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

Using an Embedded Reality Approach to Improve Test Reliability for NHPT Tasks

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Abstract— **Research into the use of haptic and virtual reality technologies has increased greatly over the past decade, in terms of both quality and quantity. Methods to utilise haptic and virtual technologies with currently existing techniques for assessing impairment are underway, and, due to the commercially available equipment, has found some success in the use of these methods for individuals who suffer upper limb impairment. This paper uses the clinically validated assessment technique for measuring motor impairment: the Nine Hole Peg Test and creates three tasks with different levels of realism. The efficacy of these tasks is discussed with particular attention paid to analysis in terms of removing factors that limit a virtual environment's use in a clinical setting, such as inter-subject variation.**

I. INTRODUCTION

It has been estimated that, each year, 15 million people suffer a stroke [1]. A stroke occurs when the blood supply to the brain is disrupted; this can be caused by either a blockage (Ischemic Stroke) or a rupture of a blood vessel (Haemorrhagic Stroke). Without blood supply, the affected brain cells will die, which can lead to a wide array of problems and disabilities post-stroke, some minor, some major; affecting all aspects of everyday life. According to the World Health Organization, stroke is the biggest single cause of major disability in the United Kingdom [1].

Research conducted in 2008 [2] suggested that there is still a lack of adequate methods of rehabilitation for impaired upper limbs, following stroke and other neurological conditions, compared to rehabilitation efforts for the lower limbs. Upper limb impairment is a major limiting factor in the patient's ability to perform everyday tasks, with many patients requiring further rehabilitation following discharge from a clinic [3].

In order to devise patient specific rehabilitation regimes, methods of assessing the level of impairment are required [4]. Typically a patient will be required to perform numerous tasks that give an indication of the level of functional impairment in areas such as: gross motor control; fine motor control; manual dexterity; strength; and proprioception.

A common method of assessing fine motor control following stroke is the Nine Hole Peg Test (NHPT) [5]. The NHPT is a clinically established and validated tool for the assessment of upper limb motor control [6]. The test apparatus consists of a board with nine, evenly spaced, holes (10mm in diameter) arranged in a 3 by 3 grid and nine pegs (9mm in diameter). Typically, the patient is seated in front of the apparatus and is asked to place the pegs, in turn, into the holes on the board (see Fig. 1). The time taken to complete the task is recorded. Faster times suggest better arm function [7].

Following the recent development of advanced robotic and haptic systems, a number of studies into the use of haptic virtual reality for rehabilitation and assessment have been conducted [8]–[11]. The major benefit of such systems lies in the ability to record specific information regarding the subject's movement, such as: speed, position in the environment, forces exerted, and orientation of the end effector; in comparison to the conventional NHPT where only task completion time is available. Furthermore, virtual environments provide the unique ability to create tasks that otherwise would not be feasible to set up in the real world, and improve test–retest reliability by reducing the potential for variation and human error during the setup of the task.

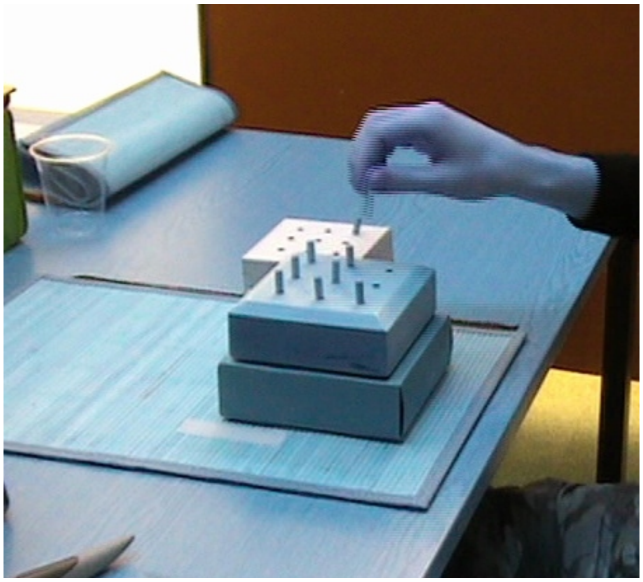

Fig. 1. This shows the setup of the standard Nine Hole Peg Test for this experiment. The positioning of the apparatus allowed the workspace dimensions to be mimicked across all three of the tasks that subjects performed.

