An Immersive Environment for Experiential Training and Remote Control in Hazardous Industrial Tasks

Nicholas Caporusso[1,2], Luigi Biasi[1], Giovanni Cinquepalmi[1], Vitoantonio Bevilacqua[1]

[1] Polytechnic University of Bari, Via Edoardo Orabona, 4, Bari, Italy
[2] Fort Hays State University, 600 Park Street, Hays, United States
n_caporusso@fhsu.edu, vitoantonio.bevilacqua@poliba.it,
{luigi.biasi91, cinquepalmigianni}@gmail.com

Abstract. Inadequate training and lack of risk awareness are among the main causes of work-related accidents in manufacturing facilities and during hazardous tasks. In the last decade, Virtual Reality was introduced as an effective tool for improving individuals' skills in their tasks in several different contexts by simulating operating scenarios. Nowadays, advances in interaction paradigms and novel devices create opportunities to further enhance training and work safety. In this paper, we introduce an immersive system based on affordable wearable devices for providing on-the-job training. In addition to its advantages for instructional purposes, we discuss the results of an experimental study about the performance of system as an assessment tool for evaluating the presence of incorrect movements that lead to work-related conditions.

Keywords: Wearable · Haptics · Training · Safety · Industry 4.0

1 Introduction

In 2015, over 2.8 million workplace injuries were reported in the US alone, rating work-related nonfatal adverse events at approximately 3% of workers' population [1]. Similar figures have been reported in other countries, with an average rate of 1.12 fatal accidents per 100.000 full-time equivalent workers [2]. Recent statistics show a continuously descending trend since the last decade. However, specific sectors in the goods-producing industry, such as, construction and manufacturing, maintain a high-risk profile, with an average rate of 24.6 nonfatal accidents per 100 workers [1].

Indeed, hazardous tasks, which are inherently associated with specific risk factors, have a direct impact on the occurrence of work-related injuries. Furthermore, the literature clearly shows that employees are more likely to have an accident at work in their initial period of employment in a job; also, turnover is associated with higher rate of adverse events [3]. Among work-related illnesses and complaints, the most common self-reported accidents are musculoskeletal disorders, with conditions involving the upper limbs (and especially the hands) ranking second [Muggleton]. Additionally, young employees and newcomers are a high-risk population especially because inadequate learning leads to habits and behaviors which potentially cause injuries and clinical conditions (e.g., carpal tunnel syndrome) [4].

As lack of awareness on potential risks is a major, yet preventable, cause of accidents and fatalities, proper instruction is crucial for reducing adverse events [5]. In this regard, Virtual Reality (VR) has been introduced as a viable tool for completing traditional training. The advantages of simulated environments include hands-on experience, fast design and scalable usage, and long-term cost reduction. In addition, VR can increase opportunities for delivering accurate training, and it has been demonstrated to improve learning performance.

In this paper, we introduce an immersive system based on wearable technology and on a novel haptic interface. The system is especially designed for delivering task-specific, experiential training in a simulated on-the-job situation. In addition to providing users with a more realistic interaction with the work environment, the proposed system can be utilized to acquire and analyze individuals' movements and to assess potentially hazardous behaviors which can lead to work-related conditions of the hand. Finally, we detail the results of a preliminary study about the performance of our system.

2 Related work

In the last decade, several projects introduced the use of Virtual Reality (VR) and Augmented Reality (AR) for training purposes in different mission- and life-critical contexts. Applications, such as, fight and flight simulators, driving simulators, and virtual intensive-care units, have been successfully adopted in the military, automotive, and healthcare industries, respectively [6, 7]. Moreover, in the recent years, VR and AR have increasingly been utilized for job training, in other sectors, such as, public safety. For instance, the authors of [6] propose a simulated environment for improving spatial navigation in firefighters. The use of VR-based simulation in safety training programs has been explored in the construction and mining industry [8], and it has been subsequently adopted by the manufacturing sector, where simulations are utilized to deliver just-in-time training for operations and maintenance purposes in addition to safety. Several studies, such as, [9], focused on healthcare, demonstrated the effectiveness of practicing on virtual equipment and in training the workforce on complex procedures [6]. More sophisticated applications include cooperation with and remote control of equipment, industrial machinery, and robots, or for learning additive manufacturing processes [10]. Nevertheless, most of the actual implementations of VR and AR in the industry regarded environments and models in which trainees can watch instructional demonstrations and interact with elements in the 3d scene. Unfortunately, although they increase the outcome of training, their performance might suffer from limited engagement, which, in turn, might undermine their applicability to actual scenarios. For instance, the authors of [11] proposed the use of VR as a tool for personnel selection in the early 2000, though other systems (e.g., Social Networks) received more attention as a screening tool for human resources. Moreover, the advantages of implementing collaborative multi-team VR environments was described in [12], though further research and development are required to enable physical participation of members from multiple teams in the same space.

