

## Learning in a Virtual Environment Using Haptic Systems for Movement Re-Education: Can This Medium Be Used for Remodeling Other Behaviors and Actions?

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### Abstract

Robotic systems that are interfaced with virtual reality gaming and task simulations are increasingly being developed to provide repetitive intensive practice to promote increased compliance and facilitate better outcomes in rehabilitation post-stroke. A major development in the use of virtual environments (VEs) has been to incorporate tactile information and interaction forces into what was previously an essentially visual experience. Robots of varying complexity are being interfaced with more traditional virtual presentations to provide haptic feedback that enriches the sensory experience and adds physical task parameters. This provides forces that produce biomechanical and neuromuscular interactions with the VE that approximate real-world movement more accurately than visual-only VEs, simulating the weight and force found in upper extremity tasks. The purpose of this article is to present an overview of several systems that are commercially available for ambulation training and for training movement of the upper extremity. We will also report on the system that we have developed (NJIT-RAVR system) that incorporates motivating and challenging haptic feedback effects into VE simulations to facilitate motor recovery of the upper extremity post-stroke. The NJIT-RAVR system trains both the upper arm and the hand. The robotic arm acts as an interface between the participants and the VEs, enabling multiplanar movements against gravity in a three-dimensional workspace. The ultimate question is whether this medium can provide a motivating, challenging, gaming experience with dramatically decreased physical difficulty levels, which would allow for participation by an obese person and facilitate greater adherence to exercise regimes.

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**Abbreviations:** (3D) three-dimensional, (BWSS) body-weight support system, (JTHF) Jebsen Test of Hand Function, (VE) virtual environment, (VR) virtual reality, (WMFT) Wolf Motor Function Test

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## Background

Virtual reality (VR) simulations, when interfaced with robots, movement tracking, and sensing glove systems, can provide an engaging, motivating environment where the motion of the limb or tool displayed in the virtual world is a replication of the motion produced in the real world by the subject. Virtual environments (VEs) can be used to present complex multimodal sensory information to the user. They have been used in military training, entertainment simulations, surgical training, neuromuscular training, and training in spatial awareness and as a therapeutic intervention for phobias.<sup>1-3</sup> Virtual environments can elicit a substantial feeling of realness and agency despite its artificial nature, because participants feel they are controlling their own volitional actions. With the development of haptic interfaces, participants can interact with objects not only by sight but, importantly, by touch.

Robotic devices, interfaced with appropriate virtual simulations to train both ambulation and upper extremity movement for neurologically impaired individuals, are being developed in response to the less than satisfactory outcomes currently obtained through existing rehabilitation interventions. Evidence from basic and clinical science research emphasizes that to remodel motor behavior and to drive measurable change in neural architecture, activities must be repetitive, highly attended, rewarded, and carried out over time.<sup>4-6</sup> Task-oriented training using repetitive performance of goal directed movements<sup>7</sup> is proposed to be effective for modifying motor behavior. These activities address participatory limitations rather than specific sensorimotor impairments. Theoretical support for this approach is extensive in animal as well as human-based neuroplasticity and motor learning research.<sup>8</sup>

There is evidence supporting a dose-response relationship for repetitive task practice and improvements in motor function for persons with stroke.<sup>9</sup> This need for extensive repetitions to remodel motor behavior has driven the development of these robotic interfaces. Computerized technology has the capability to create a functionally based condition where the intensity and the dosing demands of practice can be objectively and systematically manipulated to create the most appropriate, individualized motor-learning paradigm. Over 500 repetitions/day have been reported in the average robotic training paradigm, whereas, in a clinical setting, 85 repetitions/day have been reported.<sup>10</sup>

Additional variables important to the remodeling of motor behavior are the specificity and frequency of the feedback provided during practice. Augmented feedback related to the nature of the movement pattern that was produced (knowledge of performance)<sup>11</sup> or feedback related to the nature of the result produced in terms of the movement goal (knowledge of results)<sup>11</sup> is known to enhance motor skill learning in normal adults,<sup>12</sup> in older healthy populations,<sup>13</sup> and in individuals post-stroke.<sup>14</sup> Feedback provides information about the success of the action, informs the learner about the movement errors, and is known to motivate the learner by providing information about what has been done correctly. These systems are particularly well-suited for providing just such feedback.

