The analysis and evaluation of the influence of haptic-enabled virtual assembly training on real assembly performance

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Abstract

This paper reports the results of an investigation carried out to analyse and evaluate the influence of haptic-enabled virtual assembly (VA) training with respect to real assembly tasks. The aim was to determine how well virtual assembly training transfers knowledge and skills to the trainee in order to improve their real-world assembly performance. To demonstrate this, a comprehensive analysis and evaluation of the influence of VA training on the real assembly performance, is presented. This influence is assessed in terms of the effectiveness and efficiency when performing the real assembly task after undergoing VA training. The study considers the use of three training modes and several assembly tasks with increasing complexity and number of parts. The results indicate a significant improvement (of up to 80%) in the real assembly performance of subjects who undertook VA training first when compared to those trained conventionally. Moreover, haptic-enabled VA training led to greater levels of effectiveness than without haptics. The results also revealed that the effectiveness of VA training depended on assembly task complexity, i.e. the greater the task complexity, the greater the effectiveness. Consequently, maximum VA training effectiveness was

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obtained with a combination of haptic-enabled VA training and high-complex assembly tasks.

Keywords: Virtual assembly (VA); virtual assembly training; assembly task; task completion time (TCT); effectiveness; real assembly performance.

1. Introduction

Global competition has forced manufacturers to speed up the product development process and reduce production time and cost whilst assuring high quality and reliability. Attempts to speed up product process planning by developing computer aided process planning (CAPP) systems have not yet been successful, even when product design has been carried out using modern computer aided design (CAD) systems [1]–[3]. One of the main reasons for this lack of success is that assembly planning depends on a high level of expertise which has proved to be very difficult to capture and formalize [4]. Moreover, current CAPP systems have a number of disadvantages: (i) they lack the usability required by conventional industry, (ii) they are not intuitive and require considerable training due to complex user interfaces and system inflexibility, and (iii) the results output from such systems are not always feasible and optimal [2].

Virtual reality (VR) technologies have enabled more multidisciplinary process planning approaches, such as virtual mechanical assembly planning and simulation, the next generation of Computer Aided Assembly Planning (CAAP) systems. Instead of using an abstract algorithmic assembly planning method, an engineer can perform the assembly task in a more intuitive and manipulative VR environment [5] which supports the humans' assembly cognition and ergonomic capabilities. This has led to the rise of virtual assembly (VA) systems that, incorporating the human in the loop, can interactively analyse and simulate both the product’s design and assembly operations [6]. For instance, the Toyota Motor Corporation shortened its lead times by 33%, reduced design variations by 33%, and reduced the product development costs by 50% when using digital manufacturing tools [7]. On the other hand, Ford Motor Company dramatically reduced its assembly-related worker injuries by improving the design of the assembly workstations as a result of adding motion tracking to its virtual assembly process for ergonomics simulation. In addition to this the quality of new vehicles improved 11% [8].

In recent years, VA methods have become increasingly popular at the early design stage, in particular product engineering design reviews which are critical for downstream manufacturing and assembly [9]. More recently, haptic technologies have emerged to provide the user with a sense of touch and force feedback to feel, touch and manipulate virtual objects in a virtual environment. Haptic technologies can enhance VA systems, resulting in a more intuitive and natural user interaction with which to assess the assembly process at the design phase, even before any physical prototype is created. For these reasons the integration of virtual reality and haptic techniques are well-suited for the development of assembly simulators, planners and trainers.

The primary objective of virtual training (VT) is to transfer knowledge and skills to real-world use. VT is a powerful tool for preparing humans to perform tasks which are otherwise difficult, expensive and/or dangerous to duplicate in the real world. It is widely used for industrial machine operating [10], [11]; the operation of electrical power plants [12]; vehicle driving, piloting, traffic control, maintenance [13]; medical procedures [14]-[16]; and military operations [17]. However, this has not been the case for the majority of shop floor assembly processes and activities.

Traditional assembly training has the main disadvantage of requiring the physical components, special facilities or even the actual production line all of which may come too late in the product lifecycle to influence a product’s design in a cost effective manner; therefore, the alternative is VA training. While continued research is driving new virtual environments, most are focused on analysing the functionalities of the proposed VA systems rather than on the analysis of the effectiveness of the virtual approach. Moreover, none of these studies have completely evaluated the influence of VA training on the trainee’s real assembly performance, particularly when different VA training modes and high-complex assembly tasks are used. Therefore, the effectiveness and efficiency of VA training still remains unknown. One method of determining the effectiveness of VA training is to evaluate the correct realization of the real assembly task after undergoing VA training first. On the other hand, the efficiency of VA training can be determined by evaluating how efficient the real assembly task is completed after undergoing VA training first. The efficiency of completing a real assembly task is commonly evaluated in terms of the task completion time (TCT) because it represents the process cost. Figure 1 illustrates the concepts of effectiveness and efficiency of VA training.

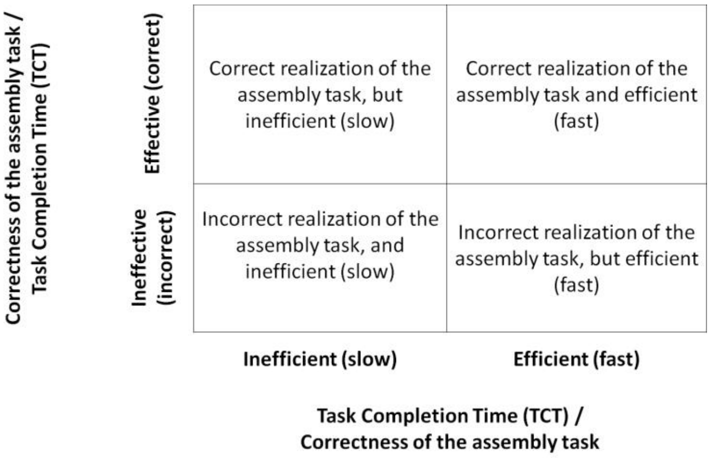


Figure 1. Effectiveness and efficiency of VA training.

In this paper, a comprehensive analysis and evaluation of the influence of VA training on real assembly performance is presented. This considers the use of three different training modes and several assembly tasks with different levels of complexity and number of parts. The research focuses on a common central issue relating to many virtual training environment: how effectively can virtual assembly training transfer knowledge and skills to the trainee in order to influence and improve their real-world assembly performance?

2. Related work

2.1 Virtual assembly

Virtual assembly (VA) research largely focuses on the simulation of spatial manipulation tasks, such as mechanical design, assembly planning and assembly evaluation. Gupta et al [5] demonstrated that multimodal simulation in a virtual environment (VE) can be used to evaluate and compare alternative designs using Design for Assembly Analysis. Adams et al [18] presented the VBB (Virtual Building Block) system that simulates the behaviour of a collection of LEGO™ blocks which can be manipulated by the human operator using a 3-DOF Excalibur interface. Chen et al [19] developed a haptic virtual coordinate measuring machine (HVCMM) to simulate a CMM's operation and measurement procedures in a virtual environment with haptic perception. On the other hand, Fischer et al [20] developed a virtual reality platform to perform common tasks at the product design, prototyping and evaluation stages, including VA and engineering analyses. Lim et al [21] proposed the VARP (Virtual Assembly Rapid Prototyping) system that allows the user to interactively decompose a model, evaluate design changes, analyse the assembly process and generate assembly plans.

It has been recommended in the literature that in order to enhance the level of realism, VA environments must incorporate the sense of touch and kinesthesia. Klatzky et al [22], introduced the term "haptics" to the engineering community, referred to as the identification of objects by the sense of touch. The benefits of haptic force feedback during VA have been demonstrated to reduce task completion time (TCT) [5], [6], [23]. The Haptic Assembly Manufacturing and Machining System (HAMMS) [24] found that haptic feedback played a key role in successful VR assembly. Vo et al [25] similarly showed that haptic interaction reduced assembly TCT, increased the accuracy of placing virtual objects and produced steadier hand motions along 3D trajectories when compared to visual methods. Bordegoni et al [26] developed a low cost application for testing a mixed reality approach for the evaluation of manual assembly of mechanical systems. They combined a haptic Phantom arm and a Wiimote to simulate user interaction with both hands. The haptic device provides force feedback and the Wiimote provides tactile feedback through vibration. Iglesias et al [27] focused on a collaborative assembly training application using different network topology architectures and strategies. Their results suggest that client-server architectures provide good results if network conditions are good enough and objects managed by users are sufficiently separated. A peer-to-peer architecture was also proposed in order to support a collaborative assembly task with certain network delay; the results were satisfactory with different network conditions, however there is not a global solution to the problem yet.