Recent development in interactive technology and the introduction of physically immersive systems, such as, Cave Automatic Virtual Environments (CAVE) enhanced simulations, as they provide trainees with a completely different experience with respect to conventional screen-based VR software and improved users' engagement level with tasks, individually and in teams [13]. CAVE systems enable navigating a virtual scenario by actually walking in it, which is especially beneficial in training for hazardous operations, and harsh and extreme environments. However, they suffer from several drawbacks, such as, issues in depth perception [14], high maintenance costs, and complex logistics. As a result, they are mainly employed in experimental studies. Conversely, head-mounted-displays (HMD) are the preferred technology for work-related contexts. In [15], the authors present an immersive virtual environment for training and collaboration based on low-cost technology. The system utilizes an HMD and a gesture detection device to create a portable, affordable interactive solution that might be utilized for on-the-job and just-in-time tasks.

Especially in workforce training, feedback is among the crucial aspects in the use of VR and AR [16, 17]: the presence of realistic response from the environment results in improved engagement and performance. Several research projects introduced devices especially designed for custom tasks, which have issues in industrialization and affordability. Conversely, we propose an immersive training system that integrates VR and low-cost wearable devices to improve workers' training and risk awareness. Our system is especially focused on evaluating wrong behavior in tasks to improve safety, reduce the risk of injuries, and prevent long-term consequences of incorrect movement.

3 System design

The proposed system aims at enhancing standard protocols for VR-based on-the-job training by using affordable immersive technology (i.e., head-mounted-displays) to increase engagement in simulated work-related tasks. Moreover, our system integrates wearable devices to improve the outcome of current technology based on learning-by-doing approaches with a two-fold objective: (1) increase the realism of the simulation, and (2) accurately measure factors in the execution of tasks (e.g., the movement of the hand) which are relevant for preventing work-related injuries and long-term conditions. To this end, the system consists in a hardware/software platform that integrates the design of scenario-based VR simulations, devices for acquiring movement and for delivering feedback over multiple sensory channels (e.g., tactile), and a risk assessment module for the analysis of hazardous and repetitive tasks. As a result, trainees can enter the simulation using an HMD, they can actually realize the task using wearable devices that capture their movement and give them tactile feedback from the environment, and they can receive information about their proficiency. Simultaneously, the system analyzes their movement, evaluates the potential short- and long-term risks associated with their performance, and suggests prevention measures.

The architecture of the system is structured in a stimulation and an acquisition component. The former consists in a VR engine (i.e., Unity) that enable creating and navigating scenarios that represent the task to be accomplished by the trainee. Simulations can be displayed using standard screens or HMDs. Moreover, the VR engine includes easy-to-use modeling software that can be utilized for generating realistic simulations, and it has already been utilized in different scenarios, including hazardous tasks.

The acquisition component consists of motion tracking systems that can capture the movement of subjects realizing the task. For instance, images and videos of the torso or the entire body can be acquired using infrastructure-based motion tracking systems in combination with wearable reflective markers that enable collecting data points from specific regions of interest (e.g., the upper limbs), and they can be utilized for quantitative movement analysis. In addition to motion tracking, the proposed system supports multiple input/output devices, including ad hoc technology and, specifically, wearable peripherals that capture orientation and movement of the hand and of the fingers. For instance, in its first implementation, the system supports dbGLOVE [18], a wearable device that consist in a pad equipped with inertial sensors to capture acceleration and orientation of the hand over 9 degrees of freedom, and bending sensors that detect grasping and flexion of fingers (see Figure 1). The device can accurately acquire the movement of multiple joints of the hand and of the fingers, and convert them into control signals. Users can interact with the environment by directly grasping, manipulating, and holding simulated objects with their hands.

Fig. 2. Acquisition device. Orientation and movement are converted into control signals that enable reproducing the hand in the simulation, in real-time.

Simultaneously, data acquired using the wearable device enable extracting motion and inertial patterns that represent the typical conditions that increase occurrence and damage of musculoskeletal conditions. The system supports in-presence and remote analysis: in addition to data points, a 3d model of the hand can replicate the movement of the subject, so that experts and physicians have qualitative and quantitative information to support their diagnosis and to suggest prevention strategies and correct movements. Also, the proposed system can integrate Myo [19], which acquires inertial components of motion and myoelectric signals from the forearm to calculate the movement of the hand and the fingers. Furthermore, the wearable interface acts as a stimulation device, because it provides detailed haptic feedback on sixteen points over the palm which can be utilized to represent objects, pressure, touch cues, and tactile icons. As a result, users can interact and operate in a more natural and realistic fashion compared to clicking on standard controllers. Simultaneously, they can test and learn the actual movements which will be required by their activity. Furthermore, they can get feedback on their actions, and learn how to realize them better, to avoid situations associated with higher risk of adverse events, injuries, and long-term conditions.

