Developing a 3D Laparoscopy Training Application to Assess the Efficacy in Virtual Reality Environments

Ege Yosunkaya[1](✉), Sebahat Selin Şahin[2], Elif Surer[1], and Hasan Onur Keleş[2]

[1] Department of Modeling and Simulation, Graduate School of Informatics, Middle East Technical University, 06800 Ankara, Turkey
ege.yosunkaya@metu.edu.tr

[2] Department of Biomedical Engineering, Ankara University, 06830 Ankara, Turkey

Abstract. This study aims to develop a multimodal understanding of transferring an established method of laparoscopy training to the virtual reality domain. The virtual reality version of the laparoscopic box trainer is developed and tested with 15 participants. Post-experiment questionnaires showed the version of the simulation with tutorial and haptic feedback is acceptable in terms of usability and received better feedback in the technology acceptance model questionnaire. Furthermore, the kinematic behavior of participants' hands showed a significant distinction between above-average and below-average completion time groups similar to the physical and computer-based non-immersive simulation counterparts. The physiological response of the participants is investigated between rest state and during the task with an Electrocardiogram (ECG) and indicators of increased mental workload are observed with increased heart rate and decreased heart rate variability. The interest in assessing the physiological and kinematic features of trainees in a virtual reality (VR) environment is on the rise and the proposed study is very promising in terms of enhancing the development of improved training and assessment methodologies.

Keywords: Virtual Reality · Assessment · Laparoscopy · Training · System Usability Scale

1 Introduction

Virtual reality (VR) technology has rapidly advanced, offering immersive and realistic simulated environments. These virtual platforms have been extensively utilized in various fields, including aviation, military, and gaming, for training and skill development purposes. The application of VR in surgical training has shown promising results, particularly in laparoscopy by creating a safe and controlled environment for trainees to practice surgical techniques, refine their psychomotor skills, and gain experience before operating on patients. During the last several decades, laparoscopy, the most common form of minimally invasive surgery, has spread widely in high-income countries, although some of the training still takes place in a master-apprentice format. The

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advantages of laparoscopy include lower cost, short hospital stay, and rapid return to work. Many surgeons have acquired laparoscopic abilities in an informal fashion ("see one, do one"), ultimately compromising patient safety. Proper training for laparoscopy is not cheap, especially for lower-middle-income countries, and creates an accessibility barrier [1]. Moreover, laparoscopy training has been identified as one of the obstacles to the adoption of laparoscopy where resident surgeons in the USA reported a lack of case volume, unexpected scenarios, and technical familiarity with using devices such as depth perception and video-eye-hand coordination as limiting factors [2]. Laparoscopy training is different from situational awareness training because the trainee not only gains situational awareness but improves their skill by developing hand-eye coordination and getting familiar with the shift from a three-dimensional operating environment to a two-dimensional camera as well. There are specialized simulations for laparoscopy training in various levels of virtualization, and box trainers [3] provide a fully physical experience. VR-based training in laparoscopy allows trainees to interact in a real-time learning environment, which would be nearly impossible to do in the physical world. VR-based training methods have shown to be an effective means of enhancing laparoscopic skills both in the operating room and in the laboratory compared to non-VR training methods [4–7]. Commercially available VR training systems are currently accessible in a variety of forms. Two known VR systems employed in laparoscopy training are MIST-VR® and LapSim®[1]. MIST-VR® incorporates a screen and physical graspers [8], while LapSim® employs physical laparoscopic graspers in conjunction with a head-mounted display. Moreover, Diesen et al. concluded there is no significant difference between box trainers and VR in terms of time to learn and after training skill level after a long period of training [9]. However, the computer-based VR systems in the aforementioned studies use a semi-virtual environment with physical graspers, mainly because it is not possible to provide force feedback in a generic VR controller and create a virtual environment that closely simulates the real world while eliminating the necessity for physical materials to operate on.

