Modelling Movement Time for Haptic-enabled Virtual Assembly

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Abstract: Mechanical assembly consists of joining two or more components together. Manual assembly tasks include different activities to obtain functional products. In order to estimate the assembly cost and elaborate the assembly plan for a product, it is important to measure the duration of the assembly operations. The research reported in this paper aims at investigating if Fitts' law, which has been widely adopted in numerous research areas including kinematics, human factors and human-computer interaction, can be adopted as a model to estimate the movement time in assembling parts in virtual assembly environment with haptic feedback. The results reported in this paper showed that Fitts' law can be applied for modelling the movement time in assembling cylindrical parts. However, the analysis of the experimental data showed that when changing the diameter of the moved part, this could have an effect on the movement time. This is promising for the formulation of an inverted Fitts' law for cylindrical parts' assembly.

1 INTRODUCTION

Global competition has forced manufacturers to reduce production cycles and enable product design agility. In general, a manufacturing process is divided into product design, process design, manufacturing and assembly. The attempts to accelerate the process through the development of computer aided assembly planning systems have not, in general, been successful although the design has been carried out using a modern CAD system (De Mello & Sanderson). One of the main reasons for this lack of success is that assembly is dependent on a great deal of expert knowledge, which has proved to be very difficult to formalize (Dewar, Carpenter, Ritchie, & Simmons, 1997), (Nevins & Whitney, 1980). The important advances made in the recent decades in virtual reality technologies provided intuitive approaches for virtual interaction, notably for the virtualization of assembly operations and planning. Instead of abstract algorithmic assembly planning, an engineer could perform the assembly intuitively in virtual environment (VE) using VR hardware and software (Gupta, Whitney, & Zeltzer, 1997).

Assembling mechanical products by manipulating virtual parts provides an information feedback to the designer in order to refine the product design based on the information obtained from the assembly trials and the degree of feasibility of the assembly sequence generated from the interaction with VE (Boothroyd, Geoffrey. Dewhurst, Peter. Knight, 1994), (Santochi and Dini, 1992). However, in order to obtain reliable information from the interaction with the virtual world, human behavior in the VE should be similar to the behavior in real world. The virtual assembly environment must provide the user with the illusion of manipulating real parts. As such, the environment must replicate the relevant characteristics of the real assembly shop floor. Additionally, before using the VE for complex interaction such as assembly planning, it is important to show that the knowledge obtained from the real world interaction, such as Fitts' law, are also valid in VE. Then, quantitative and qualitative information derived from the VE, such as the assembly time of the vittual product and the assembly plan, can be used for the design the production system and for planning the activities in the real world.

An assembly task can be divided into six basic

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activities such as reach, select, grasp, move, position, and secure. Activities such as "reach" and "move" are generated by biomechanics of body motions. However, the activities such as “select”, “grasp”, “position”, and “secure” require cognitive skills and manual dexterity (Figure 1). For these reasons, the estimation of the time necessary to assemble a product is an important information for industry.

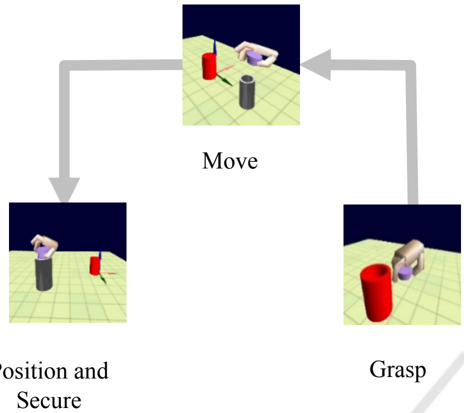

Figure 1: Segmentation of the manual assembly task.

Fitts' popular model has been proven one of the most robust, highly cited and widely adopted models to emerge from experimental psychology (Fitts, 1954), (Fitts & Peterson, 1964). It was applied in numerous research areas; including kinematics, human factors, and human-computer interaction (Kerr & Langolf, 1977), (Hand, 1997). Psychomotor studies in diverse settings have consistently shown high correlation between Fitts’ index of difficulty and the time to complete a movement task. Kinematics and human factors are two fields particularly rich in investigations of human performance using Fitts’ analogy (Fitts & Radford, 1966). Virtual reality offers the potential to improve techniques over existing computer interfaces, therefore offering benefits to applications requiring human-computer interaction. However, to obtain reliable results from VR, high perceptual capabilities must be achieved and human related factors should be taken into account in designing 3D interfaces for the interaction with VE.

