Augmented reality (AR) posture training for manual material handling: iterative design, evaluation, and recommendation for AR interface

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Manual material handling (MMH) tasks can pose risks of musculoskeletal disorders for workers, which makes posture training programs essential. The ultimate goal of this research was to design and evaluate an augmented reality (AR) based training platform, namely the virtual instructor application (VIA). Specifically, the usability problems revealed from the preliminary version (VIA-1) were addressed and enhanced features were implemented in the current version (VIA-2). The usability of VIA-2 was assessed by ten individuals with experience of MMH. Participants explored VIA-2 while performing a series of predefined tasks. A usability questionnaire was administered, and a brief interview was conducted. Results showed that VIA-2 had increased usability compared to VIA-1. While some visual content display issues occurred, a future minor refurnish can address these problems. Finally, the iterative design and evaluation scheme can be applied to the future design of AR-based training programs and evaluation protocols.

INTRODUCTION

Manual material handling (MMH) tasks include carrying, lifting, lowering, pushing, or pulling loads, which can pose musculoskeletal disorders (MSDs) risks when performed incorrectly (Deros et al., 2017). MSDs resulting from MMH tasks are prevalent worldwide. In the United States, 25% of MMH workers experienced low back pain (LBP) lasting 7 days in a 12-month period (Ferguson et al., 2019). In Asian countries, such as Malaysia, one study that investigated MSDs among 500 MMH workers in an automotive manufacturing company found that 32.6% of the workers had LBP, which was the highest prevalent MSD (Deros et al., 2010). In response to the health and safety risks faced by MMH workers, assistive devices such as trolleys, exoskeleton supports, and augmented/virtual reality devices, have been used to assist humans in the MMH work (Glock et al., 2021). Training programs and courses are used to train workers to perform MMH tasks using appropriate postures (Hermans et al., 2012).

Conventional posture training programs are administered in different formats: pamphlets, videos, training seminars led by ergonomists, etc. (Aburumman et al., 2019). However, conventional training programs have not been as effective as expected in the prevention of MSDs (Hermans et al., 2012; Verbeek et al., 2011). The trainees' awareness and knowledge of MMH techniques might be enhanced, but this knowledge did not translate to behavioral changes in the execution of MMH tasks (Verbeek et al., 2011). Several reasons suggested the lack of effectiveness of MMH training. (1) The variability and diversity of MMH tasks were underestimated in the training. For instance, varying the magnitude, shape, and size of the handling objects could influence the handlers' decision-making on how to handle the objects (Denis et al., 2020). (2) Companies provided limited time for MMH training, which restricted the learning process of new workers (Hermans et al., 2012). (3) Many training programs took place in classrooms in the form of videos or lectures, which lacked fidelity and practice (Denis et al., 2020). To promote a safety culture in workplaces and facilitate effective MMH training, novel techniques should be adopted to carry out the training programs in an interactive and motivational environment.

We have attempted to provide this novel training using cutting-edge augmented reality (AR) technology. AR enables the users to see real-world objects and virtual objects generated by the computer in the same context (Azuma, 1997) through spatial and temporal registration. Compared to conventional training programs, AR-based training has several advantages. First, novice workers are no longer limited to the classroom-style learning module. They can wear AR goggles and receive virtual, interactive workplace training (while superimposing AR content and real work environment information), and then revisit the training content later when needed. Next, they can get more involved and motivated via AR-based training programs (Yim & Seong, 2010), which are more interactive and intuitive compared to pamphlets or videos. Thus, AR-based programs have received increasing attention in the domain of education and training (Doolani et al., 2020; Klatzky et al., 2008; Mengoni et al., 2018).

As such, we used AR as a medium to deliver posture training content via a virtual instructor application (VIA) on Microsoft HoloLens. The idea of iterative design (Savage, 1996) was used in the process of developing VIA. In early 2020, the research team designed and evaluated the usability of the original VIA, or "VIA-1" (Chen et al., 2020). Based on the feedback from the usability study, we have made substantial improvements and designed the current version of the VIA ("VIA-2"), and conducted a usability study to assess it.

The purpose of the present study is to describe the process of iterative development of VIA-2 and evaluate the usability of the VIA-2 involving individuals who have MMH experience. Findings from this study will give insight into the design of future AR-based training programs, as well as the evaluation process for AR interfaces.

Related work

Here we provide an overview of VIA-1 and its usability evaluation as part of the related work (Chen et al., 2020). The overarching objective of VIA-1 was to establish an interactive and immersive training platform to facilitate MMH workers learning safer work postures. The identified MMH postures included squat lifting, stoop lifting, and overhead reaching. The novelty of this training content, in the context of ergonomics safety, was to deliver a life-size virtual instructor created using point-cloud 3D reconstruction (Figure 1A). Users were able to superimpose their own bodies to match the virtual instructor's posture in AR. Users could also walk around the point-cloud-generated virtual instructor in the lab and observe lifting postures from different angles.

