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ORIGINAL ARTICLE

# Assessment of virtual reality-based manufacturing assembly training system

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**Abstract**
Digital manufacturing concept is gaining a lot of attention and popularity due to its enormous benefits. It is considered as one of the pillars or component of Industry 4.0. With the advancements in technology, digital manufacturing is becoming a reality rather than a concept only. It is applied to various stages of the manufacturing process such as design, prototyping, and assembly training. Virtual reality (VR) is a cog in a wheel of digital manufacturing. It can be used in various phases of manufacturing. Planning and conducting assembly operations account for the majority of the cost of a product. It is difficult to design and train assembly operations during the early stages of product design. Assembly is a vital step in manufacturing, so firms provide training to their employees and it costs them time and money. Therefore, this research work extends VR applications in manufacturing by integrating concepts and studies from training simulations to the evaluation of assembly training effectiveness and transfer of training. VR provides a platform for "learning by doing" instead of learning by seeing, listening, or observing. A series of user-based evaluation studies are conducted to ensure that the virtual manufacturing assembly simulation provides an effective and efficient means for evaluating assembly operations and for training assembly personnel. Different feedback cues of VR are implemented to evaluate the system. Moreover, several case studies are used to assess the effectiveness of VR-based training. The results of the study reveal that participants trained by VR committed fewer errors and took lesser time in actual product assembly when compared against the participant from traditional or baseline training group.

**Keywords** Virtual Reality · Manufacturing assembly · Assembly training · Industry 4.0

## 1 Introduction

Manufacturing industries are moving towards smart, intelligent, and ingenious solutions to thrive in the market. Various technological advancements are applied through different stages and phases of manufacturing. Virtual reality (VR) is one of such solutions that has enormous applications and benefits in the manufacturing field. It can be applied to various phases of manufacturing successfully [1], such as design [2, 3], prototyping [4, 5], assembly [6–8], ergonomics analysis [9–11], and maintenance [12, 13].

Assembly operations are very crucial in sustainable manufacturing process. It has been calculated that assembly operations account for a significant amount of time and cost in the product development cycle [14]. To manufacture a product in a proficient manner, it is important to plan its assembly operations and provide proper training to the worker in the early stages [15]. Usually, two-dimensional (2D) drawings or expensive physical prototypes are used for assembly planning [16]. However, sequence planning becomes difficult as product complexity increases; therefore, computer-aided processes are implemented [1]. VR provides an efficient solution for assembly training [6]. It provides a risk-free digital environment with advanced input and output devices through which a user can interact intuitively with the digital components. It mitigates the gap between the physical and digital

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worlds. Moreover, the manufacturing industry is moving towards Industry 4.0 though in the assembly process [17, 18], and VR or its sister technology augmented reality (AR) is considered as one of the components. Therefore, there have been quite a lot of prominent contributions in the development of VR-based systems for assembly operations [6, 7, 19–23].

Several comprehensive reviews are available for virtual assembly simulations [24–26]. Virtual assembly (VA) has been defined by many researchers according to their own uses and understanding. Jayaram et al. [7] defined VA as:

"the use of computer tools to make or "assist with" assembly-related engineering decisions through analysis, predictive models, visualization, and presentation of data without physical realization of the product or supporting processes."

Seth et al. [24] explained VA as:

"the capability to assemble virtual representations of physical models through simulating realistic environment behavior and part interaction to reduce the need for physical assembly prototyping resulting in the ability to make more encompassing design/assembly decisions in an immersive computer-generated environment."

Recently, Xia et al. [27] presented a more broad definition of VA as:

"VA is defined as utilizing VR technology, computer graphics, artificial intelligence, assembly theory and method, to construct the virtual model of the product and the virtual environment of the assembly layout, and then interactively analyze and simulate the product design result and assembly operation process."

Based on the definitions, one can easily understand that the principal idea of VA is to develop a digital environment that accurately depicts the real one, where product models can be imported and assembled with the help of advanced hardware and software systems that help in intuitive interactions. Real-time human-machine interface methods can be implemented; users can manipulate components and perform assembly activities by interacting through gesture, vocal sound, force, and so on; meanwhile, reactions and alterations in the VE can be offered to users visually, acoustically, and, most importantly, through force feedback. The whole assembly operation is simulated and recorded in the immersive, high-fidelity, real-time-interacting virtual environment (VE) without having to build a physical prototype [26]. Im et al. [28] developed a VR-based training system for students for engine assembly and disassembly. Nash et al. [29] developed a VR-based simulator to dismantle a research reactor assembly using master-slave manipulators. Jiang et al. [30] developed a virtual training system with the objective of making assembly training easy and convincing through the usage of haptics and visual fidelity. Berg and Vance presented the contemporary situation of VR usage as a tool for decision in product design, particularly in engineering-focused businesses [25]. They visited several industries to see VR utilization in various domains. It was mentioned that VR has been extensively used especially in the automotive sector, and a few companies that are using this technology are Ford, General Motors, Rock Island Arsenal, Case New Holland, and Caterpillar. So, all these are real-world examples of the industrial use of VR.

An enormous amount of research has been conducted in the field of application of VR in manufacturing; however, the focus mainly is on applications and systems development. Most research works concentrate on using VR to design new products and to plan for assembly. Meager attention has been paid on developing VR systems that contribute to train operators on assembly operations and to bridge the gap between design and realization/accomplishment of assembly activities. Still, the manufacturing industry does not utilize VR to its potential with regard to assembly training. Even though this emergent technology is not fully implemented in terms of its applications within commercial industries, the technology as a whole, however, is seen as feasible and profitable. There are various challenges linked with the development of appropriate VEs for manufacturing assembly simulation. Some of them are data translation produced by computer-aided design (CAD) systems, modeling the physical behavior and constraints of objects, collision detection, advanced hardware peripherals, and software platforms integration, and in a few times, inadequate field of view make digital environment unrealistic to users. Therefore, most of the research work focusses on these issues, and less consideration has been given to the assessment of these systems in terms of training transfer. Kozak et al. [31] evaluated the transfer of training using VR in 1993 when the technology was in the embryonic stage. That is why the results revealed that there was no significant difference between the VR training group and the group that received no training on the task. However, a recent study compared the effect of VR-based training with the traditional method and reported that VR-based training was more effective [32]. Hence, it is necessary to evaluate the VR-based assembly training systems. Therefore, this research work extends VR applications in manufacturing by integrating concepts and studies from training simulations to the evaluation of assembly training effectiveness and transfer of training. System development and training transfer assessment methodology is presented in the subsequent sections.

## 2 System Development

In the first phase of the research work, a fully functional virtual manufacturing assembly simulation system (VMASS) was developed. The detailed procedures and capabilities of the system are explained in [6]. The developed system is based on three modules: Product Data Management System (PDMS), Product Data Conversion System (PDCS), and Virtual Manufacturing Assembly Simulation System (VMASS). Figure 1 illustrates the relationships between these three modules.

The description of VMASS hardware system is explained in detail in [6].

Figure 2 shows the various hardware peripheral of VMASS system used in this study.

The system is contingent on a set of software that is involved in various phases, and details are reported in [6]. Figure 3 depicts the software architecture of the developed system.

Therefore, a semi-immersive VR-based manufacturing assembly training system is developed. It gives a user sense of presence in the digital environment. Figure 4 shows the graphical user interface of VMASS.

The manner in which information is perceived and acted upon accordingly mainly depends on the interaction tools/system. In this work, the following tools were used for interacting with the virtual world: hand wand (an ultrasonic-based tracking device), head tracker, stereoscopic active glasses, and screen. Hand wand tracks the user's hand position in real time. A virtual hand depicts the user's hand position, and a user can pick and move the components with this virtual hand in the digital environment. With the help of the head tracker that was attached to the stereoscopic glasses, the scene view changes according to user's view. Active stereoscopic glasses and screen were used to generate 3D images for the user.

