A proof-of-concept exoskeleton for robot-assisted rehabilitation of gait

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Abstract — **Robotic gait rehabilitation faces many challenges regarding ankle assistance, body weight support and physical human-robot interaction. This paper reports on the development of a gait rehabilitation exoskeleton prototype intended as a platform for the evaluation of design and control concepts in view of improved physical human-robot interaction. The performance of proxy-based sliding mode control as a "robot-in-charge" control strategy is evaluated both in simulation and in experiments on a test setup. Compared to PID control, test results indicate good tracking performance and in particular safe system behavior.**

Keywords — **Rehabilitation robotics, robot-assisted gait training, powered exoskeleton, compliant actuator, robot-in-charge control**

I. INTRODUCTION

Locomotion training is considered an effective approach to helping incomplete spinal cord injured subjects recover their walking capabilities [1],[2]. The automation of locomotion training by means of a powered exoskeleton potentially improves training efficacy and rehabilitation outcome [3],[4]. Physiological gait patterns can be produced and adapted with higher accuracy. Automatic monitoring of the patient's progress allows the development of more adequate training schemes. The robotic device relieves strain on therapists, thus enabling longer training sessions and allowing the same number of therapists to supervise more patients.

Several research groups are developing powered exoskeletons for the rehabilitation of gait. The Lokomat (Hocoma AG, Switzerland) is one of the few commercialized step rehabilitation systems and well reported in literature [4],[5]. The Biomechatronics Lab of the University of California has developed several robotic devices to study automated gait training of spinal cord injured patients [6]. With their LOPES project the Biomechanical Engineering Lab of the University of Twente focuses on task-specific gait training of post-stroke patients [7]. Powered leg exoskeletons are also being developed at for instance the University of Delaware [8], the University of Michigan [9]. Although the clinical results of automated treadmill training reported in literature are encouraging [10], existing gait rehabilitation devices do suffer from a few limitations and future research faces some important challenges. First of all, most devices do not actively support the ankle joint, which results in poorly constrained and unnatural motion of the foot. Consequently, certain causes of gait dysfunction like dropped foot or spastic foot extension cannot be adequately countered during therapy. Secondly, the use of a suspension system with a harness leads to an unnatural body weight distribution and hinders balance and postural reactions of the patient, required in functional walking. Additionally, due to their actuation system and control approach these robots often lack compliance, which is considered an important prerequisite for safe human-robot interaction [11]. There is a growing tendency towards patient-cooperative control strategies, where, instead of predefined movements being imposed, the patient's intentions and efforts are taken into account [6],[7],[12]. Still, in many cases, either compliant behavior is only built-in on the control level or only partially built-in on the hardware level.

We hypothesize that a device providing full body weight support, active ankle assistance and adaptable compliant behavior, that is both built-in in the actuation system and taken advantage of on the control level, has the potential to improve the quality of automated treadmill training. Our goal is to develop such a device and to meet the aforementioned challenges by means of a special type of actuator: the pleated pneumatic artificial muscle (PPAM) [13]. This actuator is inherently compliant and we believe it will provide the necessary soft touch for a better human-robot interaction. Additionally, the actuator's high pulling force enables the robot to carry the full weight of the patient, without resorting to an overhead suspension system.

Before starting the development of a complete gait rehabilitation robot however, it is sensible to reduce the scale and complexity of the problem in order to identify and address technical problems in an early stage. Therefore the first phase of the project involves the development of a unilateral leg exoskeleton with a PPAM powered knee joint.

This paper reports on the mechanical design of the prototype and a study of control performance. Section II describes the mechanical design of the prototype. In section III the control approach is introduced and control performance is discussed on the basis of experiments on a

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simplified test setup. The final section gives a brief overview of future work and conclusions.

II. MECHANICAL DESIGN

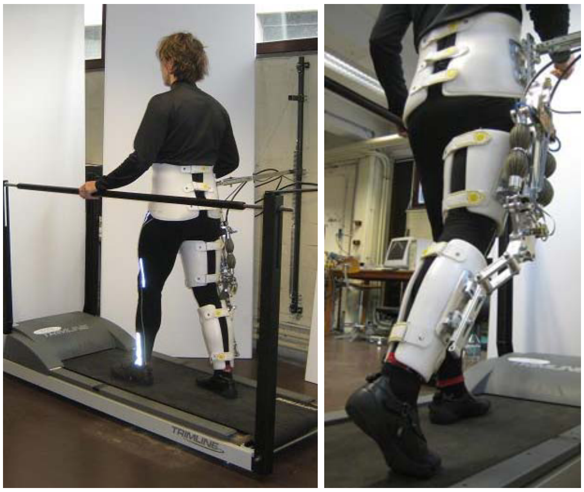

Fig. 1. Lab setup with treadmill, exoskeleton and supportive arm.

