2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

Upper Limb Assessment using a Virtual Peg Insertion Test

Marie-Christine Fluet, Olivier Lambercy and Roger Gassert
Rehabilitation Engineering Lab, ETH Zurich, Switzerland
Rehabilitation Initiative and Technology Platform Zurich (RITZ)
Emails: {mfluet, olambercy, gassertr}@ethz.ch

***Abstract*—This paper presents the initial evaluation of a Virtual Peg Insertion Test developed to assess sensorimotor functions of arm and hand using an instrumented tool, virtual reality and haptic feedback. Nine performance parameters derived from kinematic and kinetic data were selected and compared between two groups of healthy subjects performing the task with the dominant and non-dominant hand, as well as with a group of chronic stroke subjects suffering from different levels of upper limb impairment. Results showed significantly smaller grasping forces applied by the stroke subjects compared to the healthy subjects. The grasping force profiles suggest a poor coordination between position and grasping for the stroke subjects, and the collision forces with the virtual board were found to be indicative of sensory deficits. These preliminary results suggest that the analyzed parameters could be valid indicators of impairment.**

I. Introduction

Our daily activities are strongly dependent on the use of our arms and hands, and thus people suffering from functional deficits of the upper limb, e.g. following a stroke, are often severely impaired in the execution of simple tasks. The choice of appropriate therapy to recover lost abilities requires proper assessment of the functional deficits. However, current assessment tests of arm and hand function used in clinical routine (such as the Fugl-Meyer Motor Assessment Scale, the Box and Block test, the Jebsen Hand Function Test, etc.) suffer from important limitations, such as intra- and inter-rater variability, a limited amount or lack of quantitative measures, time-consuming administration, low responsiveness (ability to detect clinical changes over time) and low sensitivity (possibility for a large portion of patients to perform the test). Thus, there is a clear need for more objective, reliable and sensitive tests for the assessment of arm and hand function.

Robotic devices have a strong potential to improve current clinical assessments since they can provide a platform for objective measures of impairment. They can precisely record movement trajectories, execution time and interaction forces during well-controlled and repeatable motor tasks. Several studies used robotic devices to characterize movements of neurologically disabled subjects. For example, exoskeleton robotic devices have been used to investigate force generation or abnormal muscle synergies during reaching movements and to quantify abnormal shoulder and elbow coupling in stroke subjects [1], [2]. Other studies used planar robotic manipulanda, such as the MIT-Manus, to investigate movement smoothness in stroke subjects and found that movements

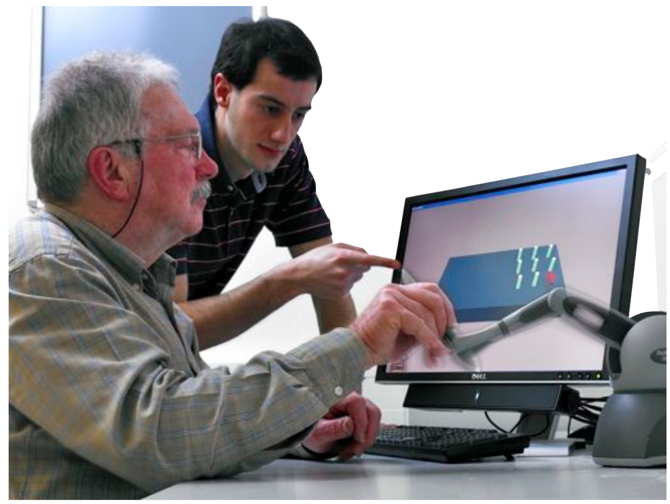

Fig. 1. The Virtual Peg Insertion Test uses a haptic interface to render physical interactions with the environment while it records kinetic and kinematic data.

tend to become smoother during recovery [3]. Attempts to investigate manipulation tasks and not only arm movements have been made using end-effector devices in which subjects were required to approach a virtual object in order to grasp it [4]. However, these studies have some limitations such as low device transparency, limited degrees of freedom or do not fully represent functional tasks that require grasping, transport of an object and precise placement.

