistance relative to muscular strength of patients an assistive controller is realized in outer loop of control concept which calculates assistive torque as follows:

$$\tau_{ass\,i} = \begin{cases} k_{pi}\left(\Delta q_i - \Delta q_{des\,i}\right) - k_{di}\dot{q} & q_{Ti} > q_i \\ 0 & q_{Ti} = q_i \\ -k_{pi}\left(\Delta q_i - \Delta q_{des\,i}\right) + k_{di}\dot{q} & q_{Ti} < q_i \end{cases} \tag{7}$$

Control law is based on corresponding desired trajectories, actual distances to targets plus desired and estimated direction of patient's motion. One kind of such controller was suggested in [20] and is based the "shrinking sphere" algorithm. The desired assistive torque $\boldsymbol{\tau}_{ass}$ is a vector of desired assistive torques $\tau_{ass\,i}$ for each joint. Thereby q_i is actual displacement of actuators and q_{Ti} is the current target position. The term k_{pi} is a proportional factor and $k_{di}\dot{q}$ is a damping factor to reduce high oscillations. The term $\Delta q_{des\,i}$ is the distance between the desired trajectory and the target position and Δq_i is the distance between the current position and the target, used to calculate desired and actual direction of patient's motion.

$$\Delta q_i = \left\| q_{T\,i} - q_i \right\|, \quad \Delta q_{des\,i} = \left\| q_{T\,i} - q_{des\,i} \right\| \tag{8}$$

Assistive controller should only generate torque if patient is not able to accomplish requested movement or moves into opposite direction. If patient's movement into requested direction is sufficient, no counteraction should be generated and therefore the assistive torque has to be reduced to zero. Hence, patient's get the opportunity to move actively on their own, using very small amount of muscle strength. Therapy device provides support in each position due to still acting gravity and optimization torque. Because of basically back-drivability of soft actuators, interaction between human and therapy device can be estimated without using expensive torque/force sensors. Therefore (9) allows the requested reduction of assistive toque:

$$\Delta q_{des\,i}(t) = \begin{cases} \Delta q_{des\,i}(t-T) & \Delta q_{des\,i}(t-T) < \Delta q_i(t-T) \\ \Delta q_i(t-T) & \Delta q_{des\,i}(t-T) \geq \Delta q_i(t-T) \end{cases} \tag{9}$$

Whereby, the term T is the discrete sample time. If patient behaves passive or is not able to accomplish requested movements, controller generates needed assistive torque to guide patient towards the targets.

$$\Delta q_{des\,i}(t) = \Delta q_{des\,i}(t-T) \Rightarrow \left\| \Delta q_i - \Delta q_{des\,i} \right\| > 0 \tag{10}$$

$$\left\| \tau_{ass\,i} \right\| > 0 \Rightarrow \tau_{des\,i} = \tau_{grav_i} + \tau_{opt_i} + \tau_{ass\,i} \tag{11}$$

As soon as patient generates own muscular strength the assistive torque will be reduced to zero and only further acting torque of gravity compensation will support patient and ensure discharge of extremity weight.

$$\Delta q_{des_i}(t) = \Delta q_i(t-T) \Rightarrow \left\|\Delta q_i - \Delta q_{des_i}\right\| = 0 \qquad (12)$$

$$\left\|\tau_{ass_i}\right\| \to 0 \Rightarrow \tau_{des_i} = \tau_{grav_i} + \tau_{opt_i} \qquad (13)$$

To specify desired position, velocity and acceleration at the beginning and the end of trajectory a fifth order polynomial is used as desired trajectory to ensure zero velocity and acceleration at the target points. Thus, a smooth motion of therapy device is assured.

$$q_{des_i}(t) = q_{S_i} + \left(g_{T_i} - q_{S_i}\right)\left(10\left(\frac{t}{d}\right)^3 - 15\left(\frac{t}{d}\right)^4 + 6\left(\frac{t}{d}\right)^5\right) \qquad (14)$$

Desired new start q_{S_i} and target points q_{T_i} are defined when patient reaches current target. Because patients are able to influence time to reach target and to ensure uniform motion in case of 2 DOF shoulder MTD, current position of each joint has to reach the current target point before setting new start and target points.

