World Academy of Science, Engineering and Technology
International Journal of Biomedical and Biological Engineering
Vol:11, No:4, 2017

Creating a Virtual Perception for Upper Limb Rehabilitation

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Open Science Index, Biomedical and Biological Engineering Vol:11, No:4, 2017 publications.waset.org/10006823.pdf

Abstract**—**This paper describes the development of a virtual-reality system ARWED, which will be used in physical rehabilitation of patients with reduced upper extremity mobility to increase limb Active Range of Motion (AROM). The ARWED system performs a symmetric reflection and real-time mapping of the patient's healthy limb on to their most affected limb, tapping into the mirror neuron system and facilitating the initial learning phase. Using the ARWED, future experiments will test the extension of the action-observation priming effect linked to the mirror-neuron system on healthy subjects and then stroke patients.

Keywords—Physical rehabilitation, mirror neuron, virtual reality, stroke therapy.

I. INTRODUCTION

THE most radical changes to the human movement system happen when there is a loss in function for one or more joints, due to an interruption/interference in the neurological communication channel. For example, impairment of the upper extremity is a common after-effect of stroke. Over 50% of approximately 4,000,000 stroke survivors in the U.S. have chronic impairments in the arm, hand, or both. For stroke, motor recovery of the upper extremity plateaus in the first year after the initial incident according to clinical and biomechanical measures. However, there is some evidence that the time needed for recovery is not limited to one year and that additional practice can improve mobility in both the sub-acute and chronic phases following a stroke [1]. The latter leads naturally to the concept of "functional potential". The additional recovery is statistically significant and provides a baseline effect with which to work. However, patients often only achieve small levels of improvement to their mobility. Given the limitations of recovery, it is necessary to find novel tools and methods for retraining the motor system.

Robotic Based Stroke Therapy (RBST) has been proven to be beneficial for patients to learn the required perception-action skill. Success of using RBST to help patients relearn other task necessary for Activities of Daily Living (ADL) has been limited [2], [3]. Observational learning of motor skills, however, has been shown to produce transfer across limbs and generalization across muscle groups in the same limb [4], as well as transfer to perceptual tasks [5], [6], [47]. Therefore, observational learning may offer a greater benefit regarding transfer to ADLs in comparison to RBST. Thus, a success indicator would be the beneficial transfer of training from the unaffected to affected limb or vice-versa.

Recent research has shown that virtual-reality environments enhance recovery after spinal cord injury [7]. For middle-aged female patients having lower back pain, a virtual reality based yoga program was shown to have positive effects on their mobility, and this program can be employed as a therapeutic medium for prevention and cure of lower back pain [8]. Virtual Reality Based Therapy (VRBT) is feasible and a cost-effective means of bringing therapy to stroke patients from lower income communities. Furthermore, VRBT has a "wow factor" not experienced through conventional therapies and is considerably safer than RBSTs [9]. Use of remotely monitored virtual reality videogames, regular use of tele-rehabilitation appears to produce improved hand function and forearm bone health in adolescents with chronic disability. Improved hand function appears to be reflected in functional brain changes [10]. Additionally, virtual/augmented reality exercise programs have been shown to improve the ambulation ability of subjects with cerebral palsy [11]. The use of virtual or augmented reality in physical therapy has produced some encouraging results which demonstrate the potential of using these techniques for all types of physical therapy, including stroke therapy [12]-[15].

Research over the past six-seven years suggests that action-observation training improves upper-limb function in children with unilateral cerebral palsy [16]. Human imaging work (PET, fMRI) has revealed a mirror-neuron network (pre-motor cortex, parietal lobe, temporal lobe) that supports our ability to learn through action imitation and action observation [17]-[19]. This direct link between human visual perception and human action execution is diminished [20] or disappears when non-anthropomorphic motion is observed [21]-[23]. Recent research started to investigate how action-observation protocols linked to the mirror neuron system may benefit recovery of function after stroke and enhance clinical training protocols to produce transfer of recovered function from the clinic to ADLs [24]-[26]. Some promises regarding the use of action-observation as a means to tap into the mirror neuron

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system in the clinic have come from training protocols that use video to help patients mimic ADL [27] and virtual reality systems that transfer the motion of the patient's real arm to a set of virtual arms in real time [28], [29].