The literature review showed that most of the reported studies used task completion time (TCT) and error rates for the evaluation of the human performance in VE. However, well-known paradigms such as Fitts’ law were not used as a tool to validate virtual environments before their adoption in the product development (Chryssolouris, Mavrikios, Fragos, & Karabatsou, 2000). For example, the extrapolation of performance data obtained in VE to the real world could only provide good results if the characteristics of the VE allow the same interactive conditions as in the real world.

In Fitts' experiment, the subject had to move a pointed stylus as quickly as possible between two fixed targets of width (W) set at a distance (A). The task requires also hitting the two targets alternatively (Figure 2.I). The analysis of the original Fitts’ law experiment and the assembly of cylindrical parts shows an analogy in the movement of the operator’s hand in executing the task (Figure 2.II). Paul Fitts suggested that the difficulty of a task could be measured using the information metric bits, and he introduced the idea that, the information is transmitted through a human sensory channel when carrying out a movement task (Fitts, 1954), (Langolf, Chaffin, & Foulke, 1976). Fitts' equation for the movement time (MT) is given by:

$$MT = a + bID \tag{1}$$

$$ID = Log_2\left(\frac{2A}{W}\right) \text{ in bits per response} \tag{2}$$

$$MT = a + bLog_2\left(\frac{2A}{W}\right) \text{ in seconds} \tag{3}$$

Where ID is the Index of Difficulty and a, b are constants.

The task index of performance (IP) is defined as $IP = \frac{ID}{MT}$ in bits/second.

Sturges and Kilani applied Fitts' law index of difficulty (ID) to quantify the dexterity and time required to assemble a product (Sturges & Kilani, 1992). They formulated the task index of difficulty as $ID = Log2\left(\frac{S}{W}\right)$ where W is the target width and S the distance between the two parts to be assembled. The manual assembly time is then obtained by multiplying the ID by the human motor capacity. However, this method did not investigate if the shapes of the manipulated parts have any effect on the index of difficulty, hence on the operator’s performance in the execution of the assembly task.

(Gupta et al., 1997) reported on a 'peg in hole' task performed using a PHANTOM device as a force feedback system to manipulate a virtual peg in a hole. The task index of difficulty was measured using Fitts' law and by substituting the target width W for the peg/hole clearance. Their formulation for the index of difficulty was $ID = Log2\left(\frac{h}{D-d}\right)$ where h is the handling distance; D is the diameter of the hole and d is the diameter of the peg. The results indicated that despite the provision of force feedback, a significantly longer total assembly time was obtained compared with the stable performance in the real task. The increase of the assembly time might be originated from the 3D interaction technique they used or the lack of physical behavior of parts not included in the virtual environment they developed.

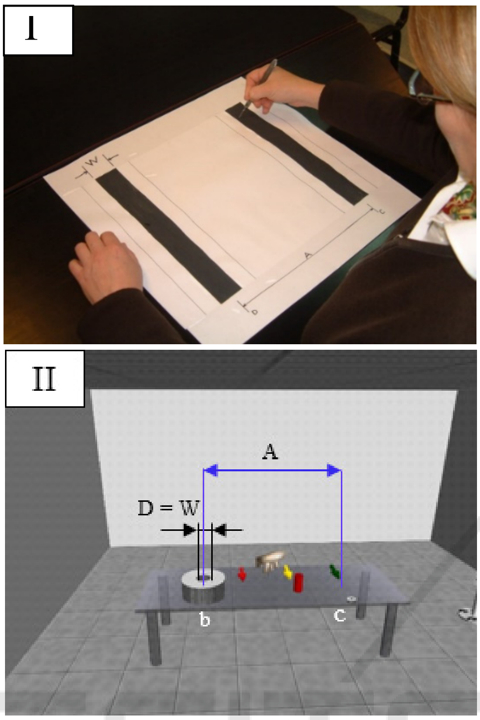

Figure 2: The analogy between the original Fitts' law (I) and the assembly of cylindrical parts in virtual environment (II).

(Deng, Geng, Hu, & Kuai, 2019) studied the factors determining the movement time (MT) of positioning an object in an immersive 3D virtual environment where they varied three factors: the object size, the movement amplitude and the target tolerance. They identified three phases: the acceleration phase, the deceleration phase and the correction phase. They found that in the acceleration phase, the movement time (MT) was inversely related to object size and positively proportional to movement amplitude but in the deceleration phase, the (MT) was mainly determined by the movement amplitude. In the correction phase, the (MT) was affected by all three factors. Hence, they proposed a three-phase model with different formulae at each phase.

