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Bimanual Haptic–Desktop Platform for Upper-limb Post–Stroke Rehabilitation: Practical Trials

Siqiao Li, Antonio Frisoli, Carlo Alberto Avizzano, Emanuele Ruffaldi, Luis I. Lugo–Villeda and Massimo Bergamasco

***Abstract*— This paper presents three haptic–based virtual applications for the undergoing rehabilitation of upper–limb post stroke patients. The three exercises are developed for their use on the multi–modal interface so–called Bimanual Haptic Desktop System (BHDS), which integrates the haptic functionalities and Video Display Terminal (VDT) within the work-plane of a desk. Firstly, two basic exercises, tracking task and lifting task, are carried out for the recovery of basic arm motion–coordination skills and steadiness of patients' upper-limb. Secondly, a video–game–like exercise, catching task, is developed to compare online the performance of healthy upper-limb with impaired ones wherein hand-eye coordination exercise of the patient is included. To this end, the proposed exercises provide to patients the potential methods to train their post–stroke upper-limbs malfunctions while reporting the quantitative parameters obtained to evaluate the improvement of patients recovery. Experimental results of a preliminary evaluation on healthy subjects are then reported and discussed to visualize in near future a pilot medical trials of the system on impaired people.**

I. INTRODUCTION

Over the past few years, several research studies have presented their development of robotic–mediated–rehabilitation devices that many of them are including Virtual Reality technologies for enhancing the application performance of upper-limb post–stroke rehabilitation, see [1].

The recovery of upper-limb rehabilitation of patients relies on the endurance and duration of exercises-based rehabilitation therapy which are manually supervised by occupational therapists [2] [3] [4].

Nevertheless practical limitations, involved hardware and the devoted time to recovering stroke patients does not exploit the maximum effect of rehabilitation that can be attained. By the way, it is well–known that manually-assisted rehabilitation lacks of repeatability and objective estimation of rehabilitation progress [5]. In contrast, robot–assisted–therapy offers the capabilities to improve the gradual outcome of post–stroke patients engaged on rehabilitation of neuromotor control in comparison with conventional therapy [6].

Bimanual rehabilitation has been pointed out as an effective way for the rehabilitation of patients with poor motor impairment of one upper extremity because of the bimanual nature of the therapy, i.e. the natural way to initiate and control the therapy and the mechanical-neurological coordination between two hands in human activities of daily living [7].

In one hand, several bimanual upper-limb rehabilitation devices have been developed in the last few years; nowadays, there are two kind of upper–limbs rehabilitation-based robots: *a)End–based effector robots* and *b)Wearable robots*, see [8].

Continuous passive motion systems are manly part of *a*), such as Nudelholz [9] and Batrac [10], which don't require an external power source for the operation. This kind of devices can be used to improve mobility of upper-limb after stroke, but are not sufficient for a complete rehabilitation because of a lack of adaptability to different patients and the one exercise drawback which makes difficult to assess the patient rehabilitation progress. Serval active interfaces that belongs to the first classification *a*), have also been presented to overcome the major limitation of passive systems, such as MIME (Mirror Image Movement Enabler) [11] [12] [13] [14], ARCMIME [15] and Bi-Manu-Track [16] [17] [18], which can be used for the training and evaluation of a wide variety of exercises, including many different tasks and daily living activities. Nevertheless, no clear benefits of robot assisted therapy on functional abilities has yet been evidenced.

On the other hand, several studies, e.g. [19], have proved positive effects associated with the use of Virtual Reality on rehabilitation, such as economy of scale and programming [20] which provide a wider range of intensive and repetitive exercises for patients suffering from a variety of diseases. Moreover, interactivity and motivation [21] is another advantage of VR-aimed rehabilitation, which can stimulate the patients mental stimuli necessary to complete daily basic exercises through video–game-like rehabilitation environments. Likewise, several devices have demonstrated themselves suitable for robotic arms rehabilitation therapy when are integrated with a VR system, such as L–Exos [1] and ARMin-II [22], both belong to the *b*) classification robots.