To provide a better tool for the assessment of arm and hand function, we combined virtual reality and an augmented haptic interface that can provide kinesthetic feedback through an instrumented handle grasped by the subject. The test consists of a functionally relevant pick and place task. It combines reaching and grasping movements and thus involves both proximal and distal parts of the limb. During the task, the position and the orientation of the hand, the grasping force and the collision forces with the virtual board are measured in function of time. These measures can provide information about movement smoothness, joint coordination, muscle strength and sensory perception, all parameters found to be important in clinical assessments.

This paper presents initial measurements with healthy and stroke subjects. The aim of these measurements was to eval-

978-1-4244-9861-1/11/$26.00 ©2011 IEEE

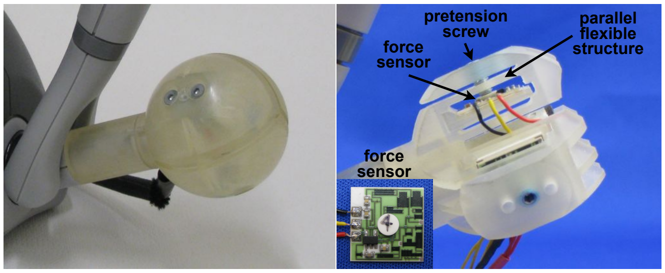

Fig. 2. Spherical handle comprising three force sensors (left). Close-up view of the opened spherical handle and a CentoNewton piezoresistive force sensor (right).

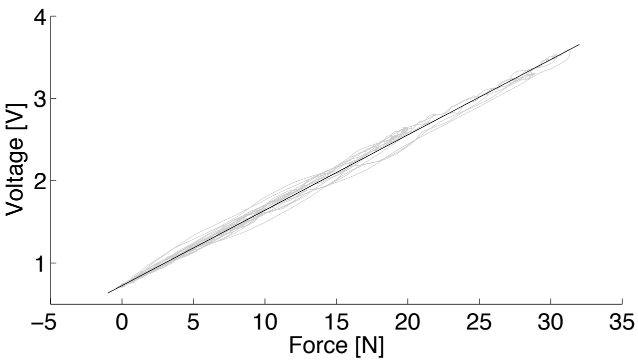

Fig. 3. Linear relationship between the applied force [N] and the output voltage [V] of one force sensor during repeated dynamic loading/unloading (light gray) and linear fit (dark gray) (y=0.0915x+0.726; R^2=0.9987).

uate the sensitivity of the test by comparing performances of healthy subjects executing the task with the dominant hand versus the non-dominant hand and to obtain baseline measures. Furthermore, these initial measurements aimed at determining the types of stroke subjects able to perform the task as well as identifying meaningful performance parameters representative of important sensorimotor functions.

II. Materials and Methods

A. Apparatus

We developed a Virtual Peg Insertion Test consisting in grasping nine pegs, one after the other, and inserting them into nine holes as quickly as possible [5]. This test combines virtual reality and haptics using a commercial, low-cost haptic display (PHANTOM Omni, SensAble Technologies, Inc., USA) which has 6 DOF positional sensing and 3 DOF force feedback (Fig. 1). The haptic interface provides kinesthetic feedback to the subject's hand in order to render a realistic reconstitution of the interaction with a real environment and precisely tracks the movement. The PHANTOM Omni is provided with a stylus that has two switches that can be pressed to perform actions in the virtual environment, such as selecting virtual objects. However, this handle cannot measure the grasping force applied by the subject.

A new handle was designed that includes three single-axis force sensors (CentoNewton 40, EPFL, Switzerland) placed on a parallel flexible structure in order to measure the grasping force (Fig. 2). The new design has a spherical shape which is easier to grasp and manipulate by stroke subjects with impaired hand function. The instrumented sphere was realized with rapid prototyping (Eden 350 V, Objet Geometries Inc., USA) using FullCure720 material (flexural modulus 75.8 MPa). Fig. 3 shows the dynamic force response of one of the three sensors integrated into the spherical handle during eleven loading/unloading cycles. The sensor was dynamically loaded and unloaded (up to 100 N/s) to three force levels (approximately 10, 20 and 30 N) against a commercial load cell (Mini 40, ATI Industrial Automation, USA) while the voltage output of the piezoresistive sensor was measured. Force data were lowpass filtered at 50 Hz and show good linearity despite the viscoelastic characteristics of the rapid prototyping material.