(Liu & Liere, 2011) introduced a 3D introduced a model for the interaction with moving objects in virtual environment. They divided the movement task into two phases: the tacking phase and the connection phase. According to their experiments, they found that the time for the tracking phase is fixed once a task has been established, However, the time for the correction phase is dependent on the path length, the velocity of the moving target and its width. The authors considered that the movement time of an object pursuit task can be minimized by determining the optimum target velocity and that their model can be used for the evaluation of the user interfaces designed for the interaction with moving objects.

(Cha & Myung, 2013) developed an extended Fitts' model for pointing task in 3D environment. The authors added to the formulation of the original Fitts' law the inclination and azimuth angles of the spherical coordinate system. The extended model showed better adequacy with the data collected from the experiments in terms statistical values of the correlation coefficient and the standard error of the residuals for the measured and predicted movement time. These results were considered by the authors important for the design of pointing tasks in 3D environment and for accurate prediction of human performance.

(Raghu Prasad, Purswani, & Manivannan, 2013) developed and experiment to predict the minimum movement time for a task involving the right index finger carried out in virtual environment. The analysis of the collected data for the movement time and the index of difficulty showed that Fitts' law is applicable for a force based virtual movement task with visual guidance.

(Lin, Caesaron, & Woldegiorgis, 2019) studied the accuracy the accuracy of egocentric distance estimation in stereoscopic virtual environment. They investigated different interaction methods with 3D objects by designing an acquisition task involving direct pointing and indirect cursor techniques. They found that indirect interaction mode allowed more accuracy than direct mode and higher accuracy was obtained for pointing task located at greatest distance from the user. They also reported that high task difficulty led to low accuracy level compared to the accuracy obtained for medium and low task di□culty. The authors consider their work useful for the design of effective interaction techniques where the accuracy is an important factor.

(Schwind, Leusmann, & Henze, 2019) studied investigated the effect the changes of model and texture of a users' avatar on input performance in a two-dimensional Fitts' law target selection task. Their research showed that task completion time was not affected neither by model nor texture changes, which supports that body ownership and spatial localization are independent the mechanism in visual-haptic integration.

(Gallegos-Nieto, Medellín-Castillo, González-Badillo, Lim, & Ritchie, 2017)studied the transfer of knowledge and skills from haptic-enabled virtual assembly environment to real-world. They used a system called Haptic Assembly and Manufacturing System (HAMS) developed by (Gonzalez-Badillo, Medellin-Castillo, Lim, Ritchie, & Garbaya, 2014). The authors conducted an experiment involving three groups of subjects and three training modes: Virtual assembly including haptic feedback, virtual assembly without haptic and training by watching a video. Compared to training by video, virtual assembly allowed up to 80% improvement in the performance of the real assembly task. Additionaly, training with haptic-enabled virtual assembly led to greater levels of effectiveness than without haptics. It was also noticed that training with virtual assembly showed more effectiveness for more complex assembly task.

(Sagardia & Hulin, 2017) developed a platform for bimanual haptic feedback for the assembly of complex virtual objects. The haptic device was made of two DLR/KUKA robot arms that include an additional force-torque sensor at each robot wrist and it displays six-DoF force feedback. The objective of their research was to solve the virtual assembly problems such as assembling objects with complex geometries, bimanual six-DoF haptic interaction for hands and arms, and intuitive navigation in large workspaces. The authors conducted an experiment of assemblig a car control box to test their system. The results showed that it was able to handle complex geometries and it allowed large upper body movements with providing force and tactile feedback to the hand and the forearm of the user.

(Wang, Huang, Li, & Liu, 2017) proposed a new model for simulating forces for virtual assembly tasks of mechanical parts with a clearance fit. They decomposed the assembly operation into free navigation state, positioning state and assembly state. Upon the contact between parts, a collision force is simulated and the assembly process enters the positioning state. For enhancing the user perception, they developed a model for the force rendered during the assembly state. The system was evaluated for the assembly of four sets of shaft-bushing with clearance fits and the results showed that force rendering was appreciated by the user eventhough shoter task completion time was obtained without providing force rendering.

(Lubos, Bruder, & Steinicke, 2015) analyzed the impact of comfort on 3D selection tasks in an immersive desktop setup. They investigated the importance of comfort for the performance in 3D user interfaces by analysing a set of most comfortable body poses for the interaction. They studied the influence of a comfortable arm rest on performance in immersive desktop setups to allow users to experience the immersive interaction without the negative aspects and to increase the user comfort. The authors conducted Fitts' Law experiment in immersive desktop setups. The results showed that comfort has a significant effect on effective throughput according to Fitts' Law in IVEs.

