

Develop and evaluate an augmented reality posture training tool to promote work safety

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Conventional work posture training tools included pamphlets, one-time training orientation, and/or videos. These tools did not always yield satisfactory training outcomes, and the incident rate of work-related musculoskeletal disorders did not substantially lower. In this research, modern augmented reality (AR) technology was leveraged to deliver interactive, holistic, whole-body visual information to convey safe work postures. The developmental procedure followed DMAIC by first defining specifications of training content, which led to the development of the training tool, including 3D reconstruction of a virtual instructor and building of user interface based on user-centered framework. This AR training tool was measured and analyzed through usability evaluation, and quantitative and qualitative data were obtained for cross-validation and usability issue source identification. Findings revealed the utility of 3D reconstruction of a virtual instructor and practicality of adopting conventional usability evaluation method for AR user interface usability evaluation. Feedback from the usability evaluation via questionnaire, think aloud, and post-task open-ended responses are employed to iteratively design the next version of the AR posture training tool.

INTRODUCTION

Work safety is of critical importance for all occupations. Yet, there has been over 3.5 million employer-reported cases of non-fatal injuries and illnesses in both public and private goods producing (manufacturing, construction) and service producing (transportation, nursing homes) industries in the U.S. (U.S. Bureau of Labor Statistics, 2019). Overexertion and musculoskeletal disorders (e.g., herniated disc, sprains, strains, and tears) accounted for the majority of these cases (U.S. Bureau of Labor Statistics, 2019). The conventional approach to prepare workers with work safety knowledge is through training using pamphlets, one-time training orientation, and/or videos. Posture training reduced risks of musculoskeletal disorders in various occupations (Jaromi, Nemeth, Kranicz, Laczko, & Betlehem, 2012; Melhorn, 1996; Westgaard & Winkel, 1997). However, it was also reported that workers only minimally change after postural training and the incident rate of MSDs did not lower substantially (Amick III et al., 2003; Hignett, 2003; Lavender, Lorenz, & Andersson, 2007; Nelson & Baptiste, 2004; Trinkoff, Brady, & Nielsen, 2003). To foster safer work practice in the future workforce, work safety should be beyond uniform and pamphlet-based training. We envision training to be better supported in an interactive environment where workers can use their body acquire safety knowledge and minimize safety risks.

Motivated by the need for an interactive posture training tool, modern technology such as augmented reality (AR) becomes an attractive medium to deliver posture training material and thereby promote work safety. Augmented reality enables users to visualize objects from the physical world and computer-generated virtual entities in the same environment through spatial and temporal registration (Azuma, 1997). Augmented reality has been widely explored for its potential applications in education and training (Klatzky, Wu, Shelton, & Stetten, 2008; Vilkoniene, 2009; Yim & Seong, 2010). Moreover, learning using AR has improved learners' motivation and efficiency (Dunleavy, Dede, & Mitchell, 2009; Huang, Rauch, & Liaw, 2010; Yim & Seong, 2010). Augmented reality is also gaining popularity in the logistics industry for the purpose of job training (Ong & Nee, 2013). However, most of

these AR training applications only overlaid simple textual information in the users' field of view (Tatić & Tešić, 2017). Displaying posture training information through holistic view of virtual instructors, along with factual information on risks for body joint stresses and strain, is the novelty of this work.

The purpose of this paper is to describe and provide developmental information of a user-centered AR posture training tool to promote safety of physical tasks (e.g., lifting, reaching), and to draw implications and identify recommendations for AR posture training tool based on the findings from the user interface (UI) usability evaluation. The AR posture training tool consists of both hardware (AR smart glasses) and UI (virtual instructor and information panel). The usability evaluation aimed to acquire user feedback regarding three interactive functions on the UI, which are associated with demonstrating safe work postures. Feedback from the usability evaluation will inform the design of the next iteration of the AR posture training tool prior to formative evaluation with actual workers from the industry.

Contributions of this work include the reconstruction of a virtual instructor using 3D captures from a person demonstrating safe work postures, and the design implications of the UI for posture training in an optical-see through AR smart glasses. Findings will illuminate the emerging sociotechnical landscape as we witness the paradigm shift toward AR posture training technology for improving safety outcomes.

METHODS

Three research tasks comprise the methods section: (1) create of a virtual instructor by reconstructing surface features of a live human, (2) build an AR user interface and integrate the virtual instructor into AR, and (3) conduct usability evaluation.