VA systems use different simulation methodologies, and include functions such as automatic feature matching recognition, constrained motion, CAD assembly constraints, physics-based modelling (PBM) and use of haptic feedback. A review [28] of the main characteristics of VA platforms drew the following observations:

- VA systems that incorporate force feedback have greater level of realism and are more intuitive, but their computational cost is high. As a consequence, most of these VA systems have been limited to the analysis of simple assembly tasks (e.g. peg-in-hole [29]) that comprise few parts with simple and semi-complex geometries.
- Although most of the VA systems have been proposed for planning, simulation and training of assembly tasks, their evaluation tests have mainly been focused on analysing the functionality of the system, obviating the analysis of the effectiveness of the virtual assembly approach.

Despite the many VA systems proposed in the literature, few focus on the analysis and evaluation of virtual assembly training itself.

2.2 Virtual assembly training

The Virtual Training Studio (VTS) by Brough et al [30] allows trainers to create training instructions, and trainees to learn assembly operations. The VTS has three training modes: 1) interactive simulation, 2) 3D animation, and 3) video. To achieve good training results, the trainee requires support from a supervisor. The supervisor can participate in the VR scenario by monitoring the user actions and assisting him/her during practicing in order to enhance the trainee's understanding of the assembly process. Critically, the VTS included data logging which is important to analyse and evaluate the training progress. They conducted a user study involving 30 subjects and two tutorials to assess performance of the system. The use of haptics was avoided in order to keep the computational cost of the system down.

Research efforts have also focused on Augmented Reality (AR) assembly training and guidance. A general procedure for AR-assisted assembly training was proposed by Iliano et al [31]. The aim was to train operators in the assembly of a planetary gearbox with the help of a hand held device and using a variant approach with feedback sensors in the work environment. Webel et al [32] developed a platform for multimodal interaction AR-based training of maintenance and assembly skills. They implemented haptic feedback by means of vibrotactile bracelets to apply vibration stimuli to the human arm, forearm, and wrist. The evaluation involved two experimental groups: Group 1—Control: participants performed once the physical task while they were watching an instructional video showing the task steps; and Group 2—AR: participants performed the physical task once using the AR platform. The results showed that after one training session, the skill level of technicians who trained with the AR platform was higher than the skill level of those who used traditional training methods. However, one of the main constraints in using AR for assembly guidance and training is the need to determine when, what and where to display the virtual information in the augmented world, which requires at least a partial understanding of the assembly workspace.

Table 1 summarizes the key characteristics of research work in the area of VA training. These main characteristics have been divided into five categories: training mode, assembly task, part manipulation, assembly performance evaluation and effectiveness evaluation.

Table 1. Key features of VA training studies in the literature.

VA training study (Authors)	Training mode			Assembly tasks			Part manipulation		Assembly performance evaluation			Effectiveness evaluation of VA training
	Haptic - virtual	Virtual	Visual	No. task	No. part/task	Geometrical complexity	Free	Assembly constrains	TCT	ANOVA	Heuristic	
Oren et al., 2012 [33]	X			1	6	SC	X		X			X
Xia et al, 2011 [34]	X	X		1	2	SC	X	X	X			
Tching et al., 2010 [29]	X			1	2	S	X	X	X			
Bordegoni et al., 2009 [26]	X			1	2	SC	X				X	
Vo et al., [25]	X	X		2	4	S	X		X	X		
Brough et al., [30]		X	X	2	11	C	X				X	
Garbaya et al., 2007 [35]	X	X		1	2	SC	X		X	X		
Jayaram et al., 2007 [36]		X		2	2	SC	X				X	
Adams et al., 2001 [18]	X	X		1	37	SC	X		X	X		X
Boud et al., 2000 [37]		X		1	8	S	X		X	X		X

S- simple, SC- semi complex, C- complex

Table 1 shows that three VA training modes have been considered in the literature: 1) haptic-virtual (force feedback is provided to the user during VA training); 2) virtual (VA training is provided to the user but without force feedback); and 3) visual (assembly training is provide with a video). Although several authors have considered the use of haptic systems in VA training activities, none of them have analyzed and compared the effectiveness of these three VA training modes.

Regarding assembly task complexity, the truest measurement of assembly task complexity could be a combination of several parameters such as the number of parts, the geometrical complexity of the parts, the number of feasible assembly sequences, the number of assembly operations, the number of part reorientation during assembly, amongst others. Goldwasser et al [38] began the study of assembly cost by introducing a collection of basic complexity measurements: fewest number of directions, fewest re-orientations, fewest number of non-linear steps, fewest number of steps and minimum depth of an assembly sequence. On the other hand, Ghandi et al [39] presented the main features of an assembly task problem from two main aspects: problem model and problem nature. They also said that when the parts of an assembly have simple geometries then the complexity of the assembly task can be measured in terms of the number of parts, n, but when the parts have more complex polygonal or polyhedral shapes, then the total number of their vertices $\boldsymbol{N}$ is the appropriate metric to reflect the complexity of the problem. Based on these definitions of assembly complexity, it can be said that high-complex assembly tasks comprise a large number of parts with complex geometries, whilst low-complex assembly tasks comprise few parts with simple geometrical shapes. Thus, from Table 1 it can be seen that VA training in the literature generally covers one or two low-complex assembly tasks with a small number of parts (typically 2 parts). Three levels of geometrical complexity have been identified: 1) simple (S), virtual parts are primitive shapes with up to one Boolean operation; 2) semi-complex (SC), virtual parts are modeled with more than one Boolean operation but are simplified models of real objects; and 3) complex (C), virtual parts corresponds to real complex components. Brough et al [30] used assembly tasks with a relatively high number of complex parts, however no force feedback was provided to the user for part manipulation. Though they recognised the benefits of haptics, it was omitted to keep the computational cost of the system down. Since haptic-enabled VA requires a high computational cost, many of the systems in the literature use simple assembly tasks such as the peg and hole.

Table 1 also shows that most of the studies in the literature have considered free manipulation of virtual parts; i.e. virtual objects have physical behavior similar to the real world and are free to be manipulated by the user. Very few works have used assembly constraints to reduce the degrees of freedom of virtual objects while performing the VA training task.

According to Table 1, the VA assembly training performance has been evaluated in terms of the Task Completion Time (TCT), which is the most representative performance parameter in an assembly process because it implicitly represents the assembly cost, the assembly complexity and the user's ability to carry out the assembly. ANOVA and Heuristics analyses have also been used to evaluate the performance and usability of VA training systems. The ANOVA analyses are used to demonstrate the significance and validity of the statistical data related to VA training. Heuristic evaluations have been also used to evaluate the overall VA system performance based on user perception, satisfaction and feedback questionnaires.

Although several research works have been focused on the analysis and evaluation of VA training, a limited number of investigations have evaluated its effectiveness. Boud et al [37] explored the effect of using VR for assembly training on human operators. The results showed that TCTs were longer for the participants who trained using a 2D-drawing before assembling the real product than those participants who undertook a VR assembly training. They also observed that the most significant limitation was the lack of haptic feedback in the VE. Adams et al’s [18] VBB (Virtual Building Block) experimental tests showed a significant performance improvement when virtual training with force feedback was used in comparison with traditional training using a video. Oren et al [33] compared the learning transference of VA training versus real training based on the training times and real assembly of a 3D wooden puzzle. The results indicated that virtual training reduced the real TCT in comparison with physical training. However, none of the studies in the literature have analyzed and compared the effectiveness of VA training when using different training modes and assembly tasks with varying levels of complexity. Therefore, more research work is needed to fully assess the impact and benefits of VA training on real assembly performance.

In this paper a comprehensive analysis and evaluation of the influence of VA training on the real assembly performance is presented. The effectiveness of VA training is evaluated by considering three training modes and several assembly tasks with variable levels of complexity and number of parts. The results are analyzed by comparing the real task assembly performance of all individuals who went through the different training modalities.

