Motivating Rehabilitation by Distorting Reality*

James Patton, Yejun Wei, & Chris Scharver
Sensory Motor Performance Program (SMPP)
Rehabilitation Institute of Chicago
Chicago, Illinois USA 60611
j-patton@northwestern.edu

Robert V. Kenyon
Electronic Visualization Laboratory (EVL)
University of Illinois at Chicago
Chicago, Illinois, USA

Robert Scheidt
Dept. of Biomedical Engineering
Marquette University
Milwaukee, Wisconsin, USA

***Abstract* – We have found, through a series of recent experiments, encouraging evidence that the neuro-motor system is motivated to change motor patterns when exposed to visuo-motor tasks. We have also shown that the learning of these tasks can be heightened with forces and/or visual distortions that appropriately manipulate the error. This process does not require intense concentration and it is often considered a game. We describe the next generation of robotic large-workspace, three dimensional haptics/graphics systems for rehabilitation.**

***Index Terms* – learning, adaptation, rehabilitation, human, stroke.**

I. INTRODUCTION

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. Research has recently answered questions relevant to rehabilitation, haptics (the study of artificially rendering touch), motor control, and human-machine interactions. Most importantly these devices have shown how humans adapt under altered environmental conditions [1-8]. Here we focus on experiments and technology to harness the adaptive process for rehabilitation.

The recovering nervous system, such as in an individual who has suffered a stroke, is an excellent candidate for such adaptive training. The surviving stroke population in the US is over 3 million and growing [9], and roughly one-third of all individuals who experience a stroke will have some residual impairment of the upper extremity [10]. Labor costs for rehabilitation comprise roughly 60 to 70% of what the U.S. spends – about $30 billion per year [11]. If new technology could remove just 5% of the labor costs on 10% of only the largest population (stroke survivors, about 30%), the savings would be $300 million. Although Medicare's 2001 incentives are for shortening the length of stays and of therapy in hospitals, recent studies support intensive therapy or "massed practice" for stroke survivors [12, 13] and the constraint of the less-effected limb [14, 15]. It would appear that the tireless, precise, and swift capabilities of a robot certainly allow for massed practice while simultaneously logging progress.

Moreover, the human brain and spinal cord remain modifiable, even in the adult, and even following many brain injuries [16-20]. This neuroplasticity indicates that the structure and function of the brain can be altered continuously in response to sensory stimulation and changing physical environments. Plasticity is a pivotal element of neuroscience and rehabilitation, since it is likely to be the primary mechanism that underlies recovery from chronic neurological illness. Devices that encourage and facilitate plasticity can also be used with drugs that further enhance the effects. Thus, it makes good sense to study new and more efficient treatment involving technology, robots, and virtual reality.

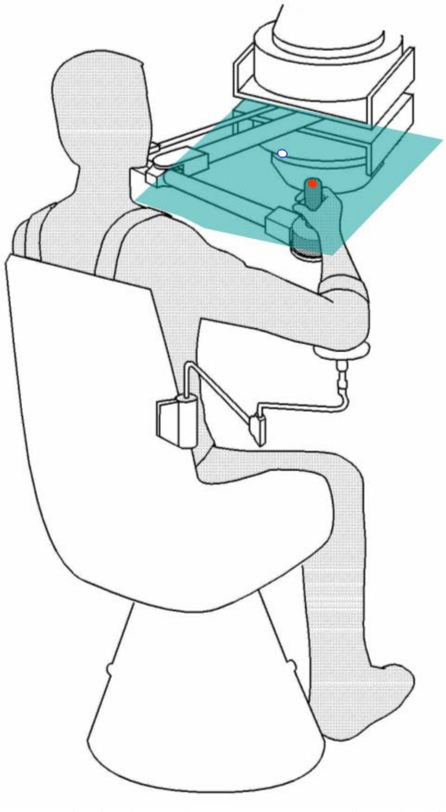

Fig. 1. Planar manipulandum robot. Forces are monitored with a load cell at the handle (ATI F/T Gamma30/100) and encoders record position (Teledyne Gurley 25/045-NB17-TA-PPA-QAR1S). Motors (PMI JR24M4CH) render forces at the subject's hand.

---

* This work is partially supported by American Heart Association 0330411Z, NIH R24 HD39627, NIH 5 RO1 NS 35673, NIH F32HD08658, NSF BES0238442 and the Falk Trust.