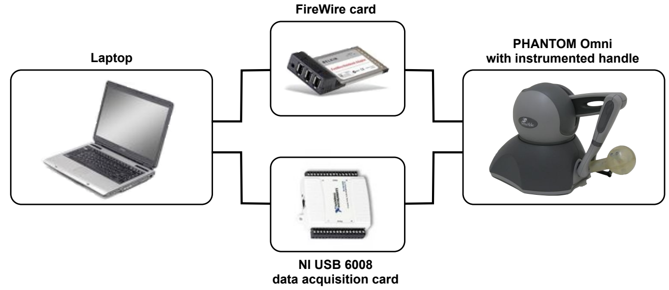

Fig. 4. Connection diagram. The PHANTOM Omni communicates with the laptop over a PCMCIA FireWire card. The grasping force is acquired through a USB data acquisition card.

Grasping forces are acquired over a USB data acquisition card (NI USB 6008, National Instruments, USA) while the position, angles and collision forces are acquired through a firewire connection, which also sends the commands from the physics engine for the forces to be displayed to the device. The task is implemented in Microsoft Visual C++ and OpenGL is used for graphic rendering. All signals are sampled at a rate of 1 kHz and are stored on a laptop (IntelCore 2, 2.67 GHz, Windows XP). The connection diagram is shown in Fig. 4. The complete setup is compact and can be easily transported and integrated in a clinical environment.

B. Subjects

Three groups performed the Virtual Peg Insertion Test, two groups of 8 healthy subjects each and one group of 14 chronic stroke subjects. The first group (three females and five males, age 29±5 years) performed the task with their dominant hand, the second group (one female and seven males, age 29±3 years) with the non-dominant hand and the group of stroke subjects (three females and eleven males) with their impaired hand. Stroke subjects were recruited on a patient-by-patient basis from our clinical partners at the ZAR (Center for ambulatory rehabilitation, Zurich). The ZAR classifies patients into four categories based on their motor impairment level as described in Table I. Subjects of all four levels of impairment were tested (one A0, two A1, three A2 and eight A3). Five

TABLE I
CLASSIFICATION OF MOTOR FUNCTION FOR STROKE SUBJECTS AT THE ZAR.

Impairment level	Description
A0	no arm movement
A1	arm movements are significantly restricted
A2	fine motor skills are restricted (impairment is pronounced)
A3	fine motor skills are restricted (impairment is mildly pronounced)

subjects reported sensory deficits in the hand during a pre-session interview. All subjects were required to have normal vision, 3D perception, the ability to understand the task and had to provide informed consent.

C. Procedure

Subjects were seated in front of the laptop and held the handle in its initial position with the elbow flexed about 90 degrees and the shoulder abducted about 45 degrees. A blue board was displayed with nine pegs aligned vertically on the left which had to be moved and inserted into nine holes displayed in a 3x3 matrix on the right. To execute the task, the subject had to manipulate the handle which is represented by a cursor on the screen. The cursor had to be properly aligned with a peg before grasping, and the peg would fall if the grasping force was not maintained above a defined threshold. Information about the different colors of the cursor and the pegs was given to the subject before the experiment was started. The cursor is transparent yellow when no peg is held, turns orange to indicate that it is properly aligned with a peg, green when a peg is currently held and red when excessive grasping force is applied to the handle but no peg is held. The subject was instructed to insert the nine pegs into the nine holes as fast and as precisely as possible using only the tested hand. In order to insert a peg into a hole, the grasp had to be released below the force threshold. The test was completed once all pegs were inserted into the nine holes. The pegs could be taken in any order and inserted into any free hole. The difficulty of the task was adapted to the level of impairment of the stroke subjects. To do so, two task parameters were varied: the grasping force threshold, calculated as the mean of the three force sensors (between 1 and 5 N, 5 N for healthy), and the maximal distance between the cursor and the peg for the alignment (between 3 and 8 mm, 3 mm for healthy). The alignment was calculated as the mean of the distance between the top of the cursor and peg and the distance between the bottom of the cursor and peg in order to account for both the position and the orientation. During a recording session, subjects performed two test trials during which they received the instructions and were allowed to experience the force feedback. This was followed by five repetitions of the test (two for the strongly impaired stroke subjects).

