Patient-Cooperative Control: Providing Safe Support without Restricting Movement

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Abstract— **Patient-cooperative behavior of a rehabilitation robot can be seen as a tight interplay of three control components: The first and most important is the intervention paradigm, which can for example be assistance, resistance, or error augmentation. The second and third are more related to the underlying properties of the robot: On the one hand the robot should be transparent in "free" movements, and on the other hand it should provide a safe training frame with appropriate virtual constraints for the movement. In this paper, control strategies to enhance transparency and to constrain movement with virtual tunnels are presented using the examples of the ARMin and the Lokomat, which are rehabilitation robots for upper and lower extremities, respectively. Differences and similarities in control of these robots are outlined in terms of the control strategies for transparency enhancement and movement constraints. The control concepts *Generalized Elasticities* and *Path Control* are described, which improve transparency in free movements inside an allowed spatial region, and which impose movement constraints to confine the user to this allowed region. *Generalized Elastic Path Control* unifies both control approaches within a single potential field, and preliminary results of this controller on the Lokomat are shown.**

Keywords— **Rehabilitation robotics, patient-cooperative control, transparency, motion constraints, potential fields**

I. INTRODUCTION

Recent multicenter controlled trials showed that subacute and chronic stroke patients still profit more from conventional manual therapy than from robotic gait training, at least when the robot imposes movements via position control along a fixed reference trajectory [1], [2]. New results on motor learning and neural plasticity can help explain this by the fact that position control does not allow the human to make errors, which is necessary for learning and the formation of an internal task representation [3], [4]. Furthermore, the robot induces motion and does not require active participation of the patient, which is a key element for recovery [5]–[8]. These results encourage patient-cooperative control of rehabilitation robots, which allows the human to make errors. Three components are needed to achieve such patient-cooperative behavior: First, undesired interaction forces between robot and human must be reduced to a minimum in order to give maximum freedom to the human, meaning that the robot must be *transparent*. Second, the robot must provide a safe training frame and prevent injury. Kinematic *constraints* are an important means for this. Third, the robot may assist or perturb the human in performing the motion, which corresponds to the desired *intervention*. While the first two features are universal requirements for most rehabilitation robots, the third depends on the specific paradigm to induce motor learning. There may of course be some overlap between the three aims. In the following, we will focus only on transparency and constraints.

When talking about transparency, this refers to apparent robot dynamics the user feels in "free space" motion, when the user moves the robot and should not feel it. Forces that need to be overcome when moving a robot are inertia, gravity, Coriolis and centrifugal forces, and friction. A lightweight construction and/or compliant actuation [9], [10] reduce these forces, but this reduction is limited, especially when the robot is supposed to stiffly guide severely affected patients. There are also control strategies available to reduce apparent robot dynamics. However, these strategies cannot fully compensate the robot, where the main problem is generally to hide inertia. The most prominent strategy to reduce inertia is force feedback, realized via admittance or impedance control concepts [11], [12]. However, due to stability limits, the user will always feel some residual apparent inertia [13].

Concerning the second demand, a safe training frame, control approaches are often based on the concept of *Virtual Fixtures* [14], where rigid constraints or walls are introduced that confine the motion to a certain (safe) domain. These constraints can also facilitate correct motion execution, comparable to a ruler that simplifies drawing a straight line. To define an allowed region, virtual tunnels around a prescribed reference motion pattern can be defined. Depending on the width of the tunnel, strategies aiming only at safety or also at assistance [15], [16] can be realized.

This paper gives an overview on current control research activities for the Lokomat lower extremity robot [17] and the ARMin upper extremity robot [18], with focus on transparency and virtual motion constraints. Both the ARMin and the Lokomat are exoskeleton-type robots, and they aim at assisting upper and lower extremity rehabilitation, respectively (Fig. 1). A comparative analysis of differences and similarities is presented from a control engineering point of view. A special focus is on the newly developed method of Generalized Elasticities [19] and its extension to Generalized Elastic Path Control [20], which can serve two purposes in a unified way: The controller improves robot transparency by hiding the robot's apparent inertia beyond the capabilities of closed-loop force control, and it can also be used to