A. Contribution

In this contribution, we present three haptic-based virtual exercises on the extended application of the Bimanual Haptic Desktop System (BHDS) for the undergoing rehabilitation of upper-limb post–stroke patients. BHDS, developed at PERCRO lab, is a multi-modal interface, which integrates the haptic functionalities and Video Display Terminal (VDT) inside the work-plane of a desk [23].

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All authors are with the PERCRO Laboratory, Scuola Superiore Sant' Anna, via Rinaldo Piaggio, 34, 56025 - Pontedera (Pisa),Italy. {s.li,a.frisoli@sssup.it.}

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Basically, two basic exercises are set up: tracking task and lifting task, programmed for the recovery of the basic motions skills and the steadiness motions of patients' upper-limb. The third one concerns with a video–game-like exercise, catching task, which is developed to compare online the performance of one healthy upper-limb with impaired one simultaneously analyzing the hand-eye coordination of the patient.

The preliminary experimental results on healthy user are promising; the set of proposed exercises are able to provide to patients a useful platform to train their post–stroke upper-limbs malfunctions while reporting the quantitative parameters obtained to properly asses the improvement of patients recovery process.

B. Organization

The remainder of this paper is organized as follows: section II gives a brief description of BHDS's characteristics, underlining the main features which make the device useful for rehabilitation purposes;a description of the designed VR exercises on the BHDS may be found in section III. Section IV presents and discusses the experimental results of the preliminary evaluation performed by healthy subjects. Finally, section V summarizes the contents of this study and gives our immediate future work.

II. BIMANUAL HAPTIC DESKTOP SYSTEM

The bimanual haptic desktop system (BHDS) is an integrated system which merges haptic functionalities and Video Display Terminal (VDT) systems into standalone application, shown in Fig. 1. The hardware integration has been designed to show ergonomic features and provide high-quality performance of human-computer-interaction (HCI) [24].

Fig. 1. Bimanual Haptic Desktop System.

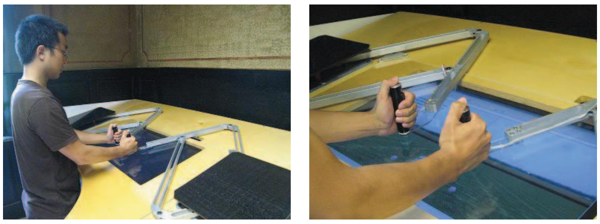
Haptic functionalities of BHDS are generated by two parallel planar interfaces with two degrees of freedom, which have been mounted on a desk. The performances of the mechanism have been optimized to fulfill the basic haptic interaction requirements: the wider admissible workspace allows to users interacting in the whole area of the graphical monitor, no backlashes in mechanical design, a high isotropy of the mechanical parameters turns out into the workspace and exploits the force feedback with a maximum continuous value of 10.0 N and a maximum peak value of 12.0 N.

A high integration of the hardware system is achieved to embrace multi-level control procedures and drivers within the hosting OS kernel (Windows 2K) [23]. The electronic design is embedded on the designed desk, which lets to get communication with the host computer through the USB protocol, so the desk plane is bulky–free and the operator has direct access to the visual and mechanical–haptic systems.

In order to use the BHDS for the rehabilitation purposes, an adjustable height support has been created, so the desktop can be adjusted to different positions and gradients depending on the ergonomic needs of each user (as a standard, the inclination value of the desktop plane has been fixed to 16°). Two operating handles with activation or emergency buttons are also mounted on the end-effecter of the device.

The graphical visualization is also integrated on the desk to carry out the completely coherent and co-located interaction between the force stimuli and the visual information, which can greatly enhance the user performance in HCI while reducing the mental load of the interaction [25]. The transparent cover on the monitor is made of a plastic material with low refraction index to guarantee a clear sight and safety of subjects.