## 3 Assessment of VMASS

In the second phase of the research, the developed VR-based manufacturing assembly training system was assessed using user-based studies with different feedback mechanisms. In this research, the developed VMASS system was used for training assembly operations on the selected case studies. Design of experiments techniques were used to conduct a series of user-based studies to evaluate the different types of feedback on assembly task performance in terms of time and accuracy. Since the assemblies used in the case studies were simple, and the focus was on various VR conditions, the authors opted to focus on assembly completion time as a key performance measure. Most of the researchers used subjective measures and questionnaires only to evaluate this kind of system [33–35]. However, there are only few studies that consider objective factors; in that, also the completion time is considered as the most important factor, and the other factors such as error rate [36, 37]. Subjective questionnaires were also used; however, analyses based on that are not included in this research work. Transfer of training evaluation was conducted to determine the effect of different types of training feedback on real-world task performance [38, 39]. Figure 5 illustrates the concepts associated with assembly training system evaluation.

**Table 1** Training completion time in trial-1 with various feedback conditions

| Participant | VR1 | VR2 | VR3 | VR4 |
|---|---|---|---|---|
| 1 | 8.20 | 13.54 | 15.00 | 14.29 |
| 2 | 9.59 | 10.67 | 11.12 | 11.18 |
| 3 | 8.73 | 9.42 | 9.57 | 9.50 |
| 4 | 9.52 | 15.00 | 11.23 | 10.34 |
| 5 | 4.34 | 12.48 | 15.00 | 13.24 |

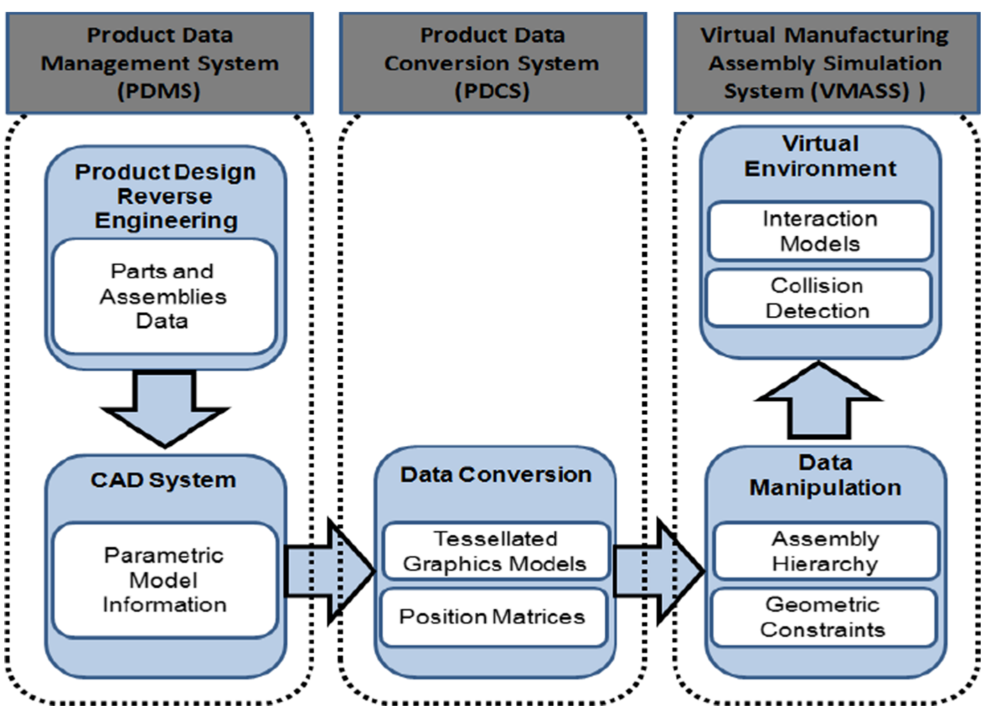



**Fig. 1** Relationship between PDMS, PDCS, and VMASS (adapted from [6])

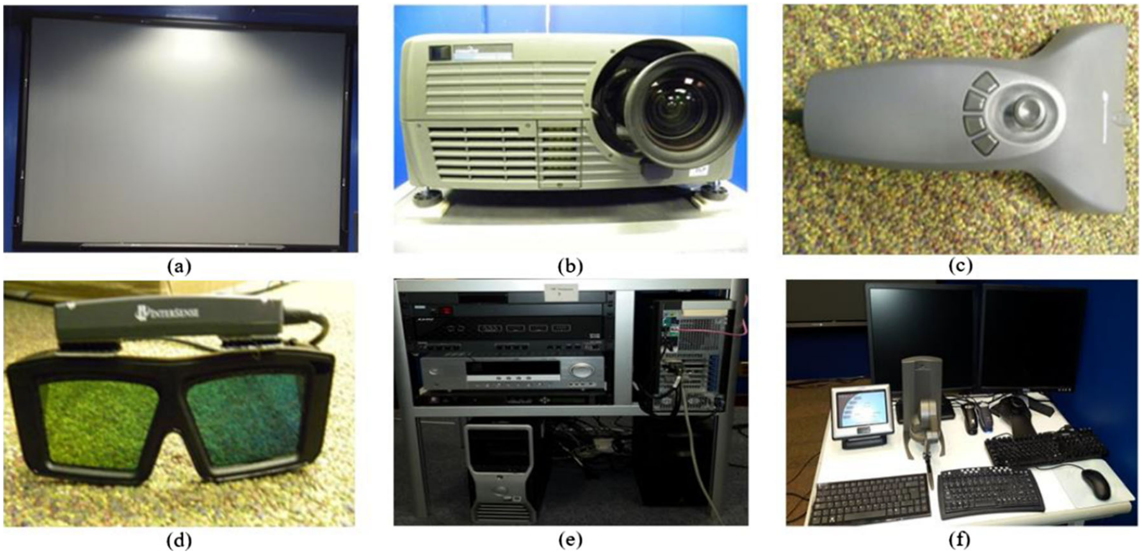



**Fig. 2** Hardware peripherals. **a** Screen. **b** Rear projector. **c** Hand wand. **d** Shutter glasses with head tracker. **e** VR hardware controller with workstations. **f** AMX Controller with space mouse and space ball

For each selected case study, a user-based evaluation of the virtual assembly was carried out. Each evaluation experiment consists of a pre-test, post-test, and three training trials. In addition, transfer of training was evaluated by asking the users to complete the assembly task using original/fabricated parts. The pre- and post-test session trials did not contain feedback cues. The three training trials contained feedback cues (visual, auditory, or combined). The feedback cues were designed to support an event-based approach to learning [40, 41]. The study utilized within-subject design with a single between-subject factor (i.e., type of feedback). The performance measure used was time to complete the assembly task. Training effectiveness was assessed using performance on the pre-test as a baseline. Both feedback cueing effects on task performance (comparing last training to the pre-test) and near-term transfer of skills (comparing post-test with pre-test) were evaluated [42].

## 3.1 Selection of case studies

To assess the VMASS, case studies were selected in such a way that they can be assembled manually, could be easily available or fabricated, and could be assembled in a reasonable time. The CAD models were developed in CATIA and SolidWorks. Three case studies were selected for performing the user-based analysis and evaluation of the developed VMASS. The selected case studies were:

1. Street scooter assembly
2. Adjustable mid-bearing assembly
3. Multi-function cart assembly

1. Street scooter

   Street scooter is used by children for fun riding. It consists of 16 unique components and 25 parts in total. Figure 6 shows the CAD model and exploded view of a street scooter.

2. Adjustable mid-bearing

   Bearings represent a very important and widely used class of mechanical component. Therefore, an adjustable mid-bearing was selected as a manufacturing assembly case study. It consists of 8 unique components and a total number of 13 parts. The CAD model and exploded view of the bearing is shown in Fig. 7.

3. Multi-function cart

   A multi-function cart can be used for different purposes. It consists of 14 unique components and a total number of 35 parts. Figure 8 shows the CAD model and exploded view of the multi-function cart.