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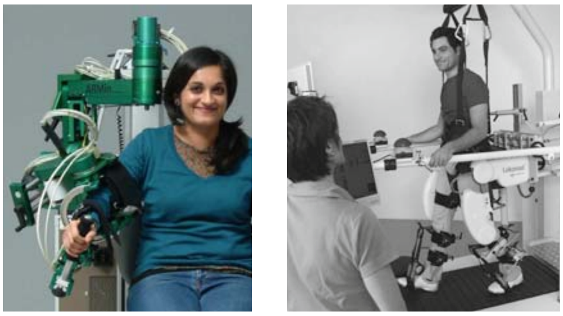

Fig. 1. ARMin and Lokomat upper and lower extremity exoskeletons (Lokomat photo courtesy of Hocoma AG, Switzerland).

enforce motion constraints. The method ensures passive robot behavior, which is a sufficient condition for stability in contact with any other passive environment. Preliminary results with the Lokomat are presented.

II. Transpareny Enhancement Using Generalized Elasticities

In arm rehabilitation robots like the ARMin, robot inertia is in general not a serious problem. The patient's reaching movements are rather slow, and gravitational forces are dominant. Therefore, the ARMin is not equipped with force sensors for closed-loop force control, and there is only a feed-forward gravity (and viscous friction) compensation.

In gait rehabilitation robots like the Lokomat, the case is different: Human gait is a very dynamic, even ballistic motion, such that the robot's inertia causes high undesired interaction forces acting on the human's legs. Therefore, mechanisms are necessary that compensate this inertia. Firstly, the Lokomat is equipped with force sensors between actuators and exoskeleton. Closed-loop force control can reduce at least inertial forces caused by the robot's DC motors with high transmission. There is residual actuator inertia, however, and also the dynamics of the exoskeleton legs remain uncompensated by this procedure. The common strategy in robot control would be to tolerate this remaining inertia and to compensate "at least" the other force components, especially gravity of the exoskeleton legs. However, we have shown that gravity compensation of the robot is not always an effective means to reduce interaction forces [19]. On the contrary, gravity compensation of leg exoskeletons during gait is even counterproductive, and it increases interaction forces. This can be explained by the natural dynamics of the robot, which resemble those of a pendulum during the swing phase: The leg swings easily with gravity helping to accelerate and decelerate the inert mass. Without gravity acting on the exoskeleton leg, accelerating and decelerating forces have to be induced by the human to overcome the exoskeleton's inertia, which severely increases interaction forces between human and robot.

Recently, we have proposed the concept of *Generalized Elasticities* as a generic tool to hide robot dynamics, including inertia, during dynamic movements in contact with a human. [19]. This strategy is inspired by the above observation that the Lokomat's natural dynamics cause less interaction forces than a gravity-compensated Lokomat, meaning that the earth's gravitational field partially compensates robot inertia during gait. Generalized Elasticities go one step further, they represent a potential field that *optimally* compensates robot dynamics during certain types of movement (such as walking). Using a robot model, a cost function that penalizes interaction forces, and a guess for the dynamic movement primitives (in the Lokomat case, a gait pattern), a parameterized potential field is optimized off-line. With the constraint of passivity, the resulting robot behavior is optimal in terms of interaction forces. Instead of compensating gravitational forces of the robot, the outcome of the optimization might even be the opposite strategy. Only as a special case for quasi-static movement, the resulting optimal potential field will once again simply cancel robot gravity.

As it is formulated as a potential, this field leads to passive behavior of the robot, which ensures stability in interaction with the human. Passive behavior means that the same behavior could theoretically be obtained by adding a multitude of mechanical elastic elements, and passivity ensures that the robot will be stable (in a control theoretic sense) when coupled to any other passive environment [13]. Generalized Elasticities can, thus, be imagined as multiple elastic bands spanning one or multiple joints. These elasticities store, release, and transfer energy between joints, such that minimum work needs to be transferred to the robot by the user to perform a given motion.