II. PRELIMINARY DATA

In the last couple of years, Robson et al. [30]-[35] have been working on human motion planning experiments. The research is a part of a collaborative effort to develop computational models of human motion planning with future applications in the development of novel devices for the physical training of post-stroke patients and in the design and control of prosthetic upper-limb devices. The recent experimental setup included action observation techniques of both a computer-generated stick figure and a video of a biological arm in four healthy subjects (age 25 to 35). The first experiment examined whether a video of an actual arm facilitated the learning process better than a computer simulated stick figure. A four-camera Vicon Motion Capture system with four reflective markers attached to the right arm (shoulder, elbow, wrist, and finger) was used to develop both visual displays. The video of the human arm was stripped of background to further ensure that the two videos were similar. In one condition, participants were shown a video of a human arm tracing a trajectory with flexion/extension motion of the elbow constrained by a brace at a certain degree (Fig. 1). Participants were then asked to replicate the motion while wearing an elbow brace.

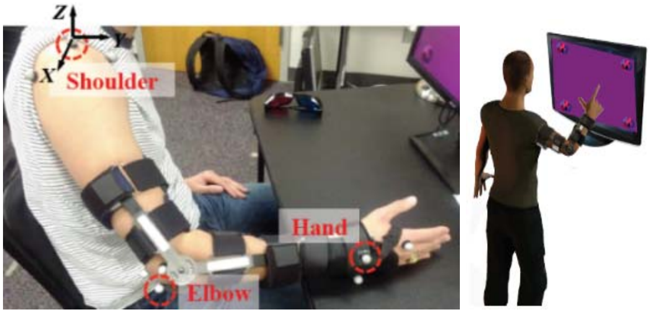

Fig. 1 Experimental setup of human motion planning with constrained elbow joint using a brace

In a second condition, participants were shown a video of a stick figure arm producing a trajectory with the elbow constrained and asked to replicate the motion. Each condition was repeated ten times. Data analysis focused on quantifying the error between the reference trajectory and the trajectory produced by the participants. For three of the four participants, error values were similar between the human arm and the stick figure arm conditions, with no significant decrease across trials. This pilot study utilized minimal practice and did not produce a significant decrease in error. However, it showed that participants respond to both videos positively in terms of the observed action. A second phase of the experiment dimmed out the visual effect of the biological limb and the stick figure during the training intervals. The results from the second phase showed a clear drop in the error for three of the participants, indicating a motor learning effect. Overall the pilot data showed that people with physical constraints on joint motions can respond to computer animations, map those animations onto joint motions, and learn to move successfully with a constraint. In addition, Buchanan and Wright [4] have recently used computer-generated stick figure animations as a means to examine observational learning processes in three post-stroke individuals, age 36 to 62. The data show that stroke patients can respond to computer animations and map those animations onto joint motions and required postures. Further work is needed to investigate if a photorealistic looking arm, versus a stick figure, will improve motor learning or if a combination of the two may offer the most satisfactory training procedure.

The ARWED technique builds upon the above-mentioned idea and pilot data obtained, allowing the use of observational and physical practice training protocols based on motor learning theory to train patients with reduced upper limb mobility by mirroring motion of the complete limb onto the impaired limb and then reducing the mirror effect over training intervals. The ARWED is expected to yield benefits in the training of post-stroke patients or patients with neurological disorders and may also prove beneficial in retraining individuals with other motor disabilities since its design is based on the action-observation priming effect that has been shown to be successful with other motor disabilities [7], [16].

III. DEVELOPMENT OF THE ARWED

Virtual-reality systems aim to integrate additional, computer-generated information within the human perception of the physical world [36]. In our case, human vision is targeted and the aim is to modify visual input of some object within the visual field of the subject. If the original object is an upper limb with a limited range of motion, then the modified object is a realistic 3D model of the subject's upper limb. In order to perform the virtual/modified perception, the object needs to be identified and tracked within the visual field. Its kinematic structure needs to be determined to calculate its motion, all in real-time. For this research, mapping of the active motion of the unaffected limb onto the affected one was used. In order to do so, the subject's unaffected, healthy hand and forearm was tracked using a Leap Motion sensor, and the resulting tracking data were mapped on to a virtual representation of the affected arm and forearm in the virtual environment (Fig. 2).