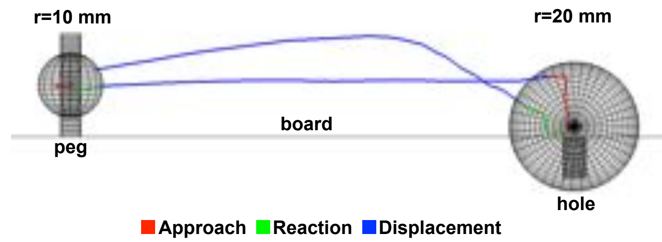

Fig. 5. Front view of the decomposition of one trajectory into approach, reaction and displacement phases based on a spherical area around the peg (r=10 mm, centered on the middle of a peg at its initial position) and around the hole (r=20 mm, centered on the middle of a peg when inserted in the hole).

D. Data analysis

During the execution of the Virtual Peg Insertion Test, the position profile shows a specific pattern that is repeated for each peg. The movement can be decomposed into six sequences as follows: approach of the cursor to the peg for alignment and grasping, reaction phase once the peg is grasped, coarse displacement up to a hole, approach of a hole to insert the peg, reaction phase after insertion and coarse displacement to the next peg (Fig. 5). From the movement data, nine parameters were calculated and compared between the different groups of subjects to evaluate arm and hand function. Some of the parameters were restricted to specific phases of the movement and averaged over the nine trajectories.

- The execution time T_{ex} is the time to execute the task from the approach of the first peg to the insertion of the last peg.
- The grasping force is calculated from the mean of the three force sensors integrated into the handle. The average grasping force F_g is calculated during the coarse displacement, giving one value for the transport of a peg (go) and another value for the return.
- The number of zero-crossings of the acceleration is normalized by the duration of the movement during the go and return displacement (N_{zc}).
- The number of times a peg is dropped during the transport is counted (N_{dp}).
- The trajectory error E_{traj} corresponds to the distance between the trajectory and the straight line in the horizontal plane normalized by the trajectory length during displacement (go/return).
- The mean collision force F_{cmean} represents the averaged force exerted against the board during the task from the approach of the first peg to the insertion of the last peg. The collision force is estimated from the motor currents required to render the haptic feedback during the collision with the board.

For each parameter, a one-way ANOVA was performed to test for statistically significant differences between the two groups of healthy subjects performing the task with the dominant versus non-dominant hand. The level of significance was set to 0.05.

TABLE II

PERFORMANCE PARAMETERS OF SUBJECTS PERFORMING THE TASK WITH THE DOMINANT VERSUS THE NON-DOMINANT HAND AND SIGNIFICANT DIFFERENCES BETWEEN THE TWO GROUPS (LEFT). PERFORMANCE OF FOUR STROKE SUBJECTS PERFORMING THE TASK WITH THE IMPAIRED HAND (RIGHT). HAND DOMINANCE IS INDICATED AS D FOR DOMINANT AND ND FOR NON-DOMINANT.

