Analysis of the results from use of haptic peg-in-hole task for assessment in neurorehabilitation

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Haptic and robotic technologies have the potential to provide assessment during interaction with humans. This manuscript presents our earlier research during the I-Match project where a haptic peg-in-hole test was used in order to compare between healthy volunteers' performance and those with neurological impairment. Subjects all performed a series of haptic virtual peg-in-hole tasks with varying degrees of difficulty determined by the hole diameter. Haptic instrument, Phantom Desktop 1.5, allowed for recording of biomechanical data which is used to present some variant features between the two subject groups. This paper analyses the placement time, maximum peg transfer velocity, collision forces recorded during peg placement and also insertion accuracy. The first three parameters showed statistically significant differences between the two groups while the last, insertion accuracy, showed insignificant differences (p=0.152). This is thought to be due to the large clearance value between the smallest hole diameter and the peg. To identify differences between the haptic peg-in-hole and the established NHPT, we are currently in process of conducting a further experiment with a haptic replica of the NHPT test, in order to investigate effects resulting from addition of haptic force feedback compared to the original NHPT test, as well as allowing to explore influences caused by the 1mm clearance value as originally proposed by Wade.

Furthermore, in order to investigate if this method can identify differences between subjects with different neurological conditions, a larger group of subjects with neurological conditions such as stroke, multiple sclerosis, and traumatic brain injury is required to explore potency of this approach for identifying differences between these different conditions.

Keywords: haptics; peg-in-hole; i-match, robotic for assessment, outcome measures

Introduction

The *I-Match* project, funded by the European Commission under the Information Society Technologies (IST) thematic program, was a three-year project that began in November 2002. It focused on quantifying users' upper limb performance and skills in order to aid in selecting the most suitable interface for use with his/her assistive device. The project provided a series of haptic tests, including the peg-in-hole test, aiming at distinguishing the differences seen in between healthy volunteers and subjects with neurological impairment with the longer-term objective of providing accurate and comprehensive measures of precise hand function. This approach also holds the promise of use in a tele-rehabilitation setting where the clinician may be remote from the patient.

This paper presents the peg-in-hole haptic test and proceeds to detail the associated clinical assessment. It then analyses the results using statistical models and graphs to support the argument that biomechanical parameters identified during haptic interaction can record differences observed between different subject groups, mainly healthy volunteers versus subjects with neurological conditions.

Background

A user's ability to operate an interface is, to a major degree, dependent upon the quality of hand and arm control. While the commonest method of assessing hand control is to use one of the clinically based scales (e.g. Jebsen et al [1], Action Research Arm Test [2]), a number of researchers have looked at more quantitative approaches. The Southampton Hand Assessment Procedure (SHAP) is an example of testing hand function in its contextual environment [3]. Using a different technology, Spyers-Ashby and colleagues [4] have used a six-degrees of freedom electromagnetic sensor to quantify upper limb tremor. In the field of robotic neurorehabilitation, the MIT-MANUS group has used haptic approaches to promote and measure upper limb function. In studies using their haptic interface, kinematic data have been used to quantify human arm movements and recovery in stroke patients [5-7]. Similarly, Reinkensmeyer et al have used the "Arm Guide" to assess tone, spasticity and lack of coordination for patients after chronic brain injury [8]. Salazar-Torres et al used a biomechanical device to investigate the excitability of muscle stretch reflexes in order to quantify spasticity [9]. Moreover, to assess coordination and upper limb functional state of a group of patients with different neurological disorders (e.g. Friedreich Ataxia, Parkinson's disease, Multiple Sclerosis and Muscular Dystrophy), Bardorfer et al have used a PHANToM haptic interface and a virtual labyrinth [10]. It is acknowledged that the aforementioned studies represent only a small number of the existing and ever-growing research aiming to quantify upper limb function.

The haptic peg-in-hole test

The peg-in-hole task consists of two haptically rendered holes and a cylindrical peg, which is to be alternately inserted in each hole. Figure 1 shows the graphical user interface presented for this task, correlating with dimensions of the haptically rendered model.