The user interface (UI) design of VIA-1 followed the 3D UI design guidelines (LaViola Jr. et al., 2017; Perez et al., 2019). The UI (Figure 1B) had several interactive blocks (click buttons, dropdown menu, checkboxes) to enable users to play/pause the virtual instructor's animation, switch between work postures, and hide/show compression/shear forces posed on the lower back region of the virtual instructor, respectively.

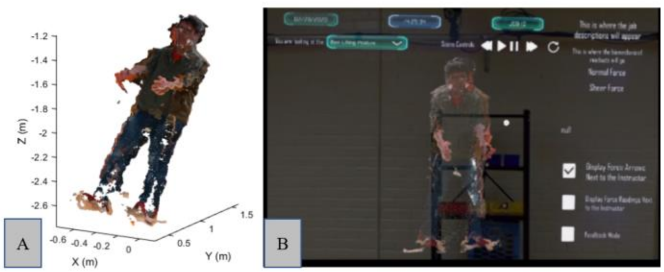

Figure 1. Adopted from (Chen et al., 2020)**:** (A)The virtual instructor reconstructed from point cloud (B) UI of the VIA-1 from the view of HoloLens 1. The virtual instructor is at the center of the UI, the top area has the dropdown menu and the series of play/pause icons, as well as the date and time elements. The upper right section shows the descriptive information. The lower right has toggle checkboxes to hide/unhide forces exerted on the instructor's back.

VIA-1 was delivered using an AR headset, specifically HoloLens 1 (Microsoft HoloLens, Microsoft, WA). The usability evaluation of VIA-1 reflected several major areas for improvement (Chen et al., 2020). (1) The interaction boxes (buttons, dropdown menu, and checkboxes) were hard to gaze at and interact with. (2) Quality of the virtual instructor was low. (3) There were no real lifting animations from the virtual instructor. (4) The gesture interactions of HoloLens 1 were limited, and air tap using gaze and finger tap was not easy to control. To address these usability challenges, we have iteratively designed VIA-1 accordingly and thereby developed VIA-2 for the subsequent round of usability evaluation.

METHODS

Participants

Ten participants with mean ages of 23.1 years old (range 18-42) were recruited from the local community to evaluate VIA-2. Informed consent, approved by North Carolina State University's Institutional Review Board was obtained from all participants. To be eligible, participants needed to spend at least 50% of their working time on the MMH tasks. Individuals were excluded if they were susceptible to motion sickness or were unable to use hand gesture controls. While the usability evaluation for VIA-2 was planned to be conducted with full-time MMH workers at our partnering facilities, the on-site managers were unable to obtain approval from site supervisors due to the COVID-19 pandemic. The advantage of an on-site usability evaluation further considers the workplace context and actual surroundings in which the product was intended to be used. Given the constraint, the present study was conducted in our Biomechanics Laboratory instead of in the facility where MMH tasks were performed.

Instrument

An AR headset, specifically HoloLens 2 (Microsoft HoloLens 2, Microsoft, WA) was used to deliver the posture training content, which had a larger field of view, increased resolution, and more powerful processor than the HoloLens 1.

User interface design

An iterative design process was employed to address the usability problems of VIA-1 (outlined in the previous section): (1) created several sub-menus to declutter the UI and thereby support the gaze activation of and interaction with modules; (2) enhanced the quality of the virtual instructor by replacing the point-cloud virtual instructor with a 3D model-based virtual instructor; (3) implemented animations of squat lifting, stoop lifting and overhead reaching for the virtual instructor; (4) employed HoloLens 2 and implemented new modes of interaction (hold, drag, and tap). As such, VIA-2 was designed with multiple menus (Figure 2): the main menu (hand menu) that linked different sub-menus, a user input menu for customizing parameters, a training selection menu to select a specific MMH movement, a play-pause menu that controlled the instructor's movements and speed during a training module, and a help menu that provided guidance on using the VIA-2.