When developing exercise systems using VEs, it is important to identify the potential benefits of using VEs for sensorimotor learning. One benefit is known physiological and behavioral advantages from movement observation, repetitive massed practice, and imitation therapies that are traditionally used to facilitate voluntary production of movement, which can easily be incorporated into VR to optimize the training experience. A second advantage is that adaptive training paradigms that continually and interactively move the subject's performance toward a targeted skill are believed to be important to optimize learning and relearning of motor skills.<sup>1</sup> Adherence to exercise programs has been shown to be variable, and on average, only 51% of a group of 29 obese females achieved the required amount of exercise prescribed.<sup>15</sup> Studies comparing traditional stationary bike cycling to bicycles linked to interactive videos and games showed significantly greater adherence to attendance<sup>16,17</sup> and a higher volume of physical activity when using the newer VR mediums.

A major development in the use of VEs has been the incorporation of tactile information and interaction forces into what was previously a visual experience, essentially. Robots of varying complexity have been interfaced with more traditional virtual presentations to provide haptic feedback to enrich the sensory experience, add physical task parameters, and provide forces that produce biomechanical and neuromuscular interactions with the VE. These interactions approximate real-world movement more accurately than visual-only VEs. Robotic-assisted arm-training devices integrated with strategically placed

virtual targets or complex VR gaming simulations are increasingly being used for the rehabilitation of upper extremity deficits. Other robotic systems are also being developed to facilitate gait training.

The purpose of this article is to present an overview of several systems that are commercially available for ambulation training and for training movement of the upper extremity. It includes the system that we have developed that incorporates motivating and challenging haptic feedback effects into VE simulations to facilitate motor recovery of the upper extremity post-stroke. This article describes how this medium is being used to remodel motor behavior and increase adherence to intensive training. The important question to be asked is whether this medium can be used for remodeling other behaviors and actions.

## Gait-Training Systems

The Lokomat System® is a bilateral robotic gait orthosis (<http://www.hocoma.com/en/products/lokomat/lokomatpro/>) used with a body-weight support system (BWSS) and a treadmill. It automates locomotion to help a person whose ability to walk has been impaired as a result of stroke, spinal cord injury, brain injury, or other neurological or orthopedic condition. The gait orthosis is adjustable to the patient's size/anatomy. As the patients walk on the treadmill, their hip and knee joints are guided by computer-controlled motors that are integrated into the exoskeleton. The movement of the gait orthosis is synchronized precisely with the speed of the treadmill. The body weight support component is used to help lift patients from their wheelchairs and to partially unload their weight during gait training. There is both an adult and a pediatric version of the Lokomat System.

Currently, in the clinically available systems, the patients' legs are moved passively on predefined trajectories. This type of training is not challenging, as patients are moved regardless of their effort and they are unaware of any improvements. In a pilot study of 20 patients with spinal cord injury, following an eight-week training period (45 min sessions, 3–5 times per week), the mean percentage increase in walking speed using the 10 min walk test and the 6 min walk test was greater than 50% of pretraining values. However, comparison of outcome performance for robotic-assisted BWSS was shown to be equivalent to therapist-assisted BWSS in the early stages after motor incomplete spinal cord injury. However, the robotic-assisted BWSS required much less therapist

participation and assistance. Preliminary data indicated decreased metabolic and cardiopulmonary requirements during passive robotic-assisted walking. It appears that passive guidance may reduce voluntary activity and physiological stressors necessary for adaptation of both neuromuscular and cardiopulmonary systems.<sup>18</sup>

A newer version, which is in the research phase, allows subjects to walk at their own speed; the forces generated by the subject are used to control the treadmill speed.<sup>19</sup> This may improve physiological adaptation. In addition, the research version has incorporated a visual VE as well as haptic feedback. Patients see their advancement as an avatar on a large screen (3 × 2 m) in an environment with obstacles. The obstacles demand variation in the gait and increased muscular effort. The subjects receive haptic feedback of an impact when they do not increase their effort to step over the obstacle.<sup>19</sup>