New technology has made possible many new and imaginative possibilities for promoting adaptation. Robotic systems can be programmed to go far beyond the initial idea of limb guidance or making the physical system easier to manage (though these programs are important as well). Recent research suggests that making conditions more difficult can trigger functional recovery [21-26] and can “trick” the nervous system into certain behaviors by giving altered sensory feedback [27-33]. Interestingly, this adaptive 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.

The sections that follow present two examples that have shown promise for engaging and motivating recovery of function in individuals that have suffered a neurological injury.

II. ERROR AUGMENTATION

Several recent robot experiments on both healthy and on stroke survivors have revealed the encouraging result that improvements occurred when the training forces tended to magnify errors but not when the training forces reduced the errors or when the forces were not present at all [17]. This led us to further investigate by custom designing a force that was proportional to the error the subjects initially made [23, 34]. During training, the force amplified their initial error, but resulted in beneficial outcome (Fig. 2). A few (3 of the 13) subjects did not preserve their beneficial after-effects to end of the experiment, (i.e., they de-adapted much like healthy people do in such experiments), but the remaining majority of subjects preserved their benefit for 75 more movements, much longer than healthy people typically de-adapt (Fig. 3). We are currently working on a follow up study that involves repeated visits to determine retention and incremental gains.

An another experiment in healthy subjects focused specifically on the type of on the error augmentation strategy [35]. This revealed new insights for robotic teaching. Four groups of subjects that each trained on the planar robot (Fig. 1) with different types of error augmentation. Trajectory error from the ideal straight-lined movement were amplified on the visual display with a gain of *2, by *3.1 or by an “offset” -- a shift in their trajectory that did not depend on the current error.

We found that error-augmentation improved the rate and extent of motor learning of the visuomotor rotation (Fig 3). Furthermore, our results suggest that both error amplification and offset-augmentation may facilitate neuro-rehabilitation strategies that restore function in brain injuries such as stroke. Interestingly, increasing the amount of error augmentation so that it is too large appears to diminish the benefits (*3.1 in Fig. 3). There appears to be several ways that error augmentation is successful in speeding up learning. More experiments are needed to identify optimal conditions that capitalize on this phenomenon.

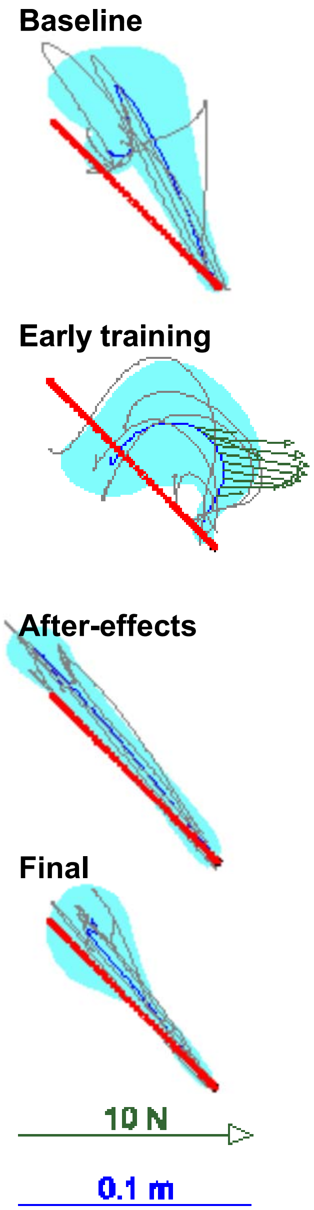

Fig. 2. Motions to one of the targets of a stroke patient in successive critical phases of an experiment. The thick lines represent average motion; thin lines represent individual reaching motion paths. Shaded areas are 95% confidence intervals; and dotted lines indicate ideal trajectories. Training forces (green arrows) were specially designed to cause a beneficial after effect. Although these forces were turned off for 120 movements after training (about 15 minutes) – 8 of the 11 stroke subjects retained the benefits (in the Final Phase) much longer than a healthy subject would have retained any adaptation effect. [Adapted from [34]].

In summary, distortions that reshape the visual (via a display) and mechanical (via a robot) experience can be designed to amplify error, and they result in desired changes in the motor learning process. These results led us to a new family of technology that takes these “testbed” experiments on the simple haptic/graphic display system to a more to functionally relevant, large workspace, three dimensional haptic/graphic system that can train individuals on everyday tasks.