**Table 2:** Training completion time in trial 3 with various feedback conditions

| Participant | VR1 | VR2 | VR3 | VR4 |
|---|---|---|---|---|
| 1 | 6.44 | 9.59 | 13.54 | 12.04 |
| 2 | 6.50 | 7.50 | 8.08 | 5.56 |
| 3 | 6.20 | 6.24 | 5.32 | 7.03 |
| 4 | 12.09 | 12.44 | 5.02 | 5.10 |
| 5 | 4.00 | 5.29 | 8.00 | 8.38 |

## 3.2 Experimental Protocol

To achieve a consistent test experience for participants, each experimenter followed the steps written in a document when administering a testing session.

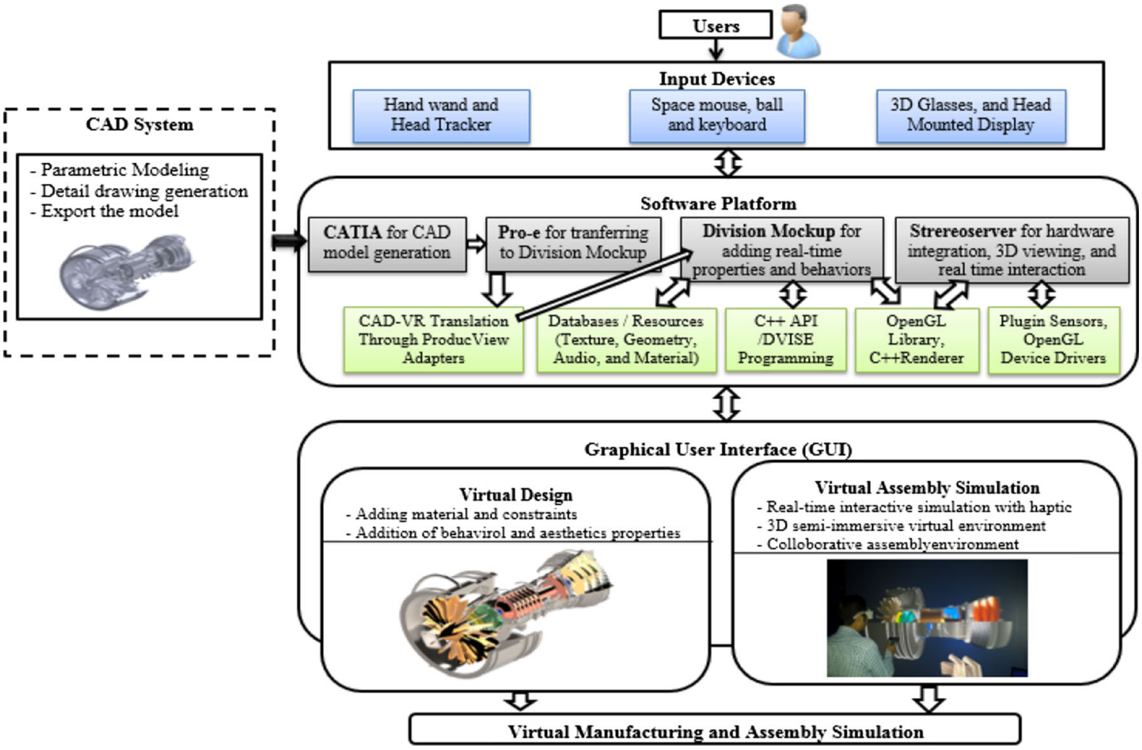



**Fig. 3** Software architecture of the developed system

### 3.2.1 Experiment objective

The objective of this experiment is to evaluate the effect of using VR and the effect of different feedback mechanisms within VR on the performance of manual assembly training transfer.

### 3.2.2 Experiment

Each testing session will take about 2 h—including time for completing questionnaires, training, and performing the actual assembly task. Participants will be randomly assigned to one of five training groups. Group 1 will receive training with the help of paper-based drawings and PPTs. Groups 2, 3, 4 will receive general VR familiarization. Each VR training session consisted of a familiarization scenario for being acquainted with the system followed by four training scenarios. The four feedback mechanism scenarios within VR are with no feedback, audio feedback, visual feedback, and audio-visual feedback.

**Table 3:** Training completion time in pre-test with various feedback conditions

| Participant | VR1 | VR2 | VR3 | VR4 |
|---|---|---|---|---|
| 1 | 7.26 | 15.0 | 15.00 | 15.00 |
| 2 | 13.14 | 14.4 | 15.00 | 14.28 |
| 3 | 15.00 | 15.0 | 15.00 | 15.00 |
| 4 | 15.00 | 15.0 | 8.54 | 7.32 |
| 5 | 7.03 | 15.0 | 15.00 | 15.00 |

### 3.2.3 Experimental task

A randomization sheet gives the assignment of participants to (1) traditional training (baseline training); (2) virtual reality with no feedback; (3) virtual reality with audio feedback; (4) virtual reality with visual feedback; and (5) audio-visual feedback. Then, the experiment's steps were followed based on the group assigned. Objective measures were recorded during different sessions by the experimenter and the subjective measures were recorded with the help of questionnaires. The following scenarios were compared for each case study:

1. Baseline training
2. VR training (with no feedback) [VR1]
3. VR training (with visual feedback) [VR2]
4. VR training (with audio feedback) [VR3]
5. VR training (with audio-visual feedback) [VR4]

Hypothesis testing was performed to evaluate the various aspects and conditions of the developed system. The following hypotheses were evaluated for each case study:

- Hypothesis 1: The mean training completion time in trial-1 is same for all conditions


**Fig. 4** VMASS graphical user interface (adapted from [6])

- Hypothesis 2: The mean training completion time in trial-3 is same for all conditions
- Hypothesis 3: The mean training completion time in pre-test is the same for all conditions
- Hypothesis 4: The mean training completion time in post-test is the same for all conditions
- Hypothesis 5: The mean completion time for actual assembly for VR1 is same as Baseline
- Hypothesis 6: The mean completion time for actual assembly for VR2 is same as Baseline
- Hypothesis 7: The mean completion time for actual assembly for VR3 is same as Baseline
- Hypothesis 8: The mean completion time for actual assembly for VR4 is same as Baseline
- Hypothesis 9: The mean completion time for actual assembly is the same for all training condition groups
- Hypothesis 10: The mean number of error for actual assembly is the same for all training condition groups

**Table 4:** Training completion time in post-test with various feedback conditions

| Participant | VR1 | VR2 | VR3 | VR4 |
|---|---|---|---|---|
| 1 | 4.45 | 6.06 | 8.5 | 10.53 |
| 2 | 6.41 | 8 | 6.41 | 4.14 |
| 3 | 5.19 | 11.08 | 5.34 | 10.27 |
| 4 | 8.55 | 6.26 | 4.32 | 4.02 |
| 5 | 5 | 7.24 | 10 | 6.54 |

### 3.3 Participants

For each case study, 25 participants were recruited from King Saud University. Therefore, for three case studies, a total of 75 participants were selected. The sample was composed of students and employees from various departments of King Saud University. Participants were randomly assigned to different training condition groups. Each training group comprised of five participants. All the participants completed the training procedure and the actual assembly task. None of the participants had the experience of assembling the case study product that had been assigned to them. The participants were

