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Haptic Constraints for Rehabilitation Robots: An Overview

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Abstract

Rehabilitation robots are versatile tools for assisting therapists in the rehabilitation of neurologically impaired patients. To enhance motor learning, current control strategies for rehabilitation robots aim at allowing patient-driven movements, i.e. movements which patients can initiate and execute on their own account. A widely used mechanism in these patient-cooperative control strategies are virtual haptic constraints, which guide the patients spatially without enforcing a specific timing. In this paper, we present an overview about the application of haptic constraints in rehabilitation robotics, illustrated by examples from the rehabilitation robots ARMin and Lokomat. Experience with haptic constraints shows that they enable patients to move faster and more successfully, thus they increase the number of possible patient-driven task repetitions per training session. Future research needs to investigate ways to progressively adapt haptic constraints to the patients' abilities in order to provide optimal learning conditions for the human nervous system.

1 Introduction

Rehabilitation robots have been developed to reduce the physical burden of rehabilitation training for physical and occupational therapists. Current evidence suggests that intensity-matched manual and robot-aided training is equally effective [1,2], while manual training imposes a higher work load on therapists than robot-aided training [3].
The first generation of rehabilitation robots alleviated the work of therapists notably, but at the same time these devices also allowed patients to remain passive during the training. However, basic research on motor learning has shown that movements during rehabilitation training should be patient-driven [4]. Therefore, a variety of control strategies which aim at allowing and challenging patients to actively participate in their training are currently being developed for rehabilitation robots [5].
Moreover, there is a trend toward non-actuated robot-like rehabilitation devices, which e.g. unload the weight of a disabled limb by passive spring mechanisms so that patients can practice movements in an environment with reduced gravity [6]. In contrast to actuated robotic systems, these devices are often more lightweight and less complex, which makes them well suited for more advanced patients and better affordable for rehabilitation centers.
However, robots still have many advantages when severely affected patients with poor remaining motor function and partially strong spasticity need to be trained. Their capability to produce arbitrary forces in any position of their work space gives them more flexibility than non-actuated systems can provide. A unique feature of robotic systems is the ability to render virtual haptic constraints, which – similar to a ruler simplifying drawing straight lines – allow patients to "correctly" initiate and execute movements regardless of limited motor control abilities.

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

In this article, we will provide an overview about the application of such haptic constraints in the field of rehabilitation robotics. Furthermore, we will illustrate the concept of haptic constraints and its application with examples implemented with the rehabilitation robots ARMin and Lokomat (Fig. 1).

2 Haptic Constraints

2.1 Original Application

Haptic constraints have originally been proposed by Rosenberg [7] as one realization of "virtual fixtures" intended to simplify and improve the operability of telemanipulators. When using a ruler to guide the movement of a pen, the degrees of freedom are coupled in a way that favors moving along a straight line. Other fixtures can be used to

simplify drawing curved lines. If the degrees of freedom of an input device for a telemanipulator are restricted to a task-specific haptic template, performing movements in accordance with the template becomes very simple.
One of the most important fields of applications for this technology is in surgery robotics, where hand movements of the surgeon can be restricted in a way that facilitates making the desired incisions, while at the same time protecting sensitive structures from lesions by unintended movements or tremor of the surgeon [8].