Manuscript received January, 2010. This work was supported in part by the EU FP7 ICT-215554 project LIREC.

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Recent studies [8], [11] have displayed promising results regarding the use of haptic peg-in-hole systems and their effectiveness in assessing patients with neurological disorders. However, much benefit can be gained by taking a deeper look into how variation between tasks and their setup can be reduced in order to improve the reliability of such 'hapto–virtual' tests before they can be considered in a clinical setting.

This study has been designed to explore three different methods of completing the NHPT: Real (a modified NHPT), Embedded (a mixture of both real-world and virtual environments) and Virtual (NHPT in a virtual workspace). Each task mimics the others in terms of physical workspace dimensions and proportions. It is proposed that, by using an embedded reality approach to the NHPT, we can work towards validating a valuable assessment tool by improving inter-subject variation and limiting human error in task set-up, to produce a method of haptic assessment that can enhance the capabilities of non-haptic measures.

II. EXPERIMENT

The experiment gathered a total of 60 healthy participants aged between 19 and 57 (mean 27.5 ± 9.2 standard deviation) and included 38 male and 22 female subjects. The experiment consisted of three major components: a real NHPT with physical pegs and pegboard; a virtual NHPT, where the pegs and board reside in virtual environment, with all the interaction being delivered haptically; and, finally, an embedded reality approach to the NHPT, where the subject uses the stylus to move a real peg into the pegboard. In all of the three tasks the dimensions of the apparatus in the workspace and their location in the workspace in relation to the subject were kept the same in order to reduce the differences between the three environments as much as possible. The embedded reality approach allowed for the capture of task specific information, such as position, orientation and velocity, whilst having the advantage of using physical equipment to reduce the potential cognitive load of the virtual world.

This section will first present the haptic environment that is used to perform the experiments and describe the interaction that this environment enables. Following on, the descriptions of the tasks and the experiment setup are introduced.

A. Haptic Environment

The system used for this set of experiments utilised the PHANTOM Omni haptic controller (www.sensable.com) this is a relatively small haptic device, with a stylus or pen-like grip. The device allows for 3 active degrees of freedom and 3 passive degrees of freedom. This enables force feedback in all three axes (Cartesian coordinate system), with the added ability to record the orientation of the stylus. The haptic environment was built using the H3DAPI, which allows for rapid prototyping of 3D environments with the use of an XML SceneGraph and python. Haptic force feedback is generated at the rate of 1000Hz. In order to simulate the peg-hole interaction, a method of multi-point collision was employed based on the work described by Amirabdollahian et al. [8]. This enabled the full 3D interaction of the peg with the rest of the environment.

Fig. 2 shows the haptic environment for the fully virtual method of NHPT. As seen, the environment consists of a pegboard and 9 pegs, with some on screen instructions. The pegs and the board match their real-world counterparts 1:1 in terms of size and also in their position within the subject's workspace.

We decided that it was important that, throughout the 3 tasks (real, embedded and virtual), the size and position of both the virtual, and the real objects remained constant, so as to limit any external factors that may affect the results of the task such as the distance between pegs, the ratio of peg diameter to peg hole diameter, or event the position and orientation of a subject's arm whilst using the stylus. In order to achieve precise positioning of the physical apparatus, the PHANTOM Omni, pegboard, and peg holder were attached to a mat, thus maintaining a fixed position throughout the trials.

A virtual laser pointer was also added to the virtual environment, helping subjects to gauge the distance between the tip of the stylus and the intersection between the laser beam and the object.

B. Experiment Setup and Procedure

Sixty healthy subjects performed this experiment. Eight subjects stated that they had used some form of haptic technologies in the past. Before commencing the study, the ethics application was approved under the University's ethical regulation and procedures. All subjects consented to take part in the study. Subjects were first asked to complete a demographic questionnaire, then were asked to perform the experiment. After the experiment, subjects were asked to