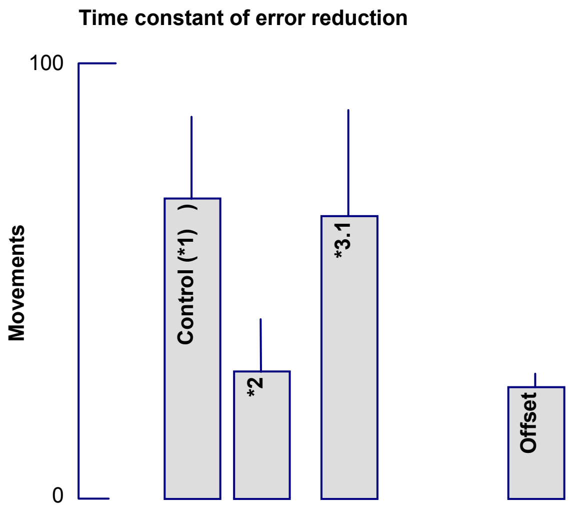

Fig. 3. Time constants of error reduction in healthy subjects (mean of subjects) for different types of error augmentation. The *2 & Offset groups learned in half the time. Error bars indicate the 95% confidence interval for all subjects in the group.

III. AUGMENTED REALITY TECHNOLOGY THAT ENGAGES THE PATIENT

Much of this research has been constrained by the limitations of available technologies. Most systems are small with 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. Recent research also supports “task-specific activity for rehabilitation,” in which motions relevant to activities of daily living should be part of recovery [16, 36]. In order to achieve significant advances in the diverse fields, the next generation of human-interface robots must be strong, large, three dimensional, safe, backdrivable (i.e., allow the user to easily push back) and have an accompanying three-dimensional visual interface. Our current development work focuses on such a system [37].

The Virtual Reality and Robotic Optical Operations Machine (VRROOM). VROOM is an integrated system combining virtual reality graphics environment, haptic robotic force feedback, and tracing of limb segments using a magnetic tracking system (Fig. 4). The system’s primary component is the visual display system, the Personal Augmented Reality Immersive System (PARIS), developed in the Electronic Visualization Lab at the University of Illinois at Chicago. PARIS is currently the highest quality see-through augmented display system available. Most virtual reality displays are computationally burdened by rendering an environment with objects that in the end often do not look that real. Consequently a display that is slow with long latencies can hamper performance even in the healthy [38-43] and cause motion sickness [44]. Furthermore, when one also is controlling a haptic robotic device, delays can lead to catastrophic instabilities [45, 46]. Our focus along with others [47-49] is on reducing the amount of processing. PARIS projects stereographic images onto a half-silvered mirror, allowing users to view virtual objects superimposed onto the real world. Through adjusting the relative lighting levels under the mirror, subjects are able to view their own limb and the actual environment, with only the artificial virtual elements that are needed [50]. Special design attention is given to brightness (luminosity), field-of-view, and resolution. A cinema-quality digital projector (Christie Mirage 3000 DLP) displays the images over five-foot-wide 1280x1024 pixel image resulting in a 110º viewing angle. Infra-red emitters synchronize the display of separate left and right eye images through LCD shutter glasses.

The VRROOM system also integrates an Ascension Flock of BirdsTM magnetic tracking system that tracks head position so that the visual display is rendered with the appropriate viewer-centered perspective. The magnetic tracking system currently uses two sensors to track other body segments with continuous position and orientation information. We propose to purchase two more sensors so that head, back/trunk, shoulder, upper, and lower arms segments can all be tracked. It is important to note 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.

The VRROOM system also integrates several robotic arms that suit different needs for generating end-effector forces or motions on varying scales. Two PHANToM robots (the Omni or the larger 3.0) provide a workspace measuring up to 900 x 900 x 300 mm with a maximum continuous force of 3 Newtons (N) with transient peaks of 22 N. The hardware-resident controller runs asynchronously with the computer, assuring stable, uninterrupted control. The WAM (Barrett Technologies) can be used for strong impedance control applications that require precisely controlled forces and torques. Finally, the Haptic Master (FCS technologies) can be used for strong admittance applications that require precisely controlled motions.

IV. SUMMARY, DISCUSSION AND CONCLUSIONS

This paper discusses adaptive training to teach movements that does not require explicit instruction or a large amount of attention, and can provide motivation simply by heightening the error and providing an immersive and engaging experience. Our experimental results all point to a single unifying theory: the judicious manipulation of error (through forces and/or visual distortions) can lead to lasting desired changes by inducing adaptation. 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. Based on ours and others’ inspirational studies, these systems inevitably should lead the way to new clinical practices and commercialization.