2.2 Haptic Constraints in Rehabilitation

In rehabilitation, it is desired to simplify movements for patients in a way that allows them to perform the movements safely and successfully on their own account.
Reinkensmeyer et al. [9] implemented the concept for the "ARM Guide" device with a non-virtual, mechanical fixture. The ARM Guide consists of a linear guide which allows patients to train straight line reaching movements by moving a handle. Along the direction of movement, supportive or resistive forces can be exerted by an actuator.
The disadvantage of a mechanical fixture is apparent: Training with such a device is limited to one specific movement (in case of the ARM Guide it is restricted to linear reaching movements). Therefore, the Gentle/S project, which aimed at developing a more versatile robot-aided training tool based on the HapticMaster robot, introduced virtual and thus flexibly reprogrammable haptic constraints [10]. When the robot is operated in "bead highway" mode (named with respect to the picture of a bead moving along a rigid string or wire), the end-effector of the robot is coupled to a virtual bead via a virtual spring and damper system. By applying forces to the end-effector, the patient can pull the bead along the virtual string, which defines the possible path of the bead. The string is described by a 7^{th} order polynomial, and it can be adapted to different tasks in virtual training scenarios.
A similar controller has been implemented for the MIT-Manus [11] for linear reaching movements towards varying targets. The robot renders zero impedance in the desired direction and a virtual spring and damper in the direction orthogonal to the desired movement. The spring and damper push patients back to the desired movement path if they do not move towards the target. The range of motion in the desired direction of movement is limited to a window. The front wall of the window is fixed to the target, whereas the back wall moves from the starting point to the target. Thus, patients who move actively and faster than the back wall can perform the movement on their own, only corrected by the controller which acts orthogonal to the movement. Patients who need more support will be pushed towards the target by the moving back wall. The limitation to planar straight line movements allows a straight-forward implementation of the approach: By rotating the Cartesian coordinate system in a way that aligns one axis with the desired direction, two independent, orthogonal controllers can generate the desired behavior.

The first virtual haptic constraints for walking movements were presented by Cai et al. [12]. With their rehabilitation robot for mice, they investigated the effects of different control paradigms on the rehabilitation of spinalized mice. They compared an approach with two independent haptic tunnels – one for each hind limb – which provided spatial templates for the movement of the ankle joint, a second approach with two moving windows for the ankle joints which allowed a certain amount of movement variability but kept both hind limbs synchronized, and finally a classical position control approach, which allowed the mice to remain passive during the training. The two synchronized moving windows caused better rehabilitation outcome than the two other approaches.
Inspired by this work, Banala et al. [13] developed a haptic tunnel for their "active leg exoskeleton" (ALEX), a single-leg device intended to improve the gait pattern of the affected leg of hemi-paretic stroke subjects. Banala et al. implemented their tunnel by a nearest-neighbor search, which finds the closest point to the actual position on the spatial reference path and then uses an impedance controller to bring the leg back to a position within the tunnel if necessary. Within the tunnel, an adjustable flow in the direction of movement can be used to facilitate moving the leg.
At the same time, our group developed the "Path Control" strategy, a similar haptic tunnel for the gait rehabilitation robot Lokomat [14]. As the Lokomat is an exoskeleton for both legs, we implemented two independent haptic tunnels, one for each leg, but combined the tunnels with an additional moving window of adjustable size capable of keeping the legs synchronized. With this window, we expected to exploit the beneficial effect shown by Cai et al. [12] in the experiment with mice. Furthermore, we were able to successfully adjust the approach to the individual needs for guidance of spinal cord injured patients with varying levels of impairment [15].
For the training of arm movements involved in activities of daily living (ADLs), we adapted the Path Control strategy to the arm rehabilitation robot ARMin [16]. In this context, a special feature of the approach is the dynamic generation of haptic tunnels based on the patient's starting position and different virtual ADL scenarios.
A further improvement of the approach was achieved by incorporating the method of "Generalized Elasticities" [17]. In this method, a conservative force field is optimized based on a family of desired movements, such that it both renders a haptic tunnel around the spatial path of the movements and reduces undesired dynamical effects of the robot. The second aspect allows the patient to move more freely and more natural within the haptic tunnel than with other ways of compensation [18]. The conservative force field used in this "Generalized Elastic Path Controller" couples all degrees of freedom (in case of the Lokomat, these are the two hip and the two knee joints) in a way that implicitly induces a soft synchronization of both legs, similar to the moving window in some of the approaches mentioned above.

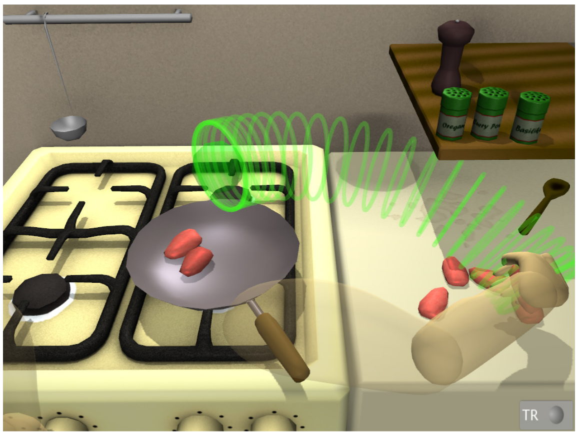

Figure 2 Virtual tunnel for a reaching task with ARMin.