3. System description

In order to investigate the influence of haptic VA training on real world assembly tasks, a haptic-enabled virtual assembly training platform for planning and simulating such tasks has been developed based on HAMS (Haptic Assembly and Manufacturing System) [28]. The proposed platform has the architecture outlined in Figure 2.

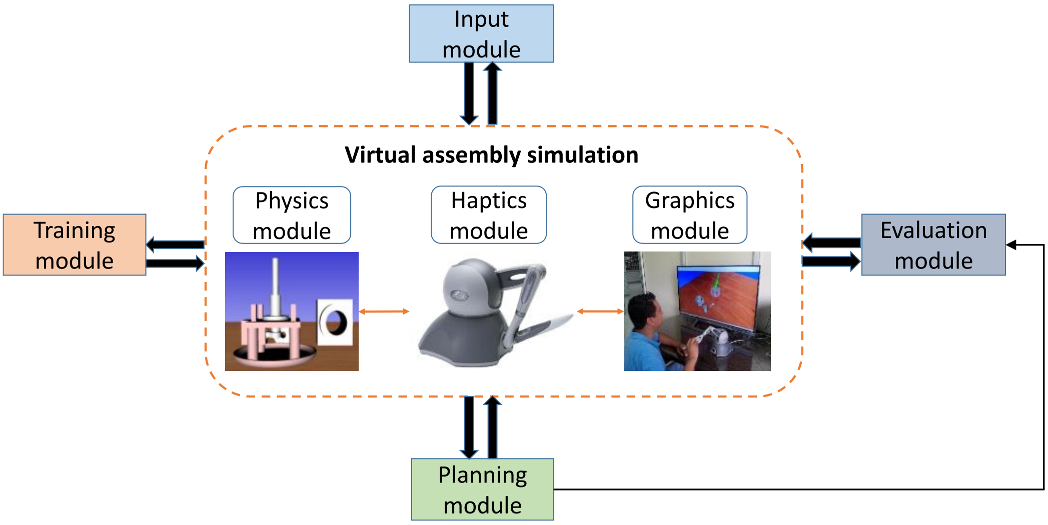


Figure 2. HAMS general architecture.

HAMS comprises seven main modules:

1. *Graphics module*: responsible of graphics rendering, which includes the creation and representation of the virtual scene and 3D models, the visualization of assembly paths, messages and assembly information, the creation of buttons and widgets to configure the simulation parameters. This module uses the Visualization Toolkit libraries (VTK 5.10).
2. *Physics module*: enables physical based behavior of virtual objects, allowing them to have dynamic and realistic motion and collision response. This module allows the use of three different physics simulation engines (PSEs): Bullet, PhysX v2.8 or PhysX v3.1.

3. *Haptics module*: provides force feedback to provide the user with the sense of touch and kinesthesia. OpenHaptics (v3.0) is used to support the Phantom Omni haptic devices.
4. *Input module*: responsible of importing and uploading the virtual models into the system (*.stl, *.obj, *.vtk), and also for defining the model properties.
5. *Training module*: responsible of the assembly training activities and the data logging and evaluation of the user progress.
6. *Planning module*: responsible of the data logging and analysis of the user movements during the virtual assembly in order to generate the assembly plan.
7. *Evaluation module*: responsible of the analysis and evaluation of the assembly plans based on several criteria and according to the user needs.

The haptic VA training interface of HAMS is shown in Figure 3.

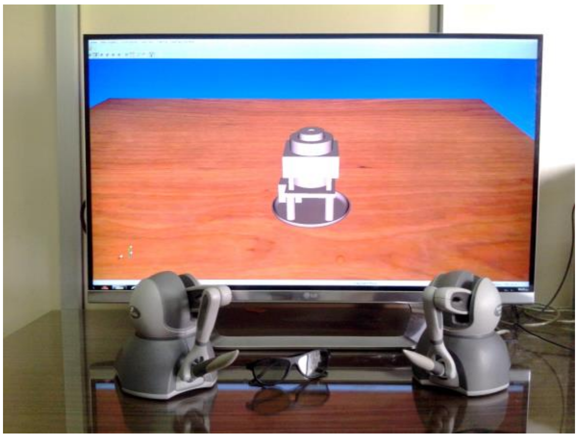


Figure 3. Graphic and haptic user interfaces of HAMS.

3.1 Haptic manipulation

HAMS physics–based modelling (PBM) allows dynamic interaction with virtual objects, resulting in a simulated physics behaviour similar to the real world. The contact response between objects prevents virtual objects from penetrating each other, enabling the assembly of components. The manipulation of virtual objects in HAMS is calculated as follows, see Figure 4:

- The haptic shape is coupled to the physics model trough a mass-spring-damper (MSD) system defined as:

$$m\ddot{x} = -kx - c\dot{x} \tag{1}$$

- The haptic model is moved directly by the position and orientation of the haptic device.
- If the haptic model is moved, a force ($m\ddot{x}$) is computed using the MSD system.
- The resulting force is then applied to the physics model, producing its movement.
- Finally, the graphics model is updated through a transformation matrix using the position and orientation of the physics model.

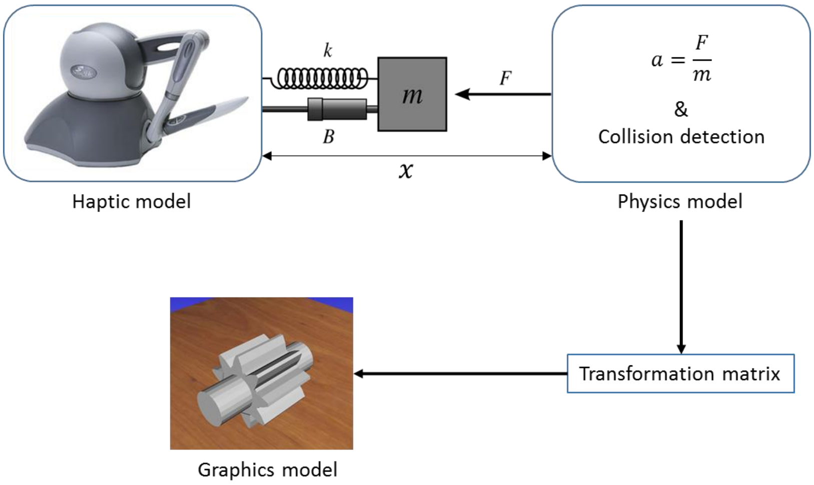


Figure 4. Virtual object manipulation.

3.2 Assembly training module

Figure 5 illustrates the operational flow of the HAMS training module. Three assembly training modes are considered:

1. *Haptic-enabled mode.* VA training is performed with dynamic behaviour of virtual objects and with the sense of touch and kinesthesia to the trainee by means of the haptic device.
2. *Haptic-unabled (virtual) mode*. VA training is carried out with dynamic behaviour of virtual objects but without haptic force feedback to the trainee.
3. *Visual mode*. Training is provided by means of a video that explains the assembly instructions of the assembly task performed by an expert.