There are several possible causes for why not all patients appear to retain the benefits of adaptive training. First, it is possible that there are secondary, chronic contractures in the peripheral passive tissues, common in chronic stroke survivors. Such causes cannot be attributed to faulty motor programming and hence cannot be manipulated using adaptation. Second, shifts in movement patterns may have been “buried in the noise” of motor variability because higher variability is common for stroke survivors [17, 51-54].

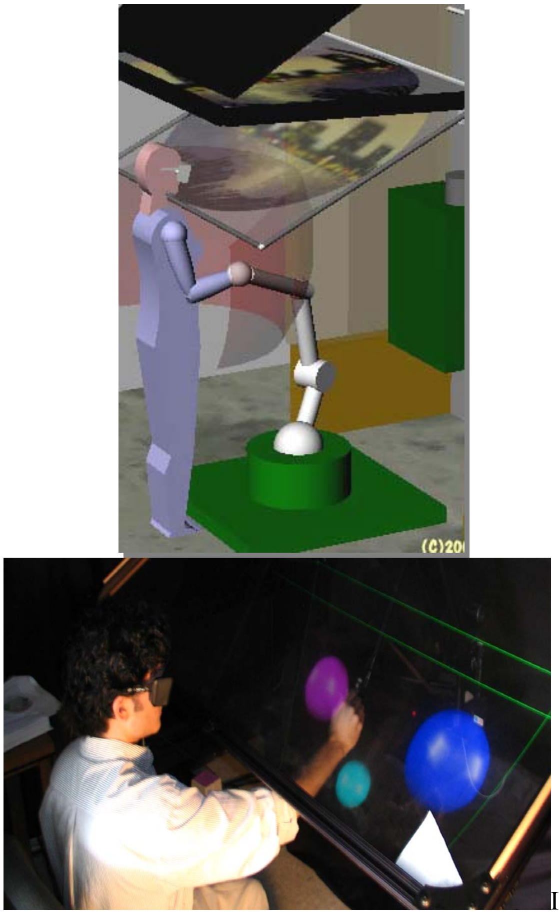

Fig. 4 Design concept of the VRROOM system, and the actual system being used. The subject should be able to either stand or sit in front of a large-workspace, 3-D robotic device and an accompanying 3d display that allows the user to also see their own limb.

IV. DISCUSSION

The reasons why adaptive training shows promise are not yet clear. One possible reason is that stroke survivors have fewer remaining motor pathways, and their new descending motor command signals are only a subset of their pre-injury signals, and are therefore inappropriate. Adaptive training may bring about a “motor epiphany,” much like how a coach gets an athlete to try the proper strategy. It is also possible that spastic activity can be reduced by such repeated training. Another possible reason may be that such learning is implicit, bypassing the areas of the brain that are affected by the injury. Implicit learning involves more primitive neural pathways [55-57], with more automatic recall [58]. Finally, the impaired nervous system may require larger errors to begin to change, and adaptive training may “wake up” the learning process. Intensifying error also leads to larger signal-to-noise ratios for sensory feedback and self-evaluation. In many artificial neural networks, the error signal drives the learning process [19, 59-62]. Hence, going beyond virtual reality to distorted reality such as error augmentation is currently of great interest to our group [37].

ACKNOWLEDGMENT

Thanks to Sandro Mussa-Ivaldi for his insights and participation in some of the studies mentioned. The authors thank Xun Lou for his assistance in some of the computer science and William Townsend of Barrett Technologies for some of his input on robotic theory.

REFERENCES

[1] M. A. Conditt, F. Gandolfo, and F. A. Mussa-Ivaldi, "The motor system does not learn the dynamics of the arm by rote memorization of past experience," *Journal of Neurophysiology*, vol. 78, pp. 554-560, 1997.

[2] R. Shadmehr and F. A. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *Journal of Neuroscience*, vol. 14, pp. 3208-3224, 1994.

[3] R. Shadmehr and Z. M. Moussavi, "Spatial generalization from learning dynamics of reaching movements," *Journal of Neuroscience*, vol. 20, pp. 7807-15, 2000.