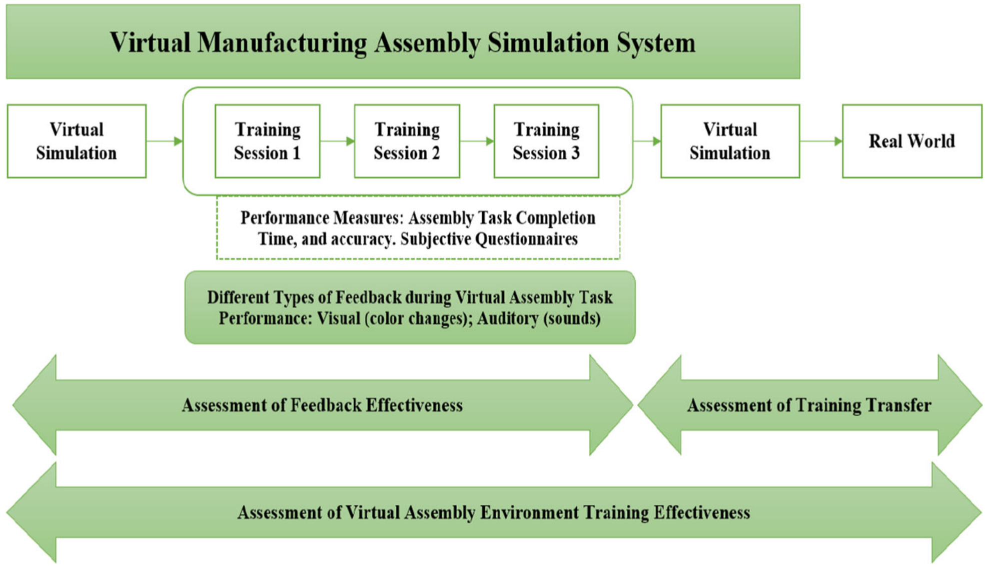



**Fig. 5** Virtual manufacturing assembly training system assessment

randomly assigned to different experimental groups: baseline, VR1, VR2, and VR3.

### 3.4 Apparatus

For the baseline group, the CAD drawings and 3D model printouts on the standard A-4-size paper were used for training. For VR groups, the apparatus used is explained in detail in Section 2. It consists of a semi-immersive multi-interactive VR system.

### 3.5 Procedure

The procedure is followed as defined in Section 3.2. For baseline training, the participants were trained using conventional CAD models and drawings, while the VR groups with different feedback mechanisms were trained using VMASS. The VR-based training followed the principal of "learning by doing." The product components lie on the table in the same way in the virtual environment, as the participant will get in the actual assembly process. However, haptic or force feedback is not available in the virtual environment, so the user has to rely on his visual capabilities only, since in the real world, the force feedback plays an important role while doing assembly. Hence, different colors were assigned to the components in the virtual environment to make it easier for the user to recognize the limits while doing the assembly. Then, the participant performs the virtual assembly with the help of a virtual hand that is controlled by the hand wand tracking system. Even the scene view changes according to the view of the user with the help of the head tracker. Images below show the participants performing various tasks in the training process for different case studies. If the feedback mechanism is applied to the assigned group, then, with the help of the collision detection feature, the assigned feedback is generated such as audio, visual (color changes for the component), or audio-visual if the interference occurs between two components.

**Table 5:** Mean completion time for actual assembly for baseline and VR1

| Participant | Baseline | VR1 |
|---|---|---|
| 1 | 16.05 | 5.1 |
| 2 | 15.21 | 7.08 |
| 3 | 14.27 | 3.5 |
| 4 | 10.55 | 6.54 |
| 5 | 16 | 4 |

#### 3.5.1 Case study 1 (street scooter)

Figure 9 shows a participant performing assembly in the virtual environment.

Figure 10 shows the disassembled components of the case study 1 in the real world.

Figure 11 shows a participant performing assembly in the real world for case study 1, and Figure 12 shows an assembled product in the real world.

#### 3.5.2 Case study 2 (adjustable mid-bearing)

Figure 13a shows a participant performing assembly in the virtual environment, and Fig. 13b shows the disassembled components of case study 2 in the real world.

#### 3.5.3 Case study 3 (multi-function cart)

Figure 14a shows a participant performing assembly in the virtual environment, and Fig. 14b shows the disassembled components of case study3 in the real world. Figure 15a

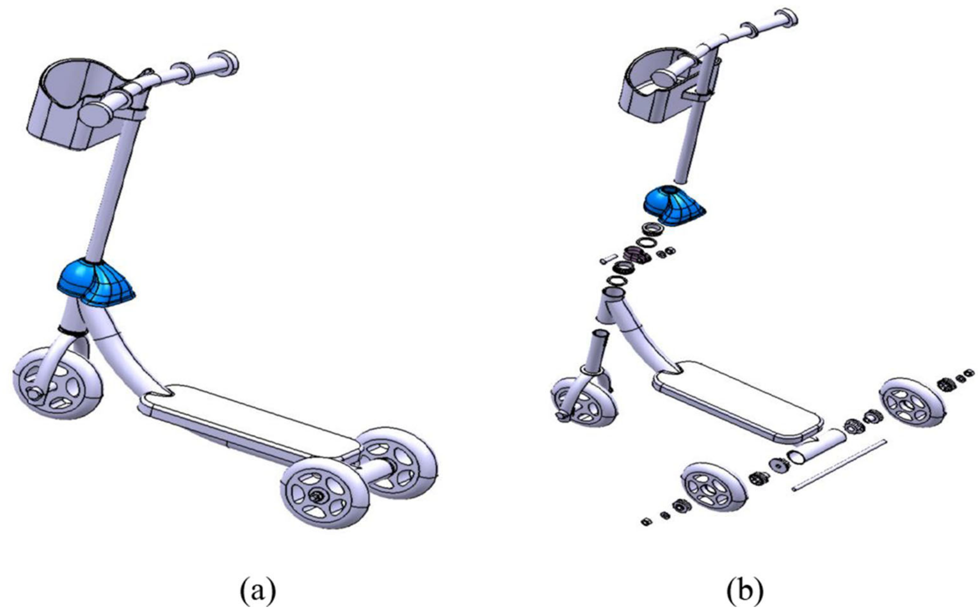



**Fig. 6** **a** CAD model of a street scooter. **b** Exploded view

shows a participant performing assembly in the real world for case study 3, and Fig. 15b shows the assembled actual product.

## 3.6 Analysis and results

Descriptive statistics, ANOVA (analysis of variance), and *t* test analysis are used to (1) analyze and compare participants' characteristics of the three groups; (2) assess their acquisition of the competence during and after the training, (3) differences in training times, and (4) differences in learning of the training task; and (5) analyze the differences between the post-training performances of the different groups.

### 3.6.1 Analysis of case study 1 (street scooter) data

**Descriptive statistics for training time** The mean of the training time for the baseline group was 2.5 min, for VR1 was 8.01 min, for VR2 was 13.06 min, for VR3 was 13.44 min, and for VR was 14.05 min. Based on the descriptive test analysis of training time data, it can be said that training time for VR-based group is more when compared against baseline group.

**Table 6:** Mean completion time for actual assembly for baseline and VR2

| Participant | Baseline | VR2 |
|---|---|---|
| 1 | 16.05 | 4.42 |
| 2 | 15.21 | 3.06 |
| 3 | 14.27 | 2.42 |
| 4 | 10.55 | 1.48 |
| 5 | 16.00 | 9.00 |

### 3.6.2 Hypothesis testing between various conditions and trials

- Hypothesis Testing 1:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean training completion time in trial 1 is the same for all conditions |
| Alternative Hypothesis ($H_1$) | At least one mean is different |

Table 1 shows the training completion time in trial-1 with various feedback conditions. One-way ANOVA was performed to test the stated hypothesis, and Tukey's comparison was made. Based on ANOVA, it can be seen that *p* value (=0.023) is less than 0.05. Therefore, we have to reject the null hypothesis. It means that at least one mean is different. The box plot (Fig. 16) depicts that in trial 1, the mean completion time for the no-feedback condition is significantly different from the other three training conditions. The same fact is verified by Tukey's test (Fig. 17) that VR1 trial 1 completion time is significantly different from VR2, VR3, and VR4; however, there is no significant difference in trial 1 completion time among these three training conditions. Therefore, it suggests that with no feedback, the training time is less when compared against other environments with feedbacks.