The test is inspired by the validated and established Nine- Hole-Peg-Test (NHPT) used in clinical assessment. The NHPT requires inserting nine pegs in holes arranged in three rows and three columns. The completion time or the number of pegs inserted in a given time is seen as a reliable measure of subject's skills and performance [11]. As seen in Figure 1, the haptic peg-in-hole test provides only two holes and uses only one peg during any one session. It is intentionally designed to be different from the conventional test as it provides a chance to assess many other aspects of the performance, for example: it is hypothesized that repetitive movements to the same positions allow for investigating both repeatability and extent of learning to perform better; with a two-hole-peg-test where subjects either perform a left-to-right or a right-to-left half-cycle, it is possible to compare performance variations towards and away from the dominant hand, while due to the freedom given in choosing the pegs in the conventional NHPT, this is not possible; furthermore the two hole setting also provides a simple base for comparing the performance using the conventional Fitt's model for motor control [12].

Haptic presentation of the virtual world is created using the PHANToM desktop 1.5 haptic interface from SensAble Technologies, USA (www.sensable.com). Being developed as a virtual world, the peg-in-hole test also allows for altering experimental parameters such as: peg diameter, peg height, peg weight, hole diameter, separation distance between holes and clearance (peg vs. hole). The peg collision with the holes and the other solid surfaces such as walls shown by Figure 1 is detected by detecting collision between these objects and slices of the peg, which are sectioned as shown by dots in Figure 2. Using a novel mathematical collision detection algorithm, multiple contacts between the peg, the table and holes are detected and haptic feedback is produced upon collisions.

Experimental settings and procedures

The PHANToM offers 3 active and 3 passive degrees of freedom. The orientation of the virtual peg mimicked that of the PHANToM stylus in real-time. The virtual table was placed on a horizontal plane as presented in Figure 1. Shadow cues were used to provide better depth perception.

The virtual table created for this experiment presented the holes with 150 mm separation distance between them. The hole diameter (HD) varied between 80mm, 60mm or 40mm resulting in three distinct experimental settings. The peg diameter was 30mm leaving a 10mm clearance between the peg and the smallest hole.

Participants ranged from healthy volunteers (HV) to subjects recovering from multiple sclerosis (MS), stroke (S) or traumatic brain injury (TBI). Subjects with neurological impairment were patients at the Hunters Moor hospital, Newcastle upon Tyne. Fifty three subjects participated in the trial. Subjects had no prior knowledge of test objectives and peg-in-hole was presented as a potential robotic exercise, which could influence recovery. All subjects gave informed consent to participate and could leave the experiment at any point. From these, 41 subjects completed the experiment and their demographic details are presented in table 1. These resulted in four subject groups: HV, MS, S and TBI. Due to the difficulty of matching subject numbers between the three groups with neurological impairments (MS (n=14), S (n=2) and TBI (n=2)), and given that main objective of this study was to investigate differences between healthy subjects and those with neurological conditions, the three groups are merged as neurological group in this study.

Subject sat comfortably in front of the PHANToM desktop device as shown in Figure 3. They were instructed to insert the peg into the left hole, remove it and insert it into the right hole (starting from mid-position). This was to be performed 20 times (10 cycles) before moving to the next experimental setting. They were instructed to move as quickly as possible while trying to minimise the collision with the table and the walls of the holes during peg placement and removal. The visual and auditory cues were also explained. The peg insertion and removal was accompanied by a downward or upward guiding arrow presented on the screen (shown in Figure 1). A loud audio beep was also played once at each successful peg insertion.

Results and Analysis

Data were logged at an average sampling frequency of 1000Hz. Force, Position, Orientation, Velocity and Contact/Collision reaction Forces were recorded as vectors in Cartesian coordinate frame (*x*, *y* and *z* attributes). During the data logging, data were coded with tags allowing easy selection of relevant data related to each half-cycle. In order to investigate differences between repetitions, five full cycles were selected (cycles 4 to 9) for each of the 3 settings. Figure 4 shows a 3D presentation of one typical session during the experiment produced using MATLAB. The following parameters were chosen for analysis here: the time taken to complete each full cycle, time of left-to-right (L2R) cycles, time of right-to-left (R2L) cycles, collision forces during each half cycle, insertion error and maximum velocity during peg transfer.

Analysis method

PASW 18.0 was used to analyse the results statistically. Figure 5 shows the study subject groups, experimental settings and the process followed during the data analysis. As there were 5 selected half cycles for each L2R and R2L peg placement, a repeated measures ANOVA was first used to identify differences between recorded parameters for these repetitions. All four parameters showed insignificant differences for these repetitions (p-value > 0.05).