[4] D. M. Wolpert, Z. Ghahramani, and M. I. Jordan, "Are arm trajectories planned in kinematic or dynamic coordinates? An adaptation study," *Experimental Brain Research*, vol. 103, pp. 460-70, 1995.

[5] R. Osu, E. Burdet, D. W. Franklin, T. E. Milner, and M. Kawato, "Different mechanisms involved in adaptation to stable and unstable dynamics," *J Neurophysiol*, vol. 90, pp. 3255-69, 2003.

[6] K. E. Novak, L. E. Miller, and J. C. Houk, "Features of motor performance that drive adaptation in rapid hand movements," *Experimental Brain Research*, vol. 148, pp. 388-400, 2003.

[7] T. E. Milner, "Adaptation to destabilizing dynamics by means of muscle cocontraction," *Experimental Brain Research*, vol. 143, pp. 406-16, 2002.

[8] D. W. Franklin and T. E. Milner, "Adaptive control of stiffness to stabilize hand position with large loads," *Exp Brain Res*, vol. 152, pp. 211-20, 2003.

[9] J. Broderick, S. Phillips, J. Whisnant, W. O'Fallon, and E. Bergstralh, "Incidence of rates of stroke in the eighties: the end of the decline in stroke," *Stroke*, vol. 20, pp. 577-582, 1989.

[10] C. Gray, J. French, D. Bates, N. Cartilidge, O. James, and G. Venables, "Motor recovery following acute stroke," *Age Aging*, vol. 19, pp. 179-184, 1990.

[11] D. B. Matchar, P. W. Duncan, G. P. Samsa, J. P. Whisnant, G. H. DeFriese, D. J. Ballard, J. E. Paul, D. M. Witter, Jr., and J. P. Mitchell, "The Stroke Prevention Patient Outcomes Research Team. Goals and methods," *Stroke*, vol. 24, pp. 2135-42, 1993.

[12] J. Sivenius, K. Pyorala, O. Heinonen, J. Salonen, and R. P, "The significance of intensity of rehabilitation of stroke - a controlled trial," *Stroke*, vol. 16, pp. 928-31, 1985.

[13] E. Taub, G. Uswatte, and R. Pidikiti, "Constraint-Induced Movement Therapy: a new family of techniques with broad application to physical rehabilitation--a clinical review. [see comments]," *Journal of Rehabilitation Research & Development*, vol. 36, pp. 237-51, 1999.

[14] E. Taub, N. Miller, T. Novack, E. d. Cook, W. Fleming, C. Nepomuceno, J. Connell, and J. Crago, "Technique to improve chronic motor deficit after stroke," *Archives of physical medicine and rehabilitation*, vol. 74, pp. 347-354, 1993.

[15] R. J. Nudo, "Recovery after damage to motor cortical areas," *Current Opinion in Neurobiology*, vol. 9, pp. 740-7, 1999.

[16] R. J. Nudo and K. M. Friel, "Cortical plasticity after stroke: implications for rehabilitation," *Revue Neurologique*, vol. 155, pp. 713-7, 1999.

[17] J. L. Patton, M. E. Phillips-Stoykov, M. Stojakovich, and F. A. Mussa-Ivaldi, "Evaluation of robotic training forces that either enhance or reduce error in chronic hemiparetic stroke survivors," *Experimental Brain Research*, vol. In press, 2005.

[18] C. G. Takahashi and D. J. Reinkensmeyer, "Hemiparetic stroke impairs anticipatory control of arm movement," *Experimental Brain Research*, vol. 149, pp. 131–140, 2003.

[19] N. Dancausea, A. Ptitob, and M. F. Levin, "Error correction strategies for motor behavior after unilateral brain damage: short-term motor learning processes," *Neuropsychologia*, vol. 40, pp. 1313-1323, 2002.

[20] J. Liepert, H. Bauder, H. Wolfgang, W. Miltner, E. Taub, and C. Weiller, "Treatment-induced cortical reorganization after stroke in humans," *Stroke*, vol. 31, pp. 1210-1216, 2000.

[21] M. J. Weiner, M. Hallett, and H. H. Funkenstein, "Adaptation to lateral displacement of vision in patients with lesions of the central nervous system," *Neurology*, vol. 33, pp. 766-72, 1983.

[22] C. C. Raasch, F. A. Mussa-Ivaldi, and W. Z. Rymer, "Motor learning in reaching movements by hemiparetic subjects," *Society for Neuroscience Abstracts*, vol. 924.17, pp. 2374, 1997.