(Sallnäs & Zhai, 2003) Investigated how handling over objects can be supported in virtual environment. They carried out an experiment in which subjects passed a series of cubic objects to each other and tapped them at target areas. The user performance was evaluated for the conditions where haptic feedback is provided and not provided in the interaction. The authors considered their study in the framework of Fitts' law and hypothesized that object hand off represented a collaboratively performed Fitts' law task. The results showed that task completion time was increased with Fitts' index of difficulty, both with and without haptic feedback. The time required for passing objects did not differ significantly between the haptic and no haptic conditions. However, the provision of haptic feedback allowed to reduce significantly the error rate.

In order to study the validity of Fitts' law in VE, we have developed a set of experiments in which a human operator performs the task of assembling two cylindrical parts. The objective is to investigate if Fitts' law could be applied for the estimation of the movement time for the assembly of cylindrical parts. Moreover, whether the human performance patterns are similar to that obtained in the original experiments of Paul Fitts. The task studied in this research is inverted: instead of a pointed stylus, the probe is a virtual mechanical part of finite width; it is moved to a target location that is of smaller width than the probe. These conditions represent the inverted Fitts' law paradigm in which the moved object has a larger width that the target object. These conditions are common in assembly industry. The objective is to investigate if the diameter of the moved part has an effect on the movement time of the assembly task. In these experiments, the sensation of the weight of the manipulated parts and the contact forces are provided to the operator using six degrees of freedom (DOF) force feedback system (figure 3).

In order to study the movement time, an experiment of assembling cylidrical parts was designed in virtual environment. The task execution was observed and the performance of the operator was measured in terms of the task completion time (Cochran & Cox, 1950).

2 ARCHITECTURE OF THE VIRTUAL REALITY SYSTEM

The VE software runs on a laptop PC equipped with a 2.20 GHZ Intel Dual Core processor and an ATI Mobility Radeon graphics card. The virtual scene was created in C++, using OpenGL library, and visualized on the computer screen of 15.6 inches. The frame rate of the image display was maintained at 35 frames per second (Figure 3).

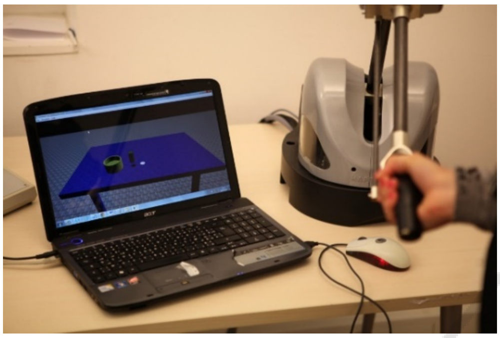

Figure 3: Hardware platform used in the experiments.

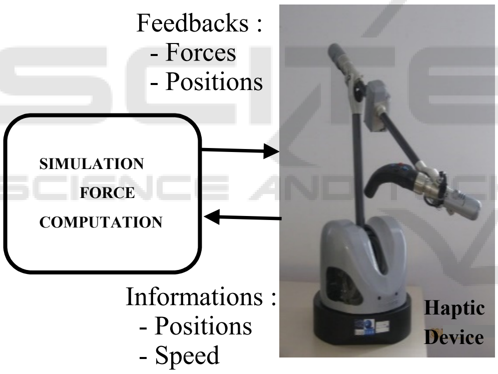

Figure 4: Principle of the generation of force feedback with the VIRTUOSE haptic device.

In order to provide the operator with force feedback during the manipulation of parts, the VIRTUOSE™ 6D haptic interface was used. This haptic interface system has 6 DOF (3 translations and 3 rotations) and renders 3D force and torque (Figures 4 and 5). Although the weight of the pointed stylus was not taken into consideration in the original study carried out by Paul Fitts', it was decided to include force feedback in the research described in this paper to represent the physical conditions of the real assembly task.