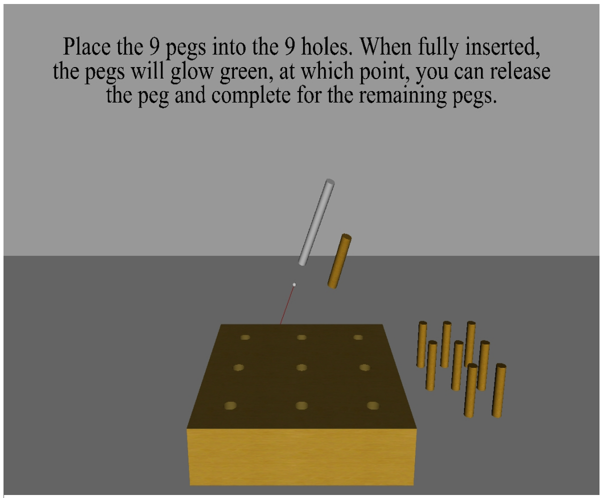

Fig 2. Here, the set up for the virtual Nine Hole Peg Test is shown. To the right of the pegboard stand the pegs. The stylus is represented by the grey cylinder and grey ball, with the laser pointer shown in red. Whist holding a peg, the stylus graphic changes to that of the peg. All objects including the walls of the environment give an appropriate level of force feedback when contact is made.

complete a questionnaire to gauge their attitudes towards the system and to assess their own performance in the tasks.

The first part of the experiment required the subject to perform a series of four training exercises that were designed to familiarise them with the environment, and ensure that they were comfortable whilst working with the PHANTOM Omni. Prior to starting the training exercises, subjects were instructed on the correct procedure for handling and holding the Omni's stylus (very similar to holding a pen). Once the training exercises were complete, the subjects were required to perform the NHPT in three different forms: real, embedded, and virtual. These tasks were performed in a randomly assigned order, helping to remove any learning effects that may occur from one task to the next. All tasks were timed to allow for comparisons to be made regarding the subjects' performance on all three tasks. Two video feeds were also recorded throughout the duration of the experiment: one video to capture the arm/hand of the subject whilst completing the task; and the second to record the subject's facial expressions whilst performing the tasks. These videos allow for further investigation of specific anomalies that may have occurred in the data to determine the cause/reason behind them.

C. *Training Exercises*

The training exercises increased in difficulty from the first to the last. The first training exercise required the subject to touch five different haptic blocks in turn, placed at various positions within the virtual environment. This exercise helped the subject to realise the depth of the virtual environment. Once the first exercise had been completed the subject moved on to the second: this required the subject to touch and grasp six different numbered blocks in a specified order. The grasping was performed by holding one of the two stylus buttons. Once all six blocks had been grasped, the order was randomized and subjects were required to repeat the task again. The third exercise required the subject to re-position an object by making contact with the block, grasping the object and then moving it to a specified position. The final training exercise required the subject to perform a simple peg in hole task, which included picking up a peg by making contact with the peg (felt via force feedback) and then griping one of the buttons on the stylus. Once the button was pressed, the peg's orientation changed to match the orientation of the stylus. The subject then inserted the peg, released the button, and continued in the same way for the remaining two pegs. All training exercises were explained verbally, and also re-explained via onscreen instructions.

These training exercises were designed to give subjects an understanding of how to control the PHANTOM Omni and, more specifically, how to perform the necessary movements required to perform the virtual NHPT.

D. *Real NHPT*

The real NHPT task was conducted using apparatus from benefitsnowshop.co.uk. This wooden block measures precisely 120mm by 120mm with the peg holes drilled at an equally spaced distance (33mm apart), with the diameter of 6mm for each hole and the depth of each hole to be 15mm, and the pegs to be 5mm in diameter and 30mm in length. Although these measurements differ from the original requirements of the NHPT test set out by D. Wade [5], more recent studies have shown that commercially available pegboards [12], also of differing dimensions, work in the clinical setting. Being from a reputable seller of clinical assessment equipment, it was therefore assumed that this apparatus was fit for this study.

As seen in Fig. 1, the actual setup of the experiment also differs slightly from the original requirements of the test. Where usually the pegs would be scattered in a tray, here the pegs are positioned in a holding box. Although this alleviates some of the difficulty of the task, this allows the creation of a complete 1:1:1 ratio in terms of size and position of the workspace between all three tasks. Previous peg-in-hole studies have shown that insertion alone can provide us with useful indicators of performance in a haptic task [8]; therefore more effort would be placed on the analysis of the insertion rather than the picking of the pegs. Furthermore, with this setup it is hypothesised that the average time for the real NHPT would be reduced from the times previously stated [5], [12], [13] due to these factors.

