SENSORIMOTOR REHABILITATION SYSTEM FOR THE UPPER LIMB WITH VIRTUAL ENVIRONMENT, EXOSKELETON ROBOT, AND REAL OBJECTS

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ABSTRACT

The Sensory Motor Training Station (SMTS), designed to provide concurrent sensorimotor hand and arm training and performance measurement features, incorporates virtual reality, an upper limb robot, and interaction with real objects to provide the nervous system with multi-modal sensory experience during movement training. One goal of the SMTS design is to provide training to view, reach, and touch real objects even when the patient is unable to move adequately enough to participate in traditional therapies. Current exercises focus upon concurrent movement and multi-sensory training to improve strategies to recognize arm location and object location to improve prehension, a particularly important skill in activities of daily living and for quality of life in persons with impaired sensory and or motor skills. In a recent experiment, eleven control subjects pointed to virtual targets or viewed and touched real objects in active or passive robot movement conditions while viewing the virtual limb proxy. Viewing and touching the real objects improved performance in an arm location task in both active and passive robot conditions.

KEY WORDS

Virtual Reality, Rehabilitation, Robot Rehabilitation, Patient Monitoring.

1. Introduction

Injury to the central or peripheral nervous system can result in sensory and or motor impairments. For example, stroke represents a serious disabling condition for people around the world affecting 1.7 million in Europe and the United States [1, 2]. Persons suffering hemiparesis of stroke (85%) experience a cascade of events affecting use of their upper limb and quality of life. Up to sixty percent of patients suffering from stroke experience loss of body sensations, ability to manipulate and use objects, and to feel stimuli [3-5]. Sensory loss can lead to a complete nonuse of upper limb even when the limb shows normal function in turn, impacting recovery of essential skills of everyday living [6].

The goal of rehabilitation is to reduce impairment and provide functional improvements resulting in quality participation in activities of life [7, 8]; early intervention following stroke can reduce loss of cortical representation [9] yet many patients are unable to produce adequate movements required in order to participate in traditional therapy.

Technology assisted rehabilitation can be used to systematically modulate, structure, organize, and control sensorimotor experiences (stimuli and feedback), activities, instructions (explicit or implicit), and dialogues to enable therapy approaches. Virtual Reality (VR) has been used to provide a wide range of therapy interventions and has been demonstrated to be effective in improving upper extremity motor function in adults with chronic stroke-related hemiparesis [10-12]. Technology can also be used to accommodate weakness; robots and functional electrical stimulation have been used to provide movement support with a range of features. For example, robots can address individual or combinations of joints of the upper limb, they can provide support against gravity, active or passive support of movement, and they can measure and adapt to the movement efforts of the trainee using a variety of algorithms. They can guide movement in spatially and temporally simple or complex models with greater or lesser emphasis on multi-joint coordination.

Hand and arm movements involve extensive networks in the brain. Motor impairments may be caused by execution related or motor planning and motor learning related issues. Strategies to reduce motor impairments might involve addressing muscle strength, tone and spasticity. A variety of strategies may be helpful in addressing motor planning and motor learning related issues and may promote cortical reorganization associated with plasticity [13]; a growing number of approaches includes intense task-oriented training, action observation and imitation, mental imagery, bimanual training, etc. [14]. Some strategies may be more effective with certain patients, perhaps due to the location and extent of injury, or at certain stages of recovery [15].

Many traditional rehabilitation strategies focus early attention on the proximal function of the upper limb despite insufficient evidence [16]. Movement practice
related cortical changes have been documented in animal and human studies [9, 17, 18] illustrating plasticity of the brain. Together with the relationship between transport and object manipulation [19], we hypothesized that adding additional sensory modalities through training view and touch of objects might provide a suitable functionally integrated activity during technology assisted upper limb training. Importantly, recent research in technology assisted rehabilitation revealed hand and arm together training resulted in greater improvements in clinical and objective measures, when compared with training the hand and arm separately [20-22]. Early focus on proximal extremity might result in undesired outcome for distal upper limb through mechanisms such as competition for cortical representation [17, 23] or expansion [24] and motivates novel hand and arm training strategies.