- Hypothesis Testing 2:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean training completion time in trial 3 is the same for all conditions |
| Alternative Hypothesis ($H_1$) | At least one mean is different |

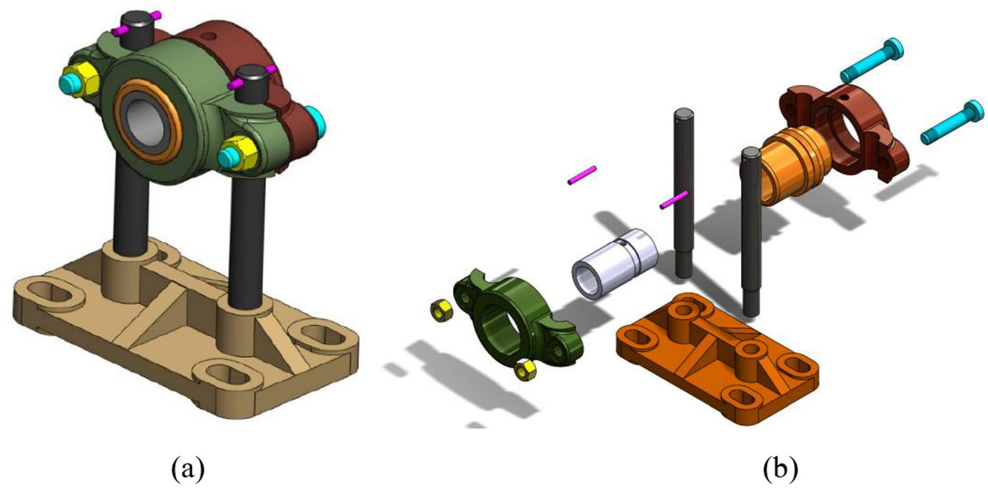



**Fig. 7** **a** CAD model of adjustable mid-bearing. **b** Exploded view

Table 2 shows the training completion time in trial-3 with various feedback conditions. One-Way ANOVA was performed to test the stated hypothesis, and Tukey's comparison was made. Based on ANOVA, it can be seen that *p* value (=0.933) is much greater than 0.05. Therefore, we cannot reject the Null hypothesis. It means that all means are equal. The box plot (Fig. 18) depicts that in trial 3, the mean completion time for the no-feedback condition is different from the other three training conditions; however, the difference is not significant. The same fact is verified by Tukey's test that VR1 trial 3 completion time is different from VR2, VR3, and VR4; however, this difference is not significant among all four training conditions. Once again, it was revealed that training time with no feedback condition is lesser than other environments with feedback even with the third trial.

**Table 7:** Mean completion time for actual assembly for baseline and VR3

| Participant | Baseline | VR3 |
|---|---|---|
| 1 | 16.05 | 5.39 |
| 2 | 15.21 | 3.36 |
| 3 | 14.27 | 9.27 |
| 4 | 10.55 | 5.00 |
| 5 | 16.00 | 5.43 |

- Hypothesis Testing 3:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean training completion time in the pre-test is the same for all conditions |
| Alternative Hypothesis ($H_1$) | At least one mean is different |

Table 3 shows the training completion time in Pre-test with various feedback conditions. Again, one-Way ANOVA was performed to test the stated hypothesis, and Tukey's

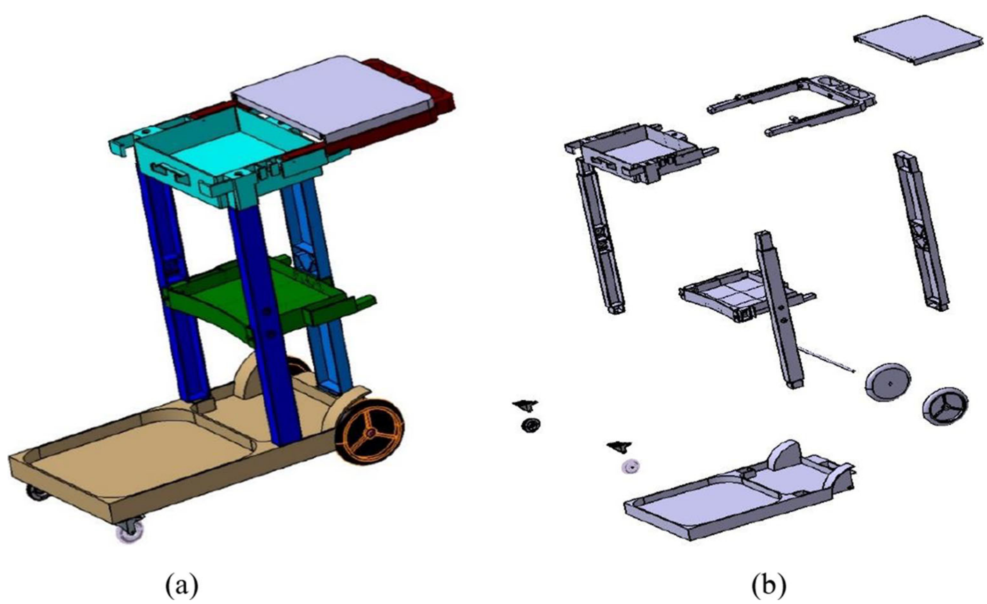



**Fig. 8** **a** CAD model of a multi-function cart. **b** Exploded view

**Table 8:** Mean completion time for actual assembly for baseline and VR4

| Participant | Baseline | VR4 |
|---|---|---|
| 1 | 16.05 | 9.40 |
| 2 | 15.21 | 3.14 |
| 3 | 14.27 | 5.47 |
| 4 | 10.55 | 2.25 |
| 5 | 16.00 | 4.33 |

comparison was made. Based on ANOVA, it can be seen that $p$ value (=0.108) is greater than 0.05. Therefore, we cannot reject the Null hypothesis. It means that all means are equal.

Box plot and Tukey's test graphs were made for each hypothesis, but to keep the manuscript concise, they are not included in each hypothesis, though conclusions based on that are included in each section.

The box plot depicts that in the pre-test, the mean completion time for different training conditions are not different significantly. The same fact is verified by Tukey's test, that mean pre-test completion time is not different among VR1, VR2, VR3, and VR4. The maximum time allotted per trial was 15 min. Therefore, it can be seen from the data that during the pre-test, since the participants were not experienced, many of them took the maximum allotted time and hence unable to complete the assembly. Therefore, percentage completion was also recorded for the participants.

- Hypothesis Testing 4:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean training completion time in post-test is the same for all conditions |
| Alternative Hypothesis ($H_1$) | At least one mean is different |

Table 4 shows the training completion time in Post-test with various feedback conditions. A similar analysis was performed, and based on ANOVA, it can be seen that $p$ value (=0.685) is much greater than 0.05. Therefore, we cannot

**Table 9:** Training completion time in actual assembly with various feedback conditions

| Participant | Baseline | VR1 | VR2 | VR3 | VR4 |
|---|---|---|---|---|---|
| 1 | 16.05 | 5.10 | 4.42 | 5.39 | 9.40 |
| 2 | 15.21 | 7.08 | 3.06 | 3.36 | 3.14 |
| 3 | 14.27 | 3.50 | 2.42 | 9.27 | 5.47 |
| 4 | 10.55 | 6.54 | 1.48 | 5.00 | 2.25 |
| 5 | 16.00 | 4.00 | 9.00 | 5.43 | 4.33 |

reject the Null hypothesis. It means that all means are equal. The box plot depicts that in the post-test, mean completion time for different training conditions, are almost equal. The same fact is verified by Tukey's test that the mean post-test completion time is not different among VR1, VR2, VR3, and VR4. Moreover, the completion time is much lower than the maximum allotted time, and the percentage completion is therefore 100% in the post-test trial. Therefore, it can be said that with more trials, the participants gain good knowledge and the effect of feedback mechanism on time was reduced.