[23] J. Patton, F. Mussa-Ivaldi, and W. Rymer, "Altering movement patterns in healthy and brain-Injured subjects via custom designed robotic forces," presented at IEEE-EMBC2001, the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), Istanbul, Turkey, 2001.

[24] Y. Rossetti, G. Rode, L. Pisella, A. Farne, L. Li, D. Boisson, and M. T. Perenin, "Prism adaptation to a rightward optical deviation rehabilitates left hemispatial neglect," *Nature*, vol. 395, pp. 166-9, 1998.

[25] J. L. Emken and D. J. Reinkensmeyer, "Robot-Enhanced Motor Learning: Accelerating Internal Model Formation During Locomotion by Transient Dynamic Amplification," *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, vol. in press, 2005.

[26] B. Brewer, R. Klatky, and Y. Matsuoka, "Perceptual Limits for a Robotic Rehabilitation Environment Using Visual Feedback Distortion," *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, vol. in press, 2005.

[27] M. A. Srinivasan and R. H. LaMotte, "Tactual discrimination of softness," in *J Neurophysiol*, vol. 73, 1995, pp. 88-101.

[28] M. Ernst and M. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, pp. 429-433, 2002.

[29] G. Robles-De-La-Torre and V. Hayward, "Force can overcome object geometry in the perception of shape through active touch," *Nature*, vol. 412, pp. 445-448, 2001.

[30] J. R. Flanagan and A. K. Rao, "Trajectory adaptation to a nonlinear visuomotor transformation: evidence of motion planning in visually perceived space," *Journal of Neurophysiology*, vol. 74, pp. 2174-8, 1995.

[31] B. R. Brewer, R. Klatzky, and Y. Matsuoka, "Effects of Visual Feedback Distortion for the Elderly and the Motor-Impaired in a Robotic Rehabilitation Environment," presented at IEEE International Conference on Robotics and Automation (ICRA), New Orleans, LA, USA, 2004.

[32] R. L. Sainburg, J. E. Lateiner, M. L. Latash, and L. B. Bagesteiro, "Effects of altering initial position on movement direction and extent," *Journal of Neurophysiology*, vol. 89, pp. 401-15, 2003.

[33] K. P. Kording and D. M. Wolpert, "Bayesian integration in sensorimotor learning," *Nature*, vol. 427, pp. 244-7, 2004.

[34] J. L. Patton, M. Kovic, and F. A. Muss-Ivaldi, "Custom-designed haptic training for restoring reaching ability to individuals with stroke," *JRRD*, vol. in press, 2005.

[35] Y. Wei, P. Bajaj, R. A. Scheidt, and J. L. Patton, "Visual Error Augmentation for Enhancing Motor Learning and Rehabilitative Relearning," presented at IEEE-International Conference on Rehabilitation Robotics (ICORR), Chicago, IL, USA, 2005.

[36] C. M. Dean and R. B. Shepherd, "Task Related Training improves performance of seated reaching tasks after stroke: A randomize controlled trial," *Stroke*, vol. 28, pp. 722-728, 1997.

[37] J. L. Patton, G. Dawe, C. Scharver, F. A. Muss-Ivaldi, and R. Kenyon, "Robotics and Virtual Reality: A Perfect Marriage for Motor Control Research and Rehabilitation," presented at IEEE Engineering in Medicine and Biology Society Conference (EMBC), San Francisco, CA, USA, 2004.

[38] S. Teal and A. I. Rudnicky, "A Performance Model of System Delay and User Strategy Selection," presented at Human factors in Computing Systems, 1992.

[39] A. Rushinek and S. Rushinek, "The Effects of Sources of Applications Programs on User Satisfaction: An Empirical Study of Micro, Mini, Mainframe Computers using an Interactive Artificial Intelligence Expert-System," presented at 21st Annual Conference on Computer Personnel Research, 1985.

[40] W. Kuhmann, W. Boucsein, F. Schaefer, and J. Alexander, "Experimental Investigation of Psychophysiological Stress-Reactions Induced by Different Response Times in Human-Computer Interaction," *Ergonomics*, vol. 30, pp. 933-943, 1987.

[41] R. E. Barber and H. C. Lucas, "System Response Time, Operator Productivity, and Job Satisfaction," *CACM*, vol. 26, pp. 972-986, 1983.