The system utilizes low-cost technology that enables its adoption directly at the workplace, where the availability of training tools has several advantages in addition to the possibility of using them for instructional purposes. Also, the system can be utilized continuously for task rehabilitation, after the training phase, to identify and mitigate the potential presence side effects of incorrect behavior caused by work experience. Furthermore, the system might be utilized for rehabilitation therapy of work-related conditions.

4 Experimental study

In this section, we detail the results of a preliminary study about the efficacy of the proposed system. The objective of the study was two-fold: (1) evaluate the accuracy of the control device in acquiring and discriminating correct movement patterns from potentially hazardous actions; and (2) validate the performance of the proposed system as a training tool in terms of risk awareness and task proficiency over time. To this end, we designed two experimental tasks that were realized in a virtual environment simulating a simple scenario involving operational constraints and risk factors.

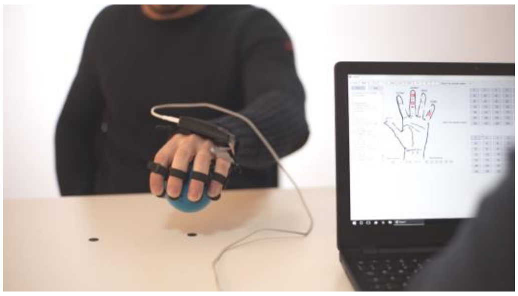

Fig. 2. Application of the system to in-presence risk assessment or rehabilitation contexts.

In Task 1, subjects were asked to operate a control room consisting of a knob which they had to close by rotating it clockwise in the least amount of time, to prevent spilling of hazardous material. In a preliminary experiment, we recruited 30 male participants who matched the characteristics of a novice worker. The purpose of the task was to evaluate the tendency of individuals of realizing movements that could lead to potential musculoskeletal conditions. We utilized the wearable component of the system to measure how subjects moved their hand during the tasks and we added some physical constraints to the virtual environment: users were required to grasp the virtual knob to rotate it.

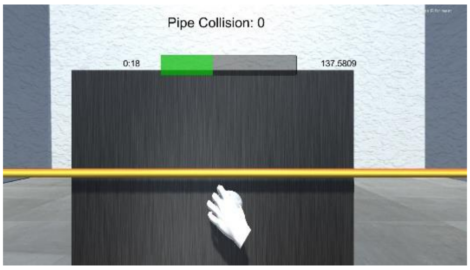

Fig. 3. The simulated environment of Task 2. Users are required to interact with a control panel in which they must accomplish the rotation of a knob placed relatively close to a hot metal bar.

In Task 2, participants were asked to accomplish the same operation as in the previous experiment. In addition, we included a hazardous component: a metal pipe was placed in close contact with the knob in the simulated environment, to simulate the presence of an element that would lead to an immediate accident at work. Therefore, subjects were required to realize more accurate movements and rotations of the knob to avoid incurring in an accident. 15 male participants aged 24-30 were recruited for this task.

Each subject repeated the task 5 times to evaluate the effectiveness of the system in delivering training. Acceleration and orientation acquired from the wearable device were converted into quaternions representing the rotation matrix, which was then utilized for real-time visualization of the hand and for calculating the following parameters:

- number, degree, and time of positive (clockwise) rotations of the hand, which counted towards accomplishing the task (both Task 1 and Task 2);
- number, degree, and time of negative (counter-clockwise) rotations of the hand, which involved additional effort and time to compensate the lost progress (both Task 1 and Task 2);
- number of collisions with the pipe (only Task 1), which represented incidents.

5 Results and discussion

All participants successfully understood and completed the experiment. The device showed high accuracy in recognizing the rotation of the hand and the movement of fingers, though some modifications to its parameters were needed to increase its responsiveness with respect to the requirements of the task and to the individual configuration of the hand (i.e., changes in values acquired using bending sensors due to different length of participants' fingers).