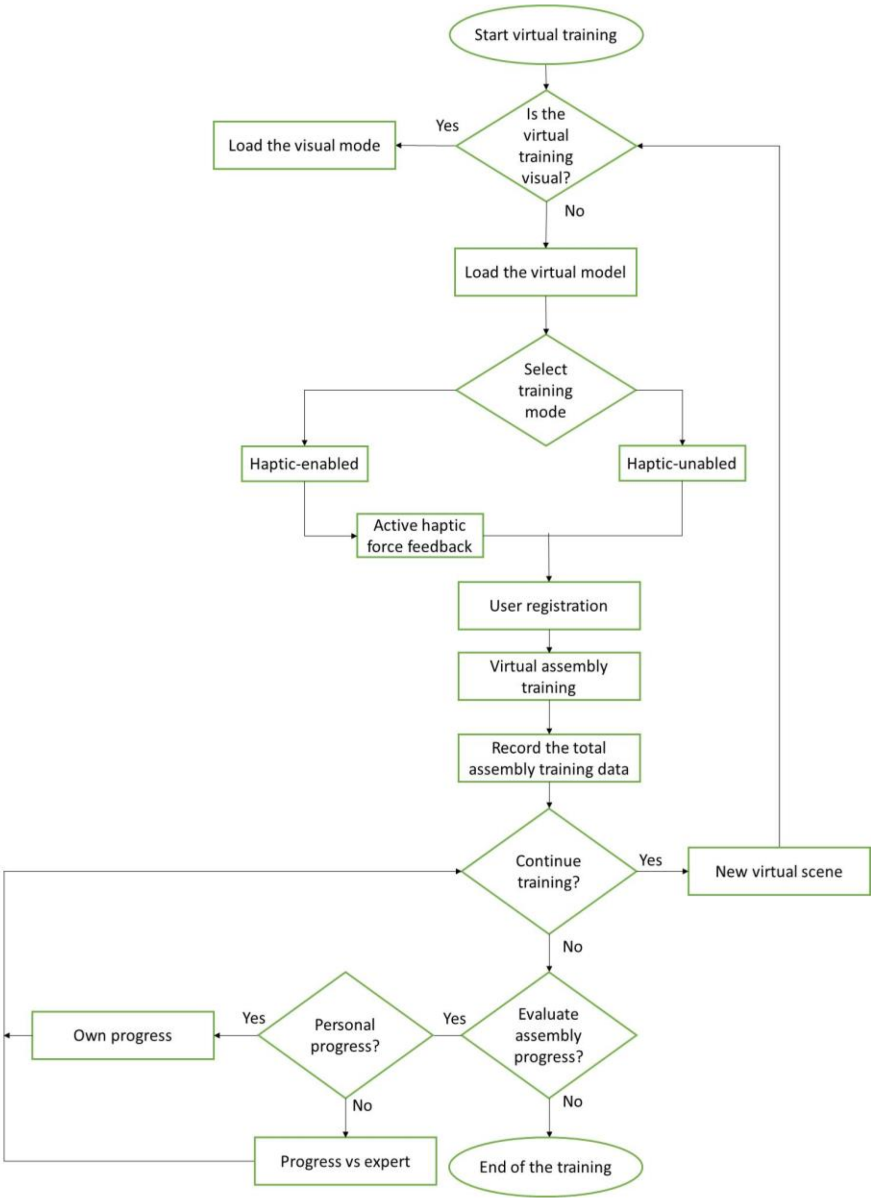
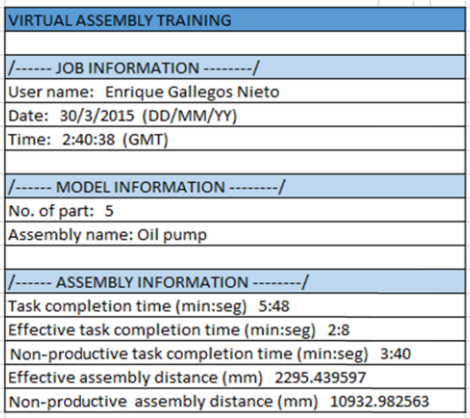


Figure 5. Training module process flow.

The first two modes allow the user to automatically log the assembly data in order to identify the user's progress and to make further assessments. These data are saved as an *.csv, *.txt or *.doc file that contains the following information, Figure 6:

- Job information: User’s name, date and time.
- Model information: Number of parts and assembly task name.
- Assembly information: VA training information in terms of the assembly time and assembly distance parameters as defined in Figure 6b. These parameters were selected because assembly time and assembly distance are the main variables commonly used to evaluate the performance of assembly tasks.



VIRTUAL ASSEMBLY TRAINING

/------ JOB INFORMATION --------/
User name: Enrique Gallegos Nieto
Date: 30/3/2015 (DD/MM/YY)
Time: 2:40:38 (GMT)

/------ MODEL INFORMATION --------/
No. of part: 5
Assembly name: Oil pump

/------ ASSEMBLY INFORMATION --------/
Task completion time (min:seg) 5:48
Effective task completion time (min:seg) 2:8
Non-productive task completion time (min:seg) 3:40
Effective assembly distance (mm) 2295.439597
Non-productive assembly distance (mm) 10932.982563

Parameter	Description
Task Completion Time (TCT)	Total assembly time to complete the task, including productive and non-productive times.
Effective Task Completion Time (ETCT)	Total productive time, when manipulating parts.
Non-productive Task Completion Time (NPTCT)	Total non-productive time when not manipulating parts.
Effective assembly distance (EAD)	Total productive travel distance when manipulating parts.
Non-productive assembly distance (NPAD)	Total non-productive travel distance when not manipulating parts.

(a) (b)

Figure 6. Assembly data: a) report, b) parameter definitions.

Assembly training may require a supervisor to assist, monitor and evaluate the trainee. A video of the virtual task performed by the user is also recorded by the HAMS system. The evaluation of the trainee’s progress can then be made by using a combination of the logged data and the video, which are accessible to both the trainer and the trainee. Moreover, the logging can be used to clarify the cognitive insights of the human operator [24].

4. Experimental methodology

To evaluate the effectiveness of VA training a set of experiments were conducted as follows.

4.1. Assembly tasks

Five assembly tasks were designed: 1) a cube puzzle, 2) a pyramid puzzle, 3) an oil pump, 4) a linear actuator and 5) a compressor. Both the virtual and corresponding real models used in these assembly tasks are shown in Figure 7. The real models were fabricated from their virtual counterparts. The virtual models were used during VA training while the real models were used to evaluate real assembly performance.

The cube and pyramid puzzle assembly tasks are directly related to cognitive processes, i.e., information processing, thinking, short term memory, visual memory, etc. On the other hand, the oil pump, linear actuator and compressor assembly tasks were chosen as they are real assembly tasks obtained from the industry.

Howard Gardner's multiple intelligences theory proposes eight types of intelligence [40]: verbal-linguistic, logical-mathematical, special-visual, bodily-kinesthetic, musical, interpersonal, naturalist and existential intelligence. This theory assumes that humans are skilful for some things and unskilful for others. To override this inherent intelligence shortcoming from the proposed experimentation, participants were selected from a mechanical engineering undergraduate program (third and fourth year students).