	Healthy			Stroke			
Performance parameters	N=8 D	N=8 ND	p value	S1 ND	S2 D	S3 ND	S4 ND
T_{ex} [s]	25.8±6.6	26.6±7.1	0.66	**93.0**	**48.5**	**76.0**	**149.1**
F_g [N] (go/return)	15.0±5.1 0.73±0.42	12.5±3.5 0.80±0.58	**0.0002** 0.32	**6.3** 0.83	**7.3** 0.33	9.6 0.99	**7.4** 1.02
N_{zc} (go/return)	7.5±1.9 8.0±1.4	6.9±1.5 8.6±1.7	0.22 0.24	**16.4** **14.5**	**17.4** **12.9**	**14.0** **13.9**	**8.5** **13.9**
N_{dp} [peg/trial]	0.13±0.28	0.05±0.09	0.40	0	0	0	**0.5**
E_{traj} [cm] (go/return)	0.24±0.13 0.50±0.14	0.28±0.12 0.43±0.18	0.12 0.08	**0.42** 0.42	0.23 0.43	0.17 0.31	**0.52** **0.78**
F_{cmean} [N]	0.70±0.43	0.63±0.41	0.47	0.37	0.29	**1.82**	**1.28**

III. RESULTS

A. *Hand dominance in healthy subjects*

The performance parameters of the two groups of healthy subjects were first compared in order to determine if the performance significantly changed when the task was performed with the dominant versus the non-dominant hand. For each parameter, the mean values and the standard deviation for all subjects and all trials were calculated. The results of this analysis are presented in Table II. Small differences were found among the two groups. For example, the group performing the task with the non-dominant hand needed more time to complete the task, but this difference was not significant. This result is in accordance with our previous study on a similar manipulation task [5]. Only the grasping force applied on the handle was found to be significantly smaller for the group performing the task with the non-dominant hand compared to the group performing the task with the dominant hand (p=0.0002). Theses results reveal that hand dominance should be taken into account when analyzing the grasping force, but not for the other parameters.

B. *Test sensitivity in stroke subjects*

Among the 14 tested stroke subjects, subjects with no remaining motor function in the arm (A0) or significantly restricted arm movements (A1) could not complete the task without assistance. However, A1 subjects could perform the task when an arm support compensated for the weight of their arm. Stroke subjects with remaining fine motor skills (A2 and A3) could perform the task with appropriate task parameters adjusted to their impairment level, meaning that the grasping force threshold and the alignment tolerance were adjusted. For valid comparison in the following analysis, we included only the four strokes subjects (S1-S4) who could perform the task with the same difficulty level as the two groups of healthy subjects (impairment level S1: A2, S2: A3, S3: A2, S4: A3).

C. *Comparison between healthy and stroke subjects*

Performance of the stroke and the healthy subjects were compared in order to evaluate if the parameters analyzed could be used as indicators of arm and hand impairment. Representative trajectories of a healthy subject and a stroke subject during one complete trial are presented in Fig. 6. Healthy subjects tended to follow a straight trajectory from the peg to a hole and little adjustments around the pegs and the holes were needed compared to stroke subjects. The grasping force in function of time is shown in Fig. 7 for the same trials. The grasping force applied by the healthy subject on the handle clearly showed a repetitive pattern for the nine pegs. Healthy subjects tended to apply a strong force to initially grasp the peg and slowly decreased the force during the transport of the peg. The mean grasping force applied by healthy subjects during the transport of a peg was much larger than the threshold to hold the peg. The force profile of stroke subjects showed that they often needed several attempts to grasp the peg, represented by the red peaks in Fig. 7. This was due to the application of force without proper alignment of the cursor with the peg. Additionally, the maximal forces applied on the handle by the stroke subject after taking a peg were much smaller and the mean grasping force during the transport of a peg was only slightly above the threshold of 5 N.

For each parameter, the mean values of all the trials were calculated for each stroke subject and are presented in Table II. For each parameter analyzed, the values differ from the healthy subjects for at least one stroke subject except for the grasping force during the return trajectory. The grasping force during the go trajectory tended to be lower for the stroke subjects while the execution time, the number of zero-crossings of the acceleration, the number of dropped pegs and the trajectory error tended to be higher. Two of the four stroke subjects (S3 and S4) suffered from sensory deficits and showed higher mean collision forces while the two other subjects showed normal values. Although some similarities can be seen, each stroke subject has his/her own set of impaired functions that has to be identified.