Advances in wearable technologies allow easy physiological data collection from the surgeon during the training in the physical box and the VR-based methods. Although several studies focused on the effect of the physical box on human physiology [10, 11] the assessment of VR-based training is still new and has many unknown questions regarding human physiology. In addition, there is a lack of deep understanding of how Virtual Reality can influence complex learning in medical education. Our preliminary results will help to assess how skills acquired through Virtual-Reality enabled training transfer to the field.

In surgical education, objective assessment of surgical skills is essential because performance in training and performance is difficult to correct without objective feedback. Traditional approaches to studying skills use bulky equipment, behavioral metrics to measure performance, and surveys of subjective experience. These inhibit the ability to collect data in realistic settings or provide only intermittent data, or intrusive methodologies. In the literature, heart rate (HR), and heart rate variability (HRV), have been correlated with mental workload scores as well as task complexity in similar simulation-based

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[1] Surgical Science Ltd., Gothenburg, Sweden, https://surgicalscience.com/simulators/lapsim/, Last accessed: 2023–07-01.

tasks [12, 13]. Few studies focused on combining VR environments and physiological sensors during general virtual reality learning context and surgical training [14–16].

In this study, we developed VR-based training environments using standardized tasks including Peg Transfer and String Pass. We evaluated the VR-based training on human subjects using kinematic, psychological, and subjective measures. Our aim is to develop the VR-based training platform as a multimodal assessment tool rather than just a laparoscopic trainer.

This study proposes methods for transferring established methods of psychomotor training into a virtual reality environment and investigates how skill evaluation methods translate for fully immersive environments. The simulation is implemented using the Unity3D game engine[2] and Oculus Quest 2 as VR hardware. To evaluate the usability and technology acceptance aspects of the simulation, 15 higher education students performed the tasks and answered System Usability Scale (SUS) [17] and Technology Acceptance Model (TAM) [18] questionnaires. Motion tracking is implemented into the game to track the position and rotation of both hands and the head-mounted display to find relations between task performance and kinematics. Moreover, a three-channel ECG is recorded during the tasks for each participant.

Our work integrates kinematics, psychological responses, and subjective feedback to provide multi-dimensional understanding for fully immersive simulations in psychomotor training. Furthermore, this study has been expanded upon in a Master's thesis [19], incorporating a larger number of participants. Additionally, the simulation's design phase has been thoroughly examined, and the topics addressed in this study have been discussed.

2 Methods

2.1 Task Design

Two laparoscopy standardized training tasks, peg transfer and string pass are selected to be implemented in a virtual reality environment. The peg transfer requires the user to pick a small object using the graspers, change hands without dropping the object, and insert the object into the target location. In string pass, the user grasps a thin rope and moves it between circles in a pre-determined order. Both tasks are designed by medical professionals to help entry-level trainees develop the required motor skills, depth perception, and hand-eye coordination to conduct minimally invasive surgeries. Moreover, both tasks require the user to develop depth perception with the two-dimensional camera and hand-eye coordination for both hands. The users are evaluated by completion time, and the task is ended after six minutes if not finished.

2.2 Game Design

The game was developed with the Unity3D game engine and tested with Oculus Quest 2. We used official integration libraries to establish communication between the Quest and the game engine. The grasper models are open-source and used from Unity Asset

[2] Unity Real-Time Development Platform, https://unity.com, Last accessed: 2023–06-28.

Store. The operation room, task materials, and all other UI elements are designed from scratch. The objective of the simulation is to replicate the authentic experience provided by the box trainer. Consequently, initial trials are conducted on the physical box trainer prior to the commencement of simulation development.

The controls are mapped to reflect the box trainer, where the user holds the grasper with the "PrimaryHandTrigger" button on the controller and controls the tip of the grasper with the "PrimaryIndexTrigger" button. Moreover, the thumbstick of the controller controls the rotation of the tip of the grasper.