The CAREN® System consists of a six-degrees-of-freedom (number of directions that a robot can pivot or move a joint) haptic motion platform that provides translational and rotational perturbations ([http://www.motekmedical.com/caren\\_base.html](http://www.motekmedical.com/caren_base.html)). The platform, usually mounted below the floor, is integrated with a real-time motion-capture system and a visual-projection system with surround sound. When a treadmill is placed on top of the CAREN platform, you can perturb walking or simulate walking uphill/downhill. Virtual environments projected onto a screen are synchronized with the speed of the treadmill and the motion of the platform. These components are integrated into a CAREN system by means of CAREN software.<sup>20</sup>

## Upper Extremity Exoskeleton Haptic Robotic Systems

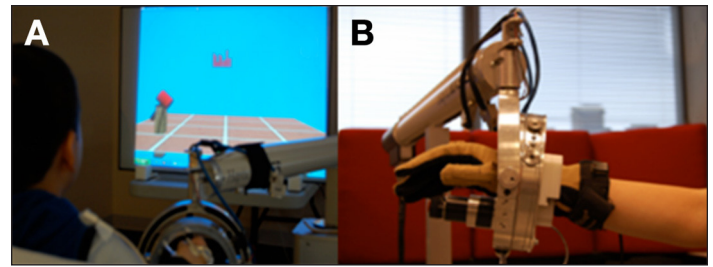
Several systems have been developed to train the upper extremity in patients with motor deficits.<sup>21–24</sup> All are interfaced with VEs of varying complexity and provide haptic effects of varying complexity during upper extremity activities. The MIT-Manus, developed in 1997, was the first robot to receive extensive clinical testing.<sup>25</sup> While their arm is supported, the subjects move their shoulder and elbow in a horizontal plane moving a handle that, in turn, moves a cursor on the screen toward a two-dimensional pattern of targets. Motors actuate the shoulder and elbow joints while force and position sensors record the hand trajectory and how much effort the patient exerts. Arm trajectories of the participant are shaped utilizing a haptic channel that limits

movements that deviate from a predetermined trajectory. Additions have been developed to train shoulder movements in the vertical or diagonal planes as well as wrist movements. The ARMin system facilitates a patient interacting in VEs, utilizing a principle described as minimal intervention.<sup>26</sup> This robot provides assistance only when the subject moves outside predetermined trajectories or the range of joint torques.

A body of literature has shown positive changes in motor function and strength using these devices. A review of robot-assisted therapy on upper limb recovery after stroke in 218 patients showed a positive trend toward robot-assisted therapy for the proximal portion of the upper limb when compared to conventional treatment interventions. However, they did not find significant effects for recovery of activities of daily living.<sup>27</sup> This may be due to the lack of hand training in many of these studies. Currently most of the upper extremity robotic devices are designed to exercise only the proximal limb segment.

The NJIT-RAVR system trains both the upper arm and the hand.<sup>1</sup> It uses the Haptic Master<sup>®</sup> (Moog FCS Corporation),<sup>28</sup> a three-degrees-of-freedom, admittance-controlled (force-controlled) robot. Three more degrees of freedom (yaw, pitch, and roll) can be added to the arm by using a gimbal, with force feedback available only for pronation/supination (roll; **Figure 1**). This allows the robotic arm to act as an interface between the participants and the VEs, enabling multiplanar movements against gravity in a three-dimensional (3D) workspace. The haptic interface provides the user with a realistic haptic sensation that closely simulates the weight and force found in upper extremity tasks.<sup>1</sup> A Cyberglove<sup>®</sup> is used to measure 22 joint angles of the hand. The system consists of this external hardware integrated with interactive VR simulations.