Create point cloud virtual instructor

The interactive posture training tool includes a vivid, human-like virtual instructor who demonstrates how to lift or bend safely. This virtual instructor was created by capturing the surface features of a real human using **Red Green Blue-Depth** (RGB-D) cameras (Mao et al., 2017). The RGB-D data were

stored in the form of point clouds, which contained the coordinates (x,y,z) and color information (RGB). This 3D reconstruction approach helped retain some human life-like features, as well as joint movement subtleties that were not easily articulated in cartoon-like graphics.

Point cloud capture. Four RGB-D cameras (Intel RealSense D415, Intel, Santa Clara, CA) were oriented 90° relative to each other and then calibrated. An individual assumed ready position (standing upright) at the center of the four cameras and faced one of the four cameras (Figure 1). The individual performed a lifting task by lifting a box from the floor using a stoop lifting posture (Occupational Safety & Health Administration, retrieved 2020). The four cameras captured unique views of the individual who demonstrated the lifting task (Figure 2). Each camera generated one set of point cloud data, which was stored as a pcd (“point cloud data”) file.

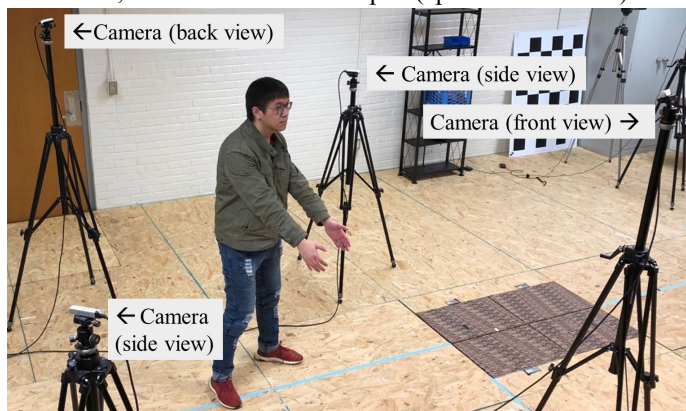


Figure 1. Relative placement of the four RGB-D cameras.

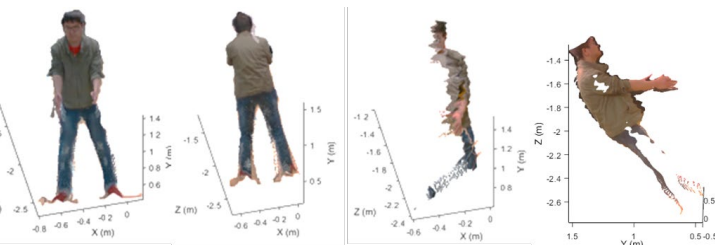


Figure 2. The front, back, left, and right side views, capture by the four RGB-D cameras (starting from the leftmost).

Noise removal. The next step was to remove environmental information (floor, wall, lab furniture) and noise (unclear regions of the human) using MATLAB (MathWorks, Natick, MA) (Sinko, Kamencay, Hudec, & Benco, 2018). A native MATLAB filter function, *pcdenoise*, was applied to improve the quality of virtual instructor (Figure 3). There were two critical parameters in the *pcdenoise* function: (1) the

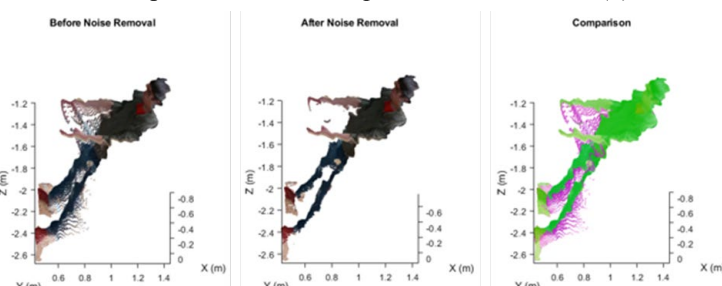


Figure 3. Point cloud before noise removal (left) and after noise removal (middle), and the pink/purple regions depict the noise removed (right).

number of neighboring points n , and (2) the cut-off threshold t . In other words, a point is considered noise if the average distance to its n nearest points is above threshold t . By adjusting these two parameters, we could find a balance between accuracy and computation time.

Registration and stitching. The four separate pcd files (Figure 2) needed to be reconstructed (“merged”) into a single pcd file to produce a complete, 3D virtual instructor. The pcd files shared common overlapping points, which enabled the four pcd files to be reconstructed. Prior to reconstruction, a downsampling process (*pcdownsample*, *GridAverage* in MATLAB) was applied to support computational efficiency. Next, all point clouds were verified (or “registered”) to be in the same coordinate system. The quality of registration depends on the quality (e.g., resolution) of point clouds and the quantity of overlapping sections. Point cloud registration algorithm was *iterative closest point* (ICP) algorithm, which is commonly employed in point cloud registration (Besl & McKay, 1992; Chen & Medioni, 1992). The goal of ICP is to minimize the Euclidean distance between two matching point clouds. As an example for registering point cloud data, the side view pcd file was selected and a transformation matrix was applied to convert it into the same coordinate system as the front view point cloud, and they were merged into a new pcd file using function *pcmerge*. This process was repeated until all pcd files were merged into one, which was then denoised (Figure 4).