The ARWED system can be used as a standard desktop system or as a head-mounted virtual reality system using Oculus Rift. The goal was to have fast tracking and rendering so that the virtual limb tracks seamlessly the movement of a real limb. Some challenges to this are: quick rendering of a photorealistic representation of the subject's affected limb; motion smoothness; shadow casting; calculation or estimation of appropriate translation, orientation and scaling parameters of the virtual limb to smoothly align with the object(s) in the real environment; discontinued rendering of the virtual limb in the presence of occlusion or sporadic loss of tracking data to reduce/eliminate the loss of persistence for the user, among others. Some of these problems are detailed in [37], [38]. The main tasks necessary to build the ARWED and their description can be found in the following subsection.

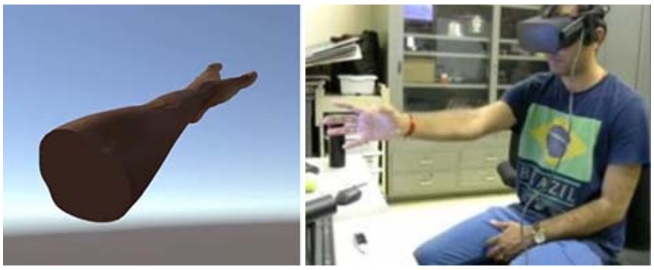

Fig. 2 ARWED system where the subject's right hand is mapped to the virtual left hand