We implemented two versions; the first version has no tutorial, and the physics of the graspers is more realistic. The second version has the tutorial, and the grasper physics is eased with snapping. Moreover, the second version has haptic feedback to help the user understand if the tip of the grasper touches a solid object to mimic force feedback. Given that the VR training version does not have force feedback to restrict the movement of trainees' hands during collisions, it becomes crucial to replicate this tactile sensation in an alternative manner. The implementation of haptic feedback from the controllers presents a viable method to address this issue. We designed a minimal user interface to not intervene with the immersion, the tutorials have a button for skipping the tutorial and on-screen guidance text, whereas the real task only shows the elapsed time, the number of targets remaining, and the number of errors made.

The tutorial part of both tasks is divided into subtasks that show the required movement, for the peg transfer, the user needs to grab one peg, switch hands, and drop into the target location. The tutorial for string pass uses one solid object that subrogates the tip of the string. The user is required to grab the object, pass it through the ring, grab it with the other grasper, and drop it into the target zone. User is guided with texts in each step of the tutorial and can reset their state to initial if needed. The task starts after the user clicks the "Finish Tutorial" or "Skip Tutorial" buttons, and an automatic timer is started when the user grabs both graspers and records the finish time when all required tasks are completed. Moreover, with the grabbing of two graspers, the simulation starts to record the positions of both hands in 3D space and the rotation as a quaternion. It is saved to the device file system with unique identifiers when the task finishes or if the user quits the application. Sample scenes from the game for tasks and their respective tutorials can be seen in Fig. 1.

2.3 Experiment Setup

All subjects voluntarily participated and were briefed about the ECG and motion data collection as well as post-experiment questionnaires and properly instructed before the experiment began. Ethical approval of this research was initially granted by the Middle East Technical University Human Subjects Ethics Committee in December 2021 (454-ODTU-2021) and revised to include physiological data collection in April 2023 (0171-ODTUİAEK-2023).

The experiment is carried out with the participant assuming a standing position and wearing the Oculus Quest 2 head-mounted display together with the controllers. The second version is performed subsequent to the completion of the first one. In the second version, the user proceeded to engage in each task by initially completing the related tutorial section. Following this, a resting ECG was collected for a duration of one minute,

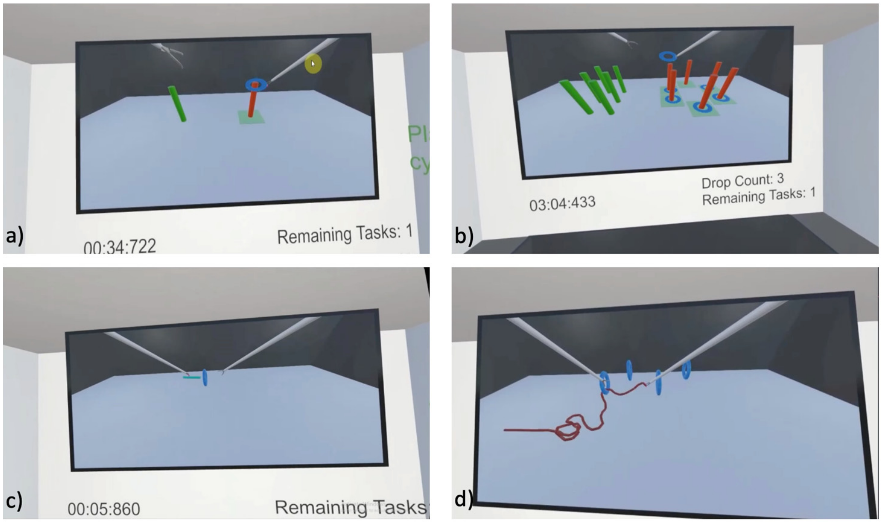

Fig. 1. Sample in-game point-of-view screen captures from the (a) Peg Transfer tutorial, (b) Peg Transfer task, (c) String Pass tutorial, and (d) String Pass task.

after which the user resumed the real task. An observer watched the user's perspective while the user was playing. The playing of the first version took about 15 min. The second version, with the preparation of ECG, resting records, and tutorials took about an hour. Thus, the total process was approximately 90 min per participant. The questionnaires are filled out by the participants after the procedures are done. The flow of the experiment can be seen in Fig. 2.