Evidence shows that acute stroke patients in rehabilitation receive only one to two hours per day [25, 26] and approximately ten to twenty repetitions per session for their upper extremity during the chronic phase [27]. Access to effective hand and arm therapy is needed since even mild deficits lead to impairment of most activities of daily living with impact upon quality of life. Combining technology assisted interventions in the presence of interactions with real world objects in peripersonal space may increase salient properties of the exercise environment, and may increase access to motor planning and motor learning therapies in intensities required to promote plasticity for hand and arm rehabilitation; accommodations of technology may extend therapies even to very weak patients. Such a platform might increase potential to provide the nervous system with realistic concurrent sensory experiences during exercise in ways unachievable through conventional means.

2. Motivation

Technology platforms can serve in research and rehabilitation capacities. Platforms for concurrent multi-sensory experience can extend the intensities, variety of techniques, mechanisms available for modulation during exercise, and extend therapies available to the weak and severely impaired. They increase the diversity of populations that can be studied useful to identify sub-populations for which specific therapies may be effective. Technology can also introduce novel problems in sensory motor experience that warrant investigation.

A number of technology assisted rehabilitation systems have been designed, developed, and evaluated that focus on upper limb rehabilitation. Technologies are evolving in sophistication and ease of use; evidence supports VR environments for rehabilitation of the upper limb [10, 28, 29]. Robots are also used with a variety of approaches [30-32]. We are interested in providing technology assistance to facilitate hand and arm together therapies that will optimize the potential for recovery of the hand function which is important to reduce dependence on others. Therefore, we incorporated multi-sensory experience with real objects into our design.

Object Interaction

One of the most important behaviors characteristic of the human motor repertoire is the ability to reach, grasp, and manipulate objects. Motor observation, planning and execution of complex upper limb tasks, including communication gestures, grasping and manipulating objects and tools, and other dexterous behaviors characteristic of the human motor repertoire engage extensive cortical neural networks. It is known that for some patients with brain injury, integrating multi-sensory information and processing information about objects becomes challenging motivating investigations of the application of technology to this rehabilitation problem.

Loss of body sensations can lead to a disintegrated body schema, sense of one’s own body and its location, and can alter sensory dependent motor skills; faulty processing of object-related information influences voluntary motor skills production, can result in problems such as ideomotor apraxia or hemispatial neglect, and can lead to loss of independence. Localizing external objects within peripersonal space plays an important role in the strategies of accurate human movement, towards targets and for obstacle avoidance. Movement velocity measures, grasp apertures, and direction adaptations characteristic of reach to grasp of stationary or moving objects and reach to grasp in the presence of obstacles vary in the presence of virtual or real objects. Spatial and temporal features of movement are influenced by the context and the presence of objects in the workspace. Object affordances and functional task constraints influence movement profiles in natural settings that may not be resolved using the traditional robot minimum angular jerk model [33]. Efforts afoot involve developing new control strategies for arm rehabilitation robots to more closely represent natural complex movements such as interactions with objects in activities of daily living. Many existing control models use point to point two dimensional movements. Additional investigations of this topic are warranted.

Recent research demonstrated that subjects reaching to a target in the presence of obstacles collided with virtual objects as often as forty percent of the time in some conditions [34], whereas testing avoidance of real obstacles resulted in collisions in less than one percent of the movements [35, 36] indicating that online movement planning and execution changes in the presence of real objects. Real objects may be engaging multiple sensory motor mechanisms that warrant further investigation. Salient properties of three dimensional real objects in the training environment may provide important exercise conditions for learning or relearning spatial and temporal motor strategies for the upper limb that are relevant in activities of daily living.