IV. DISCUSSION

The aim of the current paper was to evaluate the Virtual Peg Insertion Test, an objective, easy and fast to administer assess-

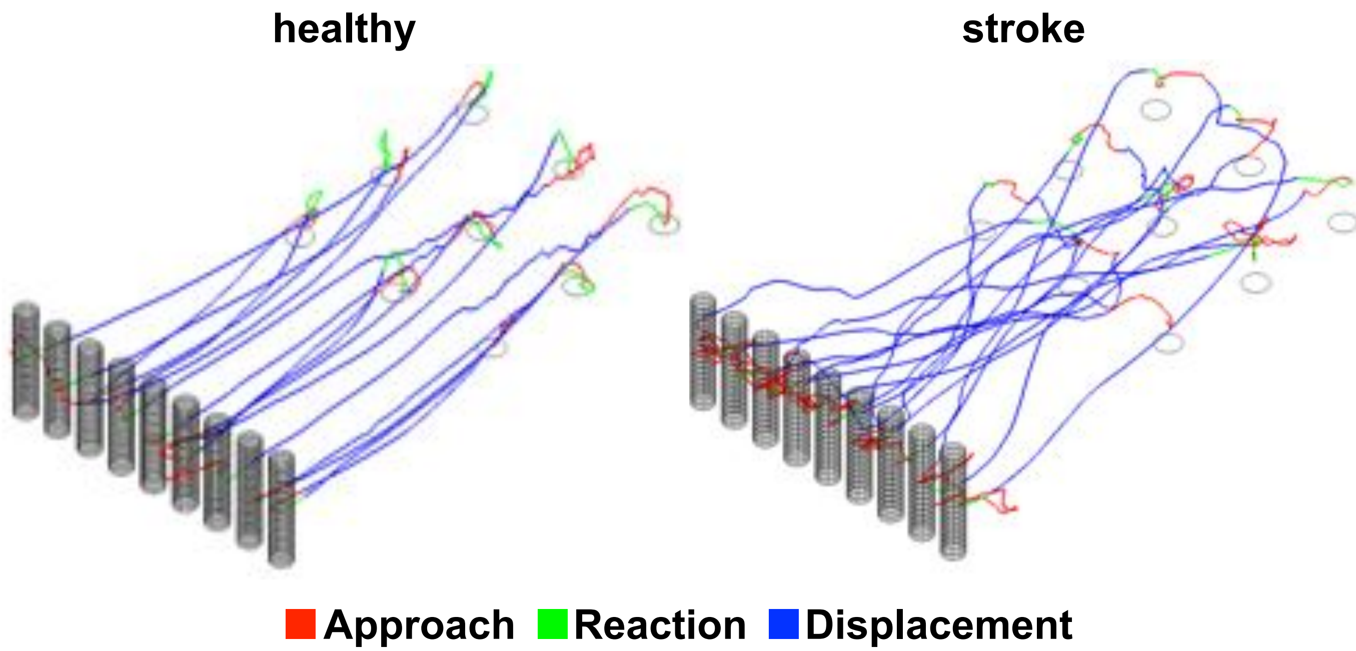

Fig. 6. Trajectory of a representative healthy subject and a stroke subject (S1) during the execution of a complete trial of the Virtual Peg Insertion Test. The trajectories are divided into the different task sequences: approach of a peg (red), reaction after taking a peg (green), coarse displacement during the transport of a peg (blue), approach of a hole (red), reaction after inserting a peg in a hole (green), coarse displacement during the return (blue).