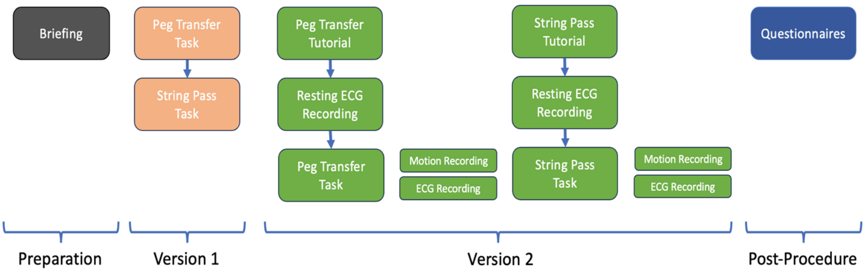

Fig. 2. Flow of the experiment procedure.

2.4 User Experience Evaluation

The implemented simulation is an immersive experience, and it is important to receive feedback on how users felt during the tasks. Moreover, usability and acceptance of the system are important for the simulation to be effective and used as a valid replacement for physical methods. The experience is evaluated on two aspects; the usability of the system, which is evaluated by the System Usability Scale (SUS), a 5-point Likert scale questionnaire of 10 questions. SUS has both negative and positive questions and it has the scoring method that is commonly used in literature. The other aspect is technology acceptance, which focuses on self-perceived usefulness and ease of use. The Technology Acceptance Model (TAM) questionnaire is a 7-point Likert scale and helps us to understand if this newly introduced technology is accepted.

2.5 Kinematic Analysis of Participants' Hand Movements

The motion of both hands is captured during the tasks to analyze the relationships between motion and participant success in a VR environment. It has been previously shown that there are significant relations between velocity and jerk and psychomotor skill level in a box trainer environment [20]. Moreover, the motion capture data is processed the extract significant kinematic features, such as velocity, acceleration, and jerk. The mean velocity of a participant's hand is calculated by finding position change per frame and differentiating by the time between each frame and calculating the sample mean of the observed velocities by difference of position between frames (Eq. 1), where n is the number of frames. Likewise, the mean jerk is calculated as the second derivative of the velocity (Eq. 2).

$$\frac{1}{n}\sum\sqrt{\left(\frac{dx_i}{dt}\right)^2+\left(\frac{dy_i}{dt}\right)^2+\left(\frac{dz_i}{dt}\right)^2} \quad (1)$$

$$\frac{1}{n}\sum\sqrt{\left(\frac{d^3x_i}{dt}\right)^2+\left(\frac{d^3y_i}{dt}\right)^2+\left(\frac{d^3z_i}{dt}\right)^2} \quad (2)$$

2.6 Analysis of Participants' Heart Rate and Heart Rate Variability

The ECG recording starts after the tutorial finishes. Participants are verbally briefed before the procedure starts and warned again about staying still until the observer presses the button located on the wireless recorder to mark the end of the 1-min resting period. The raw ECG signals collected from the participants are cleaned with the NeuroKit2 python package [21]. The peaks of QRS complexes are identified and heart rate (HR) and heart rate variability (HRV) are calculated. In some studies, a decrease in HRV is found as an indicator of mental workload [22]. Moreover, frequency domain features of HRV are also shown to be indicators of mental and physical load [23], thus low frequency (LF) and high frequency (HF) components of the HRV signal are calculated and included in the study.