The system includes a library of gaming simulations that exercise the hand and the arm separately as well as the hand and arm together. Several distinctive haptic effects have been incorporated into these simulations. The goal of the “reach/touch” gaming simulation is to improve speed, smoothness, and range of motion of shoulder and elbow movement patterns. This is accomplished in the context of aiming/reaching-type movements (**Figure 2A**). Subjects view a 3D workspace aided by stereoscopic glasses to enhance depth perception, to increase the sense of immersion, and to facilitate the full excursion of upper extremity reach. The participant moves a virtual cursor through this space in order to touch 10 targets presented



**Figure 1.** The NJIT-RAVR System combines (A) complex 3D VEs with (B) a haptic robotic interface that can train the shoulder, arm, and fingers and accommodate a wide variety of participant anthropometrics and physical ability levels.

randomly. A haptically rendered activation target (torus at the bottom of the screen) cues movement initiation. In this simulation, there are three haptic mechanisms used to accommodate varying levels of impairments. The first mechanism is an adjustable spring-like assistance that draws the participants’ arm/hand toward the target if they are unable to reach it in five seconds. The spring stiffness gradually increases when hand velocity and force applied by the subject do not exceed predefined thresholds within five seconds after movement onset. Current values of active force and hand velocity are compared online with threshold values, and the assistive force increases if both velocity and force are under threshold. If either velocity or force is above threshold, spring stiffness starts to decrease in 5 N/m increments. The second mechanism, a haptic ramp (invisible tilted floor that goes through the starting point and the target) decreases the force necessary to move the upper extremity toward the target. This can be added or removed as needed. Finally, a range restriction limits the participant’s ability to deviate from an ideal trajectory toward each target. This restriction can be decreased to provide less guidance as a participant’s accuracy improves.

The “hammer task” trains a combination of 3D reaching and repetitive finger flexion and extension. Targets are presented in a scalable 3D workspace (**Figure 2B**). There are two versions of this simulation. One game exercises movement of the hand and arm together by having the subjects reach toward a wooden cylinder and then use their hand (finger extension or flexion) to hammer the cylinders into the floor. The other uses supination and/or pronation to hammer the wooden cylinders into a wall. The haptic effects allow the subject to feel the collision between the hammer and target cylinders as they are pushed through the floor or wall. Hammering sounds accompany collisions as well. The subjects receive feedback regarding their time to complete the series of hammering tasks. Adjusting the size of the cylinders, the amount of antigravity assistance provided by the robot to the arm



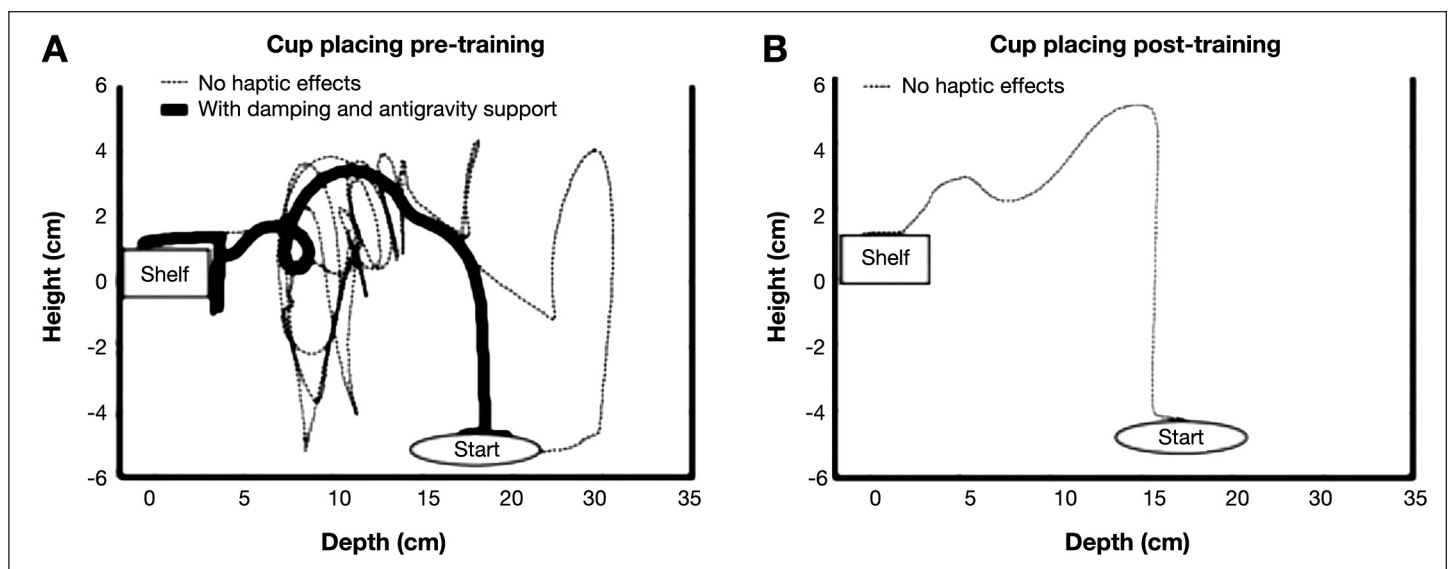
**Figure 2.** NJIT RAVR Simulations: (A) reach touch trains 3D reaching using haptic effects to maximize participation while allowing for consistent effort; (B) placing cups trains functional reaching using haptic effects to shape trajectories and scalable workspaces to accommodate anthropometric differences; and (C) hammer task trains pronation and supination in a 3D workspace and utilizes gain adjustments to match game play to the movement abilities of participants.