During the operation, the user sits down or stands before the desktop system, with his/her hands grasping the two operating handles and a graphical screen on the desk displaying the virtual scenario, this fact has shown in Fig. 2) whereas Fig. 2 (b) has been taken during the lifting task.



(a) (b)

Fig. 2. One of the subjects performing the lifting exercises on the BHDS, (a) the overview of the BHDS with subjects, (b) example of subjects performing the required exercises during the lifting task.

III. BHDS EXERCISES

To access the rehabilitation purpose of the BHDS, three different tasks and corresponding exercises have been designed to evaluate certain abilities of subjects. The Virtual Rehabilitation scenario have been developed by means of the XVR Development Studio [26]. The three exercises are diverse enough to allow for a combination of tasks in one therapy session which can be scheduled by therapists based on the personal situation of patients.

A. Tracking Task

In this realm, the first exercise aims to the recovery of the basic motion arms skills of patients' upper-limb. The represented scenario is composed of two fixed circles, as shown in Fig. 3. The positions of the patient's hands are recorded as two red cursors, which are moved according to the handles on the device.

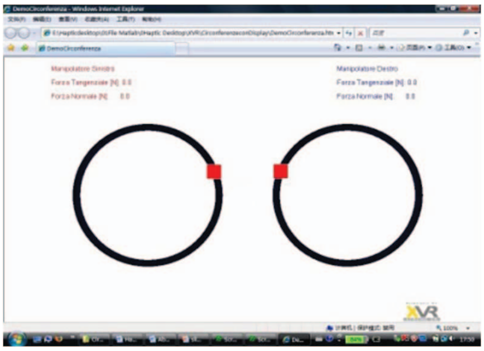


Fig. 3. Example of the tracking task with two red cursors constrained on the circular trajectory.

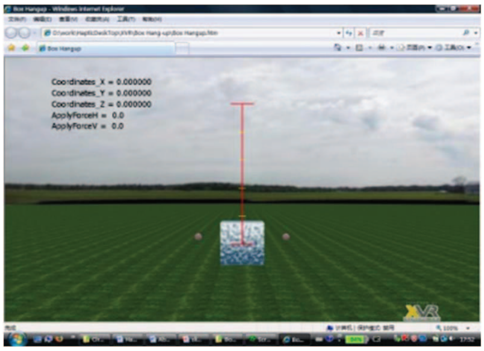


Fig. 4. An example of the lifting task with symmetric mode of two planar devices.

During this exercise, the patient is asked to move his/her hands along a circular trajectory, where it is spatially constrained by an impedance control. The virtual constraint is activated through a button located on the handles, which can also be used as an emergency button to stop and restart the exercise by the patient when accidents or malfunctions, such as a long time exercise fatigue of upper-limbs for naming one of them.

There are two kinds of assisted movements, symmetric mode and isometric mode, which can be chosen by the therapist according to recovery requirements of the patient. Meanwhile in each mode above, there are three master modes - left hand, right hand and also no master hand - decided by different stroke situation of the patient.

During the exercise, the therapist can set either force guidance or free–motion on the master hand when the patient is moving within the given trajectory, including value and the direction of the guiding force. Position and scale of the circular trajectory can also be changed online, which allows the patient to move within different effective workspace.

B. Lifting Task

In the second exercise, the patient is asked to lift a box[1] represented in the virtual environment, shown in Fig. 4. This application is designed for the recovery of the action of upper-limbs motion and the steadiness properties of their movements. The movements of the patient's hands are displayed by two spheres in the application, which are moved with the motion of end-effectors.

For this task the device is controlled with a direct force control, with the interaction force computed by means of virtual springs. When both of the two spheres touch the box, the texture of them is changed to notify the patient to lift the box. Besides the pressure force between the sphere and the box is sent to the patient; the patient can also feel the gravity of the box, which need to be conquered to perform the lifting object. When the box is lifted to the top position which the patient can reach, the patient can loose the two spheres on the box and repeat the task from the start position.