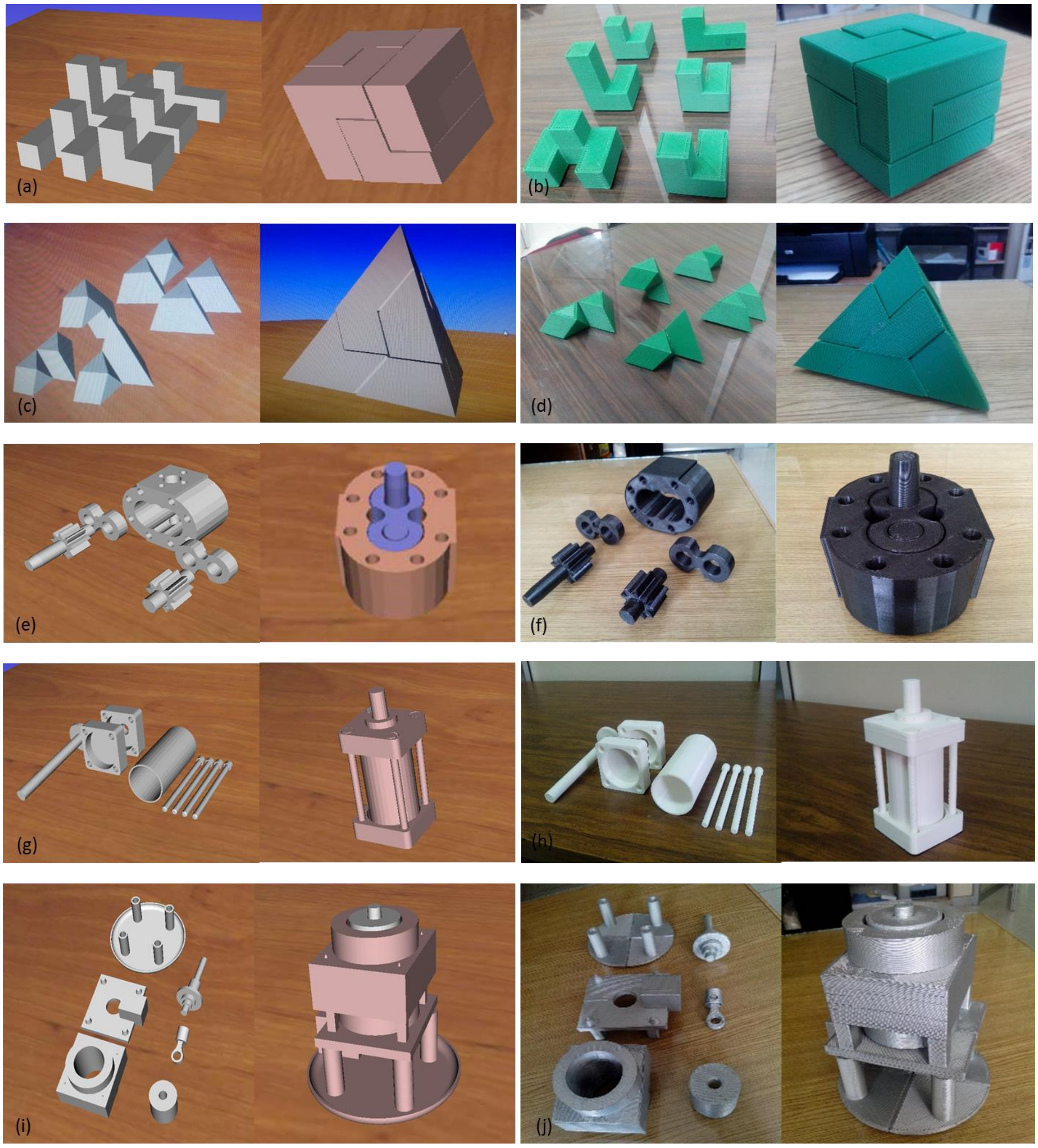


Figure 7. Virtual (left) and real (right) assembly models from the top: a), b) cube puzzle; c), d) pyramid puzzle; e), f) oil pump, g), h) linear actuator; and i), j) compressor.

4.2. Assembly training modes

Three modes for assembly training were considered as follows:

1. *Haptic-enabled virtual assembly training*.

   VA training with haptic force feedback provided to the participants.

2. *Virtual (haptic-disabled) assembly training*.

   VA training without force feedback provided to the participants.

3. *Traditional (visual) assembly training*.

   Assembly training is provided to the participants by allowing them to watch up to three times the assembly task performed by an expert and before carrying out the real assembly task.

4.3. Participants

A total of 15 people with ages ranging from 19 to 30 years were randomly selected to participate in the experiments. The participants consisted of male and female mechanical engineering undergraduate students with no previous knowledge of the assembly tasks, virtual reality and haptics. They were randomly divided into three groups according to the training modes:

Group 1. Haptic-enabled virtual assembly training.

Group 2. Haptic-disabled virtual assembly training.

Group 3. Traditional assembly training.

4.4. Experimental procedure

The experimental procedure comprised the methodology illustrated in Figure 8, which is described below.

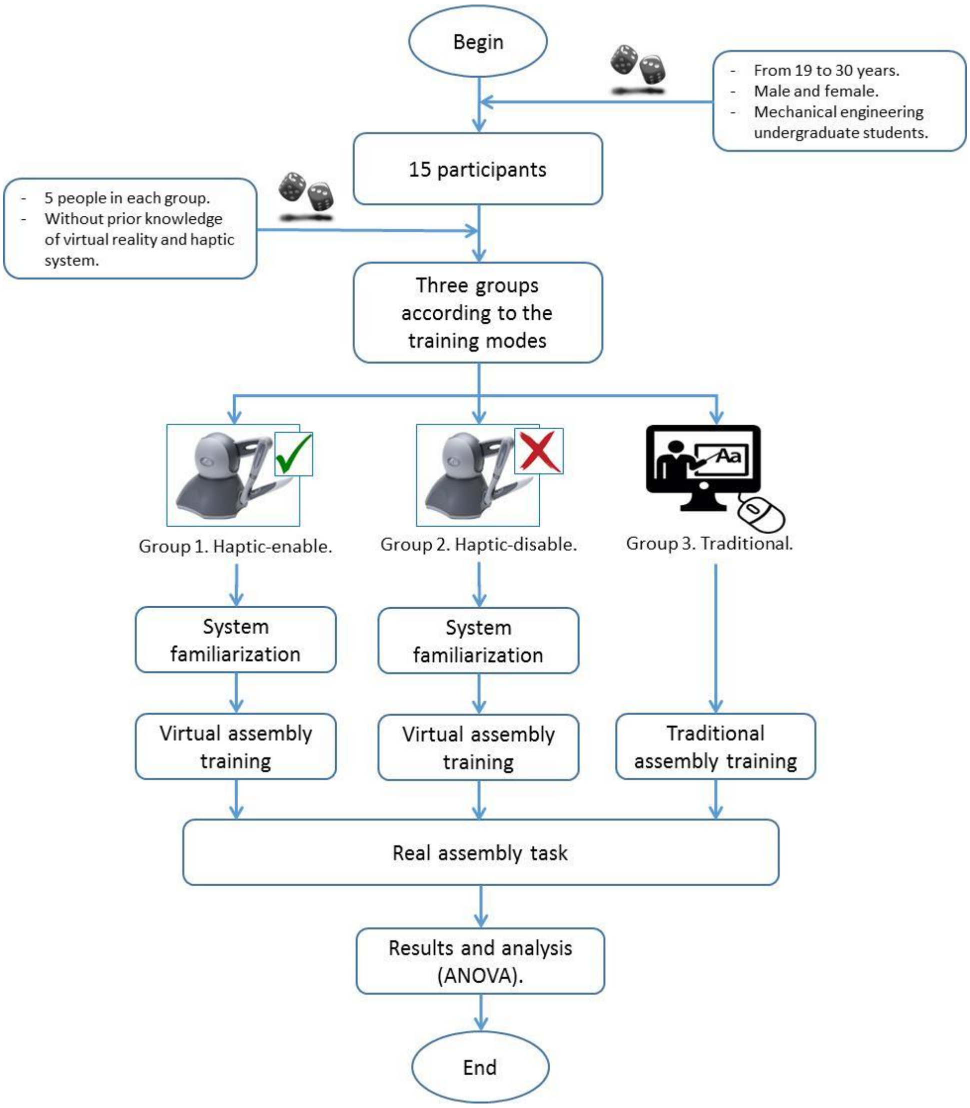


Figure 8. Experimental methodology.

1) Introduction

At the beginning of the tests, all participants were informed about the general background relating to the experiment, the conditions in which they would be working and the relevant experimental procedure.

2) System familiarization

Participants of Groups 1 and 2 were instructed on the use of HAMS including short explanations about the various views, camera manipulation and haptic device. They were also allowed to ask questions and receive further explanations. Then, the participants were given the opportunity to carry out and practise a virtual assembly task, allowing them to familiarise themselves with the system for thirty minutes

3) *Assembly training*

Participants in Groups 1 and 2 went through a virtual training period for each assembly task. Before starting the virtual training, they were asked to observe each virtual assembly task being performed by an experienced user, allowing them to understand the assembly sequence. Each training session lasted a maximum of 30 minutes and included a short explanation about the virtual task. The effect of gravity and collision detection was enabled in both virtual training groups but force feedback was only enabled for participants of Group 1. It has to be mentioned that virtual training was carried out with a single haptic device in order to reduce system's synchronization and instability problems.

Participants of Group 3 undertook a traditional training period which consisted of observing an expert performing each real assembly task once or twice as requested by the user, and up to three times for complex assembly tasks in order to understand the assembly sequence used by the expert.

4) *Real assembly*

After undergoing their relevant training, participants in Group 1, 2 and 3 were asked to build each of the real assemblies in turn. The real assembly tasks were carried out with a single hand to be in agreement with the virtual training. Each real assembly task was repeated 5 times with a 1 minute short break in-between.

5) *Real assembly performance*

All participants were observed during the real assembly task executions. To evaluate assembly performance, the task completion time (TCT) was measured for each participant carrying out each real assembly task. The TCTs were also measured during VA training.

5. Results

Figure 9a shows a participant during VA training in HAMS whilst Figure 9b shows another participant carrying out the corresponding real assembly task. Table 2 presents the average TCT and standard deviation (SD) values corresponding to each real assembly task in turn and the groups of participants. These results include the TCT and SD values for each iteration performed by the participants.

(a) (b)

Figure 9. Participants during: a) VA training, and b) real task execution.

Table 2. Average TCT and SD of the real assembly tasks.