- Hypothesis Testing 5:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean completion time for actual assembly for VR1 is same as Baseline |
| Alternative Hypothesis ($H_1$) | The mean completion time for actual assembly is not equal for VR1 and Baseline |

Table 5 shows the mean completion time for actual assembly for baseline and VR1. Two-sample $t$ test was performed to test the hypothesis. Based on the two-sample $t$ test, it can be seen that $p$ value (=0.000) is much lower than 0.05. Therefore, we have to reject the Null hypothesis. It means that all completion time for actual assembly is significantly different in case of Baseline group and VR1 group. The box plot (Fig.

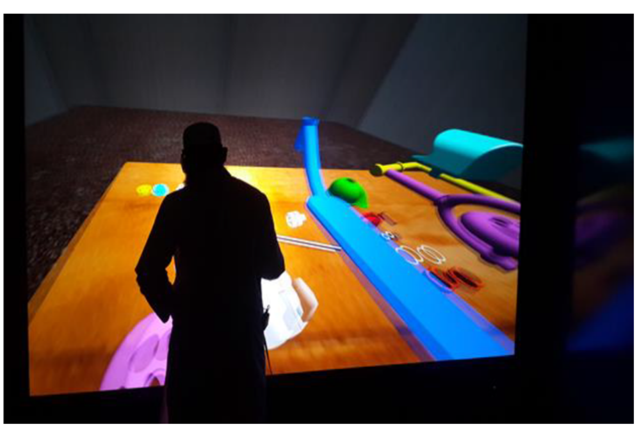


**Fig. 9** A participant going through VR-based training for case study 1

**Fig. 10** Disassembled components of case study 1

**Table 10:** Number of errors done in Actual Assembly by participants from various feedback conditions

| Participant | Baseline | VR1 | VR2 | VR3 | VR4 |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 0 | 1 |
| 2 | 3 | 0 | 1 | 1 | 0 |
| 3 | 1 | 0 | 0 | 1 | 0 |
| 4 | 5 | 1 | 0 | 0 | 0 |
| 5 | 1 | 0 | 2 | 0 | 0 |

19) also depicts that the same that the means are significantly different for the actual assembly completion time of the baseline and the VR1 groups. Therefore, it can be concluded that VR-based training methods are competent and are somewhat more efficient than the traditional one.

- Hypothesis Testing 6:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean completion time for actual assembly for VR2 is same as Baseline |
| Alternative Hypothesis ($H_1$) | The mean completion time for actual assembly is not equal for VR2 and Baseline |

Table 6 shows the mean completion time for actual assembly for baseline and VR2. Two-sample *t* test was performed to test the hypothesis. Based on the two-sample *t* test, it can be seen that *p* value (=0.000) is much lower than 0.05. Therefore, we have to reject the Null hypothesis. It means that all completion time for actual assembly is significantly different in case of baseline group and VR2 group. The box plot also depicts that the means are significantly different for the actual assembly completion time of the baseline and the VR2 groups. Therefore, it can be concluded that VR-based training

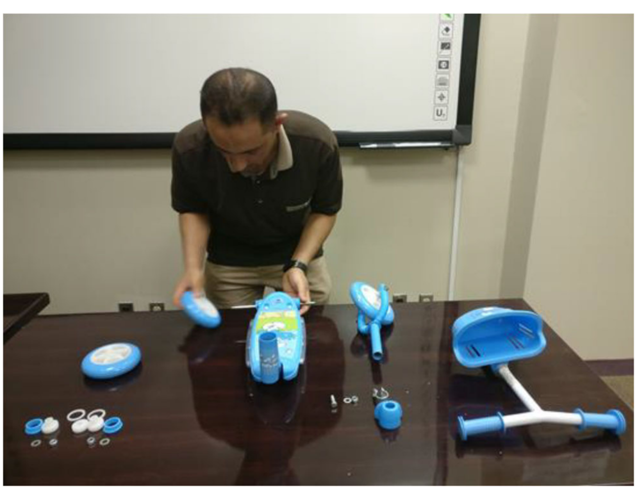


**Fig. 11** A participant performing the actual assembly in case study 1

**Fig. 12** Assembled actual product in case study 1

method with feedback mechanism are competent and are somewhat more efficient than the traditional one.

- Hypothesis Testing 7:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean completion time for actual assembly for VR3 is same as Baseline |
| Alternative Hypothesis ($H_1$) | The mean completion time for actual assembly is not equal for VR3 and Baseline |

Table 7 shows the mean completion time for actual assembly for baseline and VR3. Two-sample *t* test was performed to test the hypothesis. Based on the two-sample *t* test, it can be seen that *p* value (=0.000) is lower than 0.05. Therefore, we have to reject the Null hypothesis. It means that all completion time for actual assembly is significantly different in the case of the baseline group and the VR3 group. The box plot also depicts that the means are significantly different for the actual assembly completion time of the baseline and the VR3 group. Therefore, it can be concluded that the VR-based training method with feedback mechanism are competent and are somewhat more efficient than the traditional one.

- Hypothesis Testing 8:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean completion time for actual assembly for VR4 is same as Baseline |
| Alternative Hypothesis ($H_1$) | The mean completion time for actual assembly is not equal for VR4 and Baseline |

Table 8 shows the mean completion time for actual assembly for baseline and VR4. Two-sample *t* test was performed to test the hypothesis. Based on the two-sample *t* test, it can be seen that *p* value (=0.001) is much lower than 0.05. Therefore,

(a) (b)

**Fig. 13** **a** Participant going through VR-based training for case study 2. **b** Disassembled fabricated model of adjustable mid-bearing used for actual assembly

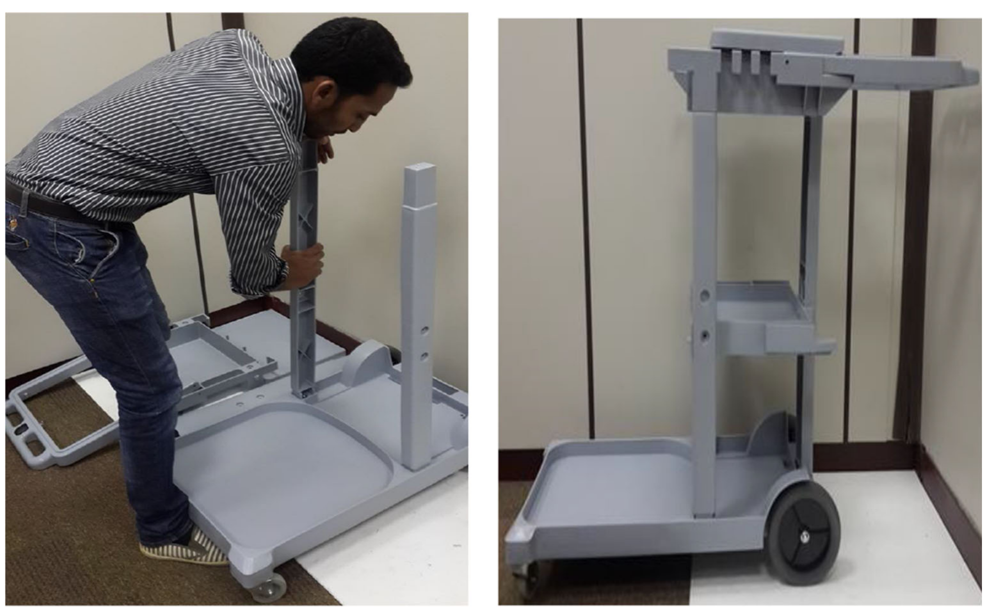
we have to reject the Null hypothesis. It means that all completion time for actual assembly is significantly different in the case of Baseline group and VR4 group. The box plot also depicts that the means are significantly different for the actual assembly completion time of the baseline and the VR4 groups. Therefore, it can be concluded that the VR-based training method with multi-modal feedback mechanism is competent and is somewhat more efficient than the traditional one.