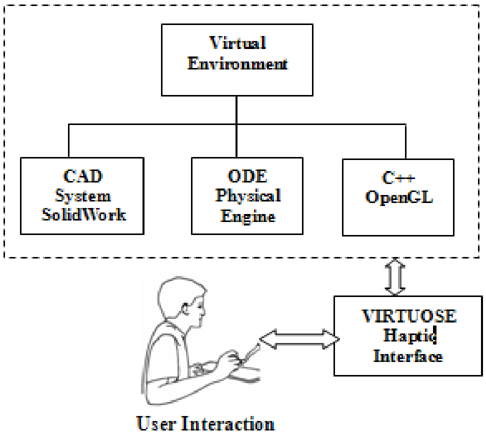

Figure 5: Virtual Reality System Architecture.

The virtual parts are created in Solidworks™ CAD system, then exported to the VR software using file format conversion process (Figure 6). The virtual assembly environment incorporates virtual representations of the components used in the experiments and the table on which the parts are located. The start and end positions are marked on the top surface of the table by two spots (Figure 8). In order to create physical behavior of the manipulated objects Open Dynamic Engine (ODE) was used. This physical engine has its proper collision detection system, which handles convex and non-convex shapes of objects.

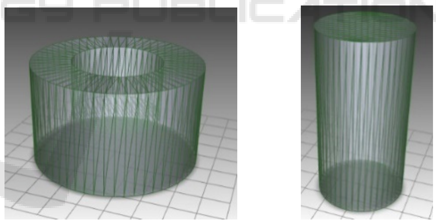

Figure 6: Polygonal mesh of 3D models of two parts used in the experiments.

3 METHOD AND EXPERIMENT DESIGN

Industrial engineers have consistently advocated that small-amplitude movements are used whenever possible in assembly work, on the ground that the time required to complete a unit of work increases as a function of its amplitude as well as a function of the precision demanded by the task. In the experiments carried out by Paul Fitts, the manipulated objects were a pointed stylus, pins and washers, these objects were considered weightless in the study of movement time he carried out.

Most of the assembly tasks involve grasping, moving and positioning parts in a fixed locating position. However, mechanical parts could have different geometric shapes and finite dimensions that might affect the operator performance in the assembly task execution. This study focuses on the manipulation of cylindrical parts and investigates the potential of applying Fitts' law to obtain a model that represents the time required to move a mechanical part during the assembly operation. By analogy with the experiments carried out by Paul Fitts (Fitts, 1954), the VE represented in the Figure 7 was used to run 3 experiments for which different combinations of the diameter of the manipulated part, the movement distance and the hole diameter of the mating part were used. The operator picks the primary part (the manipulated part) with the VIRTUOSE™ haptic device, then he/she moves the part towards the secondary part (the receiving part) and finally he/she drops it to the desired position and orientation. Then, the primary part is moved back at the start position and the task is repeated 10 times. Each subject had to execute the task ten times for each combination of the diameter of the manipulated part, the movement distance and the diameter of the hole of the receiving part. After the completion of the experiments, a second session with the same task execution and conditions took place after 3 days. An algorithm was developed to automatically record the task completion time (MT), the locating position and the orientation of the part for further analysis.

3.1 Experiment 1: Moving a Cylindrical Part with Insertion Task

The subjects were asked to move a cylindrical part having 5 cm of diameter (the primary part) from a starting position to a target cylindrical part (called the secondary part). The subject inserts the primary part into the hole of the secondary part and then returns it over the starting position, repetitively, for 10 cycles (Figure 7 and Figure 8). The secondary part is a cylindrical container for which the hole's diameter (W) is 8 or 16 cm, located at a distance (A) equal to 30, 60, or 90 cm from the starting position. The combination of the two target diameters (W) and three center-to-center movement amplitudes (A) resulted in five possible indices of task difficulty (ID) of 1,90; 2,90; 3,49; 3,90; and 4,49.

By considering the different values of the target width and amplitude of movement, six combinations representing the different experimental conditions were obtained.

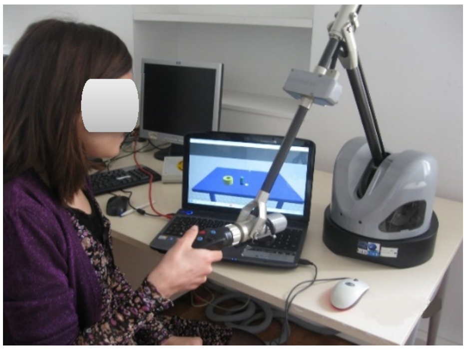

Figure 7: Task execution in experiment 1.