In the ideal case, the motion that the user performs becomes the "eigenmotion" of the robot, just like a pendular motion would be the eigenmotion of a pendulum. For gait training, this means that the robot requires only very low forces from the human to "oscillate" in a gait-like pattern. This oscillation is highly compliant, meaning that the force field is not intended to guide, support, or even force the human onto the expected trajectory. The robot only optimally compensates its own dynamics along this trajectory. Deviations from the eigenmotion of the robot (smaller or larger steps, different frequency, etc.) should not lead to a large increase in interaction forces, the compensation is only not optimal anymore. Furthermore, different gait patterns can be included during the optimization process, such that the resulting force field represents a very general compromise.

III. Motion Constraints

Both for the ARMin and for the Lokomat, virtual tunnels have been implemented to provide spatial constraints [15], [21]. The tunnels are implemented via a nearest-neighbor search. A predefined trajectory is stored, and the nearest neighbor to the current position on this trajectory is searched. Based on the distance from this nearest neighbor, the defined tunnel width, and the desired stiffness of the virtual walls, a corrective force is generated that pushes the human back towards the reference trajectory in the center of the tunnel. In case the human is capable of executing the movement correctly and stays inside the allowed region, no corrective force is applied.

For the Lokomat, this "Path Control" [15] can be used for two purposes: If the tunnel is wide, its purpose is limited to avoiding dangerous situations such as excessive knee flexion during stance (caused by deficient weight bearing capacity) or deficient knee flexion during swing (leading to the foot touching the treadmill and thus to stumbling). If the tunnel is narrow, assistance can also be provided to the human, comparable to rails that assure motion along the track. The reference trajectory is adapted from the recorded gait pattern of a healthy person. The trajectory is scaled based on the subject's anatomy, and based on the walking speed. The virtual walls are defined in a unified joint space for both legs, thus in four dimensions (hip and knee flexion/extension left and right leg).

For the ARMin device, the tunnel is mainly intended for assistance, and an additional collision detection prevents the robot arm from colliding with the human's body. The reference trajectory is calculated dynamically based on the next virtual task to achieve and the current position. The minimum angular jerk method to generate such trajectories has shown to be appropriate for reaching movements with ARMin [21]. The reference trajectory and the virtual tunnels are defined in the task space of the end-effector, and they can be visualized in 3D (Fig. 2).

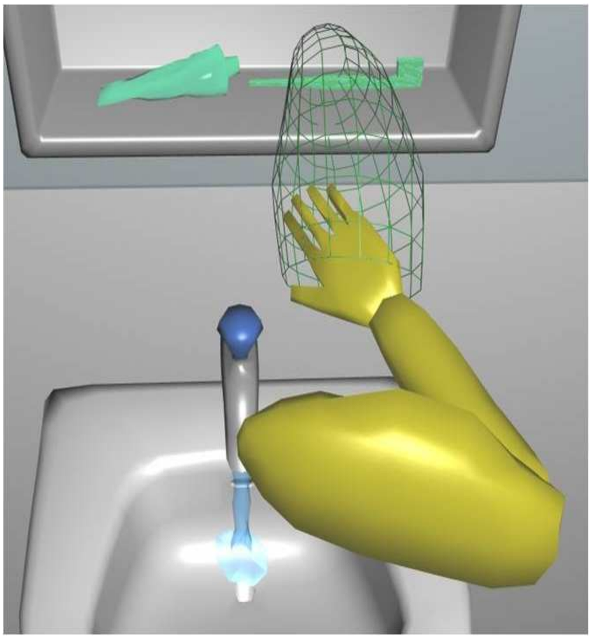

Fig. 2. Virtual tunnel to constrain motion for a reaching task with ARMin.

A main disadvantage of this implementation of Path Control is unproven stability, and cases can be constructed where the control may indeed get unstable. One example is varying tunnel width, with the aim to adapt the amount of freedom to the movement phase. Then, the behavior resulting from the nearest-neighbor-based attraction is not passive. Therefore, a modified approach is presented in the next section, which reformulates Path Control in terms of an intrinsically passive potential field.