Multi-sensory concurrent exercise experience associated with incoming information including vision, proprioception, mechanoreceptor and tactile sensations,
and their integration, and appropriate task design [37], which could be provided within a virtual environment [38, 39], targeted to activate important brain regions including secondary motor regions [40] and ipsilesional regions [41], and to provide salient real object-related experiences engaging dorsal and ventral visual systems [42], might establish an ideal platform for training and retraining following sensory motor related injury or impairment. VR systems enable the creation of protocols for various learning models including implicit learning [43], for intensive exercise [44], and practice [45], to use customized and motivating factors [46, 47] to promote sensory-enriched [48], personalized and ecologically relevant [49, 50], task-oriented with increasing complexity [51] exercise, to promote experience-dependent changes [9], in synaptic and functional connectivity across multiple sessions [52], and with intensity, could promote plastic reorganization [53, 54 2002] for example, shifting regions of motor control to adjacent tissue [17, 55, 56], or the contralateral hemisphere [57, 58] to take over functions of damaged cortical tissue.

Goals, context, task design, and level of challenge play important roles in motor planning and motor learning. In human research, matched levels of difficulty [59] in practice [45, 60] and organizing tasks [44, 61, 62], in task oriented [37], with active or passive movements [63], viewing artifacts [42, 64], or viewing one's own body or a conspecific [65], in a sensory enriched environment [48], during pointing or grasping tasks or touching [66] will facilitate motor behavior [67], understanding of goals of the task [68], or recognition of limb location [63]. Inspired by the potential to increase voluntary arm use through top-down strategies of concurrent practice and multi-sensory integration, we designed an arm location rehabilitation exercise using VR, robot support, and real objects. We target motor facilitation through multi-sensory stimulation and focus on interactions that can improve body location perception.

**Sensory Integration**

Following central or peripheral nervous system injury, inaccurate sensory integration may disrupt motor planning, learning and execution systems. Head and Holmes (1911) taught that humans are capable of integrating sensory modalities (visual, somatosensory, proprioceptive, tactile, auditory) to maintain representations of themselves and of their environment and they draw upon sensory experiences to accurately perceive and engage in goal oriented behavior such as motor planning and execution and associated dynamic interactions with the environment and objects in peripersonal space [69, 70]. Penfield and Boldrey (1937) and Penfield and Rasmussen (1950) taught that somatotopic representations show somatosensory cortical representation are larger for body parts with higher sensitivity or more frequent use such as the finger tip [66]. Postural vestibular, and haptic experiences affect the human experience of body position and peripersonal space [71], where humans often interact with objects.

Proximity of multi-sensory experiences including auditory and visual stimulation to ones’ body part modulates multi-sensory coding for peri-hand space and results in plasticity [72-74]. Spatial design of sensory stimulus appears to modulate associated brain regions and also performance; to enhance the training environment, we facilitate attention to posture and enable multi-sensory experiences in peripersonal space. Practicing finger-tip contact with the real objects may enhance concurrent performance through mechanisms of multi-sensory integration to facilitate recognition of body location and location of object within peripersonal space.

**Modulation of Multi-Sensory Experience**

Modulation of multi-sensory experience might improve therapy conditions for many patients experiencing motor impairments boosting performance and offering a practical mechanism with which to present therapies.

Modulation of sensory experience appears to influence performance of healthy humans [75], some patients [76], and the aging [77], and when sensory modulation is a benefit above real world experiences [78]. Visual experience of real objects engages important neural regions involved with recognition of the objects, properties, and location in space, and provides for online correction of movement [13, 42, 79-82]. Postural, visual, tactile, and other sensory experiences modulate sensory fields important for responding accurately to stimuli, and inform the nervous system of body position in peripersonal space relevant when moving about and interacting with real world objects [69, 71, 75, 83]. Reach to grasp involves not only arm movement, but also planning. Viewing the target object influences trajectory and grasp aperture planning and execution. The human central nervous system can improve precision in the estimate of angles of the arm when integrated into fingertip position [84-87] and recent research involving a task to locate the finger resulted in greater accuracy in determining arm position [63]. We arranged the technology support for training to present a larger selection of sensory experiences to tap into properties of mechanoreceptors, tactile, proprioceptive, visual, aural, to bolster concurrent multi-sensory experiences during the exercise experience.