With the hand placed in a resting position (by the side of the apparatus, flat, palm facing down) subjects were told to place each of the nine pegs in to a hole on the board. Subjects were instructed to complete the task 'as quickly and as comfortably' as they could. Times were recorded with a stopwatch, which was started the moment that the subject grasped the first peg. The time taken to complete the task was recorded, and would also be used to calculate the average time taken per peg-placement. As with all of the tasks, subjects were instructed to use only their dominant hand throughout.

E. *Embedded NHPT*

The embedded reality task used the same pegboard as the real task, located in precisely the same location in front of the subject. Attached to the end of the stylus was a peg (as seen in Fig. 3). Complementing this was the virtual environment which displayed all nine pegs and a virtual copy of the pegboard. Subjects could pick up a virtual peg by moving the peg attachment of the stylus to a hole in the peg holding box (the white box displayed in Fig. 3, also the same as in the real set up) corresponding to a peg in the virtual environment on screen. Once a peg had been picked, the stylus graphic also changed to that of a peg (see Fig. 2 for explanation). Once the peg attachment was fully inserted into a hole on the pegboard, the peg was released, along with the visual representation of the stylus reverting back to the default graphic, and the subject could pick the next in the same manner. The setup of the pegs prior to placement matched the layout of the holding box. Haptic cues were also provided so that the virtual pegs could be 'felt' prior to picking. The haptic cues also provided the advantage of disallowing the placement of pegs into an already occupied hole.

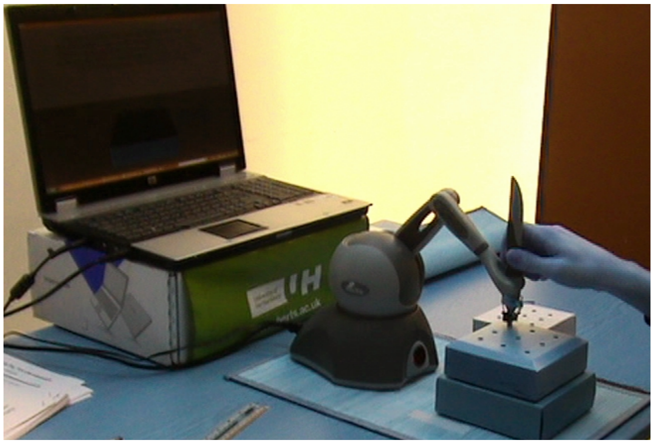

Fig. 3. This image shows the setup of the embedded reality version of the Nine Hole Peg Test. Attached to the end of the stylus is a peg, that allows the subject to experience real physical interactions, enhanced by haptic interactions that occur when the virtual stylus encounters the pegs and pegboard in the virtual environment.

Once again subjects were instructed to complete the task ‘as quickly and as comfortably’ as they could. The task was also timed, with the timer beginning as soon as the fist peg was acquired at which point, the log files were also initialised and data recording began. Data regarding position, orientation, velocity, force, buttons pressed, and events such as PICKED_PEG_X were recorded in the haptic loop.

F. Virtual NHPT

For the virtual task, the position of the PHANTOM Omni remained in exactly the same position in front of the subject as in the embedded task. This time no physical apparatus were included. All nine pegs and the pegboard resided in the virtual workspace. Subjects were instructed to pick up the pegs by using the same method described in the final training exercise (touching the peg and then gripping by pressing either of the two buttons), and to place each peg, in turn, into the holes of the virtual pegboard. Further visual cues were delivered through the virtual environment: when a subject encountered a peg it shone bright red, meaning that it was ready to be picked up; and when the subject had correctly inserted the peg into a hole on the pegboard, the peg shone bright green denoting that the peg was correctly inserted and could now be released. It should also be noted that alignment between the stylus and the peg was not needed in order to pick the peg up, only the ‘touch and grasp’ technique described was required.

As in the embedded task, the test was timed from the moment that the first peg was grasped, and all haptic data (positions, velocities, forces etc.) were recorded into a log file enabling accurate recording of subject actions throughout each task.

All of the tasks were described to the subjects verbally and by demonstration. Tasks involving the virtual environment had onscreen instructions and participants were instructed to read them prior to commencing the task. However, subjects were able to read the onscreen instructions throughout the task but, as gaze direction was not recorded, the affect that this may have had on task completion time was not analysed.