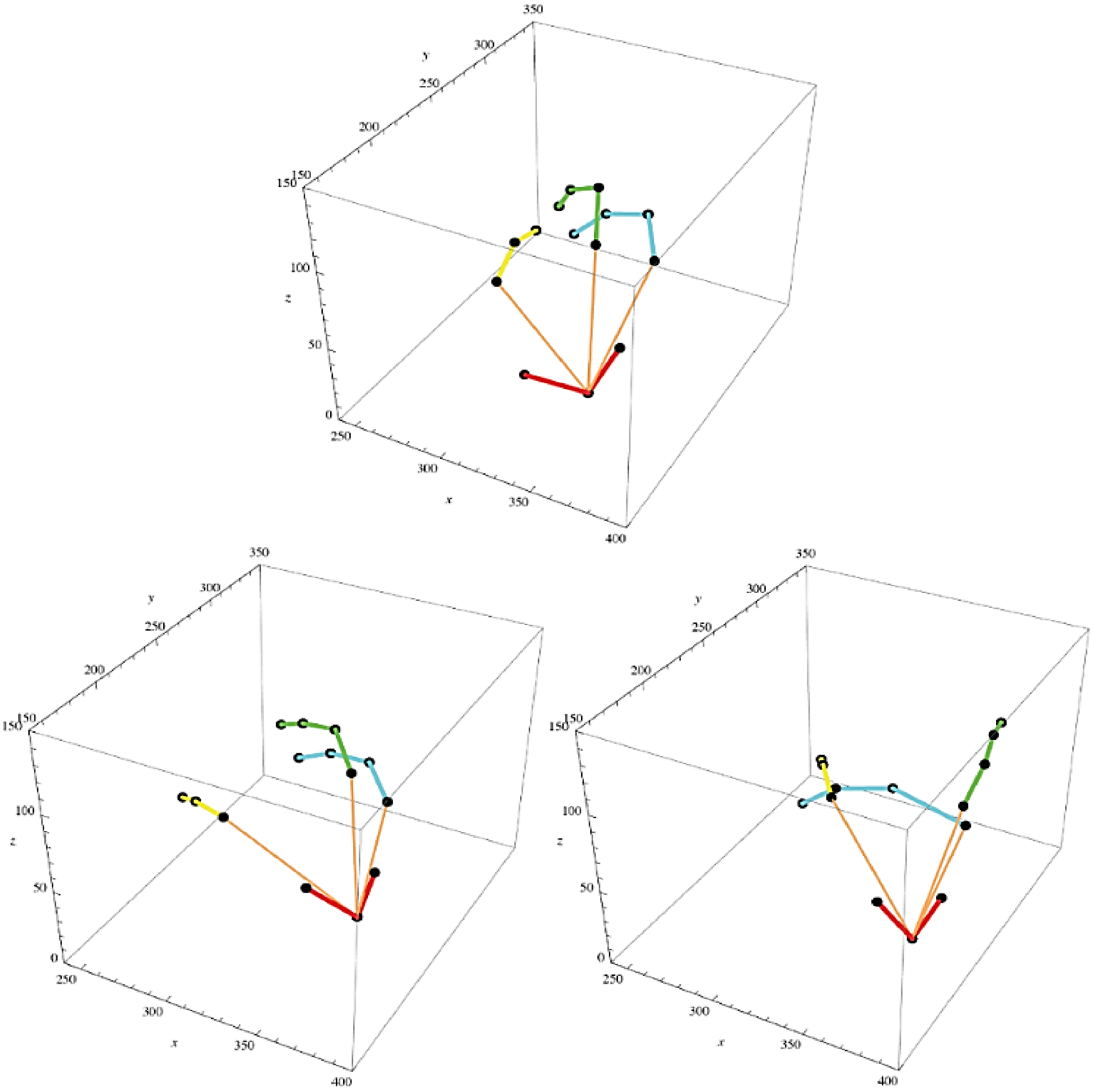

Fig. 3 Results from the kinematic skeleton extraction and reconstruction of a subject's thumb (yellow), index (green), and middle (blue) fingers, based on motion capture system data and three major training motions: pinch (right), palm open/close (left), and point (top)

A. Photorealistic 3D Hand Model

In order to develop the ARWED, a realistic 3D hand model was required, which matches the hand of the subject and performs precise motion in real time. For this task, we are currently exploring the development of kinematic arm-hand models. The overall procedure is given in 4. The hand model should match the subject's anthropometric arm data, thus the kinematic skeleton of the arm of the patient needs to be calculated. The kinematic skeleton was defined as the set of joint axis locations and orientations that recreate the motion of the hand in space. A robotics approach was used to approximate the skeleton (i.e., rigid bodies connected by revolute joints). Using this model, the motion of the arm can be expressed in a straightforward way, using a predetermined number of joint angles for each pose. A solution can be achieved by combining anatomic measurements with a motion-based kinematic synthesis (Fig. 4) [39]-[41]. This solution consists of five major steps:

i. Non-dimensional kinematic model of the arm, incorporating anatomical human arm data;
ii. Kinematic task specification that consists of higher order kinematic constraints, compatible with contact and curvature constraints;
iii. Kinematic synthesis equations, specific to the kinematic chain, solved to obtain the locations of the fixed (shoulder) and the moving (wrist) pivots;
iv. The results from the previous step define the kinematic skeleton for a specific subject within a margin of error, are then used to reconstruct the skeleton;
v. Trajectory planning techniques, that include interpolation of joint positions, velocities and accelerations, related to the higher order derivative motion task specifications from step (ii), that results in smooth and accurate human-like movement.

The skeleton must be capable of performing a realistic motion based entirely on the set of joint angles provided by the synthesis/analysis algorithm described in [39]-[41].

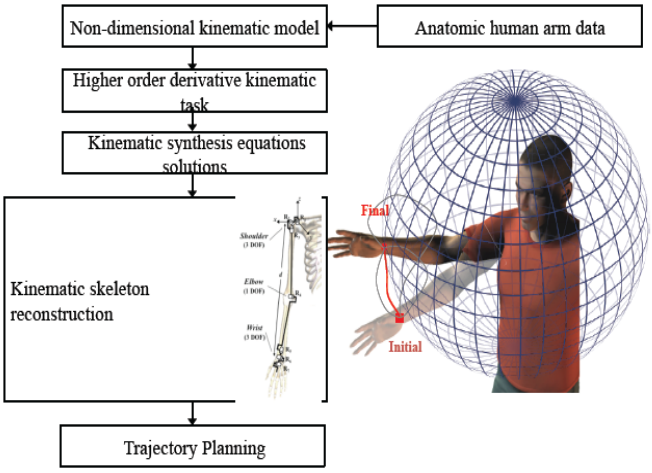

Fig. 4 Kinematic skeleton extraction and reconstruction

Fig. 3 shows results from the kinematic skeleton extraction and reconstruction of a subject's thumb, index and middle fingers, based on motion capture system data and three major training motions, i.e. pinch, palm open/close and point, shown in Fig. 6. The three action sequences were as follows: 1) the pinch, forearm semi-prone with the thumb and fingers extended and then the thumb and fingers pinch; 2) hand open, forearm semi-prone with the hand in a fist and then the thumb and fingers are fully extended; hand closed, forearm semi-prone with the hand open (thumb and fingers fully extended) and then the hand closes to a fist; and 3) pointing, the forearm is prone with the hand hanging flexed at the wrist and then the hand raises and the index finger is pointed. The models in Fig. 3 were developed and animated in Mathematica, and their performance was compared to the obtained human motion.