[1] All the defined objects inside the virtual environment posse physical properties

The exercise is also constructed in a symmetric mode with three different master ways as the first exercise. During the task, the therapist can decide whether assisted force or no assisted force feature when the patient start to lift the box, whose values can be also changed online according to different experimental requirements.

C. Catching Task

In this task the patient is asked to move a virtual pad to catch the target sphere, thus to compare the performance of healthy upper-limb online with impaired one and the exercise hand-eye coordination of the patient. The application consisted in a virtual tracking board which traces the average movement of the two hands of the patient and random virtual spheres moving in a straight line, shown in Fig. 5.

Fig. 5. The virtual scenario visualized in the catching task.

The subject can use the button localized on the operating handle to activate or stop the exercise, which is a safety guarantee on the basis of the consideration of the rehabilitation requirements. When a collision occurs in the system between the pad and the target sphere, a force feedback is exerted on hands–subjects by the two end-effector. The force feedback model is given on the basis of sine-descending curve to enable subjects to sense an instantaneous contact with the virtual sphere. There is also two master modes - left hand and right hand - designed for different stroke situations.

IV. ANALYSIS AND DISCUSSION

This section presents a quantitative evaluation of the three proposed exercises. For the consideration of rehabilitation purpose of the BHDS, a graphical user interface is designed in Matlab® for the convenience of the patient's and therapist's operation, shown in Fig. 6. During the exercise, the patient can change the parameters settings of the simulation model online and repeat the process according to the rehabilitation requirements. A standalone executable application is also generated to compute the operation locally for the practical exercise needs.

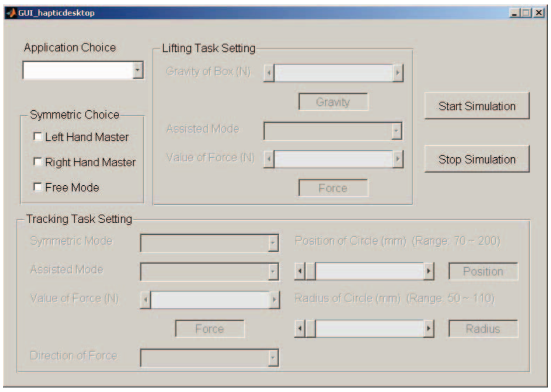


Fig. 6. Graphical user interface of the BHDS which is started from an executable application and through which the operator can change the parameter setting online.

A. Tracking Task

The subject is asked to complete the task of moving their hands along a circular trajectory for certain times. To start the exercise in a proper way, the following parameters need to be regulated by the therapist based on different situations of the patient:

- Master modes - left hand, right hand and no master hand
- Assisted movements - symmetric mode and isometric mode
- Assisted force - yes or no
- Value and direction of assisted force
- Position and scale of the circular trajectory

2D position data of hands movement of subjects have been recorded for the comparison of results between the less impaired upper-limb with the impaired one, which indicates the recovery progress of stroke rehabilitation as a quantitative value. The Fig. 7 shows an example of hands movement of subjects with the red line denoting the movement of the impaired upper-limb. It is worth to remark the bimanual rehabilitation method provide a more intuitive way for therapists to assess the improvement of stroke recovery and design the clinical rehabilitation sessions contrapuntally.

To assess the patient improvement for the constrained motion task, the task completion time for a full circular path has been recorded by means of an average value computation in a defined tracking task. The BHDS provides two potential evaluation ways for the therapist: the lateral comparison between the less or no impaired upper-limb and the impaired one during one exercise, and the longitudinal comparison of the impaired upper-limb between different tasks.