Due to this invariance, a Univariate model was then used to analyse the data from the 1st repetition for L2R and R2L half cycles.

Analysis of movement time

Due to insignificant differences between repetitions, only the first occurrences of L2R and R2L peg placement were analysed. Sample data for one subject is provided in Table 2. The Univariate model used movement time as its parameter while using subject group (1= Neurological Group, 2=Healthy Group), hole diameter (4, 6 and 8 cm), and trajectory direction (1=R2L, 2=L2R) as its fixed factors. The results showed highly significant differences between the subject groups (p-value <0.0005) while failing to identify significant differences based on hole diameter or trajectory direction. Figure 6 presents a graph comparing between the two subject groups, different hole diameters and trajectory directions.

Analysis of collision forces

Collision forces were recorded during interaction with the haptic holes, the table and the walls. During interaction, such collisions were detected and interaction forces calculated by the PHANToM device and recorded using the peg-in-hole program. For each half-cycle, these forces were summed to produce a Collision Force Vector, used to calculate a resultant collision force magnitude for this analysis.

Similar to the movement time, collision force magnitudes were analysed using the Univariate Model. The same parameters were used for this analysis and the results showed a strong effect for subject group (p-value=0.016) and interaction between subject group and hole diameter (p-value=0.017). These differences are visually presented by Figure 7.

Analysis of maximum transfer velocity

During the interaction, transfer velocity is logged as a vector in the Cartesian coordinate frame. The maximum velocity magnitude (MaxVM), was then found by a search algorithm during each L2R or R2L half-cycle. This MaxVM was analysed using the Univariate model with the same parameters as mentioned earlier. The results showed significant differences between the two groups (p-value < 0.0005) but failed to highlight differences between L2R and R2L half-cycles, or between different hole-diameters (Figure 8).

Analysis of the insertion error

An insertion error was defined as the distance between the centre of the peg and the centre of the hole during each insertion into the right or left hole. As a 2D parameter, this was calculated on the horizontal plan passing the table surface. Figure 9 presents the spread of this error for a single subject where it is clear that this point is not always close to the centre of the hole. This parameter was also analysed to compare between the two groups, different hole diameters and trajectory directions. The results

(Figure 10) show insignificant differences between the two groups (p-value=0.152) while highlighting significant differences between insertions for different hole diameters (p-value < 0.0005).

Bivariate-correlation between factors

A final step taken was to analyse the bivariate correlations between the four factors mentioned previously. This procedure was used to compute Pearson's correlation coefficient and its statistical significance. The results obtained from the correlation analysis showed that there were significant correlations between movement time and collision forces (Pearson's correlation coefficient: 0.663, significance: p-value <0.0005); and movement time and maximum transfer velocity (Pearson's correlation coefficient: -0.212, significance: p-value=0.001). However, there was no significant correlation between movement time and insertion error (Pearson's correlation coefficient: 0.041, significance: p-value=0.522), while insertion error was correlated with both placement collision force (Pearson's correlation coefficient: 0.195, significance: p-value=0.002) and maximum transfer velocity (Pearson's correlation coefficient: 0.212, significance: p-value=0.001). Collision forces and maximum transfer velocity were also correlated (Pearson's correlation coefficient: 0.352, significance: p-value<0.0005)

Discussions

A major purpose of this initial study has been to identify measurement parameters, which are likely to be of clinical relevance when measuring rehabilitation progress. Comparison of performance time between different subject groups showed significant differences between the unimpaired and patient groups. This trend was further confirmed by results from collision force and maximum velocity. However, insertion error failed to support significant differences between the two subject groups. This finding is probably not surprising since the test provides no visual of auditory feedback of insertion accuracy. Since the clearances are relatively large, it is fairly easy for the subject to avoid collision with the side of the hole with a small level of precision. This is further supported by the evidence from Pearson's correlation that movement time was significantly correlated with maximum velocity magnitude and collision force but not with the insertion error.

As might be expected, insertion error showed strong effects for the hole diameter, but this was not significantly different between the two groups. Moreover, collision force failed to show strong evidence for differences related to hole diameter again suggesting that the relatively large clearance allowed easy insertion.

Upon studying figures 6 and 7, it is clear that L2R portion of the movement time and collision force both present large variations for a 60mm diameter hole and the neurological subject group. However, neither of the Univariate models have identified subject group interaction with trajectory direction as a significant interaction.