Enhanced sensory experiences may benefit trainees in a technology assisted environment by reduce interfering effects produced by an incompatibility between body schema and body-related visual information [88, 89] or an incompatibility between task requirements and sensory experience as may occur during robot exercise [13, 90]. In a technology training environment, the tasks may not be precisely realistic. Technology enabled multi-sensory experience presented using virtual reality, virtual limbs, and objects, may serve to modulate injury related sensory impairments and help to re-calibrate body perceptions.

Concurrent visual sensory experience with exercise might matter very much in rehabilitation of sensory and motor skills. Action observation alone may
also be sufficient to induce a motor memory in the motor cortex, M1, similar to physical practice [91] and modulates formulation of motor memories if performed in synchrony with training motions relative to training alone. Observation of directionally congruent movements facilitated 11.2% extra facilitation [92]. Simultaneous observation and practice may represent more value than either independent intervention [91], particularly for aging people [93] where one intervention alone proves insufficient. Observation of a model person performing the task in a proper dynamic environment resulted in modulation of practice-dependent memory formation while performance of competing movements during skill learning interfered with action-observation dependent memory [94]. Recent research has demonstrated that viewing non-congruent movements could impair performance through competing mirror activity [95, 96]. Patients lack congruent visual feedback when they are unable to voluntarily perform motor skills. We designed our practice system to provide congruent observation and synchronous execution features to foster the formation of motor memories.

With SMTS, our goal was to investigate the feasibility of creating a technology-assisted rehabilitation system employing virtual reality, an upper limb exoskeleton robot (ARMin), and real objects for concurrent multi-sensory experience and synchronous motor practice. A number of important questions about concurrent multi-sensory experience with objects can be investigated using such a system in healthy and patient populations. In addition, investigations may be made into the technologies used to support hand and arm rehabilitation. Importantly, salient properties of real objects are incorporated into the technology-assisted rehabilitation setting.

An Experiment – Pointing to Virtual Objects, Viewing and Touching Real Objects with Active or Passive Robot Movement

We used the Sensory Motor Training System with virtual environment and robot support to investigate performance enabled by the multi-sensory experiences in the presence of the real objects. Following principles of plasticity and sensorimotor experience, such a system can support rehabilitation training of very weak people who have suffered sensory and motor injury. In our recent experiment, control subjects viewed and touched real objects to provide the nervous system with additional salient realistic multi-sensory experiences (vision and touch of real objects) to potentially benefit a therapy environment.

Eleven control subjects pointed to virtual targets or viewed and touched real objects in active or passive robot movement conditions while viewing the virtual limb proxy. Viewing and touching the real objects improved performance in an arm location task in both active and passive robot conditions. The presence of real objects in the technology-assisted training resulted in better performance in an arm location task with implications for training persons with injuries resulting in sensory and or motor impairment. Herein, we describe the SMTS design and development.

3. The Sensory Motor Training System

The Sensory Motor Training System (SMTS) is a versatile and extensible easy to use technology-assisted rehabilitation training system inspired by neuroscience research findings to optimize concurrent multi-sensory experiences through reaching and touching in virtual environment and with real objects in peripersonal space to stimulate important brain networks with upper limb exoskeleton robot support for intensive movement exercise to stimulate plasticity. The training environment employs a realistic first-person perspective consistent with systems demonstrated to promote a greater sense of ownership [41, 97, 98] and a virtual arm proxy overlapping the natural limb, and concealing the view of the robot during exercise. The system is designed to deliver multi-sensory and motor rehabilitation to diverse populations, including those who are too weak to participate in traditional therapy.