G. Data Collection

For each subject, log files were created for every haptic task that they performed, including all four training exercises and the virtual and embedded reality NHPT. Each log file consisted of a timestamp that denoted the start of the task, followed by the series of data packets, separated by newlines, taken at an average sampling rate of 100Hz. For this experiment the variables that were collected were: position of the stylus within the virtual world (x,y,z); orientation of the stylus (a_x,a_y,a_z,θ) based on angle-axis convention [14]; velocity at which the stylus is being moved (Vx,Vy,Vz); forces that the subject has encountered (Fx,Fy,Fz); buttons that are being pressed; and, an event string. The event string was used to tag data samples with specific information regarding the state of the task such as, peg one grasped (HOLDING_PEG_1) or inserted into hole 3 (INSERTED_HOLE_3). The tagged information was then used to calculate the separate aspects of the movement: transfer time, and insertion time.

In addition to the log files from the device, demographic and feedback questionnaires were also collected. The demographic questionnaire gathered relevant information such as physical impairment, visual impairment, dominant hand, familiarity with computer games and previous use of haptic technologies. The feedback questionnaire gave an overall impression of subjects’ attitudes toward the setup of the task, which has provided some recommendations for the design of future tasks; however, no significant conclusions could be found between subjects’ feelings toward the tasks and their performance in the tasks and therefore were not further investigated.

III. RESULTS AND ANALYSIS

The first step taken in the analysis was to discover what, if any, demographic factors may have affected the performance times in the three tasks (Table I). Analysis of these variables was performed using IBM SPSS (www.SPSS.com). Where normality in the datasets could not be shown the p-values were calculated using the Mann-Whitney U test for independent samples, otherwise p-values were calculated using the independent samples t-test. It can be seen that: hand dominance, use of spectacles, and previous use of haptic technologies had no impact on task completion times. However, there was a significant difference attributed to subjects’ familiarity with computer games, of which 25 out of the 60 participants stated that they were either quite or very familiar with 3D computer games, spending an average of 8.12 hours per week playing computer games. Although familiarity with computer games was shown to have an impact on task completion times, and should be considered when discussing the results; there was no impact on the pattern of reduction of variability in task completion times, which decreased in the same manner as seen for all participants and shown in Fig. 4.

TABLE I
EFFECTS OF DEMOGRAPHIC FACTORS ON TASK PERFORMANCE

Task	Hand Dominance	Wearing Glasses	Previous Use of Haptics	Rated Quite/Very Familiar with 3D Computer Games
Real	p=0.123	p=0.228	p=0.871	p=0.168
Embedded	p=0.641	p=0.946	p=0.811	p=0.005[a]
Virtual	p=0.292	p=0.548	p=0.144	p=0.002[a]

This table shows the p-values from comparing the means of the demographic factors with the task completion times.

[a]Where p is less than 0.03 the effect of the variable is significant at the 97% confidence interval.

Fig. 4. The graph shows the variations for task completion times in each of the three tasks: real, embedded and virtual. As elements of reality are removed from the task, the time to complete the task increases, as do the inter-subject variations in completion times.

In order to obtain an overview of the performance of each task compared to its counterparts, a box plot of the completion times was first produced (Fig. 4). From this it can be seen that times to perform the task increase from the real NHPT test to the embedded NHPT and finally to the virtual NHPT. Of note here is the variation in task completion time for the three tasks which also increases with time taken for the three tasks. The reduction in the variation of task completion times seen between the virtual and embedded tasks implies a higher degree of inter-subject consistency for the embedded task. As expected, the embedded reality approach reduces task completion times compared to those seen in the virtual task which could be largely attributed to the limitations of the PHANTOM Omni, such as low position resolution (which, with other factors, has been shown to impair haptic perception [15]) and the presence of the real-world physical interaction between the peg and the peg-board, felt directly through the stylus. The embedded approach, in this scenario, is closer, in terms of speed and variation, to the real task compared to the virtual model, whilst still providing the freedom to obtain information that would not be possible in the real setup.

The reduction in time and variability could also be potentially explained by the reduced amount of cognitive load required by subjects in the form of visual processing; however, this was not explored here and would require further analysis of the video feeds in order to determine the amount of time subjects spent looking at the screen for each task.