and the time required to successfully complete the series of cylinders adaptively modifies the task requirements and game difficulty.

The goal of the “placing cups” task is to improve upper extremity range and smoothness of motion in the context of a functional reaching movement. The screen displays a 3D room with a haptically rendered table and shelves (Figure 2C). The participants use their virtual hand (hemiparetic side) to lift the virtual cups and place them onto one of nine spots on one of three shelves. Target spots on the shelves (represented by red squares) are presented randomly for each trial. The patients feel the weight of the cup as well as the resistive force of the

shelf. To accommodate patients with varying degrees of impairments, there are several haptic effects that can be applied to this simulation: gravity and antigravity forces can be applied to the cups, global damping can be provided for dynamic stability and to facilitate smoother movement patterns, and the three dimensions of the workspace can be calibrated to increase the range of motion required for successful completion of the task. The intensity of these effects can be modified to challenge the patients as they improve.

Figure 3 shows an example of the change in hand trajectories engendered through haptic guidance in a representative subject in the placing cup activity pre-



**Figure 3.** Motor training using haptic effects. (A) The dotted black line shows the reaching trajectory of a person with a stroke without any haptic effects, and the thick black line shows reaching trajectory of same subject during the same session performing the same activity using haptic damping and antigravity forces and a haptically rendered shelf. (B) The dotted black line shows the reaching trajectory of the same person performing the same task without any haptic effects; note the relatively smooth “up and over” reaching trajectory.

and post-training. **Figure 3A** depicts a side view of a trajectory generated without haptic assistance and another trajectory generated with additional damping and increased antigravity support. At the beginning of the training, the subject needed the addition of the haptic effects to stabilize the movement and to provide enough arm support for reaching the virtual shelf. However, **Figure 3B** shows that, after 2 weeks of training, this subject demonstrated a more normalized trajectory even without haptic assistance.

In a study of 12 subjects using this system, kinematic variables were tested pre- and post-training during the hammer task. The time needed to complete each hammering task decreased, showing a 47% change. The hand path decreased in length by 41% and improved in smoothness by 76%. The improvement in movement time and path length appears to be related to changes in proximal segment function, as finger extension did not change significantly. The improvements in smoothness are indicative of a decrease in the number of submovements required to complete the transport phase of the motion. Several authors cite this pattern of change as consistent with improvements in neuromotor control.<sup>29,30</sup> A decrease in endpoint deviation is an indicator of proximal stability. As a group, the subjects improved the proximal stability of the arm while the fingers were repeatedly extending during the hammering task, showing a 51% change. Lang and Beebe<sup>31</sup> cite the ability to maintain proximal segments stationary during distal task performance as an important construct in overall upper extremity functional ability.