![Figure 1 Sensory Motor Training Station](image)

The SMTS incorporates computers, projectors, multimedia displays, semi-transparent mirrors, and various lighting sources to present, conceal, or modulate visual, auditory, tactile sensory stimulus and feedback. Visual sensory stimulation is displayed on the semi-transparent mirror in a first-person perspective (within peripersonal space) in the position where objects will be manipulated for realistic interaction during technology-assisted exercise. SMTS provides flexible visual sensory experiences including: viewing agents (Virtual Avatar Teacher, Virtual Personal Proxy), observation with intent to imitate, imitation execution feedback [99-101], viewing gestures [102], and viewing virtual and real targets [10]. The system provides options for a first person and a third person [103] Virtual Avatar Teachers to demonstrate [100] the hand and arm activity, gesture, or grasp and provide sensorimotor training [40].

Action observation and imitation is facilitated using a first person perspective virtual avatar teacher. The system also provides a first person Personal Proxy limb positioned overlapping the subject’s own hand and arm, enabling concurrent visual-sensory feedback to correspond with movement intention in VE, and potentially reducing interference in robot training [90]. In Virtual Environments, the behavior of the Personal Proxy may represent an exact copy of the subject’s own hands, or the Personal Proxy movements may be systematically altered by modulating parameters such as the gain or speed and accuracy of the feedback viewed by the subject.
in response to his or her own movements. In this manner, special conditions may be met that may facilitate new therapies, such as Virtual Mirror Therapy (VMT) [21], a technology enabled modification of mirror therapy [104]. In VMT, the subject’s ipsilesional or skilled hand may be used as input to generate a Virtual Mirror Image improving the performance seen in the Personal Proxy during practice in the VE. Personalization through one’s own recorded movement profile [105] installed in the Virtual Mirror Image may provide an advantage in visual feedback over certain algorithms in computer generated movement. It is possible to present only one virtual limb during exercise in the SMTS to provide an opportunity to gain visual sensory effects of viewing the paretic limb [76]. In addition, the virtual limb proxy may be controlled by the movement of the robot offering a means to create an illusion of ownership of the virtual limb during exercise through concurrence of movement efforts and visual feedback of the virtual limb [106].

ARMin seven degree of freedom upper extremity exoskeleton robot [107] has been integrated into the system to provide assistance to weak patients enabling concurrent multi-sensory experience and movement practice during exercise which is concurrently assisted by the ARMin robot with the human in the loop. Therefore, the system may be useful to people who have suffered sensory and or motor injuries including stroke patients even during the acute stage. The SMTS with ARMin robot support may be useful to patients who are too weak to participate in traditional therapies. The SMTS uses position control in the passive movement condition when the ARMin robot moves the arm to each of the positions where a virtual or a real object is located. Otherwise, the robot provides support against gravity in the active move condition, and also measures compliance.

SMTS provides views of the virtual limb, cues and instructions, virtual reality targets, and real objects. The real objects may be viewed through the semi-transparent mirror when the light is on beneath the mirror. Exercises are mapped to specific impairments underlying dysfunction of the upper limb and are organized in levels of difficulty.

By presenting instructions, the Virtual Avatar Teacher for observation and imitation, and coordinating synchronized movement with the robot with visual sensory feedback of the Virtual Personal Proxy, SMTS facilitates concurrent sensorimotor experience and motor practice to promote plasticity. In this manner, SMTS provides visual sensory stimulus of real objects, and feedback that matches prescribed intentions of the movement. All limb joints and the end effector may be addressed within the system to promote balanced exercise of the entire limb and reduce risk of the effects of competition for cortical representation between the proximal and distal limb.

