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Robotics and Virtual Reality: A Perfect Marriage for Motor Control Research and Rehabilitation

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This article's goal is to outline the motivations, progress, and future objectives for the development of a state-of-the-art device that allows humans to visualize and feel synthetic objects superimposed on the physical world. The programming flexibility of these devices allows for a variety of scientific questions to be answered in psychology, neurophysiology, rehabilitation, haptics, and automatic control. The benefits are most probable in rehabilitation of brain-injured patients, for whom the costs are high, therapist time is limited, and repetitive practice of movements has been shown to be beneficial. Moreover, beyond simple therapy that guides, strengthens, or stretches, the technology affords a variety of exciting potential techniques that can combine our knowledge of the nervous system with the tireless, precise, and swift capabilities of a robot. Because this is a prototype, the system will also guide new experimental methods by probing the levels of quality that are necessary for future design cycles and related technology. Very important to the project is the early and intimate involvement of therapists and other clinicians in the design of software and its user interface. Inevitably, it should also lead the way to new modes of practice and to the commercialization of haptic/graphic systems.

Key Words: Human—Motor learning—Adaptation—Human-machine interface—Teaching—Neurorehabilitation.

INTRODUCTION

Recently, we have begun developing and combining state-of-the-art devices that allow humans to visualize and feel synthetic objects superimposed on the physical world for the purposes of rehabilitation. This effort stems from the need for a device that extends the current capabilities for exploring how the brain controls movements, learns new movements, and recovers movement skills after an injury. What is needed is a device that makes it possible to produce large, three-dimensional, realistic human motor tasks and environments, not currently represented in the practice of research. The platform under development, the Virtual Reality Robotic and Optical Operations Machine (VRROOM), is an augmented reality system combined with a haptic-interface robot. It is developed as a general tool for scientific exploration and eventually stroke rehabilitation. Because this is a prototype, the system will also shape new experimental methods by probing the levels of quality necessary for future design cycles and related technology. Inevitably, it should also lead the way to commercialization of systems that can simultaneously render haptics and graphics. This article's goal is to outline our motivations, progress, and future objectives, as well as to invite other researchers in related fields to join in the development.

MOTIVATIONS FOR DEVELOPING A NEW TECHNOLOGY

Need for a New Scientific Test Bed

The emergence of new robotic devices designed to interface with humans has led to great strides in both fundamental and clinical research on the sensory motor system. The programming flexibility of these devices allows for a variety of scientific

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questions to be answered in psychology, neurophysiology, rehabilitation, haptics, and automatic control. For example, simple planar robots have been used to identify the impedance properties of moving limbs (Acosta, Kirsch, & Perreault, 2000; Franklin, Burdet, Kawato, & Milner, 2003; Franklin & Milner, 2003; Gomi & Kawato, 1996, 1997; Kearney & Hunter, 1990; Mussa-Ivaldi, Hogan, & Bizzi, 1985; Shadmehr & Mussa-Ivaldi, 1993; Perreault, Kirsch, & Acosta, 1999), an important step in the understanding of how humans interact with their environment and with machines. Haptic/graphic devices have also been used to test hypotheses about how the nervous system controls movement (Ariff, Donchin, Nanayakkara, & Shadmehr, 2002; DeJong, Colgate, & Peshkin, 2004; Ernst & Banks, 2002; Fasse, Hogan, Kay, & Mussa-Ivaldi, 2000; Gottlieb, Chen, & Corcos, 1996; Hanneton, Berthoz, Droulez, & Slotine, 1997; Mah, 2001; Mah & Mussa-Ivaldi, 2003; Reinkensmeyer, Lum, & Lehman, 1992; Robles-De-La-Torre & Hayward, 2001; Shadmehr & Wise, 2005; Srinivasan & LaMotte, 1995) and have also been used to test how people adapt under altered environmental conditions (Conditt, Gandolfo, & Mussa-Ivaldi, 1997; Conditt & Mussa-Ivaldi, 1999; Franklin & Milner, 2003; Karniel & Mussa-Ivaldi, 2003; Milner, 2002; Novak, Miller, & Houk, 2003; Osu, Burdet, Franklin, Milner, & Kawato, 2003; Patton & Mussa-Ivaldi, 2004; Shadmehr & Holcomb, 1997; Shadmehr & Moussavi, 2000; Shadmehr & Mussa-Ivaldi, 1994; Tong, Wolpert, & Flanagan, 2002; Wei & Patton, 2004; Wolpert, Ghahramani, & Jordan, 1994, 1995). In our and others' laboratories, the common device used is a horizontal robotic device with two degrees of freedom and a visual feedback display (Fig. 1).

However, much of this research has been constrained by the limitations of available technologies. Most systems are one or two degrees of freedom and hence do not allow the complex behavior seen in everyday tasks. They involve a visual display that often does not realistically overlay the actual motion. To achieve significant advances in the diverse fields, the next generation of human-interface robots must be stronger, operate in three dimensions, be safe, and be back drivable (i.e., allow the user to easily push back). They must also move within a larger workspace and have an accompanying three-dimensional visual interface (Fig. 2). Currently, there are no devices made that meet all of these requirements. These functionally oriented requirements become even more important when considering the importance of extending the use of these devices for rehabilitation.