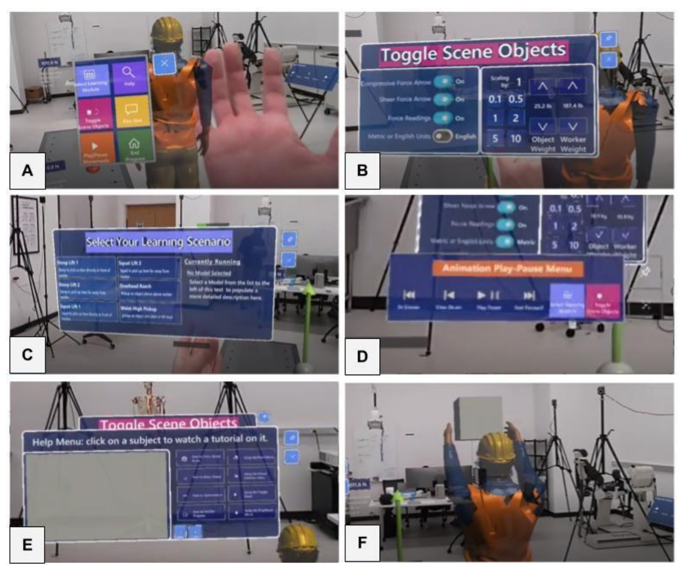

Figure 2. UI of the VIA-2 from the viewer within HoloLens 2. (A) Main menu with the options to direct to other sub-menus, end the program and search for help information. (B) User input menu, users can use this menu to turn on/off force display, change object's weight and virtual instructor's weight. (C) Training selection menu, users can select a specific training module (squat lifting, squat lowering and overhead reaching). (D) Play/Pause menu that controls the virtual instructor's movements. (E) Help menu with video tutorials on how to use the VIA-2. (F) The virtual instructor is performing the movement of overhead reaching.

As such, the major differences between VIA-1 and VIA-2 were summarized in the Table 1 below.

Table 1. Characteristics of VIA-1 and VIA-2.

	VIA-1	VIA-2
Device	HoloLens 1	HoloLens 2
Layout	Single menu	Multiple sub-menus
Instructor	Point cloud generated	3-D model
Animation	No	MMH movements
Interaction	Gaze and air tap	Hold, drag and tap

Experimental procedure

Participants that expressed interest in the study were screened for study eligibility. The participants and the usability session facilitators wore masks throughout the entire session. There were two facilitators: one was responsible for describing and guiding the usability evaluation tasks, and the other was responsible for taking notes.

The facilitators assisted the participants in putting on HoloLens 2, and trained them on how to use it. A brief introduction about VIA-2 and the evaluation tasks were described. The participants were encouraged to think aloud and provide verbal feedback when they performed the tasks.

Finally, the participants were instructed to provide their experience while using VIA-2. The post-study system usability questionnaire (PSSUQ) was administered, which was an established usability evaluation tool to assess the users' satisfaction on different aspects of the system's usability (e.g., "It was simple to use the system") (Lewis, 2002). Bipolar laddering (BLA) was conducted (Fonseca et al., 2015; Pifarreacute et al., 2009), which was a quantitative (rate + or -, and included a score for a UI element) and qualitative (provide a reason for the rating) interview and survey method. The whole session took about 45 minutes, and the participants were compensated with a gift card ($25).

Usability evaluation tasks

The evaluation tasks (Table 2) aimed to guide the users (assuming their normal role as MMH workers) to evaluate the newly implemented features from the iterative design process.

Table 2. List of the evaluation tasks.

ID	Tasks
T1	Locate the VIA-2 and start it
T2	Explore all the features on the menu by clicking buttons.
T3	Customize your lifting objects by user input boxes.
T4	Access a video tutorial to learn about using the VIA-2.
T5	List off all options for navigating and using the VIA-2.
T6	Initiate a training module and start it.
T7	Change the speed of the learning module.
T8	Switch to the overhead reaching module.
T9	Turn on/off the exerting forces on the virtual instructor.
T10	Exit the VIA-2 program and return to the Windows menu.

Outcome measures and analysis

The 19-item PSSUQ was on a 7 -point Likert scale (1 = strongly agree to 7 = strongly disagree). To identify the elements of VIA-2 that had usability problems, we followed the same PSSUQ analysis procedure for VIA-1 (Chen et al., 2020) where the items that received a score greater than 4 (i.e., neutral or disagree) from more than two participants were extracted and the number of those responses was counted.

The BLA had 16 items that were specific to the iteratively designed VIA-2, which included questions on UI interaction methods (hand and finger gestures), UI functions (buttons, dropdown menu, checkboxes, etc.), and the overall UI design (layout, navigation, font). These questions were designed based on the usability findings from VIA-1, which are now implemented in VIA-2 as part of the iterative design process. The participants' quantitative responses to the BLA included the positive and negative signs (thus the two "poles" of bipolar) that represented their perceptions of the strengths and weaknesses of the system, and the scores (ranging from 0 to 5) described the degree of strength and weakness. In other words, each item had either a positive or a negative score (-5 to +5), along with the reasons for this score. For instance, a -5 indicated that participants had strong negative feelings for the listed element, a 0 would indicate they had a neutral perception of the listed element, and a +2 would indicate the participant has a slightly positive feeling about the listed element. The analysis of BLA followed the work of Pifarreacute et al. (2009), where the mean BLA score (considering the signs) for each item was calculated along with a matrix that presented all scores for each item from each participant. The themes of the reasons for the scores were extracted and analyzed.