Once established that the embedded task was performed more quickly and with a higher degree of inter-subject consistency than found in the virtual task, a further investigation was taken as to find the root cause of these differences in times. For this, the data for each task was processed to find two key elements of the NHPT: the transfer time, and the insertion time. The transfer time was determined to be the time taken from the moment a peg was picked up, to the moment that that same peg entered the threshold of a peg hole (point of insertion). The insertion time was then calculated to be the time taken from the point of insertion until the peg was fully and correctly inserted into the hole. Analyses of transfer and insertion times for embedded and virtual tasks were performed using the Wilcoxon Signed Rank test, which resulted in p-values approaching 0.00, thus is it was concluded that there was a significant difference between the transfer times of the two tasks and of the insertion times of the tasks, with the embedded shown to be performed quicker according to the statistical test.

The forces encountered throughout peg insertions of both the embedded and virtual tasks were plotted (Fig. 5). As can be seen, far more interaction and collision forces are encountered during the virtual task than in the embedded task. In an attempt to explain this phenomenon the angle of insertion was extracted for each peg placement, for each subject, and was tested for correlation against the task time. No correlation was found (p=0.408), and it was discovered that the higher forces were actually encountered when subjects attempted to insert a peg but had misjudged the position of the hole. One likely cause for the angle of insertion not influencing performance is the use of multi-point collision algorithm [8], which ensured that pegs could only be inserted in an upright position. Further experiments need to be carried out in order to present a virtual world with more visual cues allowing subjects to perceive the depth of the environment with more accuracy.

Further analysis of the difference between the times for the transfer and insertion for individual placements under the embedded and virtual tasks was conducted (see Table II). In order to make the comparisons between the two tasks as accurate as possible, placements were only included if they were found in both of the tasks, e.g. if both the embedded and virtual tasks included placing peg 2 in hole 4; thus, the distance for the transfer part of the placements remains the same. As would be expected from previous findings, average transfer times were quicker in the embedded task; which held true for 61% of the embedded–virtual placement pairs. Also, when looking at the insertion times it was again found that the embedded task was, on average, quicker than the virtual task; holding true for 82% of embedded–virtual placement pairs. Taking these findings into account, correlation between the total time and transfer/insertion was tested for both tasks

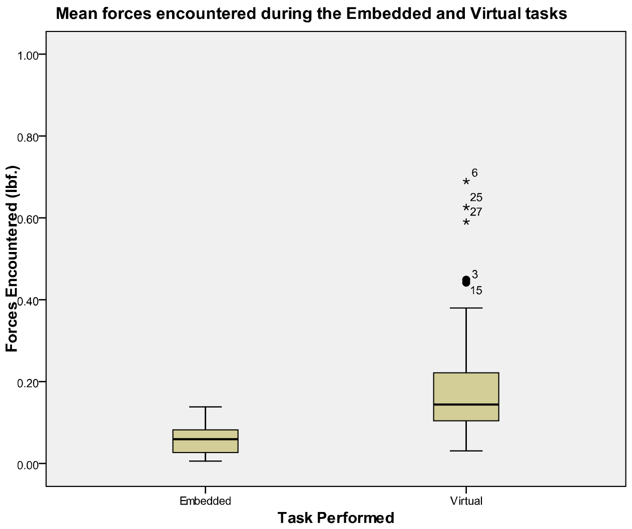

Fig. 5. The graph shows the differences in variation for the mean force encountered whilst performing the embedded and virtual tasks. Haptic force feedback was much higher in the virtual environment than that seen in the embedded setup.

using the Pearson Correlation Coefficient to determine whether one component had more of an effect on the overall placement time than the other. For each of the tasks both the transfer and the insertion times were significant to a confidence interval of 99% (Table III).

When looking at the ratio of time spent on the two elements of the peg placement between the two tasks it was found that, on average, subjects performing the embedded tasks spent 86% of the time on the transfer and 14% of the time on the insertion, whereas, in the virtual task, 70% of the time was spent on the transfer compared to 30% on the insertion; suggesting that the insertion component of the task was more difficult in the virtual task than in the embedded.

TABLE III

CORRELATION MATRIX DESCRIBING THE RELATIONSHIP BETWEEN THE COMPONENT PARTS OF A PLACEMENT AND ITS TOTAL TIME

	Pearson Correlation for Transfer Time against Total Time		Pearson Correlation for Insertion Time against Total Time	
Task	r-value	p-value	r-value	p-value
Embedded	0.833[a]	~0.00	0.645[a]	~0.00
Virtual	0.709[a]	~0.00	0.777[a]	~0.00

This table compares the correlation between the component parts of the peg placements (transfer and insertion) and the total time taken to perform the full placement.

