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Sensory-Rich, Meaningful and Usable Upper-Limb Robotic Rehabilitation

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Abstract. Robotic devices, in combination with virtual reality games, have the potential to increase therapy dosage while enhancing patient's motivation. Yet, current robotic interventions suffer from poor usability, over-reliance on the availability of trained therapists, and the inability to provide meaningful somatosensory information despite its importance for relearning skillful movements. To address this gap, we co-created two novel haptic rehabilitation robots for in-clinic and in-home rehabilitation capable of high-fidelity haptic rendering during functional reach and grasp training in motivating virtual games together with rehabilitation experts. We evaluated the usability of our solutions with therapists and patients following a mixed-methods approach, gathering quantitative and qualitative data from questionnaires and semi-structured interviews. The results showed good usability and high enjoyment, with the fidelity of virtual object interactions highly praised. Some mechanical design improvements, mainly with regard to comfort, were also identified. Our devices offer naturalistic sensations during training, paving the way for more holistic sensorimotor neurorehabilitation.

1 Introduction

With an aging society and mounting labor shortages, the limits of healthcare sustainability are rapidly being reached. A main area of concern is the care for people with acquired brain injuries, as available resources will not match the anticipated need for care.

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The state of the art in rehabilitation technology comprises sophisticated robotic devices and gamified virtual reality exercises. Although developed for their potential to alleviate the pressure in healthcare, these are still far from achieving the promised impact. Current robots do not provide somatosensory information during training, despite its importance in (re)learning sensorimotor skills such as fine object manipulation [1,2]. Moreover, these usually bulky and expensive devices only benefit a few people with severe motor impairments treated in high-tech clinics, limiting their usability and accessibility. Sustainable healthcare with equal access to all requires a transition from conventional on-site one-to-one labor-intensive interventions to minimally supervised sensory-rich rehabilitation experiences in the continuum of care at the patient's home.

To provide rich sensory upper-limb rehabilitation experiences we co-created two highly usable haptic robotic devices together with rehabilitation experts. They leverage high-fidelity sensory information for in-clinic rehabilitation (Lambda.3+; Fig. 1) and in-home rehabilitation (Portable hand trainer; Fig. 2). We present an overview of our solutions and results from usability studies to evaluate their potential.

2 Methods

2.1 Haptic Upper-Limb Rehabilitation Robot Lambda.3+

To address the lack of easy-to-use in-clinic robotic devices that leverage sensorimotor rehabilitation, we co-created a novel haptic upper-limb rehabilitation system that provides comprehensive somatosensory information through whole-hand haptic rendering. The Lambda.3+ (Fig. 1) consists of a commercial delta robotic base (Lambda.3, Force Dimension, Switzerland) with three translational degrees of freedom (DoF) for training reaching movements paired with a custom hand module with three DoFs for grasping, i.e., one DoF for flexion/extension of index to little fingers and two DoF for thumb flexion/extension and circumduction [3]. The device's end-effector structure, together with the hand module that retracts into a compact cylindrical shape during setup, makes the donning and doffing of the device simple and quick. Further, it can be easily adjusted to different hand sizes by swapping the handle of the hand module. We employed a physics engine-based approach to enable the simulation of arbitrary interactions between the patient's hand and virtual objects in engaging virtual reality games [4].

We conducted a usability study with seven therapists and seven patients (three in the early sub-acute stage, two in the late sub-acute stage and two in the chronic stage) from the University Hospital Bern, Switzerland, to evaluate the device's clinical feasibility. In a mixed-methods approach, we collected quantitative through questionnaires—i.e., usability through the System Usability Scale (SUS) and motivation through the Intrinsic Motivation Inventory (IMI)—and qualitative data through semi-structured interviews.

Fig. 1. The Lambda.3+ haptic device consists of a delta robot and a custom hand module for training reaching and grasping movements.

2.2 Portable Hand Trainer

We developed a minimally-actuated portable hand trainer to address the need for more cost-effective unsupervised neurorehabilitation at patients' homes (Fig. 2) [5]. The device incorporates an innovative, compliant shell design with back-drivable actuation for grasp training. We included a passive degree of freedom for wrist pronosupination by enabling the device to tilt around its longitudinal axis. The device is inherently safe, accommodates various hand sizes, and provides meaningful haptic feedback while grasping virtual objects. Its relatively light weight (1030 g), small size (l210 × 160 × 150 mm), and low cost (approx. 1000 EUR) make it an excellent candidate for in-home rehabilitation.

We paired our device with a serious game that challenges users to fill virtual cocktail glasses using liquid dispensers with different haptic behaviors, showcasing the device's haptic capabilities. This task simulates activities of daily living (ADL) by requiring precise grasping, force control, and timing. Additionally, the game encourages finger extension, as users must open their hands before switching between liquid dispensers using pronosupination movements.

We performed a usability study in a simulated unsupervised environment with ten naive, healthy participants and three physiotherapists from the Rijndam Rehabilitation Center, Rotterdam, the Netherlands. We also used a mixed-methods approach to gather quantitative data from usability and motivation questionnaires as well as eye tracking, and qualitative feedback from semi-structured interviews.

Fig. 2. The portable hand trainer incorporates an actuated compliant shell for grasp training and a passive DoF for pronosupination.

3 Results

3.1 Clinical Usability of the Lambda.3+

The device proved to be user-friendly and adaptable to a wide range of hand sizes, requiring minimal setup effort. Setting up the patient, including handle change, took a median duration of less than four minutes. The overall usability of the device was rated good to excellent by both patients and therapists, with median scores 76.3 (therapists) and 80.0 (patients) out of 100 in the SUS questionnaire. The reported patient enjoyment was also high, with an average score of 6.3 out of 7 on the IMI questionnaire.

Feedback collected from both therapists and patients through the interviews was very positive. Both groups reported high satisfaction levels, noting that the system's rehabilitation exercises were engaging and meaningful. Therapists particularly praised the system's DoF and its haptic capabilities, with special emphasis on the potential for transfer of the sensorimotor skills acquired during training to ADL. We also detected points to improve, e.g., providing more support to the little finger to prevent it from slipping.

3.2 Usability of the Portable Hand Trainer

The portable device was considered user-friendly overall, and participants highlighted its portability and simplicity. The intuitiveness and ease of use were reflected in the quick setup, which took less than one minute.

The device was perceived as highly usable, with a SUS rating of 77.5. Participants hardly mentioned the device's shell during the interviews, implying that the interaction felt natural and intuitive. Eye-tracking data reinforces this, as participants focused little on the device ($\sim$0.42% of total time) and emergency stop ($\sim$0.03%) while playing the game. The reported enjoyment was lower compared to the Lambda.3+ (4.9 out of 7), probably due to the involvement of only healthy participants. Points of improvement were also noted, such as the written instructions and the wrist fixation.

4 Conclusion

We developed and evaluated the usability of two haptic devices for rich sensory, meaningful upper-limb rehabilitation. Our devices offer training with high-fidelity haptic feedback and engaging tasks in the continuum of care, from in-clinic to at-home rehabilitation. The transferability of the skills gained through our haptic exercises to ADL remains to be evaluated. Yet, their proven usability and overall positive feedback from therapists and patients highlight their potential to enhance robotic neurorehabilitation.

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