[42] G. N. Lambert, "A Comparative Study of System Response Time on Program Developer Productivity," *IBM Systems Journal*, vol. 23, pp. 36-43, 1984.

[43] B. O'Conaill, S. Whittaker, and S. Wilbur, "Conversations Over Video Conferences: An Evaluation of the Spoken Aspects of Video-Mediated Communication," *Human-Computer Interaction*, vol. 8, pp. 389-428, 1993.

[44] E. M. Kolasinski, "Simulator sickness in virtual environments," US Army Research Institute Technical Report 1027, 1995.

[45] E. Colgate and M. Brown, "Factors Affecting the Z-Width of a Haptic Display," presented at Proceedings of the 1994 International Conference on Robotics and Automation, IEEE, New York, 1994.

[46] Y. Adachi, T. Kumano, and K. Ogino, "Intermediate Representation for Stiff Virtual Objects," presented at IEEE Virtual Reality Annual International Symposium (VRAIS'95), 1995.

[47] M. Olano, J. Cohen, M. Mine, and G. Bishop, "Combatting Rendering Latency," presented at ACM 1995 Symposium on Interactive 3-D Graphics, Monterey, CA, 1995.

[48] B. Conner and L. Holden, "Providing a Low Latency User Experience in a High Latency Application," presented at Proceedings ACM 1997 Symposium on Interactive 3-D Graphics, Providence, RI, 1997.

[49] B. Watson, A. Friedman, and A. McGaffey, "Using Naming Time to Evaluate Quality Predictors for Model Simplification," presented at the CHI 2000 Conference on Human Factors in Computing Systems, 2000.

[50] C. Scharver, R. Evenhouse, A. Johnson, and J. Leigh, "Pre-surgical Cranial Implant Design using the PARIS_Prototype," presented at IEEE VR2004, 2004.

[51] B. E. Fisher, C. J. Winstein, and M. R. Velicki, "Deficits in compensatory trajectory adjustments after unilateral sensorimotor stroke.," *Experimental Brain Research*, vol. 132, pp. 328-44, 2000.

[52] D. J. Reinkensmeyer, M. G. Iobbi, L. E. Kahn, D. G. Kamper, and C. D. Takahashi, "Modeling reaching impairment after stroke using a population vector model of movement control that incorporates neural firing-rate variability," *Neural Computation*, vol. 15, pp. 2619-42, 2003.

[53] M. F. Levin, "Interjoint coordination during pointing movements is disrupted in spastic hemiparesis," *Brain*, vol. 119, pp. 281-93, 1996.

[54] R. F. Beer, J. P. A. Dewald, and W. Z. Rymer, "Deficits in the coordination of multijoint arm movements in patients with hemiparesis," *Experimental Brain Research*, vol. 131, pp. 305-319, 2000.

[55] S. T. Grafton, E. Hazeltine, and R. B. Ivry, "Abstract and effector-specific representations of motor sequences identified with PET," *Journal of Neuroscience*, vol. 18, pp. 9420-8, 1998.

[56] H. I. Krebs, T. Brashers-Krug, S. L. Rauch, C. R. Savage, N. Hogan, R. H. Rubin, A. J. Fischman, and N. M. Alpert, "Robot-aided functional imaging: application to a motor learning study," *Human Brain Mapping*, vol. 6, pp. 59-72, 1998.

[57] A. S. Reber, F. F. Walkenfeld, and R. Hernstadt, "Implicit and explicit learning: individual differences and IQ," *Journal of Experimental Psychology: Learning, Memory, & Cognition*, vol. 17, pp. 888-96, 1991.

[58] R. A. Magill, "1997 C. H. McCloy Research Lecture: Knowledge is more than we can talk about: implicit learning in motor skill acquisition," *Research Quarterly for Exercise & Sport*, vol. 69, pp. 104-10, 1998.

[59] S. Lisberger, "The neural basis for the learning of simple motor skills," *Science*, vol. ##, pp. 728-735, 1988.

[60] M. Kawato, "Feedback-error-learning neural network for supervised learning," in *Advanced neural computers*, R. Eckmiller, Ed. Amsterdam: North-Holland, 1990, pp. 365-372.

[61] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, "Learning representations by back-propagating errors," *Nature (London)*, vol. 323, pp. 533-536, 1986.

[62] D. M. Wolpert, Z. Ghahramani, and M. I. Jordan, "An internal model for sensorimotor integration," *Science*, vol. 269, pp. 1880-2, 1995.