RESULTS

Post-study system usability questionnaire (PSSUQ)

Only one item in the PSSUQ received a score greater than 4 from more than two participants: "The system gave me error messages that told me how to fix problems." Seven out of ten participants gave such responses.

Bipolar laddering (BLA)

Of the 16 elements in the BLA, the highest mean score was +4.6 (E16, font type, and sizes of the texts) while the lowest mean score was +0.7 (E11, scale bars to display compressive forces against the low back). The complete list of the BLA elements and their respective mean scores are presented in Table 3. The raw scores from BLA for all 16 elements are presented as a matrix in Table 4. There are 160 cells in the matrix (ten participants across sixteen elements) where nine cells contain negative scores. The cells with negative scores were colored in gray and further analyzed.

Table 3. The 16 elements from the BLA with mean scores.

ID	VIA elements	Score
E1	Finger gesture ("click") to select an item .	1.9
E2	Hand gesture to navigate the VIA.	4
E3	Buttons in the UI interfaces.	3.4
E4	On-Off (toggle) buttons in the UI interfaces.	3.6
E5	Sense of haptics when using the system.	2.5
E6	Audio feedback after an action.	2.2
E7	Highlight of the items when interacted with.	3.6
E8	Virtual instructor models.	3.7
E9	Instructors' movements of MMH.	3.6
E10	Force display on the virtual instructor's back.	1.7
E11	Scale bars of the force display.	0.7
E12	Menu layout, organization of the options.	4.2
E13	Menu navigation, switch between menus.	4.3
E14	Availability of the options/features.	3.4
E15	Clarity and visibility of the VIA items.	3.4
E16	Font type and size of the text .	4.6

Table 4. The raw scores from the BLA, with each row representing an element (E, n=16) and each column representing a participant (P, n=10). The negative scores were colored in gray.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
E1	+2	+4	-3	+4	+4	+4	+2	+1	-2	+3
E2	+5	+5	+4	+5	+5	+2	+3	+3	+3	+5
E3	0	+4	+5	+4	+5	+4	+3	+2	+3	+4
E4	+5	+4	-1	+4	+5	+3	+5	+3	+4	+4
E5	+4	+3	+4	+5	+4	+3	+2	0	-3	+3
E6	0	+5	+3	+5	0	0	0	+1	+3	+5
E7	+5	0	+4	+5	+5	+1	+4	+5	+4	+3
E8	+5	+4	+3	+4	+5	+2	+5	+5	0	+4
E9	+1	+5	+4	+5	+5	+3	+3	+5	0	+5
E10	-3	-1	+4	+4	+4	+4	-1	+5	+1	0
E11	0	+3	0	+5	0	+3	-1	-3	0	0
E12	+5	+5	+3	+5	+5	+4	+4	+5	+2	+4
E13	+5	+2	+5	+5	+5	+5	+5	+1	+5	+5
E14	0	0	+3	+5	+5	+4	+5	+5	+2	+5
E15	+3	+2	+3	+5	+5	+3	+4	+3	+3	+3
E16	+5	+5	+5	+5	+5	+4	+4	+5	+3	+5

DISCUSSION

In 2020, the preliminary version of VIA, namely VIA-1, was designed and evaluated for usability (Chen et al., 2020), which revealed key usability problems that informed the iterative design of VIA-2. The present work is the next stage of this research, which is a description of substantial improvements to VIA-2 and usability evaluation findings involving MMH workers. The general evaluation of VIA-2 was obtained using PSSUQ, and the targeted evaluation focusing on the VIA-2's elements was obtained through BLA.

Overall, the results from PSSUQ indicated that VIA-2 has higher usability than VIA-1. Initially, the PSSUQ from VIA-1 revealed five items that received a score over 4 from more than two participants, while VIA-2 received only one item with a score above 4 from more than two participants. This indicated that the VIA-2 outperformed VIA-1 in terms of system usability. Seven participants disagreed or strongly disagreed that "The system gave me error messages that told me how to fix problems". This was likely due to the lack of consideration for potential system errors, and therefore error messages were not included in the design of VIA-2. Actually, no participants encountered situations like crash and stuck during the evaluation of VIA-1 and this item was not identified as a major problem from PSSUQ. Similarly, the participants did not experience system bugs when using the VIA-2. Yet, the participants expected to see a pop-up error message when unexpected problems happen. Although there was a help menu, it was intended to help the users in case they forgot how to use the system, rather than teach them how to solve the problems. To fix this item, we will include an element of error message in the design and test the scenarios when the VIA-2 goes wrong.