3 Examples

3.1 ARMin

To allow for versatile training of ADLs, the ARMin robot does not statically define haptic tunnels, which would always lead from a defined starting point to a defined goal. Instead, a haptic tunnel that takes the constraints of the current ADL scenario into account is calculated dynamically from the position where the patient has moved before to the goal (Fig. 2). Thus, ADL training can be performed with maximal variability: The patient does not train a standardized movement but learns to perform a task under various initial conditions. First feedback from an ongoing multicenter trial shows that patients are able to perform the tasks considerably faster with the help of haptic constraints than without, which increases the number of task repetitions achievable within one training session.

3.2 Lokomat

Preliminary data from a pilot trial with two stroke and two spinal cord injured patients receiving gait training with haptic constraints in the Lokomat shows results consistent with the observations with the ARMin robot. During a training phase of four weeks (with four training sessions of one hour each per week) where patients trained walking while the robot was controlled with the "Generalized Elastic Path Controller" [18], the haptic constraints enabled the patients to train on their own account with a walking speed similar to their speed when trying to walk as fast as possible in the 10 meter walking test (10MWT). In comparison, the speed they chose in the 10MWT when asked to walk at their preferred speed was consistently lower (Fig. 3).

4 Discussion

Our preliminary results indicate that patients are able to exploit haptic constraints provided by rehabilitation robots to facilitate their self-driven movements. Easier movements increase the number of possible repetitions per training session and provide a natural feedback of success.

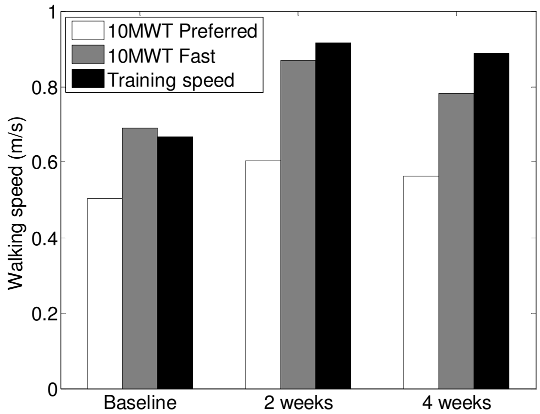

Figure 3 Walking speed of a stroke patient in a pilot trial with the Generalized Elastic Path Controller for the Lokomat at baseline, after two weeks and after 4 weeks of training (white: preferred walking speed in the 10MWT, grey: maximal walking speed in the 10MWT, black: tolerable training speed with the Lokomat).

However, the human motor system constantly tries to minimize energy expenditure [23], thus patients will learn quickly to rely on the haptic constraints, similar to a child learning to bike with training wheels. Li et al. [24] have demonstrated such an effect of constant exposure to virtual fixtures in motor learning tasks.
To prevent the patient from becoming dependent on the haptic constraints, the width of the presented haptic tunnels should be progressively increased when the patient's performance improves. Training schemes where this requirement is taken into account are presented in [11] and [19]. Furthermore, the strength of supportive "flows" inside haptic tunnels should be reduced as much as possible according to the assist-as-needed paradigm [20] in order to maximize active participation of patients. Suitable algorithms to automatically adapt such parameters have been demonstrated in [21] and [22].
Finally, modeling the reaction of the human nervous system to rehabilitation may provide important additional insights regarding the progressive changes to the training environment. For example, it could be important to have blocks of constant conditions as opposed to slowly changing haptic constraints and support parameters to allow the nervous system to optimize its motor outputs [25].

5 Conclusion & Outlook

A variety of haptic constraints has been implemented for rehabilitation robots for upper and lower extremities. These constraints provide virtual tunnels and/or moving windows, which allow patients to execute training movements on their own accord safely, with higher speed and better performance than without constraints.
Future research needs to clarify how haptic constraints can be progressively adapted to the patients' abilities in order to provide optimal learning conditions for the human nervous system and, thus, maximize the therapeutic outcome in robot-aided rehabilitation.

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