Ten subjects from the university community (1 female, 9 males) aged from 20 to 40 years old and all right-handed. They were seated on the chair in front of the computer screen and manipulates the virtual part with the VIRTUOSE™ haptic device. For ergonomic considerations, a calibration between the VE and the 3D interaction device was made so that the handle of the VIRTUOSE™ is manipulated at the users' elbow height. In order to be familiarized with the haptic device and 3D interaction technique each subject had to practice the assembly operation during a training session of 15 minutes for which the user performance was not recorded. A repeated-measures design counter-balanced by conditions was carried out. This included three experimental conditions presented to the subjects in a random order.

During the execution of the virtual task, subjects were instructed to work as accurately and rapidly as possible.

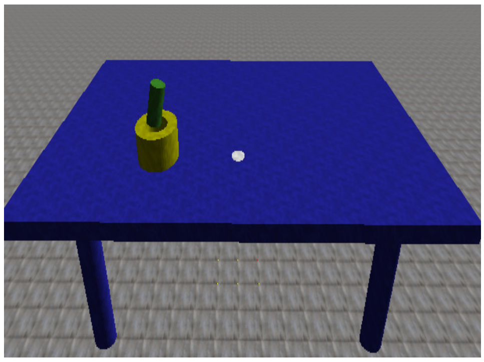

Figure 8: The virtual environment used for the experiment 1.

3.1.1 Data Analysis and Results

In order to perform the analysis of data collected from the experiment the means of movement time for each experimental condition was computed (Table 1).

The analysis of the data represented in the Table 1 showed that for each category of target diameter (W), the movement time (MT) increased progressively as movement amplitude (A) increased. It is also important to notice that for each amplitude, the movement time increased progressively as the target diameter was decreased. These trends were observed in the original Fitts' experiments of the reciprocal taping with the pointed stylus (Fitts, 1954). The index of performance can be considered constant (1,4 – 1,59) for the index of difficulty ranging from 2,9 to 4,49 but falls to 1,06 for ID = 1.9. In order to confirm that Fitts's law can be applied in the assembly of cylindrical parts, a linear regression analysis was performed on the assembly time and the task index of difficulty for the data obtained for each subject who participated in this experiment. The result showed the linear relationship between MT and ID as follows:

$$MT = a + b\ ID$$

With a correlation coefficient r = 0,742, this confirms the existence of a statistically significant correlation between the variables MT and ID of the studied model. The linear regression analysis of MT on ID yielded the following estimated model:

$$MT = 0{,}94 + 0{,}411 ID$$

The curve of the fitted model for the studied data is presented in Figure 9.

Table 1: Mean movement time and index of performance obtained in the experiment.

W (cm)	A (cm)	ID	MT (sec)	IP
8	30	2,90	2,049	1,41
8	60	3,90	2,530	1,54
8	90	4,49	2,815	1,59
16	30	1,90	1,796	1,06
16	60	2,90	2,070	1,40
16	90	3,49	2,481	1,40

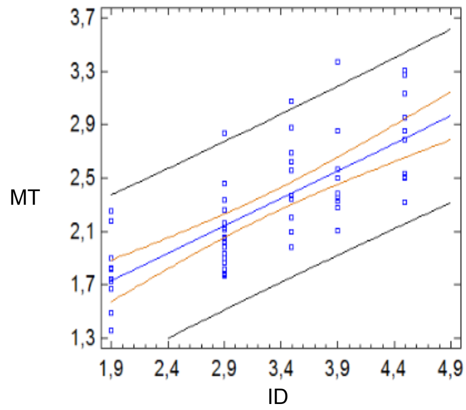

Figure 9: Curve of the fitted model of the experiment 1.

3.2 Experiment 2: Locating a Part with Finite Width in a Position without Locating Tolerance

The subjects were asked to carry out a similar task, but without inserting the primary part into the secondary part. Rather, target acquisition required subjects to perform a reciprocal taping at the start position marked by a white spot and at the final position, represented by a disk of 5 cm of diameter and 5 mm of thickness, located on the table (Figure 10). However, in all combinations, the diameter of the white spot, located at the start position, is equal to the diameter of the moved part. The taping should be carried out so that the axis of symmetry of the moved part, the center of symmetry of the white spot at the start position and the center of the disk at the final position are superimposed.

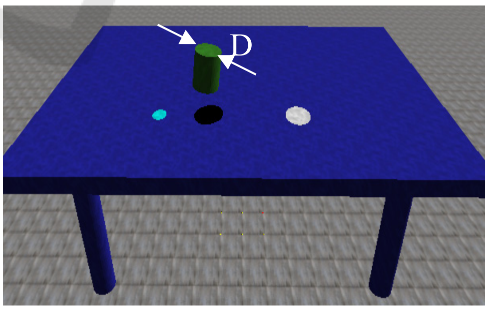

Figure 10: The virtual environment used for the experiment 2.