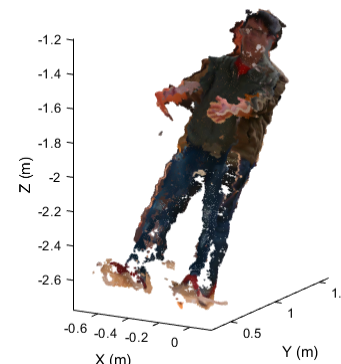


Figure 4. The registered and reconstructed point cloud human from a different view to depict the merged point clouds.

Build AR user interface to visualize safe work postures

UI design specifications. The essential content of posture training material includes virtual instructors (stationary and animated) and an information panel that presents factual information on risks for unsafe postures. In addition, a user should be able to switch to a different virtual instructor who demonstrates another posture (e.g., from a lifting to a bending task). A user should have the freedom to practice the tasks by following the movements of the virtual instructor, and therefore it is important to free up the hands of the user so he/she could practice lifting a real box simultaneously. A mixed reality smart-glasses (Microsoft HoloLens 1st generation, Microsoft, Redmond, WA) was selected as the hardware for the AR posture training tool because it could be worn over the head. It has approximately 30×17° field of view.

UI design framework. A user-centered approach was employed by first considering the target user population, which

are workers performing manual material handling tasks, who may not have had sufficient opportunity to practice the lifting task. Technical and scientific jargon were eliminated from the UI so that workers could better understand the information about risks in unsafe postures.

Leveraging a proposed model of AR design consideration and evaluation (Perez, Hidalgo, Lediaeva, Mouloua, & Hancock, 2019), the users should have the flexibility and adjustable settings. Additional UI designs were based on established and 3D UI development guidelines (LaViola Jr., Kruijff, McMahan, Bowman, & Poupyrev, 2017). Specifically, the UI elements were simplified (include only essential text) to promote learnability, minimizing the number of complex interactions and screens for memorability (avoid deep links), while providing an efficient learning environment for understanding how to work safely (includes learnability, memorability, efficiency, errors, and satisfaction) (Nielsen, 1993; Perez et al., 2019).

UI functionality. The UI information panel was built using a rendering engine (Unity 3D ver. 2018.2, Unity Technologies, San Francisco, CA), and the point cloud virtual instructor was imported into Unity as part of the UI. The safety posture content are incorporated with three interactive functions on the UI. (1) A dropdown menu that allows users to switch from viewing one posture to another. (2) A series of play/pause icons to suggest the possibility of animating the virtual instructor. (3) A block of checkboxes to toggle factual information on/off (e.g., show stress/strain at the lower back).

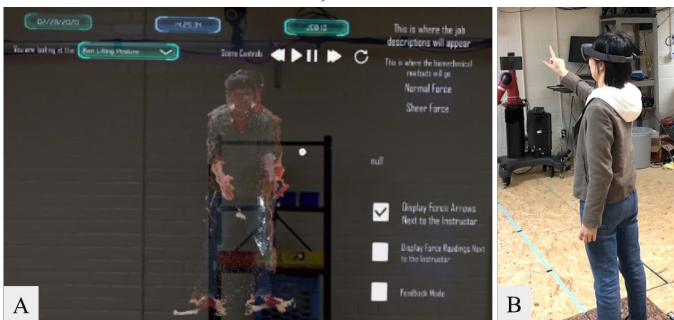


Figure 5. (A) View from the HoloLens (virtual instructor at the center and information panel). The top center area has the dropdown menu and the series of play/pause icons, as well as date and time elements. The upper right section shows factual information and the description of the task being performed. The lower right has toggle checkboxes to hide/unhide task description. (B) Participant using HoloLens.

One specific UI design challenge stems from the head-gaze cursor of Microsoft HoloLens 1st generation, which is controlling the cursor through the user's head movement. We wanted the information panel to remain in the user's field of view at all times unless the user selects the power button (Figure 5A). Locking the information panel with the user's field of view was not a practical design it would be locked into the local coordinate system as the head-gaze cursor. In other words, a user would not be able to move the head-gaze cursor independent of the information panel. To overcome this challenge, a "floating information panel" was implemented to enable the users to move the head-gaze cursor to select items on the information panel. In case a user turns the head completely away (i.e., turn to the right 90°), the floating panel would gradually catch up and appear in the user's field of view.