The BLA was specifically conducted to understand the effect of improvements based on the VIA-1 study. First, it was noticed that, as shown in the Table 4, all the scores were within the range of -3 to +5. Our approach to BLA was a slight variation from Fonseca et al. (2015): The researchers asked each user to provide three positive (+) elements and three negative (-) elements for their system and give a score for the elements. Consequently, the users might be likely to give a higher score (e.g., 9, 10 for a 0-10 score range) for the elements selected by themselves. The present study aimed to evaluate the iterative design of the VIA-2, thus the BLA elements were predefined based on the usability problems from the usability study in VIA-1. Participants justified their comments regarding the scores that they gave, commonly using words such as "acceptable", "worked fine", or "easy to use" for the positive scores ranging from +1 to +3, whereas terms such as "good" and "great" were commonly used to describe +5 scores. Scores of 0 commonly were justified with comments like "I didn't even notice that it was there", whereas some participants gave weak negative scores to elements they could not remember (-1). Scores of -2 and -3 were often justified with "difficult", "tough" or "hard" to understand, see, or interact with.

In BLA, E16 (font type and size of the texts) received the highest score of all elements in BLA (+4.6), which suggested that the texts of the UI were clear and legible for the users. While in the usability evaluation of VIA-1 many participants complained that the texts were small and not clear (Chen et al., 2020), the iterative design shows that improvements in the UI texts were effective. To address this usability problem, we also changed the distance from the user to the UI, which could also influence the clarity and legibility of texts on the UI. While in VIA-1, the UI remained in front of the user's head at a distance of 2 meters, the UIs in VIA-2 were within the range of the user's hand reach so the users could directly tap at the UIs or even resize them to fit their preference.

In addition to element E16, elements E2 (Hand gesture to navigate the VIA), E12 (Menu layout), and E13 (Menu navigation) received a mean score above 4. More hand gestures (hold, drag, and tap) were used in the VIA-2, which enabled the participants to select the UIs, move the UIs in 3D space, and select an item in the UIs. While in VIA-1, the participants interacted with the UI items through gaze and air tap, they needed to gaze at the items first and then performed air tap to activate the items. This multi-task method of interaction also made it difficult to 'tap' at the UI items accurately. The high scores from E12 and E13 showed that the design of the menu received overall good feedback from the participants. Compared to VIA-1, the VIA-2 was more logically organized, and each menu had clear contents with legible texts and color contrasts between the UI blocks.

The lowest item in BLA was element E11 (Scale bars of the force display), which received a mean score of 0.7 that included two negative responses and five neutral responses. According to P8's verbal feedback, "The change of scales was not obvious, I didn't know their meanings", and several other participants (P1, P3, P10) recalled that they did not notice the change of scales and gave a zero response, consequently. The scale was introduced in the VIA-2 to inform the users of force changes exerted on the back of the virtual instructor. We could infer that the change of force scale was not salient thus difficult for the users to notice, thus alternative changes (e.g., change of color from light to dark) are proposed to make users aware of the force change. Three participants gave negative scores for the E10 (Force display on the virtual instructor's back region), and specifically, P1 said that "the force display was not part of the virtual instructor and crowded", and P2 said, "I did not know how the force applied to my back". Thus, a more intuitive and customized design should be adopted to increase the utility of force display. E3 (Sense of haptics when using the system) received a score of -3 from P3, who mentioned that "There is actually no sense of touch when tapping at the interface". E1 (Click gesture to select an item in AR interface) received two negative responses, both two participants mentioned that it was easy to do mis-clicks while using the finger gestures.

For the limitation of this study, due to the COVID-19, the plan of testing VIA in on-site sessions with MMH workers was not achieved. In addition, the department of labor statistics reports an older average age for MMH workers. Our results may be different if gathered from an older demographic due to the novelty of the technology being used.

CONCLUSION

Overall, the results from PSSUQ and BLA showed that VIA-2 had increased usability compared to VIA-1, and future minor refurnish can be targeted at specific items like an error message and improved force displays. From the perspective of system design, the iterative process involving prototype, evaluation, and design was effective in the development of AR programs to improve system usability. The process of applying mixed-methods (quantitative and qualitative) surveys (PSSUQ and BLA) enabled the evaluation of the AR system.

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