In parallel to the development of our own 3D models, a set of available 3D hand models and images were evaluated, and a few of them that satisfy the above-mentioned requirements were selected. An online search revealed an extensive availability of high fidelity 3D human body part models, including hands. In addition, there are a large number of images of human hands available that can be used for texture mapping (Fig. 5).

Fig. 5 Examples of available human hand models

Fig. 6 Marker set up for extracting motion capture data from the three main training motions: pinch, palm open/close and point

As a next step, a model for the dysfunctional limb based on the fully-functional limb can be calculated if needed, by performing a line reflection of the obtained model. The first goal involves optimizing the location of the reflection line. Trajectories for the fully-functional healthy limb of a subject (blue/darker) and the virtual mirrored limb (red/lighter) are shown in Fig. 7.

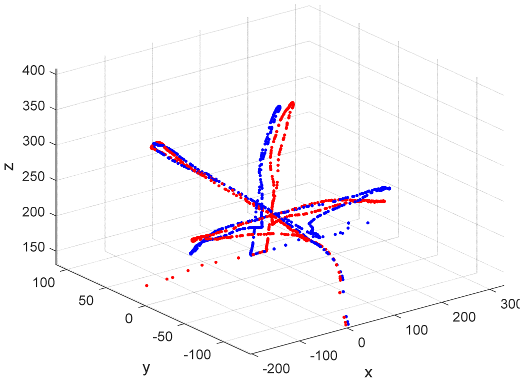

Fig. 7 Trajectories of the fully-functional healthy limb of a subject (blue) and the virtual mirrored limb (red)

B. Experiment on the 3D Model to Assess Its Performance

One key point in the development of the ARWED device is to assess whether a 3D model of a limb can create the desired priming effect in the subject, and if this effect is any different depending on the hand representation and accuracy presented to the user. In order to answer this question, a series of experiments were developed to examine automatic elicitation of hand actions in individuals without any known loss of neurological function. The experiments progressed from static priming conditions (Experiment 1 described below) [20], [22], [39], [40], [42] to dynamic priming conditions (Experiment 2 described below) [21], [33], [43]-[45].

Experiment 1 required participants to rapidly identify gestures generated by a human model or generated by a 3D model of the human arm. The gestures were presented as static pictures. Since the ARWED device blocks vision of the hand and arm, participants' hands and arms were blocked from view when producing the action. Reaction time was measured, based on surface EMG and a key pressing action provided a measure of response priming. The three different actions, a pinch, hand open/hand closed, and pointing, shown in Fig. 6, were presented as test stimuli. The task required participants to correctly identify a specific response over a series of 40 trials in a block. Each block consisted of 80% compatible actions and 20% incompatible actions, with participants only responding to compatible actions by pressing a response key. For example, if the block consists of the hand open gesture, catch trials might be two fingers raised or the thumb up. The results from Experiment 1 showed that the reaction times (both EMG and key press) and percent correct responses were similar for all four gestures for both the 3D model and human model. This implies that the 3D model limb primes the human motor system in a manner consistent with the human model.

Experiment 2 utilized the same hand gestures as Experiment 1 but presented as dynamic hand gestures; i.e., participants saw a hand pinch and then were asked to replicate the action. The same four gestures were used and presented as a video. Reaction time was measured with surface EMG (first dorsal interossei muscle), and movement time was measured from hand kinematics. Hand kinematics was recorded with a 3D motion capture system, and movement time was based on motion of the index finger. Each action was presented in a block of 40 trials with 10% the trials consisting of catch trials. Within each block of trials, the actions were completed with four different movement times. Participants were required to imitate the action and complete their action in a similar time to the animated action. The results from Experiment 2 showed that the reaction time and movement time values between the 3D model limb and the human model are similar between the two conditions. This implies that the dynamic motions of the developed 3D model limbs mimic those of a human model.