Assembly task	**Group**	**TCT (s)**	**Iteration**				
		SD (s)	**1**	**2**	**3**	**4**	**5**
Cube	1	TCT	49.20	22.06	17.94	16.42	17.28
		SD	13.39	6.08	0.77	1.44	1.55
	2	TCT	73.80	28.98	18.58	18.16	16.08
		SD	45.47	11.89	1.25	0.77	0.90
	3	TCT	197.00	61.64	19.30	18.46	16.50

		SD	71.79	35.59	1.61	0.89	1.30
Pyramid	1	TCT	66.60	30.28	21.42	22.10	20.93
		SD	41.11	14.64	1.33	1.90	1.23
	2	TCT	135.80	40.38	23.22	23.96	22.52
		SD	107.56	21.29	1.00	2.89	1.83
	3	TCT	531.40	372.00	40.08	23.40	22.72
		SD	348.00	252.09	19.30	2.72	1.57
Oil pump	1	TCT	10.74	10.02	9.62	9.62	9.16
		SD	0.60	0.41	0.33	0.33	0.71
	2	TCT	11.26	10.56	10.22	9.68	9.52
		SD	0.60	0.59	0.44	0.65	0.48
	3	TCT	13.22	10.94	10.06	9.58	9.44
		SD	2.29	1.25	0.27	0.58	0.38
Linear actuator	1	TCT	52.46	34.22	34.18	31.94	28.52
		SD	7.36	4.82	4.04	4.36	1.51
	2	TCT	63.12	35.44	29.32	32.82	30.76
		SD	16.00	5.39	0.51	1.58	2.83
	3	TCT	115.20	55.30	33.18	29.84	31.48
		SD	34.78	21.24	3.16	1.65	1.72
Compressor	1	TCT	69.69	57.87	52.21	46.83	40.94
		SD	14.91	9.67	11.31	5.32	4.90
	2	TCT	112.65	66.88	51.93	49.50	44.85
		SD	34.32	11.72	4.73	10.08	6.55
	3	TCT	262.80	125.07	68.13	54.69	47.75
		SD	101.24	40.50	9.58	5.01	4.08

6. Analysis and discussion

All participants of the three groups were able to complete the real assembly tasks; however, the results of Table 2 show that the real assembly TCT and SD values of participants who went through VA training first (Groups 1 and 2) are lower than the corresponding values for the participants who trained using the traditional method (Group 3). The participants of Group 1 and Group 2 completed the real assembly tasks faster and with less variation than those in Group 3. Moreover, haptic-enabled VA training led to greater levels of effectiveness than haptic-disabled VA training.

6.1. ANOVA analysis

A deeper analysis of the results was carried out by considering a single-factor analysis of variance (ANOVA) model. The model that describes the observations is as follows:

$$y_{ij} = \mu + \tau_i + \epsilon_{ij} \begin{cases} i = 1,2, \dots, a \\ j = 1,2, \dots, n \end{cases} \quad (2)$$

where y_{ij} is the real assembly TCT for the ith assembly training mode (i = 1, 2 or 3) and the jth observation (participants, j = 1, 2, 3, 4 and 5); μ is a common parameter to all assembly training mode called the over mean; τ_i is a parameter unique to the ith training mode, called the ith treatment effect; and ε_{ij} is a random error component that incorporates all other sources of variability in the experiment including measuring, uncontrolled factors (e.g. natural human factors), differences between the experimental units (TCTs) to which the assembly training modes are applied, and the general background noise in the process (e.g. environment noise). It has to be mentioned that since all participants were volunteers, natural human factors such as fatigue, stress, hungriness, etc., may have been present during the experimental tests but they are beyond the scope of this investigation.

The appropriate hypotheses must establish the relation or equality among the three assembly training modes:

$$H_0: \mu_1 = \mu_2 = \mu_3$$

$$\mathrm{H_1: \mu_i \neq \mu_j \text{ for at least one pair } (i, j)} \quad (3)$$

The NULL hypothesis (H_0) establishes that the effects of the three training modalities are identical. The hypotheses were evaluated with a 5% significance level, α = 0.05. The

ANOVA analyses were carried out by means of the *Data Analysis* tool of Microsoft Excel™.

The ANOVA results are summarized in Table 3. These results consider the 5 iterations performed by the participants. The results of each iteration were treated as an independent experiment and compared at each iterative stage. The F ratio (F_0 = between-treatments/error) is compared with an appropriate upper-tail percentage point of the $F_{2,12}$ distribution. The cut-off percentage point of the F distribution is $F_{0.05,2,12} = 3.89 = F$. Since $F_0 > F$ then H_0 is rejected and the TCT values for the relevant training groups differ. Observing the table, this means that VA training has a significant effect on the real assembly performance up to the first two or three iterations depending on the assembly complexity. After this the effect is not significant, which demonstrates that learning takes place during VA training.

Table 3. ANOVA results for all real assembly tasks.

Real assembly task	**F_0**					**Task complexity level**
	Repetition					
	1	**2**	**3**	**4**	**5**	
Cube	12.71	4.63	1.46	-	-	Medium
Pyramid	7.02	8.83	4.23	0.70	-	High
Oil pump	4.23	1.43	-	-	-	Low
Linear actuator	11.12	4.17	3.72	-	-	Medium
Compressor	13.23	10.66	5.32	1.54	-	High

Table 3 also shows the complexity level of the assembly task, which has been determined by considering the number of repetitions in which $F_0 > F$ is satisfied. Namely, the high-complex assembly tasks are the pyramid and compressor because the condition $F_0 > F$ is satisfied in the first, second and third repetition. In the case of the cube and linear actuator tasks, the complexity level is medium because the condition F_0

> F is satisfied in the first and second repetitions. The assembly task with the lowest complexity level is the oil pump task since the condition $F_0 > F$ is only satisfied in the first repetition.

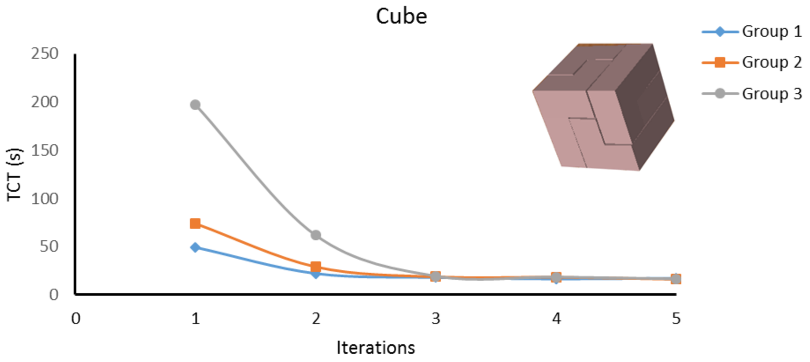
6.2. VA training effectiveness

The effectiveness of VA training can be quantified as the reduction of the real TCT after virtual training, in comparison to the real TCT when traditional training is used. Table 4 shows the percentage of effectiveness of VA training for Groups 1 and 2 relative to Group 3. In general, it was observed that VA training resulted in a significant improvement in real task assembly performance; the real assembly TCT values were reduced after undergoing VA training.

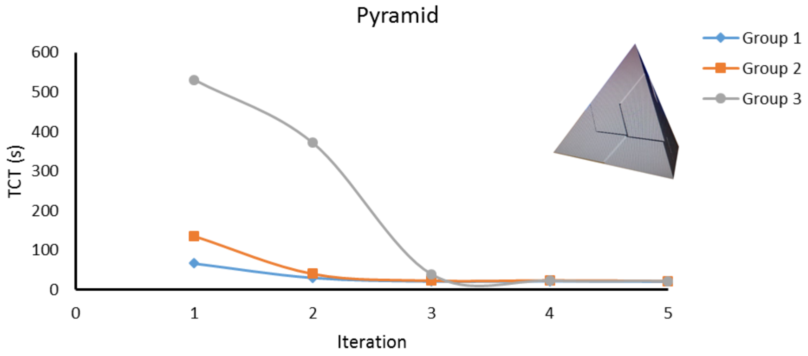
Table 4. Effectiveness of VA training.