Two tests of clinical arm and hand function were used pre- and post-training, the Jebsen Test of Hand Function (JTHF)<sup>32</sup> and the Wolf Motor Function Test (WMFT).<sup>33</sup> Six out of 12 subjects demonstrated a percentage improvement in their WMFT scores after 8 days of intensive training larger than 30% (range, 30–41), while the other half demonstrated smaller but still substantial percentage improvement (range, 10–24). The mean (95% confidence interval) decrease of 16 (13–22) seconds in the WMFT time substantially exceeds the reported group change of 2 seconds needed to be regarded as a clinically important difference on the WMFT.<sup>34</sup> The control subjects were able to complete the six activities of the JTHF on average in 33 seconds (95% confidence interval, 29–38 seconds) using their dominant hand and in 36 (31–41) seconds using their nondominant hand. The subjects with stroke required 49 (41–57) seconds to complete the six activities using their uninvolved hand and, when using their impaired hand, improved

from 122 (90–154) to 98 (66–129) seconds after training. Measures for the uninvolved hand and the controls were stable across the three time frames; only the hemiparetic hand showed improved scores after training.

## Discussion

Using this system, patients exercised the upper arm and hand of patients post-stroke using VR task-based gaming simulations. The subjects were more able to control their limb more effectively during interaction with the target as demonstrated by improved proximal stability and smoothness and efficiency of the movement path. This improved control was in concert with improvement in the distal kinematic measures of fractionation and improved timing. Importantly, these changes in robotic measures were accompanied by robust changes in the clinical outcome measures.<sup>35,36</sup>

The purpose of this article was to present several robotic systems interfaced with VR simulations and describe how they are currently being used to remodel motor behavior. The overarching goal was to provoke thought within the community dealing with diabetes, obesity, and their multiple sequelae to determine whether any of these new technologies would have a place in facilitating adherence to diet and exercise guidelines. However, there are many questions to be asked when considering extending this work beyond motor rehabilitation. Can the haptic effects and challenging feedback techniques that we have developed to facilitate motor learning and motor control be utilized in a different venue? The overarching question is whether this medium can be used for remodeling other behaviors and actions? Will these VR mediums help patients' motivation by encouraging them to spend sufficient time on strengthening exercises and aerobic activity in order to facilitate weight loss? Would people be willing to exercise for longer periods of time? Are there benefits to incorporating VEs and gaming simulations into traditional exercise equipment, or are special simulations and feedback needed? Can forces and haptic effects be incorporated into commercial VR gaming devices such as the Wii Fit? Would that provide greater energy expenditure when using the games?

An increase in strength has been demonstrated in people with neurological deficits using robots and specialized simulations and interfaces. But can these haptic robots be used to strengthen people with normal musculature? Can the robots that are used for gait training people with neurological deficits be used to provide resistance

during aerobic walking? Would that increase the energy expenditure and calories used? Perhaps robots can be utilized to accommodate the impact that morbid obesity has on a person mechanically. The ability to calibrate a movement or workspace based on the configurations of a person's body distorted by obesity or used to manage or decrease issues related to overuse and repetitive motion injures related to exercise for very obese people may be helpful. Adaptive algorithms in a robotic system could be used to gradually increase the movement amplitude, speed, and required physiologic work.

The use of VR technology for rehabilitation has moved beyond simply providing a motivating gaming environment that is suitable for intensive repetitive practice. Engineers in collaboration with clinical scientists are now developing "smart" simulations and robots that will work with the particular patient's deficits to modify the kinematics of the movement. Newer robotic controllers are becoming adaptive to the performance of the patient's motion. Technology is being embraced as a way to drive the nervous system for the rehabilitation of people with movement disorders. There are multiple ongoing clinical trials to determine the efficacy of these innovative technologies. In current society, exercise has become a programmed activity, more often done for health benefits than for its intrinsic fun and challenge. However, studies have shown that adherence to exercise programs was greater when enjoyment and challenge were a motivating factor as opposed to the goal of body-related outcomes.<sup>15</sup> It has not yet been determined whether these technologies will have a place in the treatment of obesity. Virtual reality and robotics may provide a motivating, challenging gaming experience with dramatically decreased (physical) difficulty levels. This could allow for participation by an obese person without the requisite movement abilities to participate in a comparable real-world activity.

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