Haptic training of lower extremities enhanced by visual modality

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Abstract— **We investigated the effects of combining the visual and haptic modalities on the adaptation capabilities of healthy subjects to the virtual environment. The haptic feedback was provided by the actuated gait orthosis Lokomat programmed with stepping movements employing an impedance control algorithm. The visual cueing (only the reference motion is presented) and visual feedback (the reference motion as well as the current tracking deviation are presented) were provided by a real-time visualization of a virtual teacher and a virtual self – avatar. The subjects had to track the virtual teacher during stepping-in-place movements shown on screen while being assisted by the Lokomat. The stepping task was performed by engaging three different combinations of haptic and visual modalities. The statistical analysis showed that (1) haptic feedback and visual feedback combined yielded better tracking than haptic feedback alone, and (2) haptic feedback combined with visual cueing did not improve tracking performance compared to haptic feedback alone. We concluded that in general the haptic training can be effectively enhanced by the visual modality if the latter features visual feedback rather than just cueing.**

I. INTRODUCTION

THE number of studies and experimental applications exploiting virtual reality (VR) in the rehabilitation environment has been increasing rapidly over the last few years [1], [2]. VR is a powerful tool in a rehabilitation environment, providing the patients with repetitive practice, feedback information, and motivation to endure practice. In a virtual environment, the feedback about performance can be augmented (i.e., enhanced relative to feedback that would occur in real world practice alone). Augmented feedback about motor performance can readily be provided in a virtual environment. Reprogrammable virtual tasks, virtual objects, and scenarios can enrich the training and motivate the patients to perform intensive therapies for longer durations and more often. Further advantages of the VR rehabilitative systems include various possibilities of adaptation to the patient's capabilities and

extended measurability/assessment of performance progress.

To make the artificial feedback signals perceptible and allow the patient to react to the signal, technical display devices are required, such as graphic (screens), auditory (loudspeakers), or haptic (robotic devices) displays. The goal is for the patients to feel present in a virtual environment while continuously confronted with information about their own motor performance during the training in a simple, intuitive way.

VR allows us to program a virtual teacher into the display, who performs the task repeatedly. The input of the teacher performing the repetitive movement is a powerful way to provide enhanced feedback and enables the enhancement of learning by imitation.
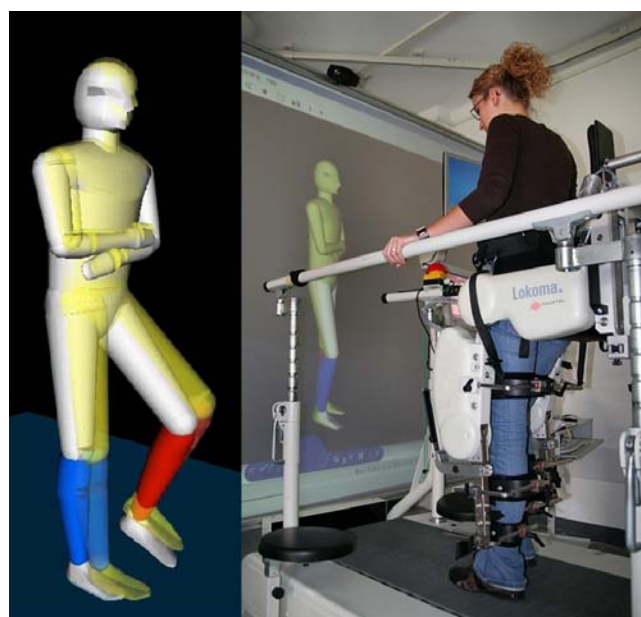

Fig. 1.   Virtual Mirror (left) in a haptic setting for lower-extremities training..

The visual modality of learning by imitation for lower extremities in this study was presented in a form of a virtual mirror. The subject performed lower-extremity movements in front of a large screen (fig. 1, right), on which two figures were shown in a three-dimensional (3D) virtual environment (fig. 1, left) from a desired viewing angle. The solid figure represented the training subject, and its movements corresponded to the subject's movements in

real time. The transparent figure represented the virtual teacher whose movements were pre-programmed. The two figures were superimposed. The task of the training subject was to follow the movements of the virtual teacher as accurately as possible, so that both figures were closely overlaid throughout the duration of the lower-extremities training.