Figure 1 depicts the gait rehabilitation exoskeleton in a lab setup for walking experiments. The exoskeleton consists of adjustable hip, thigh, shank and foot links interconnected by hinge joints. Two-piece rigid thermoplastic shells with a foam inlay and Velcro straps provide an adaptable fit at the lower and upper leg and the hip. Their position and orientation with respect to the exoskeleton frame are adjustable by means of slider mechanisms. The knee joint is powered by two pleated pneumatic artificial muscles (PPAMs, [13]) in an antagonistic configuration[14]. An optimal configuration was chosen on the basis of CGA data that provides sufficient knee joint torque to support human gait [15]. The actuators are tethered to an external pressurized air supply system with high performance pressure regulating servo valves. Mechanical limiters prevent hyperextension and hyperflexion of the knee. A telescopic supportive arm is intended to passively gravity-balance the device to avoid asymmetrical loading of the subject.

III. CONTROL

A. System requirements

Since a medical rehabilitation device closely interacts with patients, we consider safety the most important prerequisite. Safety aspects are to be considered in all stages of design and safety measures should be incorporated on the software level (control) as well as the hardware level. Thanks to the intrinsic compliance of the actuation system deviations from the target position are allowed and passively counteracted without complex feedback control mechanisms. Obviously this affects tracking performance, however our goal is to achieve functional walking without putting too much emphasis on the accuracy of the gait pattern. We envisage different control strategies: a trajectory tracking approach (“robot-in-charge”) with compliance adaptation for patients with poor motor control and a force amplification approach (“patient-in-charge”) for specific gait support of patients with sufficient voluntary locomotor capability. Intermediate or hybrid control strategies might be appropriate for patients who do not fit in either end of the spectrum. The exoskeleton prototype will serve as a test setup for the implementation of these control strategies on a single actuated joint. For the sake of simplicity, the trajectory tracking approach is investigated first. In this context we propose proxy-based sliding mode control [16]. The following section briefly explains the general idea behind proxy-based sliding mode control applied to the gait rehabilitation exoskeleton.

B. Proxy-based sliding mode control

In proxy-based sliding mode control (PSMC) a *proxy* or virtual object is simulated, that is connected to the robot’s end-effector by a PID-type virtual coupling. The proxy’s position is controlled by an ideal sliding mode controller in order to track the reference position. In [17] a modified form of PSMC is suggested, so that each robot link is controlled separately instead of solely the end-effector. Now, let us consider a simplified representation in the sagittal plane of a human leg in swing phase attached to the exoskeleton as depicted in Fig. 2. Assuming an ideal, rigid connection, we model the combined system as a 3 degree of freedom (DOF) serial linkage consisting of a hip link fixed to the reference frame and a thigh, shank and foot link. To simplify the model further we lock the ankle joint, which leaves us with a 2 DOF system. Returning to PSMC and applying the control method to the powered knee joint, we distinguish the actual position q_2 of the lower leg link, the target position q_{2d} and the position of the proxy q_{2p}, in this case a virtual lower leg link (Fig. 2). The virtual link is attached to the real link by means of a torsional PID-type virtual coupling exerting a torque τ_c. This is also the real torque applied by the actuators to the real link. On the other hand a virtual torque τ_a, the output of a sliding mode controller, is applied to the virtual link in order to track the target link. The response characteristics of the PSMC controller are largely determined by the PID gains for small positional errors, ensuring tracking performance, and in case of large deviations by the sliding mode controller part, ensuring a smooth recovering motion. In fact, PSMC can be seen as an extension to both conventional PID control and sliding-mode control.

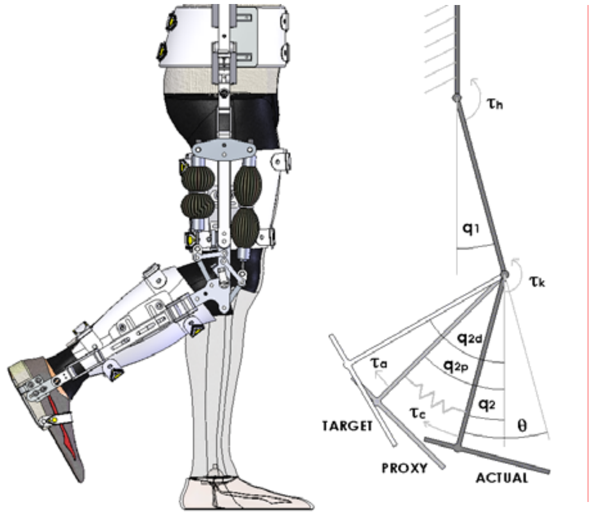

Fig. 2. Serial linkage model (right) of the system (left) consisting of the gait rehabilitation exoskeleton and a human leg in swing phase.

C. Experiments

Fig. 3. Simplified 1 DOF test setup for control evaluation

Before proceeding with the experimental validation of PSMC we have assessed control performance in a simulation study of the 2 DOF system, described in III.B. Next we have tested PSMC on a simplified test setup with one single (actuated) degree-of-freedom (Fig.3). The inertial parameters of the lower link match those of the exoskeleton's lower leg link combined with estimated body segment parameters. PID control with gravity and inertia compensation was used as a reference for evaluating system behavior. Both controllers were implemented on the setup and tuned on a trial-and-error basis.