Parameters of the floating information panel, such as the catch up speed, were explicitly examined during usability evaluation.

Conduct usability evaluation of the user interface

Participants. Ten users (6 males, 4 females) of mean age 28.6 years (range=23-38) were recruited from North Carolina State University with approval by the Institutional Review Board. Participants were at least 18 years of age and had normal or corrected-to-normal vision. Individuals were excluded from participation if they had tendency of motion sickness or inability to use hand gesture to control UI elements. Four users have had experiences using some type of AR technology (ranged from 0.5 to 5 years since their first use of AR), and all reported the current usage frequency as rarely (from rarely, occasionally, or frequently).

Usability evaluation procedure. Upon informed consent, general demographic information was obtained from the participants and then they received simple training on how to use gesture control in AR. Next, they were primed with the description of a persona, which described an average individual that represented our target audience. "You are a 45-year old warehouse worker. The work you do on a daily basis involves putting the boxes onto shelves. You perform a lot of bending, lifting, and reaching tasks, and sometimes your back is sore. You want to know how to safely perform your daily tasks."

The facilitator assisted the participants to put on HoloLens, and then briefly described the UI elements presented in HoloLens (Figure 5). The participants were instructed to think aloud, and their verbalized content written in notes by the facilitator. Each participant was given three task scenarios, which corresponded to the three interactive functions of the posture training tool. The task scenarios were: (1) You want the virtual instructor to move and demonstrate the complete motion of a safe lifting posture; (2) You want to see how much stress level in the lower back when performing a lifting task; and (3) You want to see the safe work posture for a reaching task.

After all task scenarios, participants were prompted with four open-ended questions related to the virtual instructor, the general UI, and the interactive functions. It was followed by a comparison task during which the participants compared the catch up speed of the floating information panel. Participants then completed Post-Study System Usability Questionnaire (PSSUQ) (Lewis, 2002) to evaluate the system's usefulness, information quality, and interface quality on a 7-point Likert-like scale (1=strongly agree, 7=strongly disagree).

Outcome variables and analysis. Quantitative data were collected from PSSUQ. Qualitative data were collected from think aloud and open-ended response, which were grouped into recurring themes.

RESULTS

Post-study system usability questionnaire

Six items from the PSSUQ received a rating greater than 4 (1=strongly agree, 7=strongly disagree) from more than two participants (Table 1), which indicated usability problems. All other items from the PSSUQ received ratings below 4 or N/A.

Table 1. Items from PSSUQ received ratings greater than 4 (“neutral”) from more than two participants. Frequency refers to the number of participants gave a rating greater than 4.

Item description summary	Frequency
Has all functions and capabilities expected.	4
Overall satisfied with the system.	5
Satisfied with how easy to use the system.	4
Able to efficiently complete task scenarios.	4
Felt comfortable using the system.	4
Liked using the UI of the system.	4

Think aloud

Usability comments and recurring themes (Table 2) from participants’ verbalized thought process were identified.

Table 2. Usability challenges that were identified by participants (count of recurring comments listed as frequency).

Themes from UI usability comments	Frequency
Not sure what to expect from checkboxes.	2
Problems with appearance of virtual instructor (did not seem to be scaled properly / was floating)	4
Text, button, and dropdown menus were small (hard to read and hover over).	10
UI blocked the virtual instructor, did not know how to hide/unhide UI elements.	3
UI drifted while navigating / walking around.	2
Unclear about the meaning of factual information.	1
Unclear about the meaning of force/stress vectors.	4

Open-ended responses

General feedback and its recurring themes were identified from the post-task open-ended responses. Comments from open-ended responses that were not mentioned during think aloud are identified in Table 3.

Table 3. Post-task responses related to four general open-ended questions (count of recurring comments listed as frequency).

General feedback	Frequency
AR smart glasses too heavy / interfered with glasses.	5
Small field of view.	2
Felt eye strain / sickness.	1
Virtual instructor feedback	Frequency
Would like to see more real motions / examples of incorrect postures from virtual instructor.	6
Prefer to see mesh as opposed to 3D point cloud.	1
Interactive function feedback	Frequency
Would like additional input methods (complex gestures, voice control).	2
Would like additional, sophisticated functions.	2
Display / UI feedback	Frequency
Would like different colors for different functions.	1
Would like customizable job / information for user.	1
Prefer faster catch up speed of the floating panel.	4

DISCUSSION

This work followed DMAIC (Define, Measure, Analyze, Improve and Control) during which the design specifications were first defined. The team established the essential postural training material and content that were translated into the AR environment for usability evaluation (measure and analyze), which generated results for the next step: iterative refinement (improve and control) of the AR posture training tool.