This study has presented proof of concept ideas where a clinically established and validated test such as NHPT can be replicated using the haptic simulation. Although movement time here was calculated in a different manner from the traditional test, it was still capable of distinguishing differences between different subjects and subject groups. Similarly, collision force and maximum velocity magnitude showed potential for identifying differences between the two subject groups.

There are clearly some challenges for future development. While the original NHPT used a 1mm clearance between the peg and the hole diameter, the 10mm clearance used here is thought to have not posed significant challenge illustrated by insignificant differences between the collision forces for different hole diameters.

Conclusions

This paper has presented a novel haptic test for analysing performance through interaction. By replicating and modifying one of the established clinical measures into a haptic assessment, it has shown that it is possible to identify differences between the unimpaired group and subjects with neurological conditions. This was evident from movement time, collision force and maximum velocity magnitude during peg transfer. The failure to demonstrate differences in insertion error is attributed to the use of large clearances and the absence of feedback for insertion accuracy.

While the study has shown the ability to distinguish between normal subjects and those with impairment, the small numbers of subjects with different neurological conditions made it impossible to investigate differences between different pathologies.

Further development and testing are required before proposing this test as a suitable replacement for the traditional Nine-Hole-Peg-Test (NHPT). The major requirements are further development of the system to allow smaller clearances and improved user feedback followed by larger scale clinical studies allowing validation and calibration of this new tool against the traditional NHPT and other relevant clinical measures. Further work in this area is currently being carried out to achieve smaller peg clearances and so a closer replication of the NHPT. In conclusion, the authors believe that rapid developments in haptic technology hold the promise of higher technology and low cost systems capable of detailed measurement of precise hand function and motor control.

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Last but not least, we are thankful to Mr Germano Gomes who had contributed to the development of peg-in-hole and its MATLAB analytical procedure from the start of the project to its end.

Table 1. Subject Demographic Table

	Total	Male	Female	Left Hand	Right Hand	Age
Healthy	23	6	17	2	21	38±15
Neurological	18	8	10	4	14	51±12
Total	41	14	27	6	35	44±15

Table 2. Sample data from one subject, one R2L and L2R half cycles

Subject	Session	HD	Subject Group	L2R/R2L	Repetition	Time	Force	Max Velocity	Insertion Error
2	5	8	1	2	1	2.7	14.55	267.34	2.19
2	7	6	1	2	1	3.43	83.68	297.26	1.18
2	8	4	1	2	1	4.17	66.35	285.77	1.13
2	5	8	1	1	1	2.93	16.84	366.65	1.66
2	7	6	1	1	1	5.12	88.94	257.16	0.47
2	8	4	1	1	1	4.45	49.69	281.97	1.32

Short biographical notes on all contributors

Dr Farshid Amirabdollahian is a Senior Lecturer (research) in the School of Computer Science at Hertfordshire and also an active member of Adaptive Systems Research Group at this University. He has successfully undertaken research in assistive and rehabilitation robotics since 1999, and has been involved in both the "GENTLE/S — the use of robots and haptic interfaces to assist in neuro-rehabilitation following a stroke" [QLRT-1999-02282] and "I-MATCH — matching an optimum interface to an assistive device used by a user of assistive technology" [IST-2002-37280] EU funded projects. Farshid is currently involved in RoboSkin (www.roboskin.eu) and LIREC (www.lirec.org) EC funded projects.

Prof Garth Johnson is Emeritus Professor of Rehabilitation Engineering at Newcastle University. He has a long standing interest in upper limb biomechanics from the both the neurological and orthopaedic perspectives. He is a Fellow of both the Institution of Mechanical Engineers and the Royal Academy of Engineering.

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Figure 1. Visual (on screen) representation of the peg-in-hole task.