[a]Significant at the 99% confidence interval.

IV. DISCUSSIONS

It is interesting to note that the average time for the real NHPT task explained here was faster than the original peg in hole by approximately 3.5 seconds (14.5 compared to 18 seconds). This could potentially be attributed to two factors: age and modification of the task itself. Firstly, the age range of subjects in this study was significantly lower than that of previous studies, and followed trends established by Grice et al. [12], that as age of subjects increase, so does the time taken to complete the task. Furthermore, in this experiment, the pegs were placed upright and separated at a distance of 20mm apart (in a 3 by 3 grid) in a holding cell. This alleviated some of the complexity of the task as the pegs required less manipulation, and therefore potentially reducing the average time for the task. However, this configuration also enabled the specific distances between pegs and peg holes to be recorded in all three tasks, something which would otherwise be almost impossible in the real scenario.

TABLE II

ANALYSIS OF INSERTION AND TRANSFER TIMES FOR THE EMBEDDED AND VIRTUAL TASKS

Task	Average Transfer Time (s)	Average Insertion Time (s)	Time Spent on Transfer (%)	Time Spent on Insertion (%)
Embedded	2.115	0.781	86.19	13.81
Virtual	2.483	1.760	69.83	30.17

This table compares the component parts of a peg placement (transfer time and insertion time) for the embedded and virtual tasks.

When designing this set of experiments, originally a stronger relationship between the three tasks was assumed. Very quickly, it was established that these tasks were not only inherently different from the tasks originally described by D. Wade [5], they were also different from each other. It was expected that by making a complete replica in terms of dimensions of the virtual scene and position of the workspace in front of the subject, a close correlation between the variations in times would be found; however, we found that this variation increased as more of the element of realism was removed from the task.

In order to find the cause of the variation between the embedded and virtual tasks, two key areas of the data were analysed: task completion times; and the two components of the movement itself: the transfer time and the insertion time. From these comparisons, it was be seen that insertion time in the embedded was performed quicker than in the virtual task. Also, transfer time in the embedded task was, on average, quicker than that seen in the virtual task. It is hypothesised that the properties of the embedded task account for the better performance; the physical peg attached to the stylus aids the insertion into the peg hole, thus reducing insertion time; whereas the real-world interaction alleviates some of the effects of workspace translation that may be apparent when using computerised 3D graphics.

The embedded task has been shown to improve performance over the virtual task; however, it is not without its own flaws. One of the main limitations of the setup that was noted was the need for the subject to constantly refer to the visual display in order to keep track of the pegs that had been picked up and placed. It is expected that by taking the attention away from the physical apparatus and to the screen and then back again could severely affect the time taken to perform the task. Further investigation into this matter will be performed by comparing the time spent looking at the screen (from the laptop camera) and the time taken to complete the task.

From the analysis of the insertion trajectories and differences in the orientation of the stylus between the virtual and embedded tasks, it can be assumed that force and insertion angles are not the only contributing factors to the slower times of the virtual tasks. It is also likely that the differences in the physical appearance of the apparatus for the three tasks, i.e. graphical rendering and lack of holding box in the virtual task, may have also contributed to the differences between task completion time and consistency. Once further differences and their causes are established, experiments will be reformulated to allow for closer matching between the validated NHPT, and the embedded and virtual incarnations. This includes making the pick and placement parts of the tasks more consistent with each other in order to reduce any effect that this may have on the task completion times.

V. CONCLUSIONS

The preliminary analysis of this experiment has shown that an embedded reality approach to the NHPT has enabled a more accurate and consistent set of data for a large group of subjects than that of a purely hapto–virtual reality approach. Some limitations of this experiment, namely: lack of practice attempts before the actual task, could also have contributed to the high level of inter-subject variation in the virtual task, while it is important to highlight that such differences are less obvious in the real NHPT task. Future experiments will include practice runs of the experiment before performing the task under test conditions to improve this. Furthermore, designs of the environment itself will also be adjusted, such as: removing onscreen instructions once the subject has begun the task (which should not be needed if practice runs are included), to reduce any distractions that they may have caused; better visual cues i.e. shadows, in addition to the laser pointer; and less reliance on the visual display for the embedded reality NHPT task.