The virtual instructor reconstruction process demonstrated the feasibility of creating posture training

material using 3D point cloud reconstruction, which was initially applied in computer science or medical research (Mao et al., 2017; Sinko et al., 2018). Three main takeaways will feed into the next iteration. First, there were some missing areas on the virtual instructor that may be due to camera configuration and occlusion, which will be the immediate subject of improve in the next iteration. Next, the ICP method employed for registration is the most basic and the simplest ICP algorithm, which may have contributed to slight misalignment between two pcd files. We plan to explore more sophisticated ICP algorithm that leverages color and geometric features. Finally, the noise removal parameter was preliminarily tested for this iteration of the virtual instructor, but the optimal smoothness-accuracy tradeoff will be examined.

The UI building process uncovered a consideration in display compatibility, which refers to the UI elements that appeared to be visually acceptable (complied with general heuristics) in developer mode on a computer monitor may not necessarily be acceptable for users in AR. While the research team has verified and tested the UI elements in the AR environment, the team has become accustomed to the sizes and interactive functions throughout the development process, hence the size issue was not immediately apparent until it was evaluated by the participants who have not seen the UI previously. Usability findings suggested that the size of text and interactive functions (checkbox, dropdown menu) should be designed larger than they needed to be, not only accommodate the potential size difference in AR but also to support new AR users who may have jittery controls of the head-gaze cursor.

Usability evaluation procedure adopted from the conventional interface usability evaluation (e.g., webpage) helped identify six usability problems (Table 1). This suggested that the usability framework for conventional interfaces was a practical method to assess usability of AR interface / system. Moreover, comments obtained from think aloud (Table 2) were consistent across multiple participants, which suggested that issues identified by participants were not by chance (systematic issues) and highlighted the effectiveness of the adoption of usability evaluation from conventional interfaces.

Quantitative and qualitative data enabled us to cross-validate the results and to drill into the source of usability issues. The PSSUQ revealed two primary types of usability problems: interface quality and system usefulness. For interface quality, four of ten participants indicated that the systems did not have all functions and capabilities as expected, and they did not like using the interface of the system (Table 1). More specifically, verbalized responses revealed that the participants were unclear about the meaning of factual information and force/stress vectors, and the UI drifted while navigating which resulted in occlusion of the virtual instructor (Table 2). For system usefulness, some participants did not know what to expect from the checkbox toggle functions (Table 2). Digging into verbalized responses helped identify UI and system usability problems that were reported by participants during their actual usage, which explained the data from the PSSUQ.

Feedback from the open-ended responses offered insightful features that are valuable for the next iteration of the UI. While some comments may not be addressed directly, particularly with AR hardware being unfriendly to users with

eye glasses (Table 3), we see the opportunity to leverage built-in hardware such as motion sensor and microphone to support additional input methods such as complex gestures and voice activation (Table 3). Feedback specific to the floating information panel helped us to conclude that a faster catch up speed seemed preferable as users may not want to lose UI information for too long. Finally, it was important for the team to separate comments associated “usefulness” from “user preference” because a participant had preference for a graphic virtual instructor (as opposed to point cloud) but it may be a specific future usability evaluation question as oppose to immediate implementation.

Limitations

The usability evaluation results did not include time to task completion, which may have been an indicator of system ease of use. We attempted to quantify time to task, which was defined as “the time started as soon as the facilitator finished describing the task scenario and ended as soon as the user successfully activated the corresponding UI function.” However, given the floating panel on the UI interface, it was difficult to determine an objective starting time because some users did not have the user interface at the center of the screen.

CONCLUSION

Using surface features and point cloud data to reconstruct a holistic, 3D virtual instructor enabled users to visualize whole-body safety posture in AR. Furthermore, by first establishing design specifications made the implementation of interactive functions more clear. Leveraging user-centered framework and 3D UI design provided the heuristics for UI design. Usability evaluation method for conventional interfaces could be adopted to the evaluation of UI in AR. Finally, performing cross-validation by comparing quantitative data against qualitative data helped pinpoint the source of usability issue since numerical ratings from questionnaires provided minimal clues to the specific issue of the UI feature.

The AR posture training tool provided great promise in establishing a novel training tool in which a virtual instructor can deliver holistic work movement information to workers. The next step will be completing the second iteration of the posture training tool and to evaluate it in-situ with real workers at factories to examine feasibility for in field use.

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