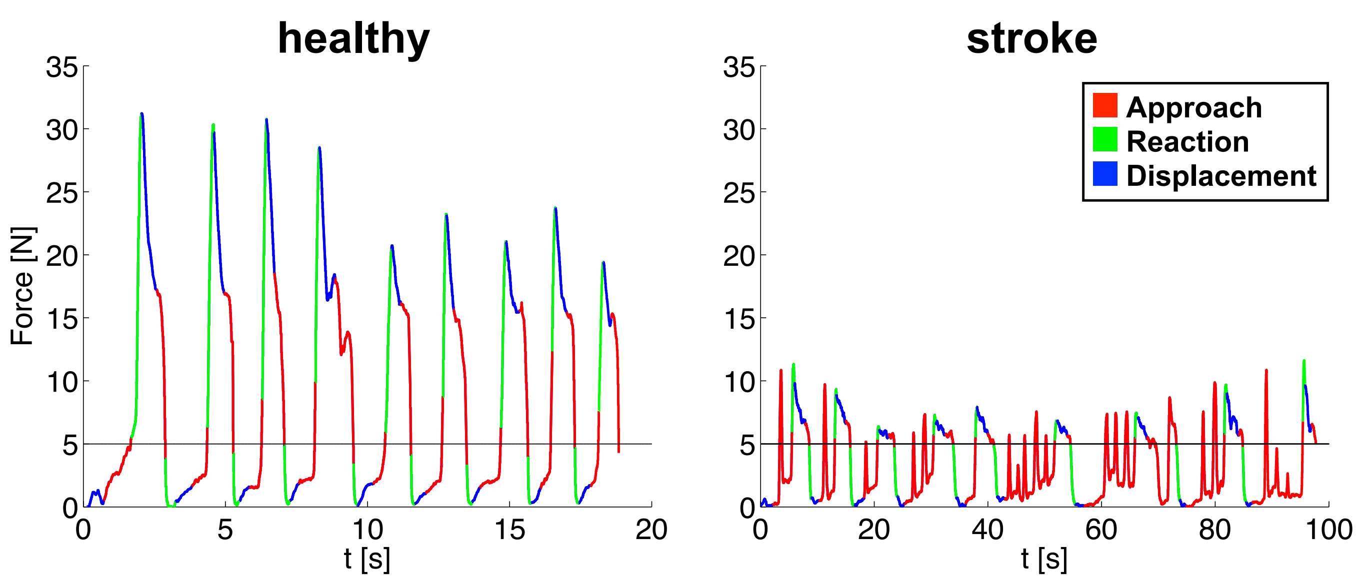

Fig. 7. The grasping force in function of time of a healthy subject and a stroke subject (S1) during the execution of a complete trial of the Virtual Peg Insertion Test. The force threshold was set to 5 N as is indicated by the horizontal dotted line. Movement sequences are indicated as follows: approach (red), reaction (green) and displacement (blue).

ment test of arm and hand function using a haptic interface and an instrumented handle which can measure grasping forces. Up to now, we have performed preliminary measurements with 14 stroke subjects and found that subjects with some remaining fine motor skills could perform the Virtual Peg Insertion Test. We identified and analyzed nine parameters related to task performance and compared results of stroke subjects to healthy subjects performing the task with the dominant and non-dominant hand. Eight of the 9 parameters analyzed showed differences between the groups of healthy and stroke subjects and thus have the potential to be valid indicators of functional impairment. Previous studies have demonstrated how similar parameters could be indicative of some impairments, such as sensory deficits, muscle weakness and abnormal joint coordination, as discussed in more details below.

The execution time seems to vary with the severity of the impairment for the first three subjects with S2 (A3) being faster than S1 and S3 (A2). However, S4 (A3) was slower, which could indicate that hand sensory deficits also have an influence on the execution time. Grasping force could provide information on muscle strength and joint coordination. The grasping force profiles showed that stroke subjects applied less force during this kind of functional task, and the presence of several peaks during the approach of a peg indicated that they had difficulties in coordinating the position adjustment and control of force. Fine precision adjustments have been shown to be characteristic of stroke subjects [6]. In the contrary, healthy subjects applied high forces, possibly with the aim of stabilizing their grip during peg transfer and maximizing their movement speed. Stroke subjects exhibited a higher number of zero-crossings of the acceleration, which has been shown to be a valid measure of movement smoothness and tends to decrease during recovery [3], [7]. Further, the trajectory error could correlate with an altered movement coordination and tends to become smaller with motor recovery [8], [9]. Studies have also shown that sensory deficits can be estimated from collision forces and collision duration [10]. Our results revealed that stroke subjects presenting sensory deficits showed higher collision forces with the virtual board compared to the other subjects.