IV. TRANSPARENCY AND CONSTRAINTS: GENERALIZED ELASTIC PATH CONTROL

The transparency-enhancing potential field represented by the Generalized Elasticities of Sec. II is optimized based on training data that lies *within* the allowed region. The path controller of Sec. III is only active *outside* the allowed region. Therefore, both strategies can easily be combined to one unified potential field, as a potential field can be used as well to encode virtual walls. To generate additional training data that can be added to the training data of Sec. II, the forces of a simulated nearest-neighbor search are assigned to the region outside the tunnel. The unified concept then still hides robot dynamics inside the allowed spatial region in an optimal way, letting the human move unhindered there, and it includes virtual tunnels to prevent the human from leaving this allowed region. The main advantage is that the potential field approximates the forces of the nearest-neighbor-based controller in an optimal way, preserving as much as possible of its behavior, but ensuring passivity. This combined strategy of Generalized Elasticities and Path Control is called "Generalized Elastic Path Control". Until now, it has only been implemented for the Lokomat.

V. PRELIMINARY RESULTS

In direct comparison with closed-loop force control with and without gravity compensation, Generalized Elasticities showed to be most effective in terms of transparency for healthy subjects walking in the Lokomat [19]. Experiments with Generalized Elastic Path Control [20] show that the described effect in transparency is maintained, and that the conservative force field also provides a safe training frame, because it prevents dangerous movements.

To illustrate the selective effect of Generalized Elastic Path Control, the results of one healthy subject are shown, who walked with Generalized Elastic Path Control in the Lokomat under two conditions: The subject walked once normally, and once simulating an isolated deficiency (in weight bearing during stance). A rather wide tunnel was used, only preventing dangerous situations.

When the subject walked normally, i.e. without weight bearing deficiencies, average interaction torques were low over the whole gait cycle (considering the high inertia of the robot) (Fig. 3). When the subject showed deficient weight bearing capacities, it can be seen that the interaction torques between robot and human at the knee joint are still low for all movement instances expect for stance. Then, the knee weakness leads to excessive knee flexion, which leaves the range of allowed movements within the tunnel, and supportive forces are generated to help the subject extend the knee.

VI. DISCUSSION

The results show that optimizing passive behavior of a rehabilitation robot can be effective to enhance transparency, and that the concept of Path Control provides a safe training frame that only generates forces when needed. Using these two fundamental components of patient-cooperative behavior

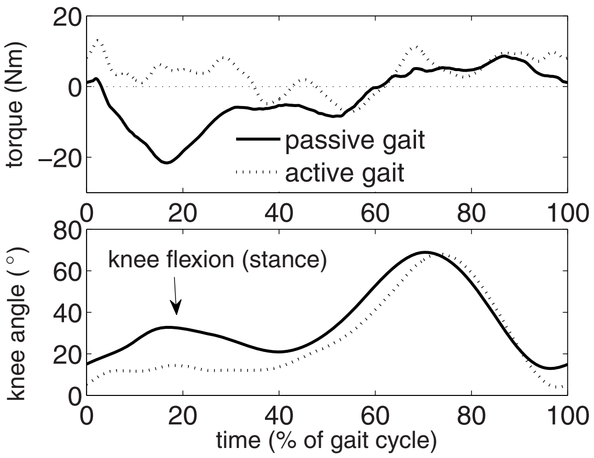

Fig. 3. Torque in response to an active gait style, and to gait with deficient weight bearing. The gait cycle begins at heel strike.

as a basis, the third control component, which encodes the individual intervention (such as assistive forces, error augmentation, etc.), can be superimposed.

VII. CONCLUSION AND OUTLOOK

In this paper, three fundamental components of patient-cooperative training have been distinguished: Transparency, constraints, and intervention. Focusing only on the first two issues, control concepts both for upper and lower extremity rehabilitation robots have been compared on the examples of the upper extremity exoskeleton ARMin and the lower extremity exoskeleton Lokomat. The control concept of Generalized Elasticities has been described, which hides robot dynamics when interacting with a human, as well as the Path Control concept, which confines the human to an allowed region. Furthermore, Generalized Elastic Path Control has been described, which unifies both transparency enhancement and movement constraints. The method is based on potential fields. Preliminary results with the Lokomat indicate that both transparent behavior and motion constraints can be realized effectively. This means that the robot provides a safe training environment while still leaving maximum freedom to the subject.

Future work will aim to incorporate Generalized Elasticities also in ARMin, in order to allow more generic and dynamic arm movements with improved transparency. A further focus will be on developing superimposed controllers for both robots that realize individually tailored interventions for each patient to maximize rehabilitation outcome.

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