Haptic feedback was realized by utilizing a Lokomat system (Hocoma, AG; fig. 1, right). The Lokomat is an actuated orthosis used to control patient's leg movements in the sagittal plane. The legs of the patient are moved within highly repeatable predefined hip and knee joint trajectories. The Lokomat is instrumented with potentiometers and force transducers, and thus, it is capable of providing online feedback about joint movement and joint moment production, respectively. However, compared to manual treadmill therapy, there is a loss of physical interaction between therapist and patient with robotic gait retraining. Hence, it is desirable to present the real-time information of the patient's performance via other feedback modalities, not only for the patient, but also for the therapist. We employed the Lokomat potentiometers to present the movements of the subjects in the virtual mirror, which added the visual feedback to the training.

We explored the capabilities of the subjects to adapt to the virtual mirror and Lokomat by performing a stepping-in-place (SIP) tracking. SIP test has a relatively long history in the clinical environment. More than 50 years ago, it was first used for detecting peripheral vestibular dysfunction [3]. During the last decade, the test has also entered the rehabilitation environment. The SIP test has been applied to stroke patients [4], patients with Parkinson disease [5], and amputees. Combined with VR, the SIP test can also be considered as a modality of lower-extremities training during rehabilitation. This cannot replace gait training and/or analysis; however, similar reciprocal rhythmic movement patterns can be observed during both locomotor activities. SIP allows the assessment of basic temporal parameters, such as stance and swing phase, double-stance phase, and step frequency.

The aim of our study was to assess the effect of visual modality added to haptic training on the adaptation of subjects to a virtual environment by employing both modalities in the same virtual scenario. To achieve this, SIP was performed in a group of healthy adults by utilizing one haptic-only mode, and two combined haptic-visual modes (employing visual cue and visual feedback, respectively). We studied spatial and temporal adaptation in all modes by assessing the spatial and temporal correspondences between the reference and the recorded goniograms.

II. METHODS

A. Virtual mirror with haptic and visual feedback

Visualization of the subject's movements in the virtual environment was based on a simplified kinematical model of the human body. During the SIP training, the subject would see two human figures superimposed in the virtual mirror, one representing the virtual teacher, and the other presenting the subject's movements in real time. The real-time information of the subject's hip and knee angles was provided by the Lokomat system's potentiometers. The measured joint angles were used to move the subject's human figure in the virtual mirror, whereas the pre-programmed SIP pattern was used to animate the virtual teacher, and presented a reference pattern that the subject was instructed to track. Lokomat system was programmed with the same SIP pattern, providing haptic feedback. Ideally, both figures would be perfectly aligned at all times, indicating that the subject was performing the SIP simultaneously with the virtual teacher.

We achieved 35 Hz VR refresh rate in real time, without detectable lag. In order to provide the subject with the desired view of the performance, it was possible to set the viewing angle and distance of the virtual camera arbitrarily. The left and right shanks of the virtual figures were of different colors, providing a clearer visual reference for each extremity.

B. Impedance Control

The default control strategy of the Lokomat system is position-based, making the orthosis feel stiff for the subjects, i.e., only negligible deviations from the reference trajectories are possible regardless of the amplitude of the applied opposing joint torques. Using a position controller would not allow any difference to be seen between the subject's figure and the virtual teacher in the virtual mirror, irrespective of the subject's efforts, and would, thus, diminish or cancel out the visual feedback loop completely. Instead, we employed an impedance-based control strategy [6], [7]. An impedance controller allows variable deviations from a given leg trajectory rather than imposing a rigid pattern, making the orthosis feel compliant. The moment acting on the subject's leg is proportional to the angular deviation from the pre-programmed reference value. The stiffness of the orthosis is subject to the setting of the mechanical impedance value; zero impedance, ideally, makes the Lokomat feel transparent, i.e., no haptic feedback can be experienced, whereas maximal impedance results in maximal stiffness, equal to the position controller. In reality, the Lokomat impedance controller does not compensate for inertia, which can cause the inertia of the orthosis' segments to be more noticeable for the subjects when the impedance is low. The compromise had to be made between making the Lokomat compliant enough for

the subjects having to exert voluntary effort to track the reference pattern, while not being encumbered by the inertia of the heavy orthosis segments. We strived for the lowest reasonable impedance value in order to prevent the haptic feedback from being overly strong. It was defined experimentally and was set to 30% of the maximal impedance that the Lokomat can exert.