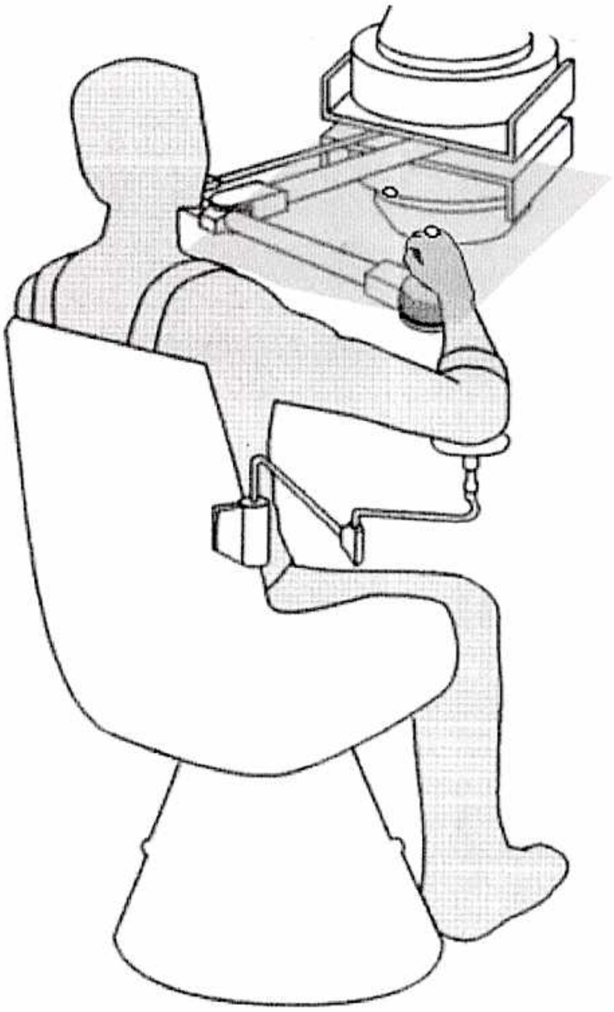

FIG. 1. Participants held the end point of a two-degree-of-freedom robot. Human-machine interface forces were monitored with a load cell fixed to the handle of the robot (Assurance Technologies Inc., Model F/T Gamma 30/100). The robot was equipped with position encoders that were used to record the angular position of the two robotic joints with a resolution exceeding 20 arc-s of rotation (Teledyne Gurley, Model 25/045-NB17-TA-PPA-QAR1S). The position, velocity, and acceleration of the handle were derived from these two signals. Two torque motors were used to apply programmed forces to the hand of the participants (PMI Motor Technologies, Model JR24M4CH).

Rehabilitation's Economic Landscape

Much of our motivation comes from the potential in the field of poststroke rehabilitation. The United States spends about $30 billion per year on physical rehabilitation, and the largest subgroup of this population (30%) consists of stroke victims (Matchar et al., 1993). The surviving stroke population in the United States is more than 3 million (Broderick, Phillips, Whisnant, O'Fallon, & Bergstralh, 1989), and roughly one third of all individ-

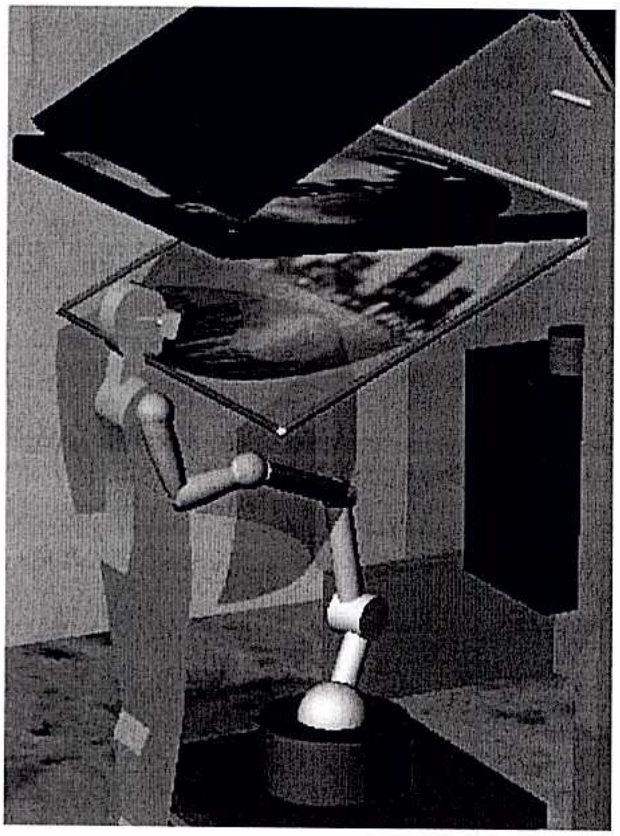

FIG. 2. Design concept of the Personal Augmented Reality Immersive System and robotic system. The participant should be able to either stand or sit in front of a large-workspace, three-dimensional robotic device and an accompanying three-dimensional display that allows the user to also see his or her own limb.

uals who experience a stroke will have some residual impairment of the upper extremity (Gray et al., 1990). Beyond age 55, the likelihood of stroke doubles every 10 years, and the number of people older than 60 years will increase by 10 million (22%) over the next 10 years. Survival rates from stroke continue to increase because of the improvement in acute medical care (Broderick et al., 1989). Labor costs comprise roughly 60% to 70% of rehabilitation costs, so if new technology could remove just 5% of the labor costs on 10% of stroke survivors, the savings would be $300 million. It would seem that it is only a matter of time before the economics of labor-intensive expenses give way to technological breakthroughs. Therefore, one application for VRROOM is to address such reductions in cost.

However, all these cost considerations are double-edged swords. Currently, there is too little money spent on labor for rehabilitation. It is a difficult task to establish waste in an economy, but a reduction of the patient's time with the therapist is certainly not optimal for brain-injured individuals. Instead, the technology should focus on patient benefit by enabling the therapist to be more productive and to allow for extended rehabilitation. Meanwhile, the money for therapy is being cut. Medicare's 2001 incentives encouraged a reduced length of stay. Moreover, despite the high cost of physical therapy, estimates are that each $1 thus invested in rehabilitation reduces future medical costs 11- to 35-fold (Dorland's Directory, 1998). We caution that the technology we present here can, of course, provide only a part of what technology as a whole might bring. In fact, technology in general can be only a part of any beneficial change. Nevertheless, one is compelled to acknowledge that there may be economic returns found in new treatments and more efficient treatment modalities, and the only way to determine if this is true is to pioneer the new technology and test it.

Massed Practice

Ironically, research supports the opposite and opposing course of action: early, intensive therapy or massed practice for stroke survivors (Sivenius, Pyorala, Heinonen, & Salonen, 1985; Taub, Uswatte, & Pidikiti, 1999), in which constraining the use of the less effected limb forces the use of the impaired limb (Nudo, 1999; Taub et al., 1993). This approach has been termed *constraint-induced therapy* (CIT; Pulvermuller et al., 2001). Recent research also supports "task-specific activity for rehabilitation," in which motions relevant to activities of daily living should be part of recovery (Dean & Shepherd, 1997; Nudo & Friel, 1999). Training on a variety of different tasks provides a better overall improvement in function than repetitions of the same task (Hanlon, 1996; Jarus & Gutman, 2001).