IV. FUTURE RESEARCH

Described in this paper is the ARWED system which is a VRBT system for physical rehabilitation of patients with reduced upper extremity mobility resulting from a stroke. The purpose of this system is to increase limb AROM. To do this, the system maps, in real-time, the patient's unaffected limb to a virtual representation of the affected limb with the intent of tapping into the mirror neuron system which will facilitate the initial learning phase.

Robotic-based stroke therapy protocols have not been overly successful in generalization of learning to other tasks and this is an essential aspect of improving performance on ADLs. It has been shown that motor skill retraining through observation produces transfer across limb and to perceptual tasks, and generalization across muscle groups in the same limb [46]. Thus, observational learning may offer a greater benefit regarding transfer to ADLs in comparison to robotic training. The development of the ARWED system is based on pilot data, which shows that people with physical constraints on joint motions can react to computer animations, link those animations onto joint motions, and learn to move successfully with a constraint.

The results on the assessment of the developed virtual photorealistic 3D hand models imply that the dynamic motions of the 3D models mimic those of a human limb model, as well as that the developed 3D models prime the human motor system in a manner consistent with the human model. The future research includes superimposing the virtual limb into the scene to obtain mixed reality display, as well as the development of series of protocols for the application of the ARWED system and experiments on its significance as a tool to improve the upper-limb mobility.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the National Science Foundation (NSF), award Id #1404011 and Qatar National Research Fund, National Priorities Research Program sub-award Id # NPRP 7-1685-2-626.

REFERENCES

[1] J. A. Beebe and C. E. Lang, "Active Range of Motion Predicts Upper Extremity Function 3 Months After Stroke," Stroke, vol. 40, pp. 1772-1779, 2009.

[2] N. Hogan, & Krebs, H. I., "Interactive robots for neuro-rehabilitation," *Restor Neurol Neurosci,* vol. 22, pp. 349-358, 2004.

[3] J. W. Krakauer, "Motor learning: its relevance to stroke recovery and neurorehabilitation.," *Curr Opin Neurol,* vol. 19, pp. 84-90, 2006.

[4] Buchanan, J.J., Ramos, J. & Robson, N, "Simulated human arm motion drives perception-action learning in post-stroke individuals," Program No. 563.17. 2013 Neuroscience Meeting Planner, San Diego, CA: Neuroscience, 2013.

[5] D. Maslovat, Hodges, N. J., Krigolson, O. E., & Handy, T. C., "Observational practice benefits are limited to perceptual improvements in the acquisition of a novel coordination skill.," *Exp Brain Res,* vol. 204, pp. 119-130, 2010.

[6] N. R. H. S. Moon, R. Langari, J. Buchanan, "How Does the Central Nervous System Govern Motions with Reduced Arm Mobility," in *ASME/IMECE*, Houston, 2012.

[7] M. Villiger, Bohli, D., Kiper, D., Pyk, P., Spillmann, J., et al., "Virtual reality-augmented neurorehabilitation improves motor function and reduces neuropathic pain in patients with incomplete spinal cord injury.," *Neurorehabil Neural Repair,* vol. 27, pp. 675-683, 2013.

[8] S. Kim, Min, W., Kim, J., & Lee, B., "The effects of vr-based wii fit yoga on physical function in middle-aged female lbp patients.," *Journal of Physical Therapy Science,* vol. 26, pp. 549-552., 2014.

[9] M. Walker, Ringleb, S., Maihafer, G., Walker, R., Crouch, J., et al., "Virtual reality–enhanced partial body weight–supported treadmill

training poststroke: Feasibility and effectiveness in 6 subjects.," *Archives of Physical Medicine and Rehabilitation,* vol. 91, pp. 115-122, 2010.

[10] M. Golomb, Mcdonald, B., Warden, S., Yonkman, J., Saykin, A., et al., "In-home virtual reality videogame telerehabilitation in adolescents with hemiplegic cerebral palsy.," *Archives of Physical Medicine and Rehabilitation,* vol. 91, pp. 1-8. e1, 2010.

[11] B. Lee, "Clinical usefulness of augmented reality using infrared camera based real-time feedback on gait function in cerebral palsy: A case study.," *Journal of Physical Therapy Science,* vol. 28, pp. 1387-1391, 2016.

[12] B.-H. Lee, "Clinical Usefulness of Augmented Reality Using Infrared Camera Based Real-Time Feedback on Gait Function in Cerebral Palsy: A Case Study," *Journal of physical therapy science,* vol. 28, p. 1387, 2016.