- Hypothesis Testing 9:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean completion time for actual assembly is the same for all training condition groups |
| Alternative Hypothesis ($H_1$) | At least one mean is different |

(a) (b)

**Fig. 14** **a** A participant going through VR-based training for case study 3. **b** Disassembled components of case study 3



(a) (b)

**Fig. 15** ***a*** A participant performing the actual assembly in case study 3. ***b*** The assembled actual product in case study 3

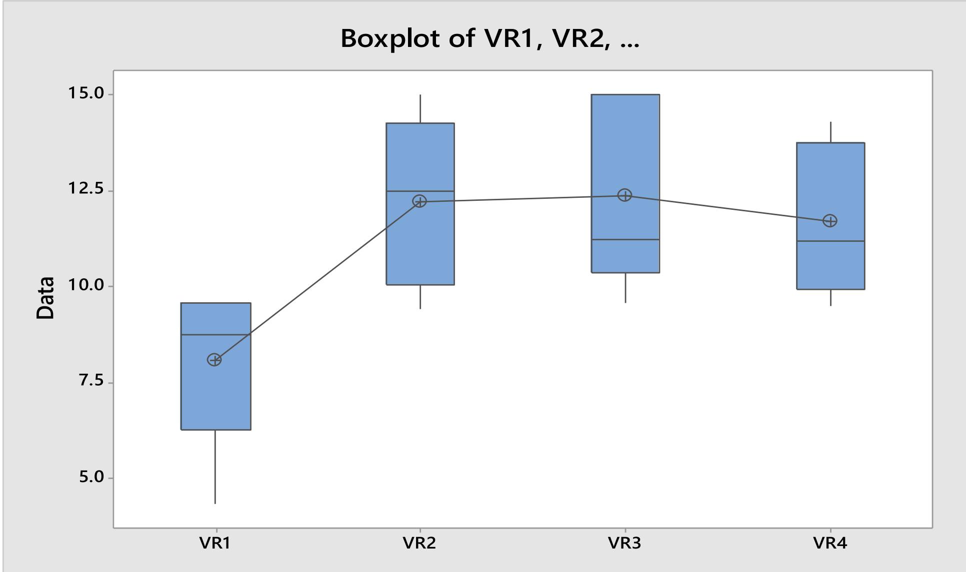



**Fig. 16** Box plot for completion time for trial 1 of different training conditions

Table 9 shows the training completion time in actual Assembly with various feedback conditions. One-Way ANOVA was performed to test the stated hypothesis, and Tukey's comparison was made. Based on ANOVA, it can be seen that $p$ value (=0.000) is much lower than 0.05. Therefore, we have to reject the Null hypothesis. It means that all means are not equal. The box plot (Fig. 20) and Tukey's test depicts that the actual assembly time of the baseline group is significantly different with all VR groups. However, the actual assembly completion time for different VR feedback groups is not significantly different. This shows that VR-based training methods are more effective than traditional ones.

- Hypothesis Testing 10:

| | |
|---|---|
| Null Hypothesis ($H_0$) | The mean number of error for actual assembly is the same for all training condition groups |
| Alternative Hypothesis ($H_1$) | At least one mean is different |

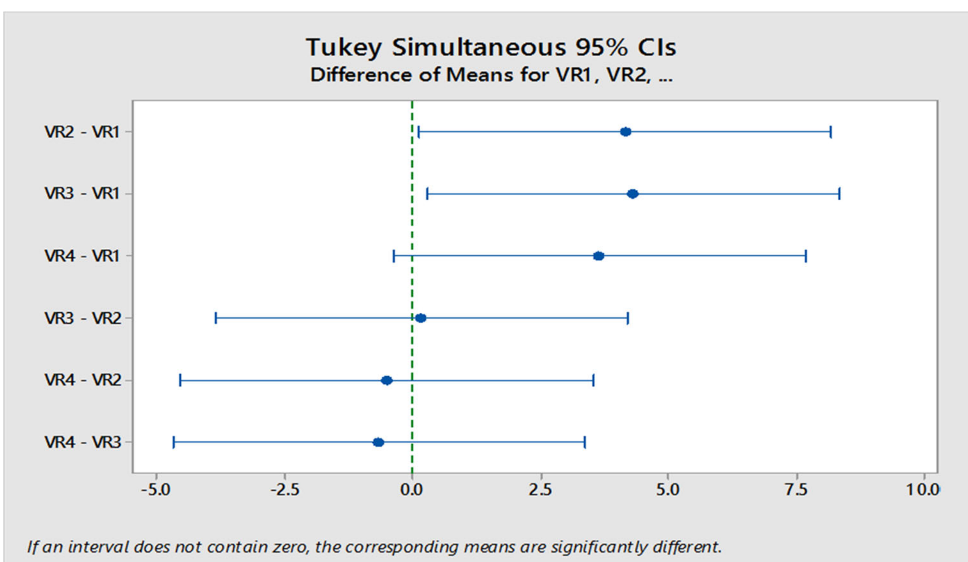



**Fig. 17** Tukey's pair-wise comparison for trial 1 completion time for different training conditions

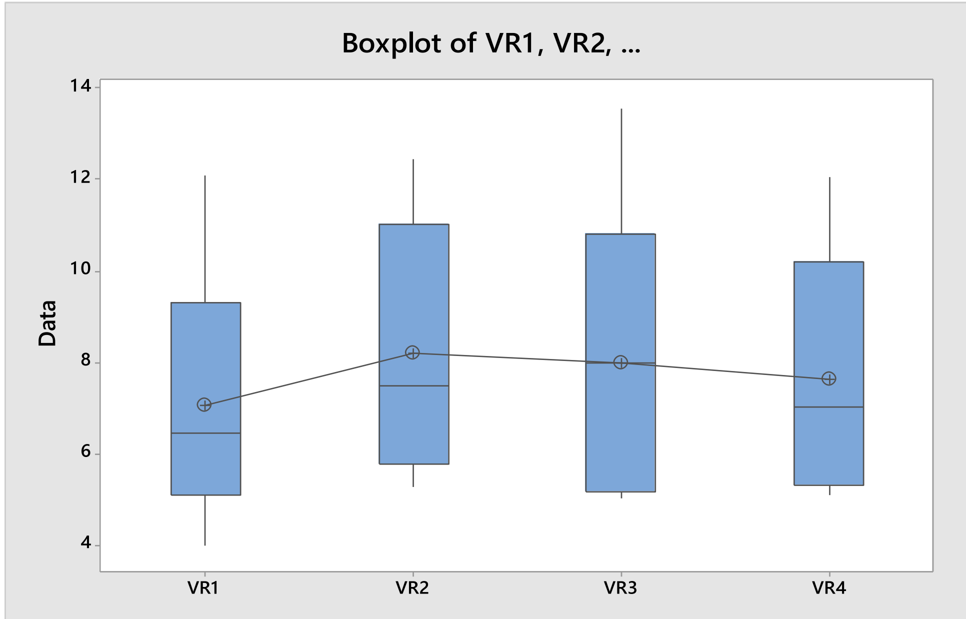



**Fig. 18** Box plot for completion time for trial 3 of different training conditions

Table 10 shows the number of errors done in actual assembly by participants from various feedback conditions. One-Way ANOVA was performed to test the stated hypothesis, and Tukey's comparison was made. Based on ANOVA, it can be seen that $p$ value (=0.026) is lower than 0.05. Therefore, we have to reject the Null hypothesis. It means that all means are not equal. Interval plot also depicts that the errors done while doing the actual assembly for the baseline group is significantly higher than those of all VR groups. However, Tukey's test does not indicate significant difference and may be the reason that the data is discrete.

- Percentage completion:

Since the first case study is simple as compared to this one, therefore, percentage completion of assembly was 100% in all cases. However, in this case study, during the pre-test, many participants were unable to complete the assembly in the allotted time (15 min). Therefore, a comparison of percentage completion is made between pre-test and post-test performance of the participants with respect to percentage comparison. Figure 21 shows the graphical comparison.

It can be seen from the above graph, that in pre-test many participants were unable to complete the assembly fully; however, in the post-test, all the participants completed the assembly within the allotted time.