It should be noted that these results will also be used to inform the design of future collaborative haptic rehabilitation systems that furthers the LIREC (http://lirec.eu) project's research into the use of robotic devices as social mediators.

ACKNOWLEDGMENTS

This work was partially supported by the European Commission (EC) and is currently funded by the EU FP7 ICT-215554 project LIREC (Living with Robots and Interactive Companions). The authors are solely responsible for the content of this publication. It does not represent the opinion of the EC, and the EC is not responsible for any use that might be made of data appearing therein.

We also greatly appreciate the efforts of everyone who took part in this study and for allowing us to record their data to further our research efforts.

REFERENCES

[1] J. Mackay, and G. Mensah,. "The atlas of heart disease and stroke." Geneva: World Health Organization, 2004.

[2] A. Chortis, P.J. Standen, and M. Walker, "Virtual reality system for upper extremity rehabilitation of chronic stroke patients living in the community". Proceedings of the 7th ICDVRAT with ArtAbilitation, Maia, Portugal, 2008, pp. 221–228.

[3] J. Broeren, M. Georgsson, M. Rydmark, and K. S. Sunnerhage, "Virtual reality in stroke rehabilitation with the assistance of haptics and telemedicine". Proceedings of the 4th International Conference of Disability, Virtual Reality and Associated Technologies, Veszprém, Hungary, 2002, pp. 71–76.

[4] B. Brewer, S. K. McDowell and L. C. Worther-Chaudhari, "Poststroke Upper Extremity Rehabilitation: A Review of Robotic Systems and Clinical Results," Topics in Stroke Rehabilitation, vol. 14(6), pp. 22–44, Nov–Dec. 2007.

[5] D. Wade, "Measurement in Neurological Rehabilitation", Council, British, Britain), National, & Britain), National.. *British book news*. London,1991.

[6] V. Mathiowetz, K. Weber, N. Kashman, and G. Volland, "Adult norms for the Nine Hole Peg Test of finger dexterity". Occupational Therapy Journal of Research. Vol 5(1), Jan 1985, 24–38.

[7] A. Heller, D. Wade, V. Wood, A. Sunderland, R. Langton-Hewer, and E. Ward, "Arm function after stroke: measurement and recovery over the first three months". Journal of Neurology, Neurosurgery, and Psychiatry, 50 (6),1987, 714–719.

[8] F. Amirabdollahian, G.T. Gomes, and G.R. Johnson, "The Peg-in-Hole: a VR based haptic assessment for quantifying upper limb performance and skills". International conference on Rehabilitation Robotics (ICORR) 2005, 2005.

[9] R. Loureiro, F. Amirabdollahian, M. Topping, B. Driessen,W. Harwin, "Upper limb robot mediated stroke therapy-GENTLE/s approach". *Autonomous Robots* 2003 , **15**(1)**:**35–51

[10] J.H. Crosbie, S. Lennon, M.C. McGoldrick, M.D.J. McNeill, J.W. Burke, and S.M. McDonough, "Virtual reality in the rehabilitation of the upper limb after hemiplegic stroke: a randomised pilot study". Proceedings of the 7th ICDVRAT with ArtAbilitation, Maia, Portugal, 2008, 229–235.

[11] C. Emery, E. Samur, O. Lambercy, and H. Bleuler, "Haptic/VR Assessment Tool for Fine Motor Control", Lecture Notes in Computer Science, Springer Berlin / Heidelberg, 6192, 2010, pp. 186–193

[12] K.O. Grice, K.A. Vogel, V. Le, A. Mitchell, S. Muniz, M.A. Vollmer, "Adult norms for a commercially available nine hole peg test for finger dexterity". American Journal of Occupational Therapy, 57(5), 2003, pp. 570–573.

[13] V.M. Parker, D.T. Wade, and R. Langton-Hewer,"Loss of arm function after stroke: measurement, frequency, and recovery". Int Rehabil Med 8: 69–73. 1986

[14] J. J. Craig, "Introduction to Robotics." Addison Wesley, pp. 50, 1986.

[15] N. Sakr, J. Zhou, N. D. Georganas, J. Zhao, and E. M. Petriu, "Robust perception-based data reduction and transmission in telehaptic systems" in Proc. of Third Joint Eurohaptics Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Salt Lake City, USA, Mar. 2009, pp. 214 – 219.