Because of the deliberately low value of the stiffness which realize the motion constraint, patients sometimes move the handles in an unstable way, bouncing from the internal side to the external side of the circle trajectory. The performance parameter P_{SD}, described in (1) can be used to analyze the data–logging mathematically, it is given as follows

$$P_{SD} = \frac{\int_0^t \Delta dt}{\int_0^t v dt} \tag{1}$$

where $\Delta \in \mathbb{R}$ is the absolute value of the deviation error in the xy-plane between the position of BHDS's end-effectors and the nearest point on the reference trajectory, and $v \in \mathbb{R}$ is the velocity of the hand movement of subjects.

The effect of the applied haptic guidance on the master hand has not been evaluated in the preliminary test, which aims at patients with both impaired upper-limbs. Through the parameters settings of value and direction of the assisted force, the device can compensate the reduced performance of subjects, even though the reduced performance is caused by a lack of effort instead of stroke. This method also provides a possibility to conquer patients' fatigue and relax their muscles after a long-time rehabilitation session, nevertheless no significant effect on the recovery has been proved by this way.

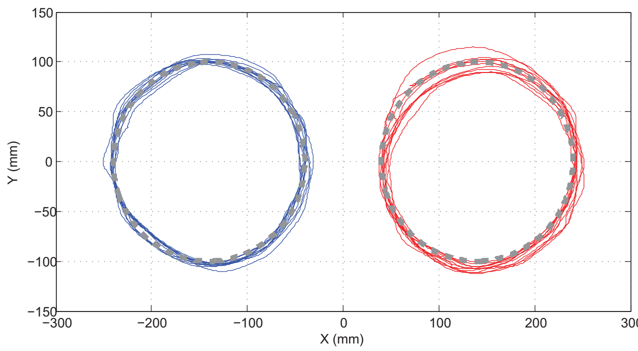


Fig. 7. Example of the hands movement of subjects during the tracking task, the dashed gray line is the reference trajectory of the hand movement, the blue line is the recorded movement of the master hand, and the red line is the slave hand's movement.

B. Lifting Task

Regarding the lifting task, the subject is asked to hang up the virtual box with both hands up to a defined height. The number of the patients holding the box to the appointed height within certain exercise time has been counted as an available parameter to measure the steadiness recovery of upper-limb movement. The following parameters need to be initialized before a rehabilitation session:

- Master modes - left hand, right hand and no master hand
- Gravity of the virtual box
- Assisted force - yes or no
- Value and direction of assisted force

The height of the box has been recorded as function of time for the analysis of the therapist. The Fig. 8 shows an example of position recording of the virtual box during one rehabilitation session. The force output on the end-effector of the device is also recorded, which indicates the haptic interaction between the patient and the rehabilitation system. The therapist can easily read the recovery information of the patient from the plotted data.

Because of the lower stiffness in the constraint for the symmetric mode movement, there exists a deviation between the reference path of symmetric movement and the real trajectory of the hand movement of impaired upper-limb.

Hence it is necessary to track the patient's hand movement, which can provide another approach to quantize the steadiness of each patient, for instance measuring the average and standard deviation of each patient's movement within one exercise. Optimally, the movement steadiness of the impaired upper-limb has reached the recovery expectation if the standard deviation is lower than the desired value appointed by the therapist.

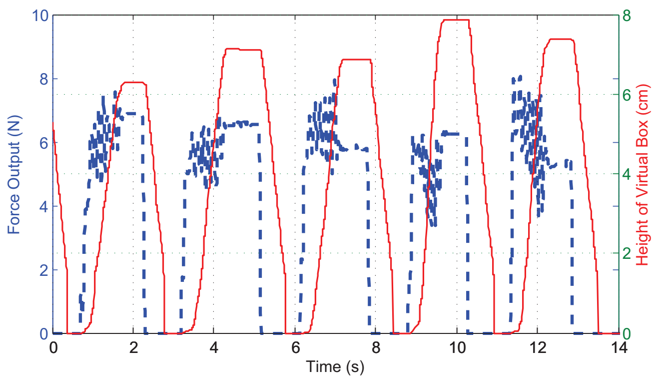


Fig. 8. Example of position recording of the virtual box during one rehabilitation session with the red line, and meanwhile the blue dashed line reports the force output on the end-effector of the device