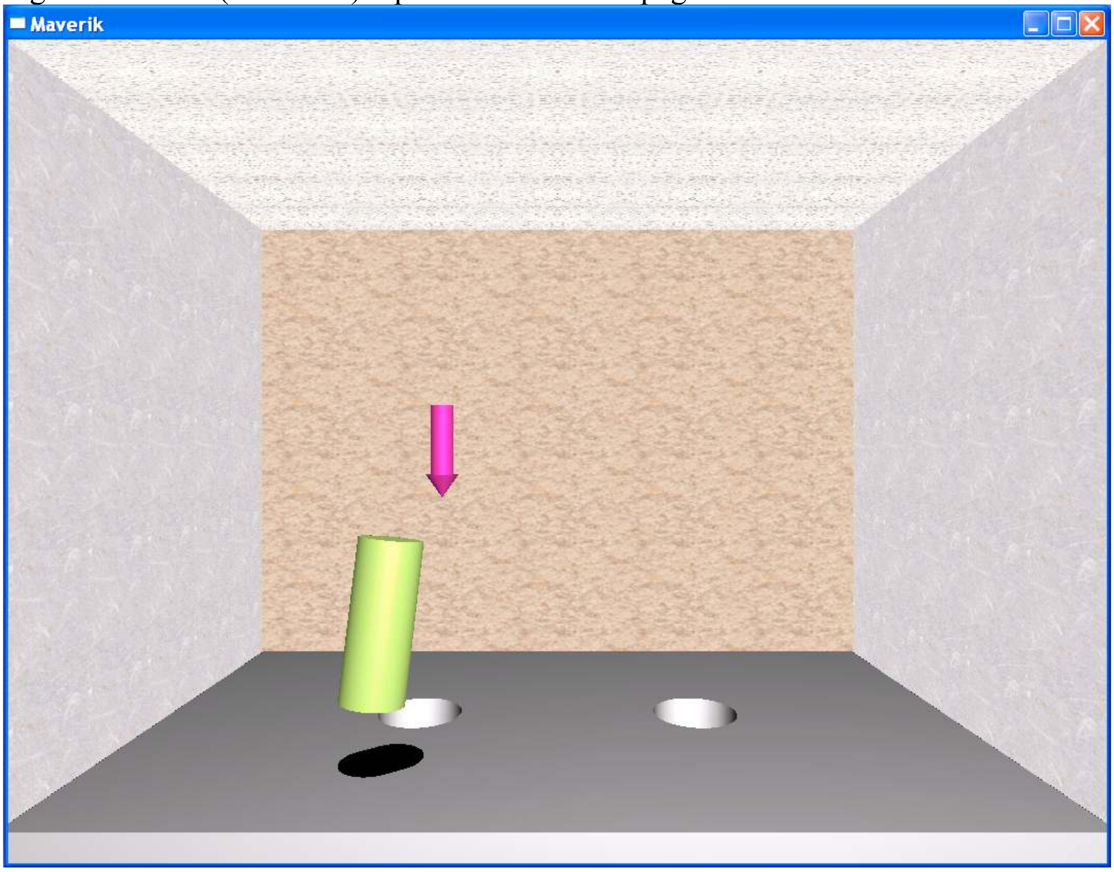

Figure 2. Slicing and sectioning the peg for haptic collision detection

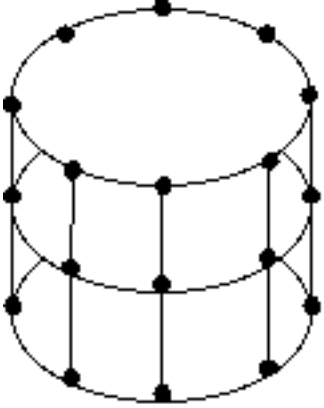

Figure 3. Experimental setup

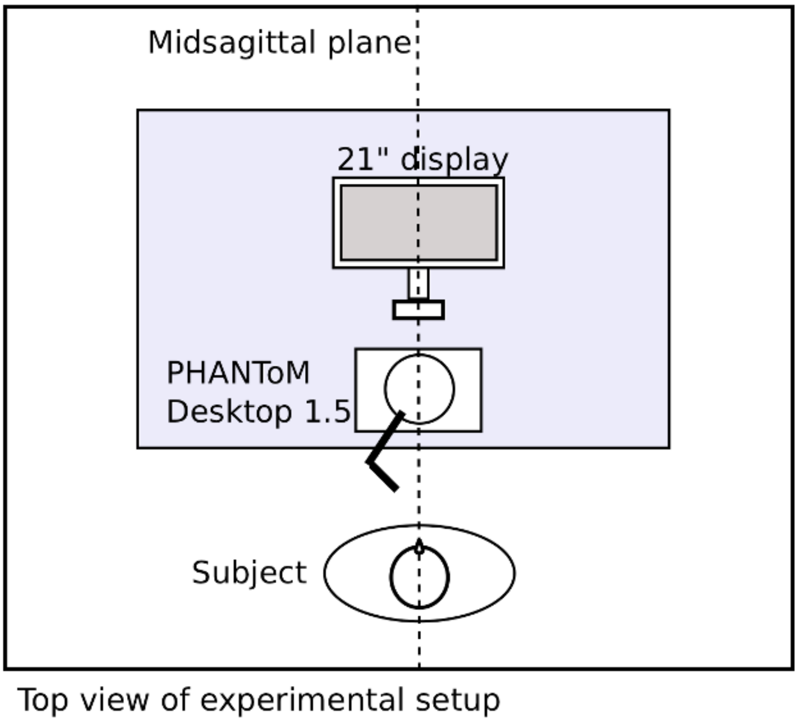

Figure 4. 3D representation of performance by one of the subjects, analysed using MATLAB