Assembly task	**Task complexity level**	**Group**	**Effectiveness (%)**				
			Iteration				
			1	**2**	**3**	**4**	**5**
Cube	Medium	1	75.03	64.21	7.05	11.05	-4.73
		2	62.54	52.99	3.73	1.63	2.55
		3	0	0	0	0	0
Pyramid	High	1	87.47	91.86	46.56	5.56	7.87
		2	74.44	89.15	42.07	-2.39	0.88
		3	0	0	0	0	0
Oil pump	Low	1	18.76	8.41	4.37	-0.42	2.97
		2	14.83	3.47	-1.59	-1.04	-0.85
		3	0	0	0	0	0
Linear actuator	Medium	1	54.46	38.12	-3.01	-7.04	9.40
		2	45.21	35.91	11.63	-9.99	2.29
		3	0	0	0	0	0
Compressor	High	1	73.48	53.73	23.36	14.38	14.26
		2	57.13	46.52	23.77	9.50	6.07
		3	0	0	0	0	0

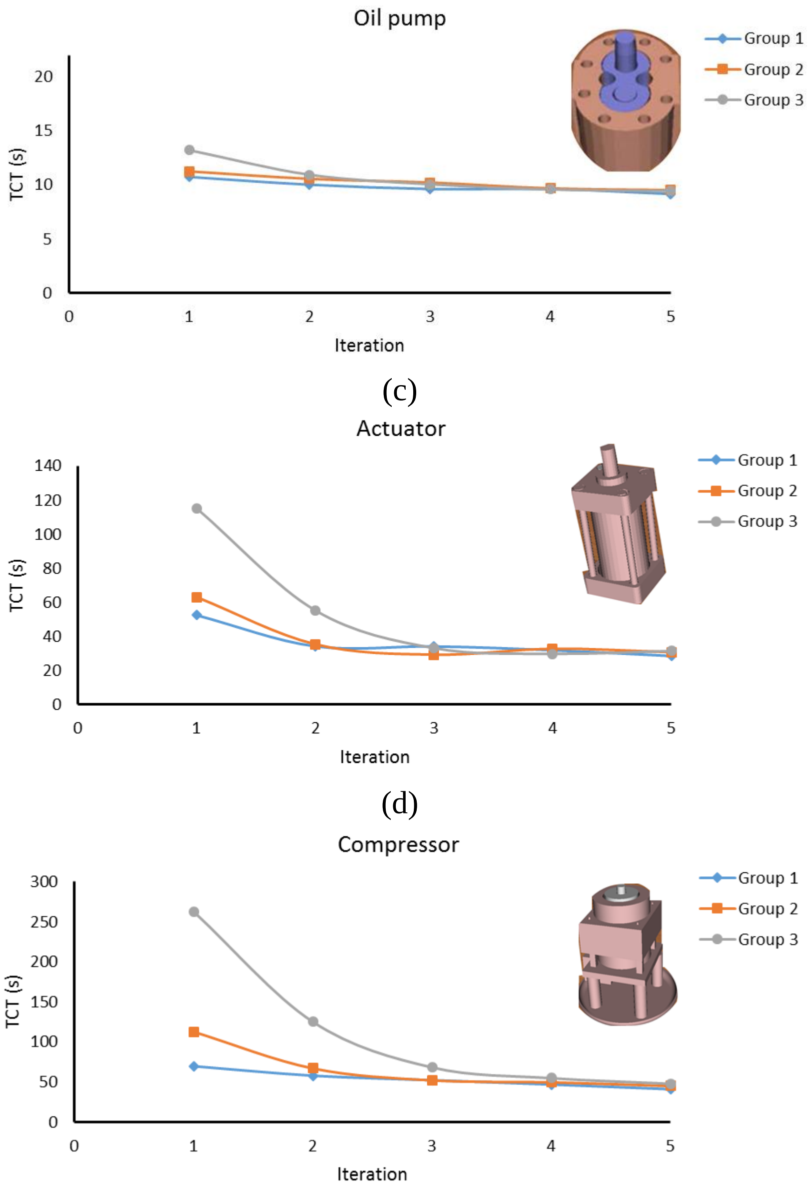
Figure 10 presents the experimental results corresponding to each real assembly task. The TCT average values for each group are plotted as a function of the iteration number. From these results it is observed that for all assembly tasks, participants who trained virtually (Groups 1 and 2) achieved better performance times in the first iteration than participants who trained traditionally (Group 3). In other words, participants who went through a training session in HAMS improved their real assembly performance. The maximum performance enhancement occurred at the first trial, and it decreased with the number of iterations. This decrement is due to the natural learning phenomenon that takes place during the successive assembly trials which is evident in the learning curves of Figure 10. In the case of the highly-complex tasks, the compressor and the pyramid, the effect of VA training on the real assembly performance remained up to the third assembly repetition; after this repetition the performance of all participants was very similar.



(a)



(b)



(c)

(d)

(e)

Figure 10. Average real TCTs for the: a) cube, b) pyramid, c) oil pump, d) linear actuator, and e) compressor assembly tasks.

Figure 11 presents the VA training effectiveness values of the first iteration as a function of the assembly task complexity and the training modes. From this figure it is observed that the effectiveness is dependent on the VA training mode and the assembly task complexity. Haptic-enabled VA training led to greater levels of effectiveness than the haptic-disabled VA training. Participants who trained with haptic feedback (Group

1) accomplished a better assembly performance than participants who trained without haptic feedback (Group 2). In general, haptic-enabled VA training led to an average improvement of 80% for high-complex tasks, 65% for medium-complex tasks and 18% for low-complex tasks; whereas the haptic-disabled VA training led to an average improvement of 65%, 54% and 15% respectively for the same tasks. These results suggest the importance of using haptic force feedback in VA training because better assembly performance can be obtained in comparison with VA training without haptics; i.e. haptic-enabled VA training is more effective than haptic-disabled VA training.

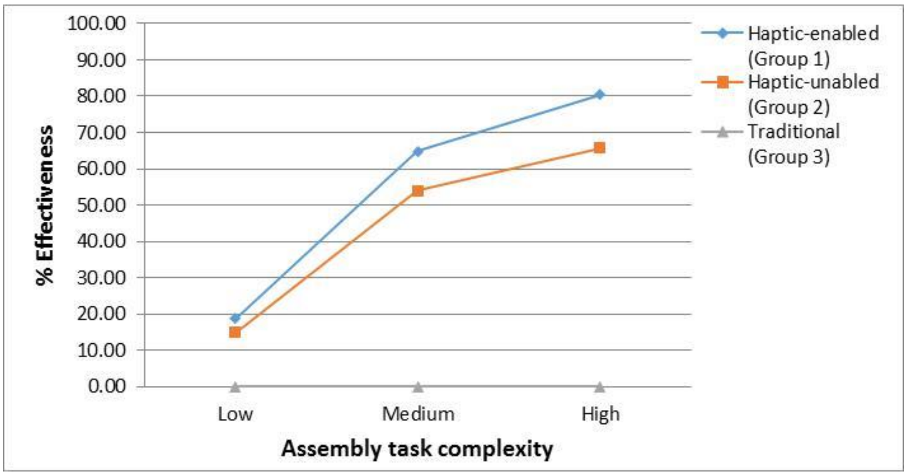


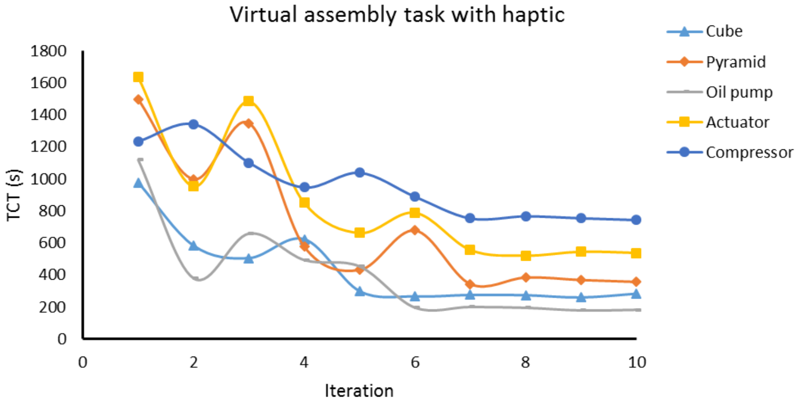
Figure 11. Effectiveness of VA training vs. assembly complexity.