Beyond the recommended therapy that strengthens and stretches (Delisa & Gans, 1993), the process of neurofacilitation, or neuromuscular reeducation, through techniques that incorporate our knowledge of the circuitry of the nervous system has been asserted to be quite promising. The simple constraint-induced therapy technique, in which the unaffected upper extremity is restrained to encourage the use of the impaired limb, has been shown to be effective (Liepert et al., 2000; Taub, 2000; Taub et al., 1993). Neuroimaging and transcranial magnetic stimulation studies show that massed practice producing sustained activity on a single task is correlated with reorganization (Taub et al., 1999). Forced use of hemiplegic upper extremities has been shown to reverse the effect of learned nonuse among stroke and head-injured patients (Wolf, Lecraw, Barton, & Jann, 1989).

More recently, research has focused on testing derivates of the CIT concept that are more compatible with current clinical practice (Sterr, 2004). Different versions of CIT have increased affected arm use, clinical scores, and daily activities better than the control participants that received conventional therapy (Page, Levine, & Leonard, 2005) and have shown that it is effective when the same training is distributed over twice the number of days. Hence, several variations on the theme repeatedly have been shown to be effective. We assert that one obvious variation of CIT is the use of automated devices, such as the VRROOM system presented in this article, that could assist or even augment this process. It would appear that the consistent, tireless, precise, and swift capabilities of a robot certainly allow for such massed practice to take place. Moreover, computerized robotic devices also function as a data logger and as a limited assessment tool. However, even more exciting benefits exist when a device is coupled with a three-dimensional virtual reality display.

A Flexible, Controlled, and Changing Environment

Virtual reality (VR) is a head-tracked, stereovision, computer-generated environment that usually displays objects at arm's length. Augmented reality preserves some part of the real while mixing in virtual elements using a stereo display, by either back projecting on a wall or by placing artificial objects on see-through displays. For example, the VRROOM display we present below uses a large semireflective mirror to superimpose images on the field of view, allowing the user to see his or her own arm and see artificial objects.

Why use virtual or augmented reality? Why not just employ physical objects and environments found all around us? This is a question that often arises in discussions with therapists. Indeed, it would appear much easier and more direct to study how a participant handles a physical glass of water instead of a simulated one. The main answer to this question is flexibility. We can easily envision a robotic system coupled with an advanced display allowing very rapid presentation of various rehabilitation tasks without any lengthy set-up and break-down time.

The more important motor tasks involve acting on objects in the environment. Deceivingly simple actions such as carrying a cup of water to the mouth, squeezing toothpaste on a toothbrush, or tying one's shoes become excruciatingly difficult after a stroke that affected the motor areas of the brain. At present, we are facing the double challenge of understanding the basic mechanism involved in such interactive tasks (Dingwell, Mah, & Mussa-Ivaldi, 2002; Mah & Mussa-Ivaldi, 2003) and of developing effective strategies for skill recovery after a variety of neuromotor disorders. In both cases, physical properties of the objects need to be changed in an instant. This element of surprise is critical for studying how the sensorimotor system reacts and adapts to novel situations, and it is also useful for rehabilitation. A glass of water might have a transition from full to empty or be replaced with a solid mass. The properties of objects may be directed to violate natural physical laws. For example, friction can be altered or suppressed, or the inertial properties of the glass of water can be reduced while the patient is in the early stages of recovery, with increasing challenge as the patient recovers function.

Distortions That Challenge the Nervous System

Distortions can be programmed to go far beyond the simple idea of making the physical system easier to manage. Recent work in our laboratory suggests that distortions that amplify the errors of stroke survivors leads to beneficial results in a short amount of time (Patton, Phillips-Stoykov, Stojakovich, Rymer, & Mussa-Ivaldi, 2004). Moreover, the human brain and spinal cord remain modifiable, even in the adult and even following many brain injuries. This modifiability is referred to as neuroplasticity. It indicates that the structure and function of the brain can be altered continuously in response to sensory stimulation and changing physical environments. Interestingly, this process appears to bypass conventional learning mechanisms that require intense concentration; results are the same if there is conversation or background music, and it is often considered a game.

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Recent work exploits the adaptive properties of the nervous system for rehabilitation (Patton, Mussa-Ivaldi, & Rymer, 2001a, 2001b). The natural adaptation process is most evident when training forces are unexpectedly removed, revealing after effects. Training forces can be appropriately designed using a model of a patient's motor deficits so that after a training session, there is a straightening or smoothing of motions to a healthier pattern. This introduces a novel way to teach movements—one that does not require explicit instruction or a large amount of attention. Recent research suggests such techniques trigger the recovery process (Patton et al., 2001a; Raasch, Mussa-Ivaldi, & Rymer, 1997; Rossetti et al., 1998; Weiner, Hallett, & Funkenstein, 1983). This suggests that plasticity is a pivotal discovery in neuroscience relevant to rehabilitation because it is likely to be the primary mechanism that underlies recovery from chronic neurological illness. Devices that encourage plasticity can also be used with drugs that might further enhance the effects.

Testing Therapeutic Theories

Haptic/graphic systems are also useful for objectively and accurately testing therapeutic efficacy. One interesting example is that two roughly conflicting theories have been proposed for clinical treatment. One source suggests that assisting or reducing errors during reaching movements may contribute positively to rehabilitation (Bobath, 1978). Robotic techniques have been employed to provide assistance by guiding (pulling) the hand toward the desired trajectory (Lum, Burgar, Shor, Majmundar, & Van der Loos, 2002; Volpe et al., 1999). However, other sources suggest resisting the reaching movements (Voss, Ionta, & Myers, 1985). Although these approaches are in some ways mutually exclusive, their efficacy has not been tested objectively, and the more effective rehabilitation algorithm(s) have yet to be determined. An objective, three-dimensional system with a large enough workspace has not yet been available to put these ideas to the test. The VRROOM system described below would be the first of its kind allowing the range of possibilities described above.