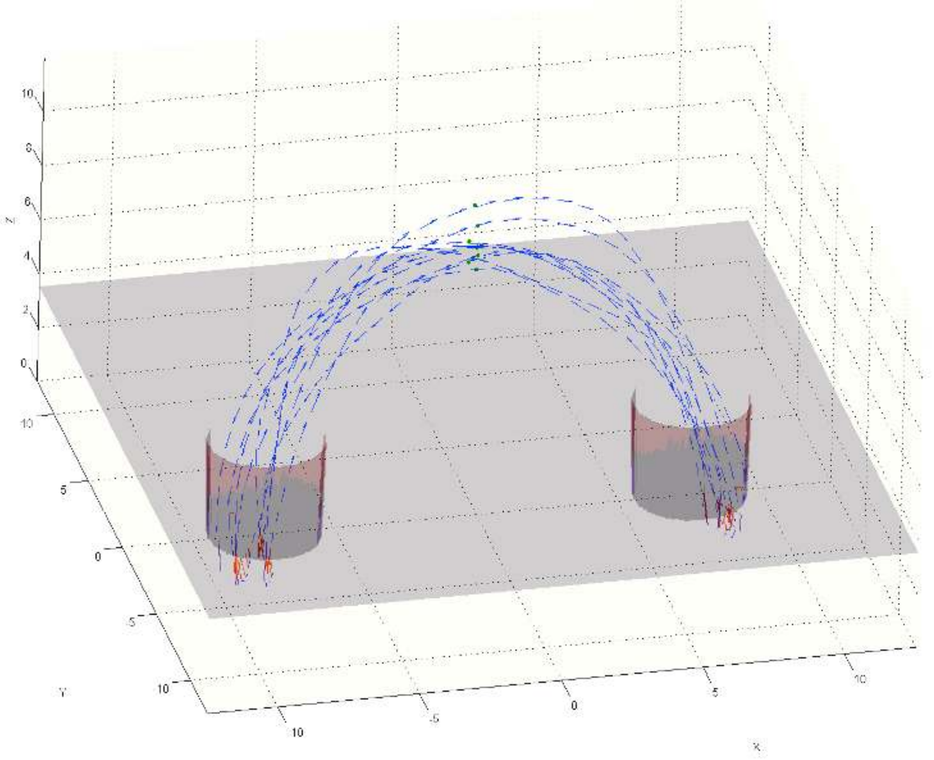

Figure 5. Study setup versus gathered and analysed parameters

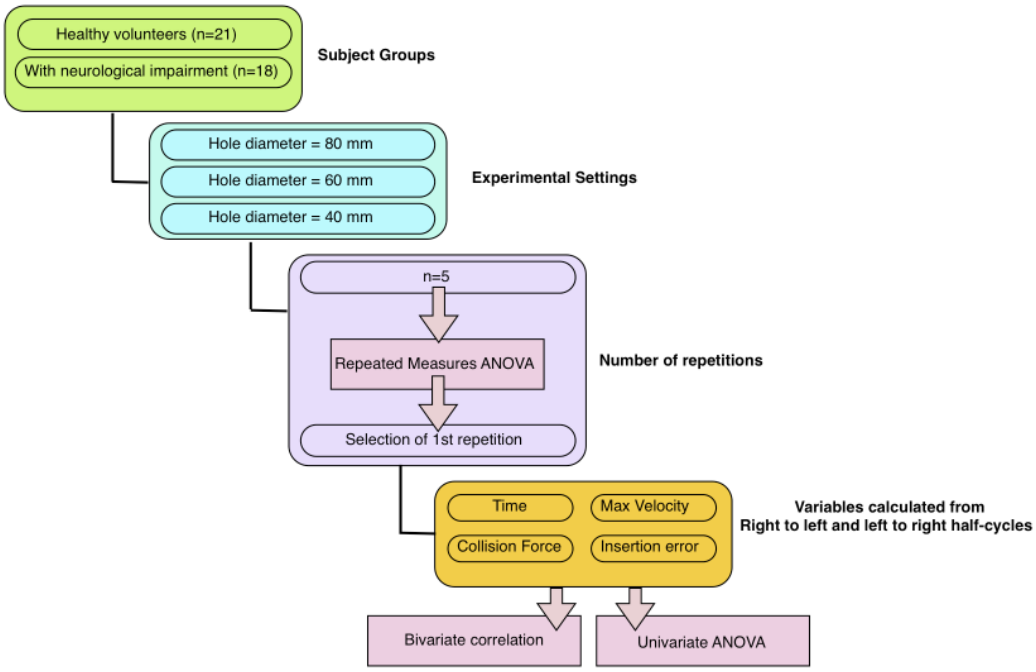

Figure 6. Comparing placement