C. SIP Tracking Task

Assessment of the subjects' ability to track the SIP movements of the virtual teacher was undertaken by performing a task consisting of varying hip angles and cadences. The movements of the virtual teacher were obtained by capturing the steps of a healthy male subject (aged 25 years), who was well familiarized with the virtual mirror. Based on his average step, a smooth, continuous pattern was synthesized, involving spatial (hip angle amplitude achieved in each step) and temporal (cadence) perturbations. Spatial and temporal parameters of the task were based on performance expectations of healthy subjects, assessed in our previous study [8], and are shown in fig. 2. The same pattern was used to drive the Lokomat reference motion to provide the haptic feedback.
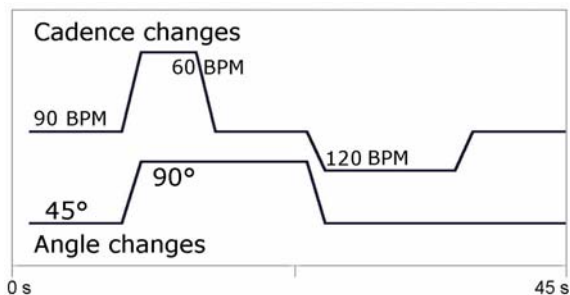

Fig. 2. Temporal and spatial parameters of the stepping-in-place task.

The task was performed in two modes with haptic-visual modality and one mode with haptic-only modality. The modes with visual modality within both settings differed in presenting either both virtual figures superimposed (virtual teacher and the subject, enabling visual feedback), or presenting only the virtual teacher (providing merely a visual cue). Features of all three modes are concisely summarized in table 1. The order of performance of all modes was randomized for all subjects. Each subject completed a trial of the task before the actual measurements took place.

TABLE I
COMBINATIONS OF VISUAL AND HAPTIC FEATURES ENGAGED IN THE 3 MODES OF THE STEPPING-IN-PLACE TASK

mode	visual cue	visual feedback	haptic feedback
1	✓	✓	✓
2	✓	-	✓
2	-	-	✓

D. Assessment of adaptation

The adaptation of the subjects to the virtual environment was assessed by comparing their hip goniograms to the virtual teacher's. We used a method developed by Giese and Poggio, based on linear superposition of prototypical motion sequences [9] rather than simply computing the root mean square error (RMSE) of the error signal. The authors promote their method as being especially well-suited for analysis of biological motion patterns. Basically, the procedure yields the optimal spatial and temporal mapping of the two patterns by using dynamic programming algorithms. A detailed description of the method is given in [9].

E. Subjects

A test group consisted of 12 healthy subjects (aged 23-32 years; mean value = 27.1 years; standard deviation = 2.4 years). None of the subjects had a medical history of significant lower limb impairments of any type. All subjects gave informed consent to participate in the study. Ethical consent was given by the local ethical committee.

III. RESULTS

Results include spatial and temporal adaptation of the subjects to the virtual teacher by analyzing the hip gonigrams in all three modes of the tracking task.
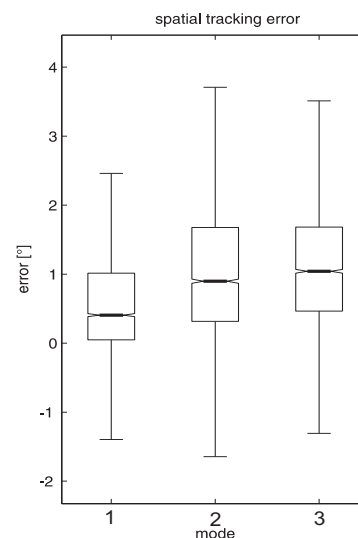

Fig. 3. Spatial tracking error in the 3 modes of the task.