Our preliminary evidence on the simpler robotic devices has also allowed us to propose and test whole new theories for therapy that were not possible without technology. Making movements more difficult during training can lead to faster and greater motor learning in the healthy and movements in stroke survivors. The haptic/graphic system allows us to expose participants to these types of experiences that do not occur in nature, a process we are now calling distorted reality (DR). Distortions of a variety of devices have been shown to powerfully encourage the nervous system to adapt (Goodbody & Wolpert, 1999; Imamizu et al., 2000; Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003; Lateiner & Sainburg 2003; Miles & Eighmy, 1980; Rossetti et al., 1998; Sainburg, Lateiner, Latash, & Bagesteiro, 2003; Sainburg & Wang, 2002; Wang & Sainburg, 2004). Techniques have already been attempted in rehabilitation, in which errors are magnified to encourage the nervous system to compensate, and the judicious manipulation of error (through mechanical or visual distortions) can lead to desired changes by inducing adaptation (Brewer, Klatky, & Matsuoka, 2005; Emken & Reinkensmeyer, 2005; Patton, Phillips-Stoykov, Stojakovich, & Mussa-Ivaldi, 2005; Wei, Bajaj, Scheidt, & Patton, 2005).

Related Technology

Substantial work has been under way elsewhere that moves in the same direction as our project. Haptic and/or graphic rendering has ranged from portable palpable machines (O'Modhrain, 2004) to robotic devices designed to collaborate with humans (Colgate, Wannasuphoprasi, & Peshkin, 1996) to devices like ours that probe the nervous system by combining graphics with a haptic robotic device (Goodbody & Wolpert, 1999; Ernst & Banks, 2002). Yet another possible approach is to create a wearable system (Luo, Kenyon, Waldinger, & Kamper, 2005; Sanchez et al., 2004). At the time of writing this, we are aware of two commercial devices that are similar to VRROOM (although many others are likely to exist as well): the Reach-In system (ReachIn, Stockholm, Sweden; http:www.reachin.se/) and the ImmmersiveTouch (Industrial Virtual Reality, Inc., Chicago, IL; http://www.ivri.com). However, these devices are scaled down and do not provide the strength, size, or modular approach that we incorporate for full ranges of movement and practicing everyday activities in an immersive environment.

DESIGN DESCRIPTION

This section provides a detailed description of the VRROOM system. The challenge is to develop a robot-assisted rehabilitation device for upper-limb rehabilitation of brain-injured individuals (Fig. 2). Preliminary research on more limited devices has shown great promise in aiding and improving clinical rehabilitation (Burgar, Lum, Shor, & Van der Loos, 2000; Fasoli, Krebs, Stein, Frontera, & Hogan, 2003; Kahn, Lum, & Reinkensmeyer, 2003; Krebs et al., 1999; Krebs, Hogan, Aisen, & Volpe, 1998; Krebs, Volpe, Aisen, & Hogan, 2000; Lum et al., 2002; Patton & Mussa-Ivaldi, 2004; Patton, Phillips-Stoykov, et al., 2005; Patton, ~~Stojakovich,~~ Phillips-Stoykov, & Mussa-Ivaldi, 2004; Reinkensmeyer et al., 2000; Stein et al., 2004; Volpe, Ferraro, Krebs, & Hogan, 2002; Volpe, Krebs, & Hogan, 2001). Although these devices were sufficient for controlled scientific studies,

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much of this research has been limited because it is small, weak, constrained to one or two dimensions, or lacking an appropriate visual display. To achieve significant practical application in rehabilitation, human-interface robots must safely operate in three dimensions with a large workspace and an appropriately designed visual interface. To implement this requirement, it is necessary to develop instrumentation allowing movement targets, feedback of force, or errors in movement. Most important, however, will be that the instrumentation superimposes images on the physical world, preserving the reality of everyday tasks. This implies the need to intimately combine a robotic device with a state-of-the-art display. The sections below describe the three main components of VRROOM we have developed: display, robotics, haptic, and software.

Display

Augmented Versus Immersive and Projection Versus Head Mounted

Currently, there are four forms of VR: head-mounted display, augmented, fish tank, and projection based (see ref. 1 and 2 for a review). A totally immersive VR system is the head-mounted display in which the participant sees only the computer-generated image (field of view of 120° horizontal × 90° vertical) and the rest of the physical world is blocked from view. Augmented VR systems often use head-mounted display technology; in these systems, both the computer-generated images and the physical world are visible to the participant. Here, computer images are overlaid on the physical world (e.g., Nomad, Microvision Inc.; Glasstron, Sony Inc.). In the so-called fish tank VR, the stereo images are produced on a monitor in front of the participant (3). These fish tank systems have limited fields of view and volume in which one may interact with the scene. Consequently, the resulting field of view is smaller than that found in other VE systems; therefore the accompanying pixel visual angle is smaller (i.e., better). These systems also lend themselves to the use of haptic devices in the performance of manual tasks (4).

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Personal Augmented Reality Immersive System

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The original Personal Augmented Reality Immersive System (PARIS) design, as proposed, was modeled and presented as a full-sized simulation in the CAVE (Johnson et al., 2000). The production PARIS was developed at the University of Illinois at Chicago at the Electronic Visualization Labs (http://www.evl.uic.edu). It employs a Christie Mirage field sequential stereo-enabled DLP projector and a double mirror-folded light path to illuminate the overhead high-contrast black screen. Their 2000 ANSI Lumen model is sufficient to generate acceptable brightness for this viewer near the screen application given the moderately high ambient lighting conditions of the modern office environment.

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The graphics displayed on the overhead screen are viewed as reflected in the sloping one-half silvered mirror presented at the user's shoulder height (Fig. 3). The robotic arm is manipulated within the volume below this mirror, the so-called augmented space. With this volume illuminated, the user sees his or her hand(s) with the graphics superimposed. Without illumination, only the graphics are visible. The slope of the one-half mirror can be adjusted to configure a variety of field of views, and the unit contains a motorized height adjuster to cover the range from seated to standing.