The task is repeated 10 times continuously without releasing the primary part. The subjects were requested to execute the task as accurately and quickly as possible. The movement amplitudes were 20, 30, and 50 cm. In addition to the variation of the movement amplitude, the diameter of the primary part was also varied across experimental conditions (5, 7, and 9 cm). Of interest was whether the diameter of the moved part contributed towards the overall task difficulty as documented by (Boothroyd, Geoffrey. Dewhurst, Peter. Knight, 1994).

3.2.1 Data Analysis and Results

This experiment aims at evaluating human performance, in terms of the time required to move a cylindrical part between two distant positions, during the execution of a manual assembly task in VE. The objective is to investigate whether Fitts' law applies when the locating tolerance (equivalent to the target width in the original Fitts' law experiment) is not allowed. The different combinations between the means of movement time MT, primary part diameters (D) and movement amplitudes (A) for the two sessions of the experiment 2 are presented in Table 2.

Table 2: Mean movement time and index of performance obtained from the experiment 2.

W (cm)	D (cm)	A (cm)	ID	MT (sec)	IP
5	5	20	3	1,310	2,29
5	5	30	3,58	1,552	2,30
5	5	50	4,32	1,787	2,41
5	7	20	3	1,276	2,35
5	7	30	3,58	1,420	2,52
5	7	50	4,32	1,694	2,55
5	9	20	3	1,261	2,37
5	9	30	3,58	1,420	2,52
5	9	50	4,32	1,736	2,48

It is noticed from the data of the Table 2 that for a fixed target diameter (W=5 cm), the movement time increased when the movement amplitude (A) was increased. Moreover, the index of performance is relatively constant (2,3– 2,5) for the index of difficulty ranging from 3 to 4,32. These results correspond to those obtained in the experiment 1. In order to ascertain the relationship between the movement amplitude and the movement time and to investigate if the diameter of the moved part affects the movement time, Two-way ANOVA analysis was carried out using the movement time recorded for each combination. The movement time is the dependant variable and the factors for this test are: the diameter (D) of the moved part and the movement amplitude (A).
Since the P-values of these factors are less than 0,05, this confirms that the movement amplitude and the diameter of the moved part have a statistically significant effect on the movement time (MT) at the 95% confidence level (Table 3).

Table 3: Results of the analysis of variance for the movement time MT.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Main Effects					
D	0,0135	2	0,0067	7,31	0,046
A	0,317	2	0,158	171,45	0,0001
Residual	0,0036	4	0,0009		
Total	0,334	8			

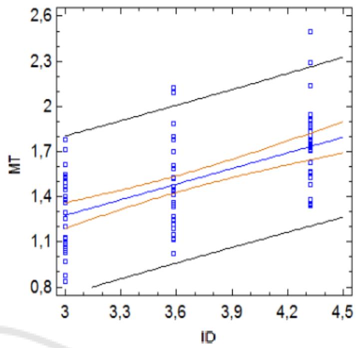

Figure 11: The Curve of the fitted model for the experiment 2.

The result of the regression analysis yielded a correlation coefficient r = 0,972. The equation of the fitted model is:

$$MT = 0,2 + 0,347ID$$

The curve of the fitted model for the experiment 2 is presented in the figure 11.

3.3 Experiment 3: Assembly Task with Different Values of the Diameter of Primary Part (D), Movement Amplitude (a), and the Diameter of the Secondary Part (W)

The subjects were asked to perform a similar task but with the condition where the diameter of the hole of the secondary part (named target width W) was varied: 4 and 9 cm as was the movement amplitude (A): 30 and 60 cm and the diameter of the primary part (D): 5, 7 and 14 cm. The combination of targets widths and movement amplitudes resulted in the following values of the task index of difficulty: 3, 32; 3, 9; 4, 32; and 4, 9 (Figure 12).

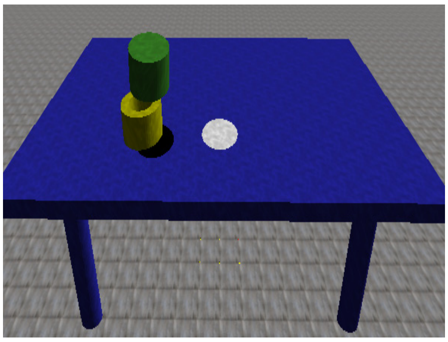

Figure 12: Virtual environment for the experiment 3.