time for R2L and L2R half cycles and subject groups

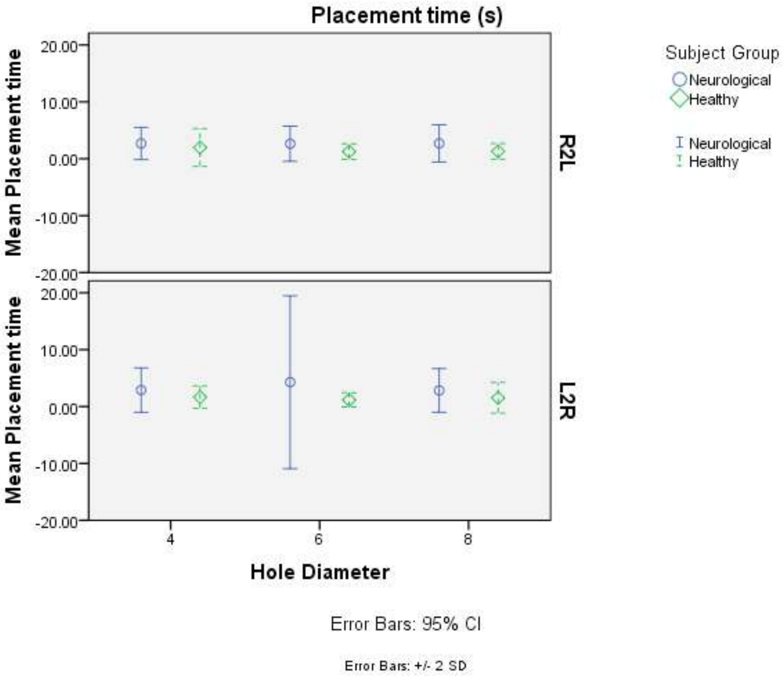

Figure 7. Comparing collision forces for R2L and L2R half cycles and subject groups