The relation between the analyzed performance parameters during the Virtual Peg Insertion Test and impaired functions needs to be further established. A way to achieve this validation would be to compare the values of the performance parameters with the results from conventional assessment tests. Other groups have used such approach to validate laboratory-based quantitative measurements in order to improve traditional clinical assessments [11]. Furthermore, additional performance parameters could be investigated, and more data with stroke subjects should be collected to establish baseline values. Finally, the possibility of using this assessment test with other types of neurologically disabled subjects will be explored.

ACKNOWLEDGMENTS

Marie-Christine Fluet, Olivier Lambercy and Roger Gassert are supported by the NCCR Neural Plasticity and Repair of the Swiss National Science Foundation and the Gottfried und Julia Bangerter-Rhyner-Stiftung. The authors wish to thank Dominique Chapuis for the design of the instrumented handle, Andreas Luft for his helpful suggestions, and Kathrin Campen and Joachim Cerny for their support with recruiting and measuring stroke subjects.

REFERENCES

[1] J. P. Dewald and R. F. Beer. Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis. *Muscle Nerve*, 24(2):273–283, Feb 2001.

[2] M. Guidali, M. Schmiedeskamp, V. Klamroth, and R. Riener. Assessment and training of synergies with an arm rehabilitation robot. *Proc. IEEE International Conference on Rehabilitation Robotics*, pages 772–776, june 2009.

[3] B. Rohrer, S. Fasoli, H. I. Krebs, R. Hughes, B. Volpe, W. R. Frontera, J. Stein, and N. Hogan. Movement smoothness changes during stroke recovery. *J Neurosci*, 22(18):8297–8304, Sep 2002.

[4] P. Feys, G. Alders, D. Gijbels, J. De Boeck, T. De Weyer, K. Coninx, C. Raymaekers, V. Truyens, P. Groenen, K. Meijer, H. Savelberg, and O. B. Eijnde. Arm training in multiple sclerosis using phantom: clinical relevance of robotic outcome measures. *Proc. IEEE International Conference on Rehabilitation Robotics*, pages 576–581, 2009.

[5] C. Emery, E. Samur, O. Lambercy, H. Bleuler, and R. Gassert. Haptic/VR assessment tool for fine motor control. In *Proceedings of the 2010 international conference on Haptics - generating and perceiving tangible sensations: Part II*, EuroHaptics'10, pages 186–193, Berlin, Heidelberg, 2010. Springer-Verlag.

[6] O. Lambercy, L. Dovat, H Yun, SK Wee, C Kuah, K Chua, R Gassert, T Milner, TC Leong, and E Burdet. Robotic assessment of hand function with the hapticknob. *Proc. iCREATe*, 2010.

[7] E. Burdet and T. E. Milner. Quantization of human motions and learning of accurate movements. *Biol Cybern*, 78(4):307–318, Apr 1998.

[8] L. Dovat, O. Lambercy, B. Salman, V. Johnson, R. Gassert, E. Burdet, Chee Leong Teo, and T. Milner. Post-stroke training of a pick and place activity in a virtual environment. *Virtual Rehabilitation*, pages 28–34, 2008.

[9] M. F. Levin. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain*, 119 (Pt 1):281–293, Feb 1996.

[10] A. Bardorfer, M. Munih, A. Zupan, and A. Primozic. Upper limb motion analysis using haptic interface. *IEEE/ASME Transactions on Mechatronics*, (6):253–260, 2001.

[11] MD Ellis, T. Sukal, T. DeMott, and JP Dewald. Augmenting clinical evaluation of hemiparetic arm movement with a laboratory-based quantitative measurement of kinematics as a function of limb loading. *Neurorehabilitation and neural repair*, 22(4):321–9, 2008.