3.3.1 Data Analysis and Results

The means movement times (MT) calculated for the combined trials of the experiment 3 are presented in Table 4.

The index of performance (IP) can be considered relatively constant within two intervals ([1.65 – 1.8] and [2.3 – 2.5]) for the index of difficulty ranging from 2.73 to 3.73 and 3.9 to 4.9, respectively. Furthermore, the relationships among the data do not correspond closely to those found in the two previous experimental conditions.

Table 4: Mean movement time and index of performance obtained in the experiment 3.

W (cm)	A (cm)	ID	MT (seconds)	IP
4	30	3,90	1,651	2,36
4	60	4,90	1,953	2,51
4	30	3,90	1,601	2,43
4	60	4,90	1,941	2,52
4	30	3,90	1,644	2,37
4	60	4,90	2,107	2,32
9	30	2,73	1,657	1,65
9	60	3,73	2,067	1,80
9	30	2,73	1,618	1,69
9	60	3,73	2,073	1,80
9	30	2,73	1,728	1,58
9	60	3,73	1,953	1,91

In fact, for each category of target width (W) the movement times increased progressively as the amplitude (A) was increased, however, for each category of amplitude (A) the movement time did note change significantly when the tolerance (W) was decreased, this result did not match with the trends found in the original experiments carried out by Paul Fitts.

The correlation test of MT with ID gives a correlation coefficient r = 0, 286. This confirms the existence of statistically significant relationship between MT and ID. The equation of the fitted model represented in the figure 13 is the following:

$$MT = 1{,}3 + 0{,}138ID$$

The result of this experiment showed that Fitts' law model can be adopted to estimate the movement time, in the case where the diameter of the primary part (D) is greater than the diameter of the secondary part (W). In practice, this case of manipulation occurs in assembly without inserting the primary part in the hole of the secondary part. However, further investigations are necessary to determine why in the conditions of experiment 3 (when the tolerance (W) was decreased) the movement time did not follow the trend of the original Fitts' law. It is also important to quantify the effect of the diameter of the moved part in the formulation of the equation of the movement time.

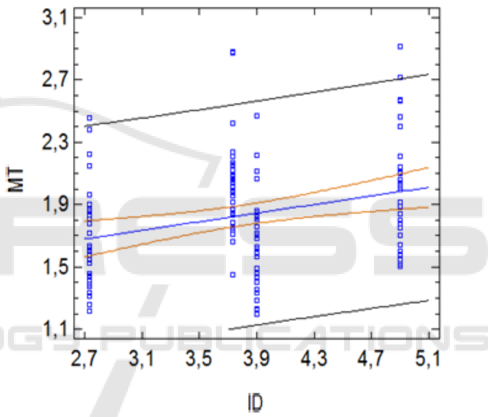

Figure 13: Curve of the fitted model for the experiment 3.

4 DISCUSSION

The experiments reported in this paper examined the use of Fitts's Law as a tool for evaluating cylindrical parts assembly tasks in virtual environment. While Fitts' Law generally held under the three virtual assembly conditions, further investigations are necessary to explain why decreasing the target width (W) in the experimental condition 3 did not increase the movement time. In order to represent real world interaction, the virtual assembly environment designed in this research provided haptic sensation to the user. However, in order to confirm the validity of Fitts's law for the assembly of cylindrical parts, it is necessary to conduct the same experiments in real world and compare the trends obtained in virtual and in real world conditions. It is also important to explore and qualify the effect of the diameter of the manipulated part on movement time.

5 CONCLUSION AND RESEARCH PERSPECTIVES

The research reported in this paper showed an analogy between the results obtained in the original Fitts' law experiments and the task of moving cylindrical parts in virtual assembly environment including haptic feedback. The rate of movement time recorded in three experiments increased uniformly as movement amplitude was increased for each category of target width, and increased uniformly as tolerance was decreased for a category of movement amplitude except for the experiment 3. The index of performance is constant over a wide range of the task index of difficulty. This confirms the hypothesis of Fitts's law stating that movement time varies with task difficulty in such a way that the index of performance is constant over a wide range of movement amplitude and tolerances. However, the results obtained in the experiment 3 require further investigations in order to evaluate the effect of the diameter of the moved part on movement time. This could lead to a new formulation of Fitts' law as a model of the movement time in assembly task. It is also worth noting that in order to ascertain the statistical significance of the results, it is planned to run the experiments with involving bigger number of subjects.

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