Robot

Back Drivability

Industrial robotic devices typically have a powerful mechanical advantage due to a transmission. This type of design provides strength while rejecting any external or inertial effects on the actions of the robot. Their problem is that the reverse possibility—the ability to push back on the robot, or back drivability—is not possible. Conversely, haptic robotic actuators have been built to have an extremely small mechanical advantage, meaning the user can easily push back and move the robot at the expense of strength. Such devices can be easily controlled with impedance control, in which the system is programmed to resist (or assist) based on a state feedback. However, servo control (moving the robot precisely thorough a series of positions) becomes difficult at low impedances, and high impedances become difficult without very strong motors. Admittance control is an alternative that allows this possibility. Here, a force sensor is used at the interface between the user and the robot, and the motions are entirely governed by the amount of force the user applies. However, the controllers have to be very fast and the sensors very accurate for such systems to be effective. One example is the HapticMaster robot described below.

Using Commercially Available Robotic Devices

We have currently been pursuing the robotic portion of our system using three commercially

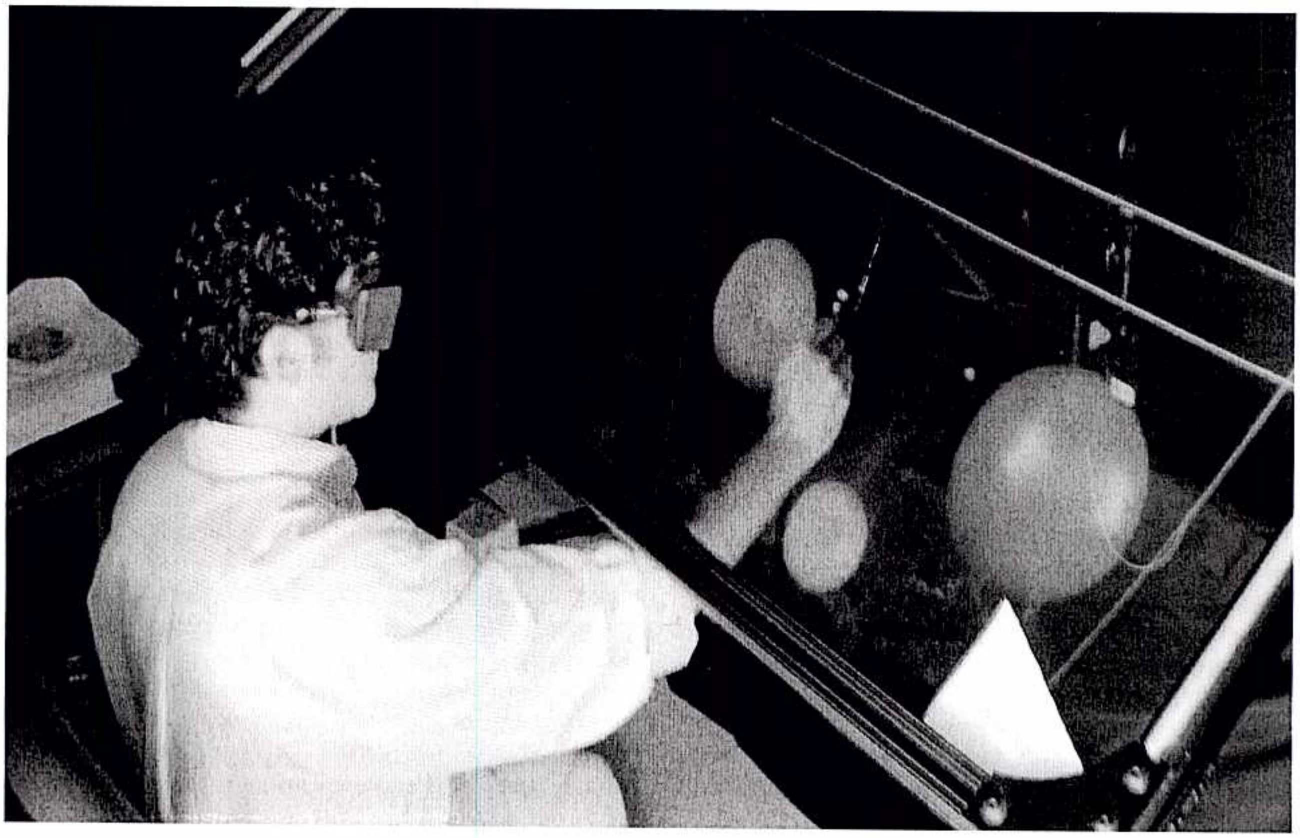

FIG. 3. Personal Augmented Reality Immersive System being used.

available robotic devices, each of which are specifically designed for haptic interaction with humans: the PHANTOM 3.0 (SensAble Technologies), the whole-arm manipulator (WAM; Barrett Technologies), and the HapticMaster (FCS Inc.). These are certainly not the only devices available but have been chosen because of their large workspace capabilities and their unique, human-oriented design. Their strengths and weaknesses make each of them suitable for different applications.

First, the PHANTOM 3.0, our current tool for development, is a large-workspace, light-touch device with an extensive library for control and rendering of haptic objects. The older GHOST library is currently being superseded by the more open and lower-level OpenHaptics library. The safety of such a device is ideal for developing a software package and testing ideas that may later be used on stronger systems that can provide large forces such as elevating a paralyzed arm against gravity.

The WAM robot is an evolving technology for which we are currently developing software tools. It offers more strength and yet is still back drivable. The WAM's enhanced safety fault tree is tied to a dynamic braking system that switches from a device that moves actively to a device that passively absorbs energy. It also allows the luxury of kinematic redundancy with independent control of up to seven degrees of freedom to avoid obstructing the participant's motions.

The HapticMaster is a large-workspace device with an extensive library for control and rendering of haptic objects. It is quite strong because of the mechanical advantages similar to an industrial robot and uses admittance control to accomplish its haptic display. It provides an excellent tool for accurate servo control of limb trajectories in space. By enforcing and/or perturbing motions, one can identify a person's dynamic properties by measuring his or her force responses, and from this, one can create a model that predicts a person's behavior (Acosta et al., 2000; Gomi & Kawato, 1996, 1997; Kearney & Hunter, 1990; Mussa-Ivaldi et al., 1985; Patton & Mussa-Ivaldi, 2002; Perreault et al., 1999; Shadmehr & Mussa-Ivaldi, 1993; Tsuji, Morasso, Goto, & Ito, 1995).