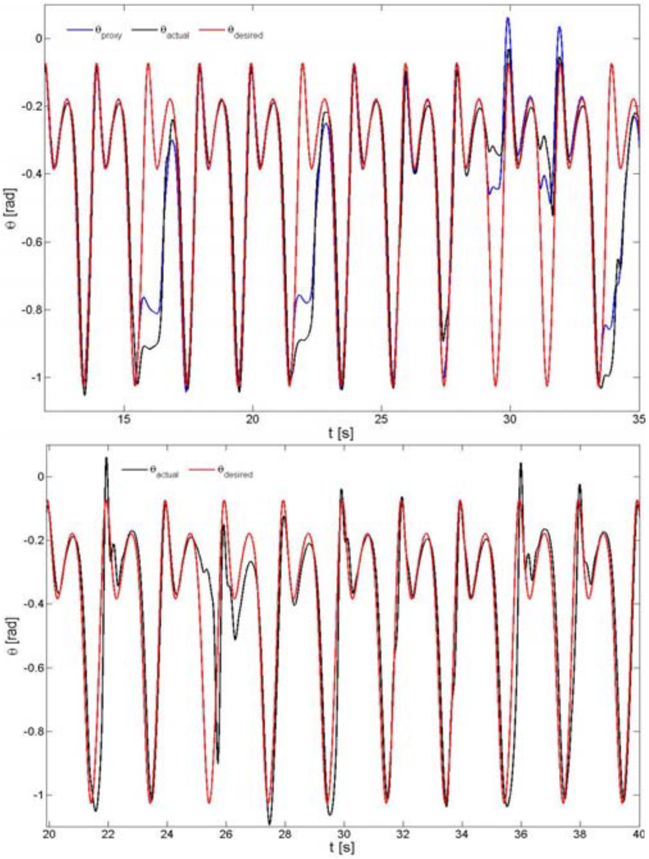

Fig. 4. PSMC (top) and PID (bottom) tracking experiment with manually imposed disturbances: desired, actual (and proxy) trajectories.

PSMC and PID showed comparable undisturbed tracking performance, but as expected very different system behavior in case of external disturbances. In Fig. 4 the desired and actual trajectories are depicted originating from PSMC and PID tracking experiments respectively, during which disturbing forces were being imposed manually. The corresponding moments of force imposed by the actuation system are shown in Fig. 5. In the absence of force sensor measurements, the latter have been estimated by means of muscle pressure measurements. In case of PID control external moments of force below the maximal moment of force output hardly cause any trajectory deviation, whereas large trajectory deviations provoke high moments of force and recovery motions with angular velocity values up to 2.5 times the maximal desired value. In view of robot-assisted rehabilitation of gait we consider such behavior not compatible at all with the occurrence of muscle spasms or voluntary muscle activity. In PSMC however the smooth, adjustable recovery motion and adjustable maximal restoring force considerably improve system safety. Thanks to the latter, the actuation system output hardly exceeds the moment of force imposed during undisturbed trajectory tracking, as can be seen from Fig. 5. These experimental results show the potential of PSMC as a safe "robot-in-charge" control strategy for the gait rehabilitation exoskeleton prototype.

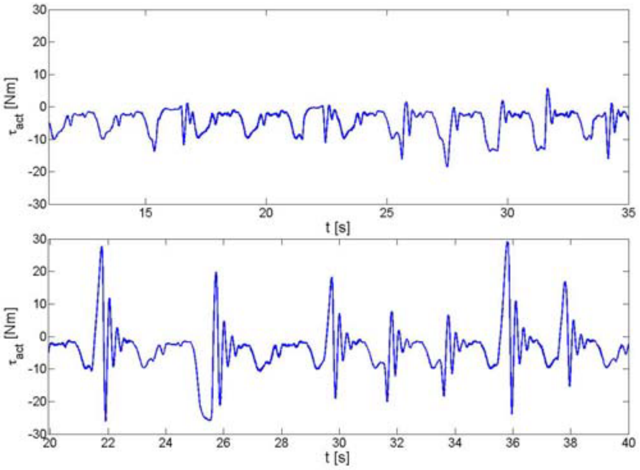

Fig. 5. PSMC (top) and PID (bottom) tracking experiment with manually imposed disturbances: estimated actuation system moments of force.

IV. Conclusion and future work

A gait rehabilitation exoskeleton prototype with a knee joint powered by pleated pneumatic artificial muscles has been developed for the assessment of design and control concepts. In view of the system's safety requirements and envisaged compliant behavior, we have focused on proxy-based sliding mode control as a trajectory tracking based approach to gait training in SCI patients with poor motor control. Control performance has been explored in experiments on a test setup, indicating good tracking performance and safe system behavior in comparison with PID control. Next, we will evaluate wearability and control performance of the exoskeleton prototype in treadmill walking experiments with healthy subjects.

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