The SMTS has been designed for integrated use with the ARMin 7 DoF robot in either Active or Passive mode. The Virtual Avatar Teacher indicates the target. During a typical limb location exercise task, the upper limb is moved to a target location, pointing to a cue, a virtual or real object, or touching a real object. The robot moves the limb (passive movement), or the person moves his or her own limb to the target (active movement). The robot measures kinematics and performance. Range of motion, extensions, flexions, repetitions, accuracy, and response times are recorded.

Once the object is touched, arm location recognition is performed. While the natural limb is concealed, through a sequence of visual prompts the person identifies the location of his or her limb using a mouse as an exercise to improve arm location recognition.

In our recent experiment with eleven control subjects, exercise in the SMTS was investigated. In a two by two experimental design with active and passive movement conditions and point to virtual targets or see and touch real targets conditions, accuracy in arm location was increased for the condition: seeing and touching real objects. Robot conditions were not a factor in accuracy of determining arm location for these subjects. Adding touch and salient properties of three dimensional real objects to the technology assisted training environment increases the number and realistic qualities of sensory modalities for integration to bolster performance of the trainee. We believe that even when the patient is unable to move by him or herself and requires assistance from the robot, top-down exercises in the presence of the concurrent multi-sensory experience and movement will be a benefit. Cognitive exercises provide additional strategies to assist the person in developing body self awareness, and recognition of the location of objects in peripersonal space.

A number of exercises have been developed for use with the SMTS. Patients are currently using the system for rehabilitation training.

**Multi-sensory Experience and Movement Therapy**

Technology Assisted Therapy has the potential to transform rehabilitation options available, and to dramatically increase the reach of today’s healthcare system. A new Sensory Motor Training Station (SMTS), a multi-purpose research and training system, has been
designed and developed to offer more opportunities to provide the nervous system with sensory experiences that are very realistic, incorporating a variety of active task-related [49] sensory motor inputs during exercise and rehabilitation training at modulated levels of difficulty for the upper limb. Approximately sixty percent of patients suffering from stroke experience loss of body sensations, ability to manipulate and use objects, and to feel stimuli. The loss can lead to a complete nonuse of upper limb reducing the effect of rehabilitation and impacting activities of daily living. Patients who have suffered from stroke receive limited upper extremity rehabilitation although evidence demonstrates improvements may be achieved in acute, sub-acute, and chronic stages. Thus access to effective upper limb therapy to address reduced body sensations and improve coordination is needed since even mild deficits reduce the potential effect of rehabilitation, leading to reduced quality of life.

One of the most important motor behaviors of the human motor repertoire is the ability to reach, grasp, and manipulate objects. We therefore designed and developed a technology assisted rehabilitation system employing virtual reality, an upper limb exoskeleton robot (ARMin), and real objects for concurrent multi-sensory experience and motor practice. In our recent experiment, the presence of real objects for view and touch during an arm location task statistically improved accuracy over pointing to virtual objects in performance of the healthy subjects.

Persons who have suffered from motor and sensory injury are currently using the system. The SMTS might be capable of providing safe and appropriate task-based sensory stimulation with assisted exercise and feedback to extend available and early therapies to those in need, also reaching those who are too weak to participate in traditional therapies by meeting needs with innovative technologies.

4. Conclusion

The presence of real objects in the technology assisted training resulted in better performance in an arm location task with implications for training persons with sensory and or motor impairment. Possible mechanisms to be investigated in the SMTS include: hand and arm together exercise, concurrent visual sensory feedback, reducing interference affects in robot rehabilitation, tactile sensory stimulation improving body schema, natural trajectories of hand and arm movement, etc.

Concurrent sensorimotor experience in virtual reality with real objects and movement assistance supported by a robot within the SMTS might be capable of providing safe and appropriate task-based goal oriented sensory stimulation and feedback to extend available and early therapies focusing on arm and hand together. The platform offers the advantage of real object presence in the training environment. Technology assisted therapies play an important role in investigating mechanisms of therapy. They extend practical therapies -- reaching those who are too weak to participate in traditional therapies.

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