Tracking of Human Motion

Although the robotic devices can all provide highly accurate information about their segment positions and orientations, there is still a need to measure the motions of other parts of the human. The VRROOM system also integrates an Ascension Flock of Birds magnetic tracking system (Ascension Technology) that tracks and stores the position of markers anchored to relevant positions on the human participant. The VRROOM system currently has four sensors to track other body segments with continuous position and orientation information so that head, back/trunk, shoulder, upper arm, and lower arm segments can all be tracked. Our tests have shown that neither the aluminum parts of the PARIS system nor the electromagnetic radiation from the motors of the PHANTOM distort the readings of the magnetic tracking system. Rapid tracking and sharing of the head sensor position makes it possible for the display software to render the images that are appropriate for the current eye locations.

Software

Multithreading, Multiprocessing, and Using Separate Machines

Real-time interactivity requires rapid communication between the different components of the rehabilitation system. There are separate software components for haptic, graphic, and display control. First, the GHOST software toolkit provides an interface for controlling the PHANTOM robot and rendering forces (a haptic display). It initializes the robot, performs force calculations, and operates the servo loop. Second, the Coin3D (Systems in Motion) library implements the Open Inventor (TGS, Inc.) scene graph, and it provides a comprehensive range of graphics and interactive objects. The CAVE Library (VRCO Inc.) manages display parameters to establish the sense of depth and scale. These three components must interact with each other very closely and must therefore be present on a single machine. The GHOST and Open Inventor objects must be consistent so that a visible object has a corresponding graphics representation. The CAVE Library must use these objects when creating the stereo display.

Several strategies are possible for dividing the labor so that multiple programming tasks are shared efficiently. First, multiple threads can split separate tasks into separate and asynchronous subprocesses running on a single machine. A more extreme step is to simultaneously run multiple processes (programs) on the same machine. A still more extreme step is to use separate machines. To facilitate the group of tracking and robotic devices as well as any other new devices that might be integrated into VRROOM, we chose a flexible and modular strategy for communicating. TrackD software (VRCO Inc.) reports information from external devices to shared memory with the main application. The main application administers a graphic display thread and data collection (Fig. 4). TrackD can operate on a separate computer connected to a server on the host or it can run on the host machine as a separate process. The signals it acquires and sends to the rest of the system is simply a matter of writing a TrackD module. This separates the job of device data acquisition and control from the rest of the actions of the system and makes it easy when a new device comes on the scene. We currently have tested this concept on the CyberGlove (Immersion Technologies) and the Wanda 3D mouse (VRCO; Fig. 4).

Although the haptics and graphics threads run within the same process on one machine, they must contain consistent representations of what the user should feel and see. The robot's thread must quickly communicate with the display thread so that graphics are synchronized with the robot's state. Libraries must be set to convert and use a consistent set of units and coordinates (nearly all devices differ). Currently, geometry is duplicated between the haptic and graphic scene graphs, so that a haptic sphere with a radius of 10 mm corresponds to a identical graphic sphere; however, as was already mentioned, distorted discrepancies between the two systems are also possible. Calibrating the graphics display places these two objects in the same location. Users feel the surface of a sphere as they move the robot's stylus along the surface of its graphic. The robot updates its position as reported by GHOST, and copying that information to the Coin3D scene graph quickly updates the graphics to correspond with the robot's movements.

Cranial Implant Design Application

The PARIS display and these software techniques with a small robot were first put into place for research at the University of Illinois at Chicago (Scharver, Evenhouse, Johnson, & Leigh, 2004a, 2004b). In that application, the device was used for interactive sculpting of custom human skull implants for people with severe skull damage. This replaces a lengthy and costly process of sculpting and casting. Using medical computed tomography data of the patient's skull, a medical sculptor can feel the contours of the skull and shape the implant that appropriately fits.