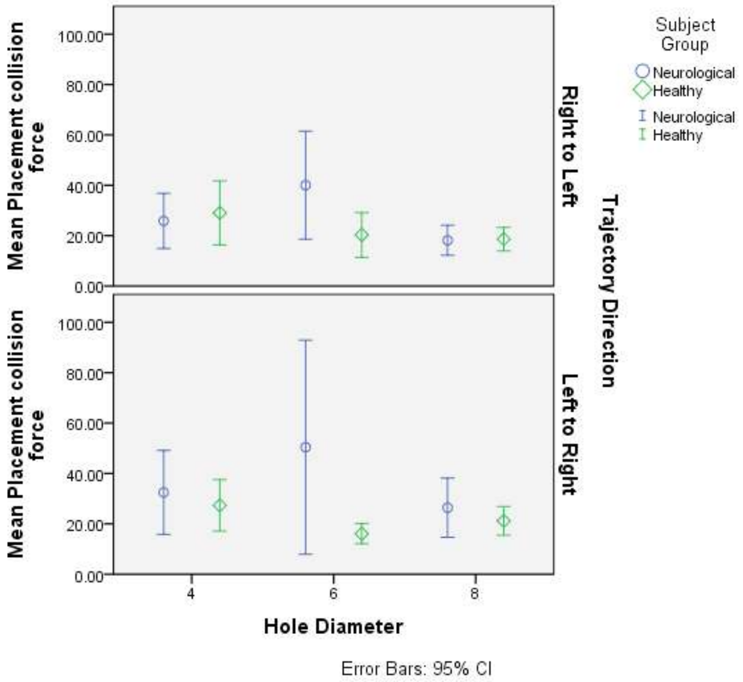

Figure 8. Comparing maximum velocity for R2L and L2R half cycles and subject groups

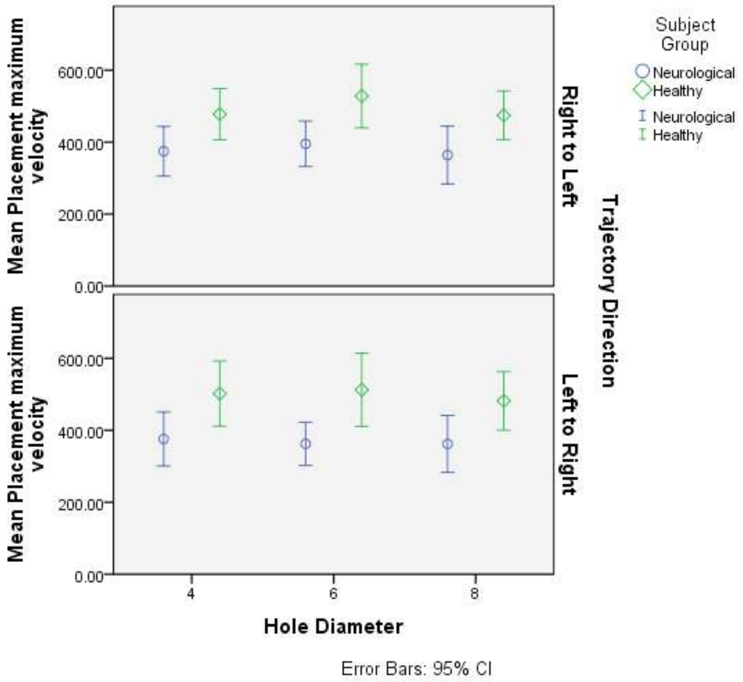

Figure 9. Insertion point at left and right holes (z = 0, table level)

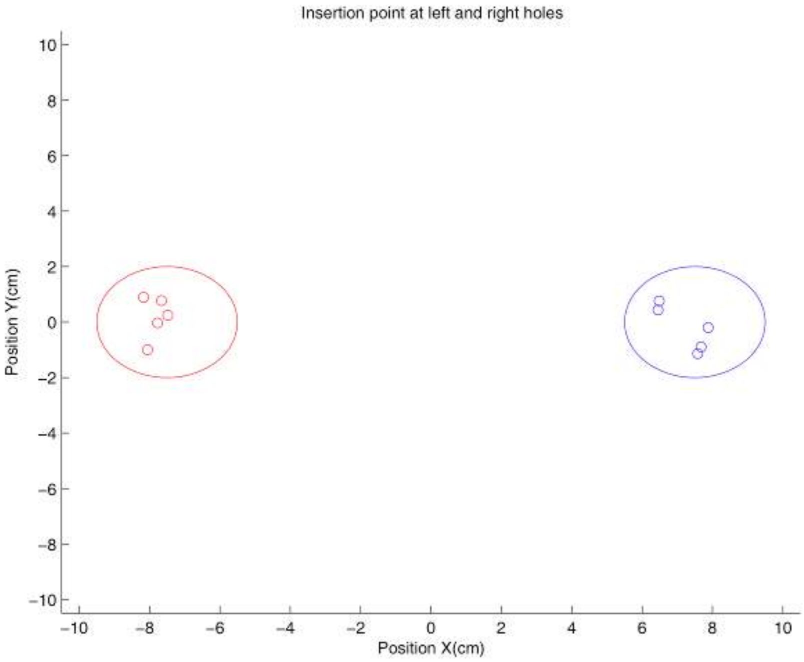

Figure 10. Comparing insertion error for R2L and L2R half cycles and subject groups