A similar analysis was performed for other two case studies and conclusions are made based on all the results and analysis.

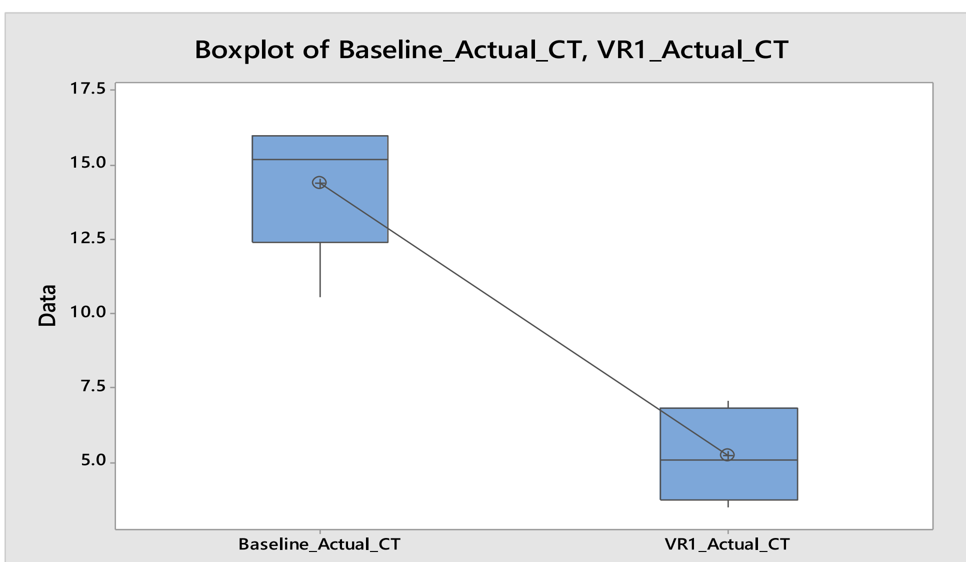



**Fig. 19** Box plot of the actual assembly completion time for baseline and VR1 group

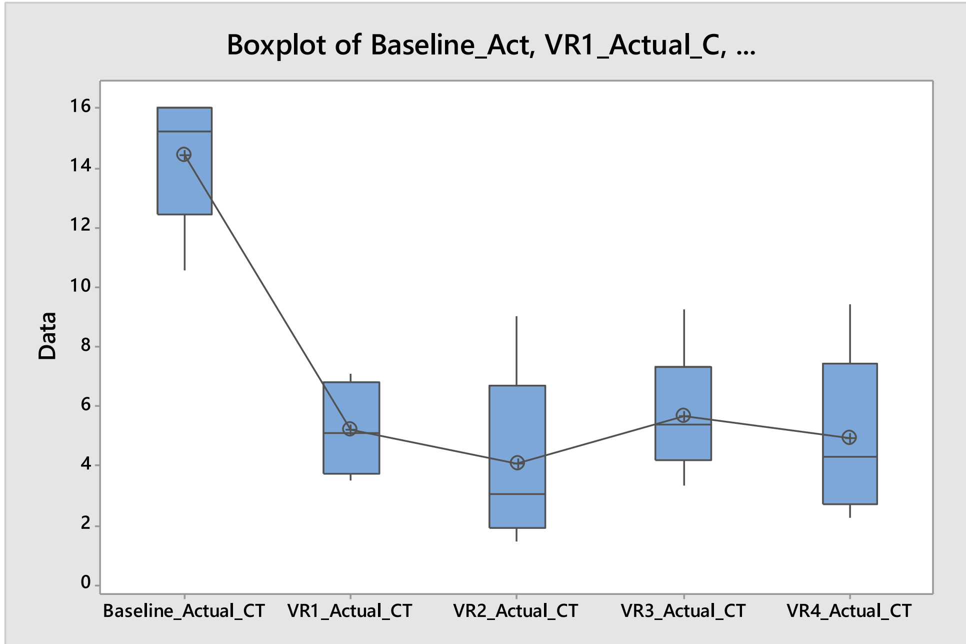



**Fig. 20** Box-plot for actual assembly completion time for various training groups

## 4 Discussion and conclusions

Several benefits of VR are mentioned by researchers for manual assembly training such as CAD models can be transferred into a virtual environment which gives a feeling of real environment instead of making physical parts which saves time; user can practice as many time as he likes in VR environment without worrying about any component failure of breakage; there is less dependency on physical trainer, since digital instructions can guide the trainee; and there is no risk involved in the assembly training of delicate parts or components [24, 25, 29, 35, 36]. Similar benefits were realized in this research work.

User-based studies were conducted to test the effectiveness and functionality of the virtual training system. This work presents a VR-based training system with the objective to make the assembly training easy and realistic through the usage of multi-modal input and output. The effect of multi-modal feedback mechanism on the performance of the users was evaluated successfully. Based on the observation, it can be said that interaction devices are key to achieve a high level of immersion, as they allow a more natural interaction with the system, and thus, skills can be transferred more appropriately.

The following conclusions are made based on the user study of the VMASS:

- Participants trained by VMASS committed fewer errors and took lesser time in actual product assembly when compared against the participant from traditional or baseline training group.

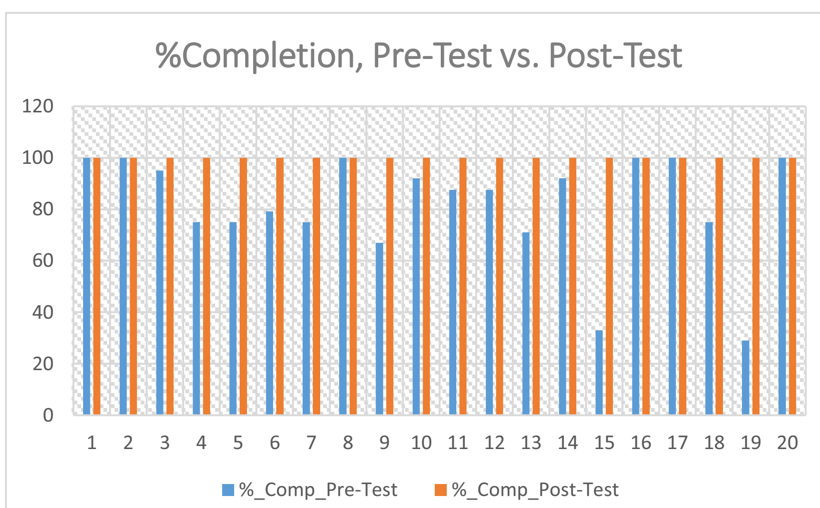



**Fig. 21** Percentage completion comparison between pre-test and post-test for case study 1

- However, the VR-based group takes much more time in training when compared with the baseline group.
- In case of more complex products, the feedback mechanism group persons made fewer errors in actual assembly when compared against the no-feedback group.
- In case of simple assembly, there was no significant difference in the performance of participants from various training groups. Therefore, it can be said that VR-based training is more effective in complex product assembly.
- VR provides a platform for “learning by doing” instead of learning by seeing, listening, or observing.
- As the complexity of the product increases, the time to perform actual assembly and the number of errors increase, but the VR-based group still performed better than the baseline training group.
- Semi-immersive virtual environment provides the user a 1:1 scale of the product in the digital environment, which augments the sense of presence in the virtual environment
- For some cases, VR-based systems might be costlier and time consuming; however, they provide risk- and injury-free environments for teaching and training.

The limitation of this study includes that the population used by the empirical evaluation was formed by young university students and employees which may affect the generalizability of study conclusions. Moreover, force feedback and physical properties were not present in the virtual environment.

Future work includes evaluating the impact of allowing participants more time during the baseline training instead of allowing them to finish early, and including assessment of the system with physical properties and force feedback applied to the digital environment. Moreover, the effect of participants' background and expertise level on the assembly training performance can be assessed.

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