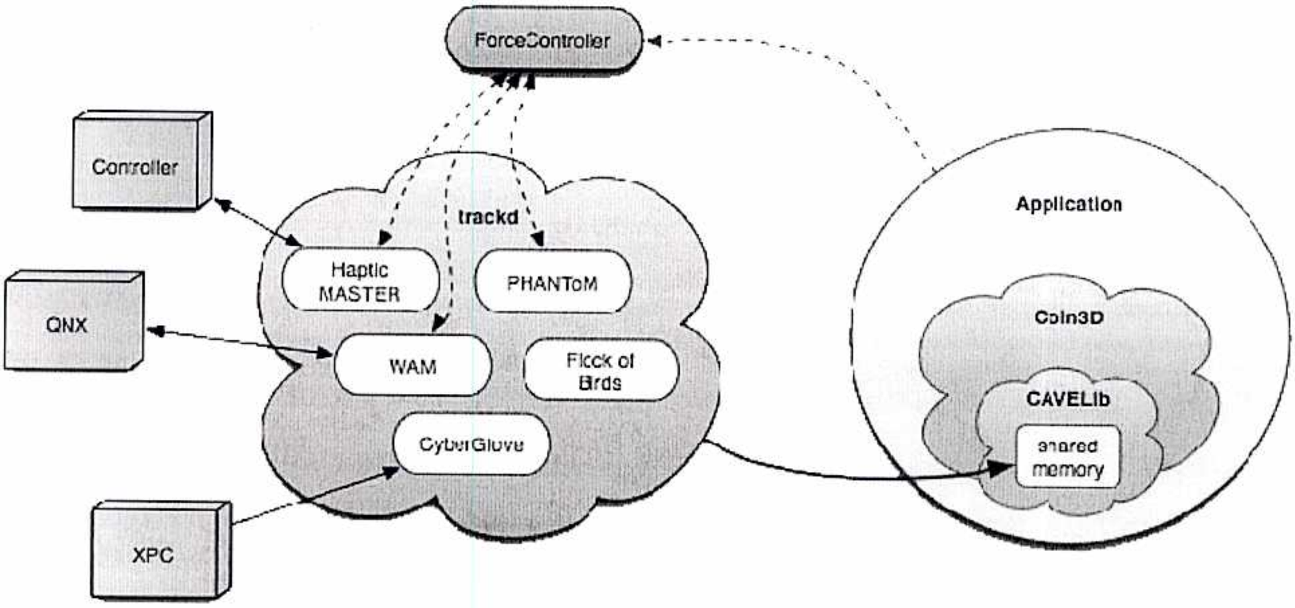

FIG. 4. Details of our process's implementation. The application's main process launches additional threads for handling both graphics and haptics. The haptics calculations and robot controls are handled by the PHANTOM'S GHOST SDK for haptics (currently being replaced by the OpenHaptics Library). GHOST spawns a separate thread that runs the haptics simulation. It provides callbacks allowing other parts of the application to access state information. These callbacks are used to update the graphics displayed to represent the environment. The CAVE Library creates a separate display thread for the Personal Augmented Reality Immersive System screen. The main thread logs information to disk and oversees the experimenter's interface, but otherwise, it does not directly control the graphics or haptics after those secondary threads have been created.

Neurorehabilitation Applications

Our philosophy to involve rather than exclude the therapist by providing choices that the therapist can decide upon on a patient-need basis: a library of rehabilitation programs. Involving the end users (clinicians, technicians, and patients) will result in a more relevant design with faster acceptance. This established an iterative process of needs specification, design, construction, testing and evaluation, outcomes assessment, needs specification, and so on. Before developing a family of programs, we want to ensure that the system is engaging, comfortable, and agreeable to the user. Issues such as contractures and weakness will be understood only by the developers once these issues are addressed and patients actually use the VRROOM system. Our current work focuses on three types of respondents (engineers, clinicians, and stroke survivors) and will review the system in two phases (focus groups followed by operational surveys). We seek to address three main concerns: (a) sentiment (we are interested in preconceptions, intimidations, reservations, and willingness to accept and tolerate such a system), (b) feedback on the design (is the system comfortable and sensible for use with patients and reasonable in its mechanical capabilities, or are alterations required for clinical use?), and (c) what programs should be developed (are there ideas we have not thought of, are our ideas sensible, and what is the priority for the programs to be developed?).

Although there are several different philosophies for the appropriate programming, all therapeutic work has focused on two major categories of foundational programming: assistive and resistive. Assisted movements can move the limb while the patient remains relaxed and maintain the range of motion in joints and flexibility in muscle and connective tissue. This may also serve to help the patient retain or reestablish important proprioceptive information. Beyond this, active-assist therapy is used in cases in which the patient cannot complete a movement independently. Resistive movements can be as simple as strength training or as complex as the previously mentioned forces that amplify error or retrain the nervous system. As already mentioned, haptic/graphic systems allow us to expose persons to these types of experiences that do not occur in nature, a process we are calling distorted reality (DR). We are now investigating how different sensory-motor distortions influence learning in healthy individuals and recovery in individuals who have suffered neurological injury.

PRELIMINARY EXPERIMENT ON MOTOR ADAPTATION

As an initial investigation that also demonstrates the capabilities of the system, we tested the system's ability to alter the way people move using repetitive training in the presence of haptic forces. We tested the hypothesis that, at the very least, the new system can produce results that we find using the precursor—the planar manipulandum robot—that has been used in many previous research studies [8]. As one might expect, this initial study investigates changes in healthy individuals but should pave the way to more sophisticated applications in rehabilitation on pathological populations.

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4, Patton et. al., 2006)

Experimental Methods

Four healthy young adults volunteered and signed informed consents based on Northwestern University guidelines. Each performed a total of 828 movements on the device, reaching targets at a fast pace. Each target was 10 cm from the previous target in a small region in front of the user. All handle movements and targets were haptically constrained to the horizontal plane at chest height. The experiment was broken into the following phases:

- 90 movements unperturbed to establish a baseline pattern
- 372 training movements with constant exposure to the so-called curl force field, which pushes the hand proportional to the hand's speed and counterclockwise to the direction of motion
- 252 movements with random, intermittent, and unexpected removal of the force field every one in eight trials (catch trials). These catch trails reveal the after effects of adaptation and are compared to the participant's baseline trails to measure the amount of learning
- 120 movements without any force, to show how the after effects of adaptation wash out and the participant de-adapts

Force and motion data were stored at 100 Hz.

Results

The resulting trajectories collected on the haptic augmented reality system (Fig. 5) did not differ significantly from those collected on the manipulandum robot. Participants made nearly straight movements when undisturbed (Fig. 5A). The force field disturbed hand movements in all participants early in training (Fig. 5B), but original movement patterns were recovered later (Fig. 5C). After effects were evident as large deviations from a straight line when the forces were removed (Fig. 5D), which slowly washed out after returning to the unperturbed condition (Fig. 5E).

Although these results repeat only previous scientific contributions that show the ability of the nervous system to adapt (Gandolfo, Mussa-Ivaldi, & Bizzi, 1996; Patton, Phillips-Stoykov, et al., 2005), these results are an important departure point for many other more exciting studies in three dimensions. Most important, they make it possible to expand the prior neurorehabilitation studies that were conducted in a simple scientific test bed (from planar robots). Procedures can now be extended to activities of daily living in a large, three-dimensional workspace. This device is an initial platform that will, it is hoped, provide a platform for exploring how the nervous system controls movements, teaches new movements, explores novel strategies for training and rehabilitation, assesses and tracks functional recovery, and tests and challenges existing theories of rehabilitation.

FUTURE APPLICATIONS

Future work will explore the kind of haptic and visual distortions (DR) that actually have therapeutic merit. One question that we seek to answer is whether movements that a stroke survivor makes can be permanently restored to a more healthy movement pattern by amplifying his or her errors. For example, a movement that is 2 cm to the left may be pushed farther to the left proportionally. Another possibility is that the display system displays a cursor that shows the hand position to be 4 cm to the left (rather than the actual 2 cm), thus amplifying the visual feedback of error. Recent research in our group has shown promising results with several different types of error augmentation (Patton, Phillips-Stoykov, et al., 2005; Wei et al., 2005). This work is supported by the facts that (a) theoretically proposed learning models learn better and faster if the error is larger (Kawato 1990; Lisberger, 1988; Rumelhart, Hinton, & Williams, 1986), (b) augmenting error may heighten motivation, and (3) augmenting error can raise the signal-to-noise ratio for feedback, hence heightening self-evaluation.