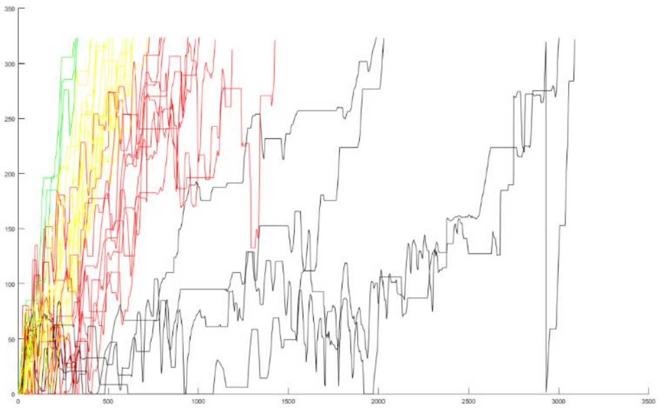

Fig. 4. Task advancement plotted as users' rotation patterns. Rotation angle is represented on the y axis, whereas the x axis shows time. Steady lines indicate intervals between rotations. The four groups are identified by different colors.

In addition, by analyzing in detail subjects' behavior during the tasks, we were able to cluster individuals with respect to their probability of having an adverse event in an actual work environment. By doing this, we could suggest additional training to subjects depending on their identified risk class. As shown in Figure 4, we identified 4 different types of behavior, which can be associated with specific intervention measures.

Table 1. Users' clusters and their centroids, with the distribution of the population, in relation to the angular coefficients of regression lines.

User	Value	Users
C1	0.08	4
C2	0.29	10
C3	0.54	13
C4	1.006	3

Also, the effectiveness of the system in training subjects is demonstrated by the number of collisions with the hot pipe, which is reduced to almost 0 after 5 trials, as shown in Figure 5, which represents the performance improvement of participants.

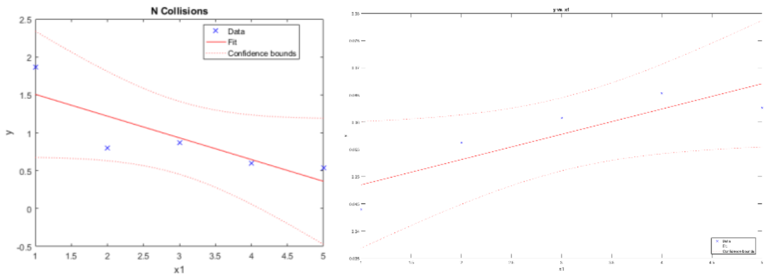

Fig. 5. Number of collisions with the metal bar over the 5 trials of Task 2 (left), and average overall performance of participants, which includes the time for accomplishing the task.

Table 2 summarizes the results for task 2: 54% of rotations involved smaller angles, associated with a lower risk, 7% regarded angles from 90° to 120°, associated with medium risk, and 39% of rotations were larger than 120°, which stress the wrist the most and require a rotation of the elbow, also. Interestingly, participants did not realize angles larger than 180°, which would involve a rotation of the torso, with additional risk for the back.

Table 2. Results of Task 2. Movements are represented as a percentage of rotation in regard to the angle.

User	<90°	90°-120°	120°-180°	time
s1	56%	13%	31%	11
s2	17%	17%	67%	14.8
s3	54%	0%	46%	11.6
s4	86%	14%	0%	30
s5	60%	13%	27%	17
s6	50%	0%	50%	12.2
s7	59%	6%	35%	13.2
s8	47%	0%	53%	17.4
s9	45%	0%	55%	11.6
s10	81%	11%	8%	18.83
s11	57%	7%	36%	21
s12	50%	0%	50%	16.2
s13	53%	18%	29%	19.2
s14	42%	8%	50%	10.2
s15	59%	0%	41%	17

On average, participants were able to complete the experiment in 16 seconds. As shown in the table, most of subjects realized smaller rotations (i.e., smaller than 90°), which have low risk of musculoskeletal conditions, on the short term. Nevertheless, more than 30% of participants (e.g., s2, s6, and s8) are at risk, because they realize larger movements, which involve excessive rotations of the wrist and, thus, stress on ligaments that can potentially cause permanent conditions, on the long term. Moreover, by analyzing the time and the frequency of the movement, we could identify potential problems due to the repeated quick rotations, which also might be dangerous.

Overall, we registered 66% improvement in task speed, and 83% increase in achieving the objective more safely.

6 Conclusion

According to the literature and to recent reports about workplace safety, of work-related injuries could be avoided by improving task training and by increasing workers' risk awareness [4]. Nevertheless, current training systems based on Virtual Reality and on the analysis of movement are not suitable for being employed in work settings due to their cost and lack of context adaptability.