V. EXPERIMENTAL RESULTS

To verify effectiveness of assistive controller a healthy person has imitated a patient with sufficient and insufficient muscular strength. Tests have been performed using the knee MTD. Fig. 4 shows the current displacement of actuator, calculated assistive and total torque, i.e. sum of assistive torque and torque of gravitation compensation. Furthermore the current pressure of the actuator chambers for extension and flexion is depicted. The supply pressure has been limited to 6 bar. While subject behaves passive in the first segment the smooth motion towards targets is shown. Assistive controller generates needed assistive torque to guide subject, whereby optimization torque and gravity torque compensate weight of therapy device and subject's lower leg. In case of sufficient cooperation, shown in the second segment, the desired assistive torque is reduced to zero and the subject moves actively with a small amount of muscle strength towards the targets, while being supported of further acting torque of gravity compensation. Target overshoots and movements against the target direction (segment three) lead to smooth increasing of torque with consequence that the subject moves into requested direction. Table 1 gives a summary of healthy subjects which have been tested the knee MTD with body sizes between 1.66 m and 1.90 m and body weights between 55 kg and 97 kg, to represent a wide range of possible patients. Currently the device is being tested in the Clinic for Orthopaedics and Trauma Surgery of Klinikum Stuttgart to prove concept in real-life conditions (Fig. 5). Simultaneously implementation of assistive control concept for shoulder MTD is in process and final results will follow.

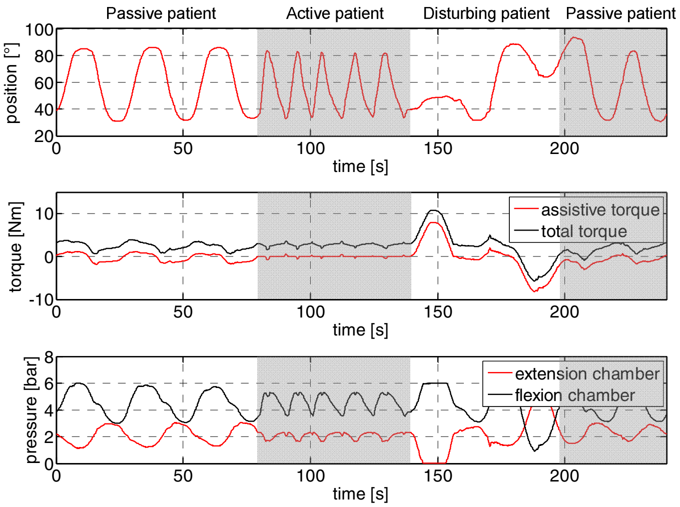

Figure 4. Different patient behavior using the assistive control concept

TABLE I. SUBJECTS HAVE TESTED KNEE MTD

subject	body size [m]	weight [kg]	leg [m]	age [year]	gender
1	1.66	63	0.84	47	w
2	1.68	85	0.90	60	m
3	1.70	55	0.90	24	w
4	1.72	72	0.96	55	m
5	1.73	82	0.78	29	m
6	1.79	74	0.96	27	m
7	1.80	80	0.94	29	m
8	1.80	62	1.08	36	w
9	1.83	78	1.02	28	m
10	1.89	83	1.15	45	m
11	1.90	97	1.05	36	m

Figure 5. Running clinical tests of Soft-Knee MTD in the Clinic for Orthopaedics and Trauma Surgery of Klinikum Stuttgart

VI. CONCLUSION

This paper describes an assistive control concept for novel MTD based on soft pneumatic actuators with rotary elastic chambers. Utilizing the inherent compliancy of actuators, interaction control is realized without using of expensive force/torque sensors. Assistive controller provides supported impact only in case of insufficient muscular strength to guide patient towards the targets. In case of sufficient strength and movement in therapeutic requested direction the assistive torque will be reduced to zero and patient is only supported by still acting torque of gravity compensation. Thus, control concept allows motion in therapeutic requested direction without generating of counteraction, even in case of position errors, which is very important for orthopedic rehabilitation. Prototype of knee MTD is currently being tested in the Clinic for Orthopaedics and Trauma Surgery of Klinikum Stuttgart. Control concept has also been developed for shoulder MTD, implementation is in process. Next step will be verification of assistive control concept for shoulder motion therapy.

Current prototypes of soft-MTD have been designed based on common CPM-machines with exoskeleton-like mechanics, to realize and prove the requested assistive behavior using REC-actuators. For lower extremities, such solution provides satisfied range of motion in knee and hip, while for upper extremities the shoulder motion is kinematical restricted. Thus, current prototype of shoulder MTD will provide the base for the development of advanced shoulder MTD with full range of motion, which can be realized using free linkage (i.e. robot arm) solutions.

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