Figure 11 also indicates that as the assembly task complexity level increases, the benefits of VA training increase. The effect of VA training is much greater for highly-complex assembly tasks than for low-complex assembly tasks. For instance, Group 3 completed the pyramid high-complex task in 531.4s, whilst Group 1 completed the same real task in 66.6s, an 87.5% improvement. Also, Group 3 completed the oil pump low-complex assembly task in 13.2 s whilst Group 1 completed this task in 10.7 s, an 18.9% improvement. Considering both haptic-enabled and haptic-disabled VA training, highly-complex tasks led to an average improvement of 73%, while medium-complex tasks led to an average improvement of 59%, and low-complex tasks had an average improvement of 17%. Note that the level of improvement is reduced with the number of trials as shown in Table 4.

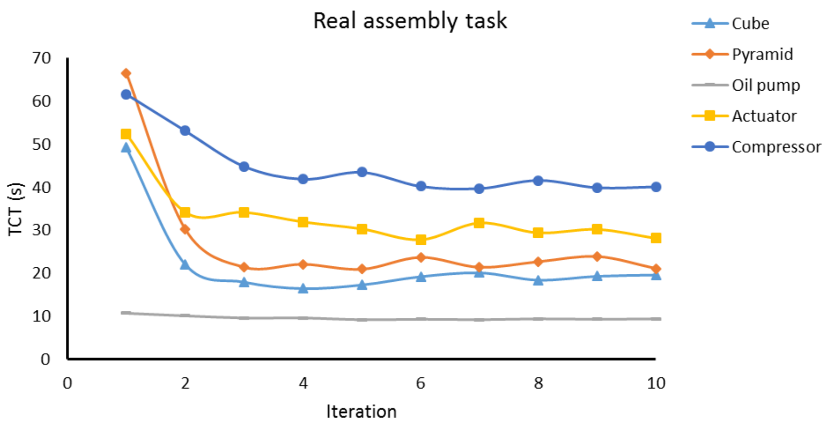
6.3. Virtual vs real assembly performance

To compare the assembly performance of the virtual and the real assembly tasks, another set of experiments was carried out with new participants, which were trained with the same conditions as Group 1 (see section 4.3). Each participant was asked to perform a single assembly task 10 times in the virtual environment and 10 times in the real world. Since for most beginners' wrists will get tired after using the haptic device for a long time, this new set of experiments were carried out with new participants and only one assembly task for each. Figure 12 summarises the results for both real and virtual assembly tasks. These results show that after some assembly trials, the TCT for each task tends to converge to a constant value due to the natural learning phenomenon. In the virtual assembly the TCTs converged after the seventh trial, whereas in the real assembly the TCTs converged after the fourth iteration. It is also observed a wider variation and oscillating nature of the learning curves for the virtual assembly against the rapid learning and constant TCTs associated with the real assembly. These results suggest that learning and perception of reality is faster in real life than in virtual reality.

On the other hand, the results also show that the converged TCT value depends on the assembly task complexity and the assembly mode (real or virtual). More complex assembly tasks require larger TCTs than less complex assembly tasks for both virtual and real assembly. It is also observed that regardless of how long it took the user to perform the first assembly trial of a particular task, the last iterations always converged to a constant TCT. In addition, TCTs for real assembly are smaller than the corresponding TCTs for virtual assembly, which confirm that real assembly tasks are carried out faster than virtual assembly tasks. However, a time-scale factor can be estimated by comparing the TCTs corresponding to the virtual and the real assembly tasks for the 10th iteration. Thus, an average TCT scale factor of 17.7± 2.05 between the virtual and the real assembly is obtained. This value means that the time taken to assemble a haptic-enabled virtual task in HAMS is 17.7 times longer than the real assembly TCT. It has to be mentioned that the TCT scale factor depends on the VA system performance, which is determined by the rates of haptic rendering, graphics rendering and physics rendering as well as computer capacity. Consequently, the value of this factor can be improved with the use of more powerful computers, which are increasingly accessible. However, the advantage of virtual training over traditional assembly training does not rely on the virtual TCT performance but on the effect that it has on the real assembly performance and the greater flexibility it provides to check assemblability prior to physical prototyping.



(a)



(b)

Figure 12. TCTs for: a) virtual assembly, b) real assembly.

6.4. Discussion

The results have demonstrated that VA training is an effective tool to enhance trainees' assembly skills since it was observed that individuals who trained in the virtual environment first, produced a superior assembly performance, in terms of real task completion time, than individuals who trained traditionally. However, the effectiveness of VA training depends on the rendering capabilities of the training system, particularly on the system's ability to provide the user with force feedback. It has been observed that when force feedback is used during VA training, the effectiveness of the assembly training is superior that when no force feedback is provided. This performance increment is associated with the fact that haptic rendering increases the level of realism and perception of the virtual environment, reducing the cognitive load in comparison with haptic-disabled virtual assembly training. As a consequence, haptic-enabled virtual assembly training has a greater effect on the worker assembly performance than virtual assembly training without haptic force feedback. Therefore, it is important to consider haptic rendering during the definition, selection or building of a VA training system.

The effect of VA training on the trainee’s assembly performance also depends on the assembly task complexity. VA training of high-complex assembly tasks will lead to larger improvements of the assembly performance than virtual training of low-complex assemblies.

The superior effectiveness of VA training is at its maximum in the first assembly trial iteration but it is reduced gradually in the subsequent repetitions. It was observed that after the third iteration there is no significant effect of VA training on the assembly performance of individuals when compared to the traditional method. These results are related to the natural learning process of all participants during the repetition of the assembly tasks in the real world.

It should be mentioned that most of the manual assembly tasks require fine movements of hands and fingers, which is difficult to replicate using current haptic devices because they are based on one single point manipulation. However, the aim of virtual training is not to reproduce exactly the movements, forces, textures, etc., of real objects in the virtual environment but to use it as a tool to practice and learn assembly strategies and procedures in order to improve the assembly performance of workers. In any training situation the task to be trained must be decomposed into its cognitive, perceptual and motor demands. These demands must be met during the training process [41]. In the experimental tests conducted in this paper, participants first tried to build the models inside their minds. Then, the gradual training allowed them to identify the location of the parts at their final assembly positions and to develop an assembly strategy to improve the task performance. After VA training participants gained assembly skills in terms of manipulation and location of the parts, leading to less errors and smaller TCTs values, as it is evidenced in the experimental results corresponding to the real assembly tasks.

Traditional assembly training requires trainers and facilities such as a floor space, a production line and the physical product components. On the other hand, VA training does not require special facilities and the physical components; the operators can train in a virtual environment, the assembly tasks can be unlimited and production is not affected by training activities. One major disadvantage of VA training is that the TCT values are larger than the corresponding real assembly values. As a consequence, VA training requires more time than traditional assembly training. However, since virtual assembly can be performed at any time without affecting production, the larger time required for VA training may not represent an additional or excessive cost to companies than traditional training.

7. Conclusions

In this work an investigation to evaluate the influence of haptic-enabled virtual assembly training on real assembly performance has been presented. Several experiments were conducted considering three assembly training modes, five assembly tasks with variable levels of complexity and different numbers of parts using several repetitions. The effectiveness of VA training was evaluated in terms of the percentage of improvement of the real task completion time, in comparison with the traditional assembly training approach. The results have shown that virtual assembly is an effective tool to enhance the individual’s assembly skills because individuals who trained in the virtual environment had a superior real assembly performance after training than those trained traditionally. The results have also evidenced that the effectiveness of VA training depends on the VA training mode and the assembly task complexity. The maximum VA training effectiveness was obtained throught a combination of haptic-enabled VA training and high-complex assembly tasks. However, the learning process in virtual assembly is slower than the natural real assembly learning process, which suggests that learning and perception of reality is faster in real life than in virtual reality. An average time-scale factor of 17.7 between the virtual and the real TCT values was obtained but this very much depends on the VA system performance. Finally, haptic-enabled virtual assembly training is more realistic, interactive, intuitive and effective than virtual assembly training without haptic rendering.

Future work will consider the analysis of the effect of multi-rendering (graphics, haptics and audio) virtual assembly training on virtual and real assembly performance. The analysis will also consider different levels of immersion in the virtual assembly environment, e.g. the use of HMD for graphics rendering.

Acknowledgments

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