C. Catching Task

The video–game-like exercise requires the patient to catch the target sphere dropping down as much as possible in certain exercise. Before starting the exercise, there are several parameters to be adjusted:

- Master modes - left hand and right hand
- Velocity of the target sphere
- Velocity of the random interferential spheres

Through the exercises of tracking task and lifting task, the catching task has been used to test the recovery situation of the impaired upper-limb, for instance allowing the impaired one as the master hand to complete the exercise. The therapist can analyze the patient's performance by the results recorded in the online database. Fig. 9 shows an example of the data information of the force output and the distance between the moving pad and the target sphere, which evaluates the haptic and rehabilitation function of the system.

This exercise can also be applied to train the hand-eye coordination motion of the subject. To stimulate the motivation of the subject on the exercise, several obstacles for the subject to finish the task can be set to increase the difficulty level of the exercise, such as increasing the falling velocity of the target sphere, and the number and falling velocity of the random sphere. But no significant evidence has been proved the effect of the number and falling velocity of the random sphere on the catching results of the subject.

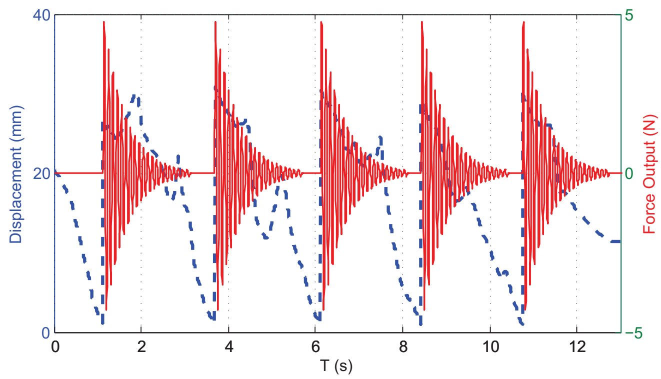


Fig. 9. Example of the data recording of the catching task, the force feedback of the device with the red line, and the distance between the moving pad and the target sphere with the dashed blue line.

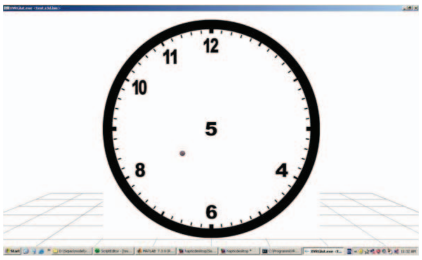
V. CONCLUSIONS AND FUTURE WORK

In this contribution, three haptic-based virtual exercises have been presented on the extended application of the Bimanual Haptic Desktop System for the undergoing rehabilitation of upper-limb post–stroke patients. The designed exercises provide subjects/patients with three main clear benefits:

- The coherent and co-located rehabilitation between the force stimuli and the visual information is performed;
- A wider choice of rehabilitation session is provided with the combination of three different exercises, and to make an assessment or a calibration of the patient, several video–game-like applications, shown in Fig. 10, have been developed, which can also be used for the evaluation of the recovery program;
- A graphical user interface is designed for the convenience of the subjects and therapists operation.

The proposed exercises provide continuous measurement and evaluation of data information to analyze the interaction between the subject and the environment during the operation. The promising results can be used for the therapist to assess the improvement of the rehabilitation and design the suitable clinical recovery session. A preliminary evaluation conducted with healthy subjects are then reported and discussed to visualize the near future clinical application.