In this paper, we described an immersive system consisting of wearable devices and, specifically, a novel haptic interface, for providing individuals with VR-based hands-on training on hazardous tasks. Moreover, we discussed the experimental study about the efficacy of the proposed system: preliminary data from a group of users in a simulated environment support its viability as a tool for improving individuals' safety using a learning-by doing approach.

Future work will include extensive trials in actual industrial scenarios, to evaluate the consistency of the training effect and the effectiveness of its portability to real-life contexts. Although in this work Task 2 simulated a highly dangerous maneuver, the system might have better applications in contexts where interaction involves less hazardous operations with risks are subtler and related to long-term conditions rather than immediate accidents. Moreover, several aspects of the proposed system will be investigated, such as, integration of the haptic component in infrastructure-based immersive environments, e.g., CAVE. Also, interesting directions for further research include human factors (e.g., evaluation of motion sickness) and physiological aspects, such as, comparison with movement patterns from individuals suffering from hand-related conditions.

References

1. U.S. Bureau of Labor Statistics, Employer-reported workplace injuries and illnesses, 2015.
2. UK Government Health and Safety Executive. Statistics on fatal injuries in the workplace in Great Britain, 2016.
3. Burt C. D. B. New Employee Accident Rates: pp. 9-22, 2015.
4. Breslin F.C. and Smith P. Trial by fire: a multivariate examination of the relation between job tenure and work injuries. Occupational and Environmental Medicine 2006; 63:27-32
5. Muggleton, J. M., Allen, R., & Chappell, P. H. (1999). Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. Ergonomics, 42(5), 714-739.
6. Bliss, J. P., Tidwell, P. D., & Guest, M. A. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. Presence: Teleoperators & Virtual Environments, 6(1), 73-86.
7. Ragazzoni, L., Ingrassia, P. L., Echeverri, L., Maccapani, F., Berryman, L., Burkle, F. M., & Della Corte, F. (2015). Virtual reality simulation training for Ebola deployment. Disaster medicine and public health preparedness, 9(5), 543-546.

8. Van Wyk, E., & De Villiers, R. (2009, February). Virtual reality training applications for the mining industry. In Proceedings of the 6th international conference on computer graphics, virtual reality, visualisation and interaction in Africa (pp. 53-63). ACM.
9. Patel, R., & Dennick, R. (2017). Simulation based teaching in interventional radiology training: is it effective?. Clinical radiology, 72(3), 266-e7.
10. Renner, A., Holub, J., Sridhar, S., Evans, G., & Winer, E. (2015, August). A virtual reality application for additive manufacturing process training. In ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. V01AT02A033-V01AT02A033). American Society of Mechanical Engineers.
11. Aguinas, H., Henle, C. A., & Beaty Jr, J. C. (2001). Virtual reality technology: A new tool for personnel selection. International Journal of Selection and Assessment, 9(1-2), 70-83.
12. Davis, M. C., Can, D. D., Pindrik, J., Rocque, B. G., & Johnston, J. M. (2016). Virtual interactive presence in global surgical education: international collaboration through augmented reality. World neurosurgery, 86, 103-111.
13. Muhanna, M. A. (2015). Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions. Journal of King Saud University-Computer and Information Sciences, 27(3), 344-361.
14. Ng, A. K., Chan, L. K., & Lau, H. Y. (2017, March). Corrective feedback for depth perception in CAVE-like systems. In Virtual Reality (VR), 2017 IEEE (pp. 293-294). IEEE.
15. Coburn, J. Q., Salmon, J. L., & Freeman, I. (2018). Effectiveness of an Immersive Virtual Environment for Collaboration with Gesture Support Using Low-Cost Hardware. Journal of Mechanical Design, 140(4), 042001.
16. Chang, T. P., Gerard, J., & Pusic, M. V. (2016). Screen-Based Simulation, Virtual Reality, and Haptic Simulators. In Comprehensive Healthcare Simulation: Pediatrics (pp. 105-114). Springer, Cham.
17. Zhao, D., & Lucas, J. (2015). Virtual reality simulation for construction safety promotion. International journal of injury control and safety promotion, 22(1), 57-67.
18. Caporusso, N., Biasi, L., Cinquepalmi, G., Trotta, G. F., Brunetti, A., & Bevilacqua, V. (2017, July). A Wearable Device Supporting Multiple Touch-and Gesture-Based Languages for the Deaf-Blind. In International Conference on Applied Human Factors and Ergonomics (pp. 32-41). Springer, Cham.
19. Taylor, K., Engsberg, J., & Foreman, M. (2016). Utility and Usability of the MYO Gesture Armband as a Fine Motor Virtual Reality Gaming Intervention. Archives of Physical Medicine and Rehabilitation, 97(10), e125.