The differences were addressed by first applying the method for assessing spatial and temporal deviations by Giese and Poggio, and then performing the analysis of variance (ANOVA). Figures 3 and 4 show the spatial and temporal tracking errors, respectively, in terms of median values (bold solid lines), 25th and 75th percentile values (error boxes), and 5th and 95th percentile values (error bars). Within the three modes, the addition of the visual

feedback improved both spatial (fig. 3) and temporal (fig. 4) adaptation (p < 0.001 for both observations); however, no significant differences were observed between the haptic-only mode and haptic-visual cue mode. While including the visual feedback reduced both the median error and the error variance in spatial adaptation, it reduced only the error variance in temporal adaptation. The median temporal error was fairly low in all modes.
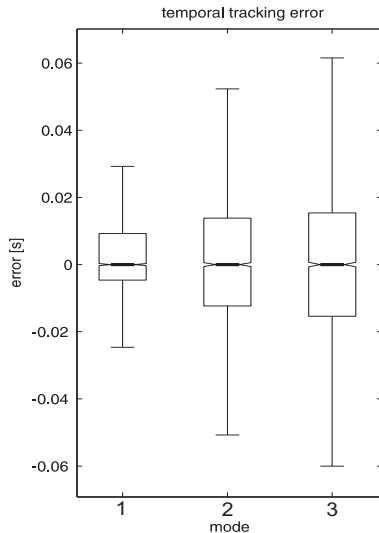

Fig. 4. Temporal tracking in the 3 modes of the task.

IV. DISCUSSION

The virtual mirror proved to be an intuitive, easy-to-learn virtual environment, effectively complementing the haptic setting in lower-extremities training. The virtual environment was sparse, consisting only of two virtual figures on a virtual floor, using no textures. According to the study by Zimmons and Panter [10], making the environment more elaborate, i.e. more details, finer rendering, textures, etc., would not affect the feeling of presence significantly. The real-time responsiveness, repeatability, and strong correlation of the actions in the real and virtual environments are far more critical factors in this regard and were, therefore, in primary focus of our technical endeavors. The feature of learning by imitation ensured that the subjects could cope with the stepping task instantly, as we observed no general improvement trend during the performances of the task in different modality combinations. SIP was chosen instead of treadmill walking for this basic study since it does not impose a programmed speed on the subjects. In this way, there was no need for the subjects to adapt their movements to the running treadmill, which allowed us to record their unbiased activity [11], based solely on the subjects' responses to the virtual environment.

The tracking performance was assessed using the linear superposition method by Giese and Poggio [9] allowing us to identify spatial and temporal tracking error separately. The importance of this distinction is best demonstrated by a situation where the subject's tracking is perfect in terms of amplitudes, but slightly delayed. The method we used in this case correctly identifies the zero spatial error component and slight temporal deviation, whereas the RMSE method yields an overly significant tracking error, providing no further information on tracking performance.

The results suggest that adding a visual modality to haptic training can improve the adaptation compared to the haptic-only setting only when the virtual environment provides the visual feedback rather than just visual cue. Real-time measurements needed to create a feedback loop are always needed for active haptics, and are, thus, conveniently available for use in such a virtual environment.

Ernst and Banks suggest in their study [12] on integrating visual and haptic information in upper-extremities task involving the estimation of object properties, that a general maximum-likelihood estimation principle determines the degree to which vision or haptics dominates. The authors conclude that the nervous system combines the visual and haptic information in a statistically optimal fashion based on the variance estimation and that the modality associated with lower estimation variance prevails. According to their findings, better tracking in a haptic-visual feedback mode in our investigation might suggest that both modalities complementing each other provide best estimation, i.e. the lowest estimation variance.

Experimental setup in the present study involved the use of relatively expensive equipment. Haptic interfaces are by default elaborate and complicated devices and, thus, are priced accordingly high; however, the best tracking performance was observed in combining both haptic and visual feedback. According to the results, we suggest that haptic feedback should be included wherever possible, whereas VR can be potentially beneficial for in-patient rehabilitation process following a stroke or other injury by upgrading the existing and new haptic interfaces with visual feedback features.

When discussing the use of VR in rehabilitation it is important to keep in mind that VR is not a treatment in itself – and, thus, cannot be regarded as either an effective or ineffective means of motor rehabilitation. Rather, VR is a technological tool that can be exploited to enhance robot-assisted motor retraining. Holden concludes in [1] that future work on virtual environments should focus on identifying which types of patients will benefit most from VR treatment, what types of training routines will work best, and which system features are critical. In this aspect, the present study offers a part of the answer to the last

question by providing an insight in what to expect from employing different combinations of modalities in VR-enhanced lower-extremities training.

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