For the future work, a mid–term in-depth analysis of the designed exercises will be carried on to define a suitable standard of the BHDS for evaluating the recovery level of the patient. A definite rehabilitation pilot protocol with identified patients has been designed and implemented in the hospital



(a) "Clock" exercise, during which the patient is asked to move the number appearing in the center of the clock to the right place.

(b) "Puzzle" exercise, one-hand exercise for moving the target parts to the right displacement.

Fig. 10. Two examples of the videogame-like applications designed for the assessment and calibration of the system.

to demonstrate the possibility of the BHDS for robotic upper-limb rehabilitation therapy.

REFERENCES

[1] A. Frisoli, L. Borelli, A. Montagner, S. Marcheschi, C. Procopio, F. Salsedo, M. Bergamasco, M. Carboncini, and B. Rossi, "Robot-mediated arm rehabilitation in virtual environments for chronic stroke patients: A clinical study," *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pp. 2465–2470, May 2008.

[2] A. Sunderland, D. J. Tinson, E. L. Bradley, D. Fletcher, H. R. Langton, and D. T. Wade, "Enhanced physical therapy improves recovery of arm function after stroke. a randomised controlled trial," *J. Neurol. Neurosurg. Psychiatry*, vol. 55, pp. 530–535, Jul 1992.

[3] D. Kwakkel, R. C. Wagenaar, J. W. R. Twisk, G. J. Lankhorst, and J. C. Koetsier, "Intensity of leg and arm training after primary middle-cerebral-artery stroke: a randomised trial," *Lancet*, vol. 354, pp. 191–196, 17 July 1999.

[4] G. Kwakkel, B. J. Kollen, and R. C. Wagenaar, "Long term effects of intensity of upper and lower limb training after stroke: a randomised trial," *J. Neurol. Neurosurg. Psychiatry*, vol. 72, no. 4, pp. 473–479, 2002 April.

[5] R. Riener, M. Wellner, T. Nef, J. von Zitzewitz, A. Duschau-Wicke, G. Colombo, and L. Lunenburger, "A view on vr-enhanced rehabilitation robotics," *Virtual Rehabilitation, 2006 International Workshop on*, pp. 149–154, 2006.

[6] G. B. Prange, M. J. Jannink, C. G. Groothuis-Oudshoorn, H. J. Hermens, and M. J. Ijzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *J Rehabil Res Dev.*, vol. 43, no. 2, pp. 171–184, Mar-Apr 2006.

[7] P. Lum, D. Reinkensmeyer, and S. Lehman, "Robotic assist devices for bimanual physical therapy: preliminary experiments," *Rehabilitation Engineering, IEEE Transactions on*, vol. 1, no. 3, pp. 185–191, Sep 1993.

[8] L. Lugo-Villeda, A. Frisoli, O. Sandoval-González, V. Parra-Vega, A. Avizzano, E. Ruffaldi, and M. Bergamasco, "Haptic guidance of the light-exoskeleton for rehabilitation tasks," *to appear on the proceedings of the 18th IEEE International Symposium on Robot and Human Interactive Communication,(RO-MAN 09),*, 2009.

[9] S. Hesse, H. Schmidt, and C. Werner, "Machines to support motor rehabilitation after stroke: 10 years of experience in berlin," *J Rehabil Res Dev.*, vol. 43, no. 5, pp. 671–678, Aug-Sep 2006.

[10] A. R. Luft, S. McCombe-Waller, J. Whitall, L. W. Forrester, R. Macko, J. D. Sorkin, J. B. Schulz, A. P. Goldberg, and D. F. Hanley, "Repetitive bilateral arm training and motor cortex activation in chronic stroke: a randomized controlled trial," *JAMA*, vol. 292, no. 15, pp. 1853–1861, Oct 2004.

[11] C. G. Burgar, P. S. Lum, P. C. Shor, and H. Van der Loos, "Development of robots for rehabilitation therapy: The palo alto va/stanford experience," *J Rehabil Res Dev.*, vol. 37, no. 6, pp. 663–673, 2000.