[13] A. Kalron, I. Fonkatz, L. Frid, H. Baransi, and A. Achiron, "The Effect of Balance Training on Postural Control in People with Multiple Sclerosis Using the CAREN Virtual Reality System: A Pilot Randomized Controlled Trial," *Journal of neuroengineering and rehabilitation,* vol. 13, p. 1, 2016.

[14] M. Sousa, J. Vieira, D. Medeiros, A. Arsénio, and J. Jorge, "SleeveAR: Augmented Reality for Rehabilitation using Realtime Feedback," in *Proceedings of the 21st International Conference on Intelligent User Interfaces*, 2016, pp. 175-185.

[15] A. J. Agrawal. (2015, 10/14/2016). *How Virtual Reality Will Change Physical Therapy Forever*. Available: http://www.inc.com/aj-agrawal/how-virtual-reality-will-change-physical-therapy-forever.html

[16] G. Sgandurra, Ferrari, A., Cossu, G., Guzzetta, A., Fogassi, L., & Cioni, G., "Randomized trial of observation and execution of upper extremity actions versus action alone in children with unilateral cerebral palsy.," *Neurorehabil Neural Repair,* vol. 27, pp. 808-815, 2013.

[17] B. Calvo-Merino, Glaser, D. E., Grèzes, J., Passingham, R. E., & Haggard, P., "Action Observation and Acquired Motor Skills: An fMRI Study with Expert Dancers.," *Cerebral Cortex,* vol. 15, pp. 1243-1249, 2005.

[18] A. Casile, V. Caggiano, and P. F. Ferrari, "The Mirror Neuron System: A Fresh View," *The neuroscientist,* p. 1073858410392239, 2011.

[19] L. Fogassi, Ferrari, P. F., Gesierich, B., Rozzi, S., Chersi, F., & Rizzolatti, G., "Parietal lobe: from action organization to intention understanding. Science," vol. 308, pp. 662-667, 2005.

[20] C. Press, Bird, G., Flach, R., & Heyes, C., "Robotic movement elicits automatic imitation.," *Brain Res Cogn Brain Res,* vol. 25, pp. 632-640, 2005.

[21] L. M. Oberman, McCleery, J. P., Ramachandran, V. S., & Pineda, J. A., "EEG evidence for mirror neuron activity during the observation of human and robot actions: Toward an analysis of the human qualities of interactive robots. ." *Neurocomput,* 2007.

[22] C. C. Tsai, & Brass, M., "Does the human motor system simulate Pinocchio's actions? Coacting with a human hand versus a wooden hand in a dyadic interaction," *Psychol Sci,* vol. 18, pp. 1058-1062, 2007.

[23] C. Urgesi, Moro, V., Candidi, M., & Aglioti, S. M., "Mapping implied body actions in the human motor system.," *J Neurosci,* vol. 26, pp. 7942-7949, 2006.

[24] G. Buccino, Solodkin, A., & Small, S. L., "Functions of the Mirror Neuron System: Implications for Neurorehabilitation.," *Cognitive and Behavioral Neurology,* vol. 19, pp. 55-63, 2006.

[25] S. Franceschini, S. Gori, M. Ruffino, K. Pedrolli, and A. Facoetti, "A causal link between visual spatial attention and reading acquisition," *Current Biology,* vol. 22, pp. 814-819, 2012.

[26] V. M. Pomeroy, Clark, C. A., Miller, J. S., Baron, J. C., Markus, H. S., & Tallis, R. C., "The potential for utilizing the "mirror neurone system" to enhance recovery of the severely affected upper limb early after stroke: a review and hypothesis.," *Neurorehabil Neural Repair,* vol. 19, pp. 4-13, 2005.

[27] D. Ertelt, Small, S., Solodkin, A., Dettmers, C., McNamara, A., Binkofski, F., & Buccino, G., "Action observation has a positive impact on rehabilitation of motor deficits after stroke.," *Neuroimage,* vol. 36, pp. T164-173, 2007.

[28] K. Eng, Siekierka, E., Pyk, P., Chevrier, E., Hauser, Y., et al., "Interactive visuo-motor therapy system for stroke rehabilitation. Medical & Biological Engineering & Computing," *Medical & Biological Engineering & Computing,* vol. 45, pp. 901-907, 2007.