Another strategy we intend to explore further is to "trick" people into trying a new movement strategy. After a brain injury, survivors often have the

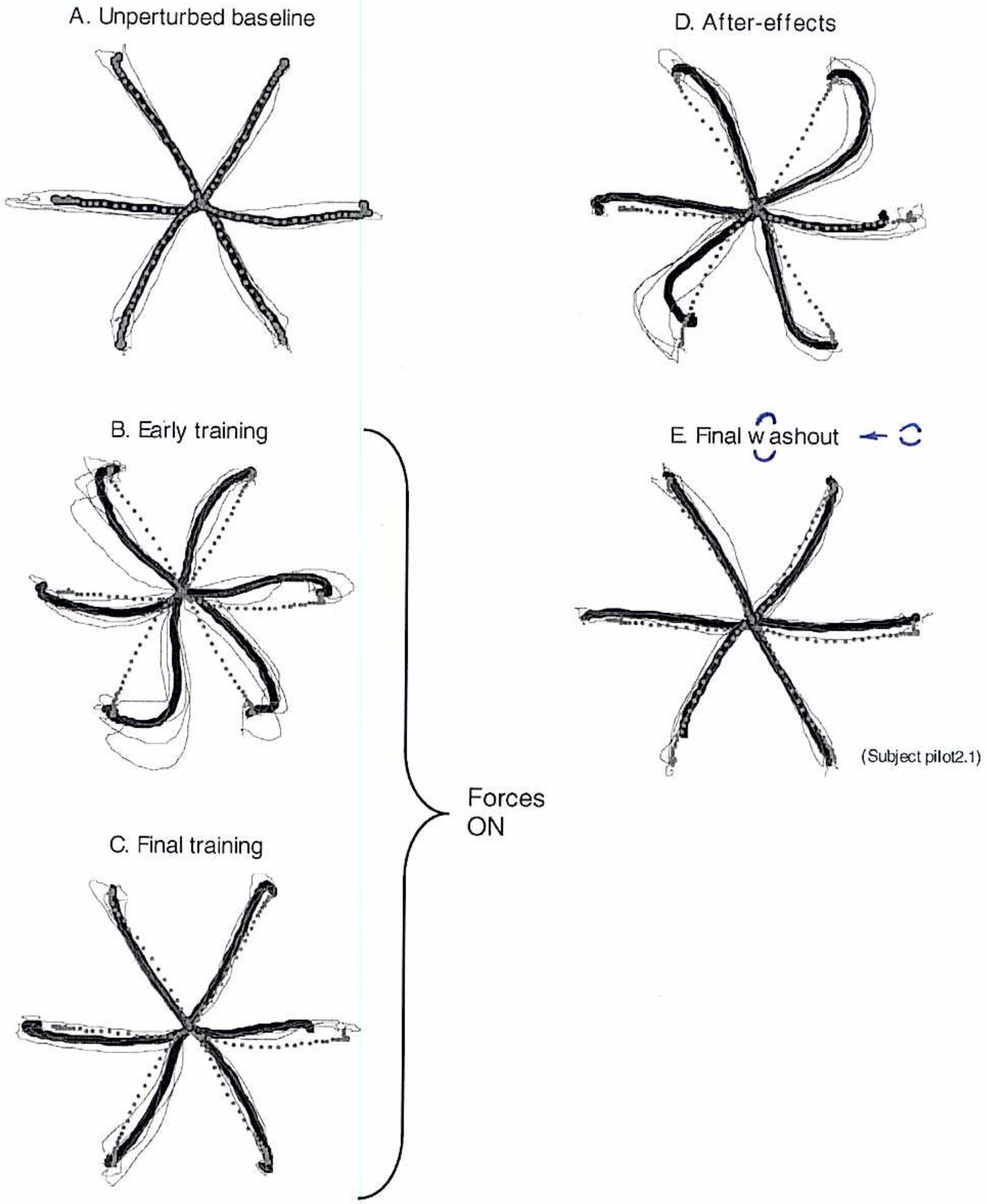

FIG. 5. Results of movements that illustrate the system's ability to cause a participant to adapt to haptic forces. Each plot shows movements from successive phases of the experiment. Hand trajectories in the horizontal plane are plotted as thin lines. Bold lines indicate average trajectories. Dotted lines show the average baseline pattern that was initially observed in (Fig. 5A) for comparison. Exposure to a force caused participants' motions to be distorted counterclockwise (Fig. 5B), which, through 372 practice movements, return to the normal pattern (Fig. 5C). Movement traces without forces seen in the catch trials (Fig. 5D) are dramatically different than those seen in (Fig. 5A) because of the results of training. Participants deadapted back to their original pattern after the forces had been off for 120 movements (Fig. 5E).

confusing challenge of making use of fewer remaining motor pathways that descend from the brain. The brain attempts to send conventional (preinjury) motor command signals, which are now ineffective because of the injury. Training methods that repetitively push on the limb in the right way can coax the nervous system to explore motor strategies that are not intuitively obvious, leading to a motor epiphany. We have found this to be the case with our two-dimensional robot (Patton, Kovic, et al., 2005), in which participants made straighter movements to targets after we removed the training forces. In this scenario, the nervous system is essentially shown the right way to execute the task, much like a coach might get an athlete to try a new nonintuitive strategy.

SUMMARY AND CONCLUSIONS

When one considers the need for extended therapeutic practice combined with the inevitable progress in the areas of computers, haptic systems, and display technology, therapeutic devices for resorting function are bound to be a part of rehabilitation. This device—VRROOM—is a developmental initial platform that we hope will provide a platform for exploring how exploring how the nervous system controls movements, teaches new movements, explores novel strategies for training and rehabilitation, assesses and tracks functional recovery, and tests and challenges existing theories of rehabilitation. Furthermore, this prototype should determine the necessary quality levels for future design cycles and related technology. Inevitably, it should also lead the way to new modes of clinical practice and to the commercialization of such systems.

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