[12] P. Lum, C. Burgar, D. Kenney, and H. Van der Loos, "Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post-stroke hemiparesis," *Biomedical Engineering, IEEE Transactions on*, vol. 46, no. 6, pp. 652–662, June 1999.

[13] P. Lum, C. Burgar, and P. Shor, "Evidence for improved muscle activation patterns after retraining of reaching movements with the mime robotic system in subjects with post-stroke hemiparesis," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 12, no. 2, pp. 186–194, June 2004.

[14] P. Lum, C. Burgar, P. Shor, M. Majmundar, and H. Van der Loos, "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke," *Archives of Physical Medicine and Rehabilitation*, vol. 83, no. 7, pp. 952 – 959, 2002.

[15] R. M. Mahoney, H. Van Der Loos, P. S. Lum, and C. Burgar, "Robotic stroke therapy assistant," *Robotica*, vol. 21, no. 1, pp. 33–44, 2003.

[16] S. Hesse, H. Schmidt, C. Werner, and A. Bardeleben, "Upper and lower extremity robotic devices for rehabilitation and for studying motor control," *Curr Opin Neurol.*, vol. 16, no. 6, pp. 705–710, Dec 2003.

[17] S. Hesse, G. Schulte-Tigges, M. Konrad, A. Bardeleben, and C. Werner, "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects," *Archives of Physical Medicine and Rehabilitation*, vol. 84, no. 6, pp. 915–920, 2003.

[18] S. Hesse, C. Wemer, E. Schonhardt, A. Bardeleben, W. Jenrich, and S. Kirker, "Combined transcranial direct current stimulation and robot-assisted arm training in subacute stroke patients: a pilot study," *Restor Neurol Neurosci.*, vol. 25, no. 1, pp. 9–15, 2007.

[19] D. Jack, R. Boian, A. Merians, M. Tremaine, G. Burdea, S. Adamovich, M. Recce, and H. Poizner, "Virtual reality-enhanced stroke rehabilitation," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 9, no. 3, pp. 308–318, Sept. 2001.

[20] G. Burdea, "Keynote address: Virtual rehabilitation-benefits and challenges," *1st International Workshop on Virtual Reality Rehabilitation (Mental Health, Neurological, Physical, Vocational) VRMHR 2002 Lausanne, Switzerland*, pp. 1–11, November 7 and 8 2002.

[21] J. C. Stewart, S. Yeh, Y. Jung, H. Yoon, M. Whitford, S. Chen, M. McLaughlin, A. Rizzo, and C. Winstein, "Pilot trial results from a virtual reality system designed to enhance recovery of skilled arm and hand movements after stroke," *Journal of NeuroEngineering and Rehabilitation*, August 2006.

[22] M. Mihelj, T. Nef, and R. Riener, "Armin ii - 7 dof rehabilitation robot: mechanics and kinematics," *Robotics and Automation, 2007 IEEE International Conference on*, pp. 4120–4125, April 2007.

[23] O. Portillo, C. Avizzano, M. Raspolli, and M. Bergamasco, "Haptic desktop for assisted handwriting and drawing," *Robot and Human Interactive Communication, 2005. ROMAN 2005. IEEE International Workshop*, pp. 512–517, 2005.

[24] C. Avizzano, M. Raspolli, S. Marcheschi, and M. Bergamasco, "Haptic desktop for office automation and assisted design," *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, pp. 4086–4091, April 2005.

[25] G. Jansson and M. Öström, "The effects of co-location of visual and haptic space on judgments of form," *Proceedings of the 4 th International Conference Eurohaptics 2004*, pp. 516–519, June 5-7 2004.

[26] E. Ruffaldi, A. Frisoli, M. Bergamasco, C. Gottlieb, and F. Tecchia, "A haptic toolkit for the development of immersive and web-enabled games," *VRST '06: Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 320–323, 2006.