[29] I. Pastor, Hayes, H. A., & Bamberg, S. J., "feasibility study of an upper limb rehabilitation system using Kinect and computer games. ," *Conf Proc IEEE Eng Med Biol Soc,* 2012.

[30] H. Moon, N. Hoang, N. P. Robson, and R. Langari, "Human Arm Motion Planning Against a Joint Constraint," in *the 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, ed, 2012, pp. 401-406.

[31] H. Moon, N. P. Robson, R. Langari, and J. J. Buchanan, "Experimental Observations on the Human Arm Motion Planning Under an Elbow Joint Constraint," in *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS)*, ed: IEEE, 2012, pp. 3870-3873.

[32] H. Moon, N. P. Robson, R. Langari, and J. J. Buchanan, "Experimental Observations on the Central Nervous System's Governing Strategies on the Arm Reaching with Reduced Mobility," in *ASME International Mechanical Engineering Congress and Exposition (IMECE)*, ed. Houston, TX: American Society of Mechanical Engineers (ASME), 2012, pp. 483-492.

[33] N. Patarinsky-Robson, McCarthy, J. M., & Tumer, I. Y., "Failure Recovery Planning for an Arm Mounted on an Exploratory Rover," *IEEE Transactions on Robotics,* vol. 25, pp. 1448-1453, 2009.

[34] N. Robson and J. M. McCarthy, "Applications of the Geometric Design of Mechanical Linkages with Task Acceleration Specifications," in *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE)*, ed. San Diego, CA: American Society of Mechanical Engineers (ASME), 2009, pp. 1105-1114.

[35] N. Robson, J. M. McCarthy, and I. Tumer, "Exploring New Strategies for Failure Recovery of Crippled Robot Manipulators," in *ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots (ReMAR)*, Z. M. S. Dai, Xianwen Kong, Ed., ed. London, UK, 2009, pp. 656-664.

[36] O. Bimber, & Raskar, R., Spatial Augmented Reality: Merging Real and Virtual Worlds: A. K. Peters, Ltd., 2005.

[37] D. Bowman, Coquillart, S., Froehlich, B., Hirose, M., Kitamura, Y., et al., "3D User Interfaces: New Directions and Perspectives," *IEEE Computer Graphics and Applications,* p. 28(6), 2008.

[38] F. Smit, Liere, R. v., & Froehlich, B., "A Programmable Display Layer for Virtual Reality System Architectures.," *IEEE Transactions on Visualization and Computer Graphics,* vol. 16, pp. 28-42, 2010.

[39] N. Robson, & Soh, G. S., "Geometric Design of Eight-Bar Wearable Devices Based on Limb Physiological Contact Task.," *Mechanism and Machine Theory,* pp. 358-367, 2016.

[40] N. Robson and S. Ghosh, "Geometric Design of Planar Mechanisms Based on Virtual Guides for Manipulation," *Robotica,* pp. 1-16, 2015.

[41] N. Robson and G. S. Soh, "Dimensional Synthesis of a Passive Eight-bar Slider Exo-Limb for Grasping Tasks," in *ASME International Design Engineering Technical Conferences*, ed, 2016, p. (Accepted).

[42] N. R. a. G. S. Soh, "Dimensional Synthesis of a Passive Eight-bar Slider Exo-Limb for Grasping Tasks," *ASME International Design Engineering Technical Conference,* 2016.

[43] I. Pastor, Hayes, H. A., & Bamberg, S. J., "A feasibility study of an upper limb rehabilitation system using Kinect and computer games," in *IEEE Eng Med Biol Soc*, 2012, pp. 1286-1289.

[44] N. Patarinsky-Robson, McCarthy, J. M., & Tumer, I., "Exploring new strategies for failure recovery of crippled robot manipulators," in *Reconfigurable Mechanisms and Robots*, 2009.

[45] J. M. M. a. I. T. N. Patarinsky Robson, "Applications of the Geometric Design of Mechanical Linkages with Task Acceleration Specifications," in *ASME Int. Design Eng. Tech. Conf*, San Diego, 2009.

[46] J. A. Ramos, "Development of a Robotic Device for the Physical Training of Human Upper Extremity," 2013.

[47] Buchanan, J.J., Ramos, J. & Robson, N., “The perception-action dynamics of action competency are altered by both physical and observational training,” *Experimental Brain Research*, 233: 1289-1305.