3 Results

3.1 User Experience

The post-experiment questionnaire for system usability for version 1 and version 2 shows average scores of 57.5 and 69.17 respectively with the positive-negative scoring of the SUS questionnaire. Moreover, the scores per participant of the first and second versions are statistically different from each other according to the two-tailed t-test ($p = 0.016$). The TAM questionnaire also shows statistical significance with p-value < 0.001 increase in the second version with mean scores 4.561 and 5.789 respectively, indicating more acceptance for the second version. Moreover, for the second version, the mean value of ~ 5.8 with a standard deviation of 0.85 shows a good acceptance outcome on a 7-point scale. The participants are asked "What is your general opinion about the application?" after the questionnaires and free text responses are collected. Sample answers in Table 1 suggest that haptic feedback, tutorials, and assistance in grabbing mechanics improve the overall user experience.

Table 1. Sample Responses Version 1 and Version 2 to Question "What is your general opinion about the application?"

Topic	Version 1	Version 2
Controls	Overhaul of the controls would definitely benefit the game	It is way better than version 1 in terms of controls. The only issue I faced was it assisted a bit too much while grabbing the objects
Haptic Feedback	Adding vibrations, flashing lights, and setting controllers to be more sensitive can make it easier to use	Adding vibrations greatly improved the user experience
Tutorial	It would be good to add a description of the tasks before starting, explaining how to do them	This version felt generally similar to Version 1. The tutorials made it easier to get the point and what the subject had to do in the steps

3.2 Kinematic Analysis

The mean completion time of Peg Transfer was ~ 2 min 9 s and ~ 1 min 35 s for String Pass among participants who were able to finish the task. Whereas three participants for each task did not finish the task in time. Moreover, one user has not been recorded in the Peg Transfer task, and one has not been recorded in both tasks due to an issue in the test device, thus those users are excluded from the kinematic analysis. Users are split into two groups according to their finish times, where we consider the top half successful. In Fig. 3, we can see the mean velocity distributions of the participants for both hands and each task. The difference in mean velocity of the two groups is statistically significant in the left hand and right hand for Peg Transfer with p-values 0.003 and 0.025. In the String Pass task, the two groups are different in terms of the mean velocity of the left hand ($p = 0.026$), however, the right-hand mean velocity did not show any significant difference ($p = 0.06$).

The jerk, a frequently used kinematic parameter, shows significance in assessing the smoothness of movement across several tasks and for both hands (see Fig. 4). This significance is supported by statistical analysis, with p-values less than 0.03 for both

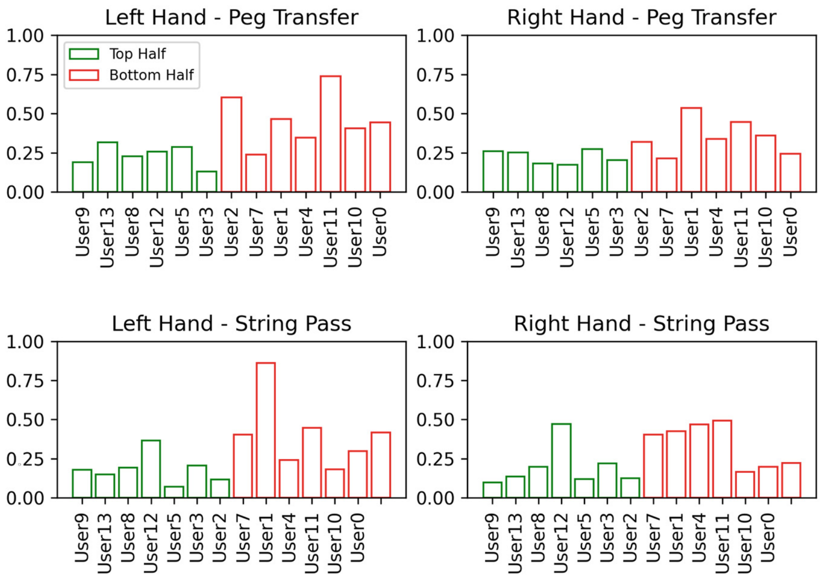

Fig. 3. Mean velocities (m/s) of each hand of the users for both tasks.

hands in the Peg Transfer task and p-values less than 0.04 in the String Pass task, measured using a two-sided t-test.

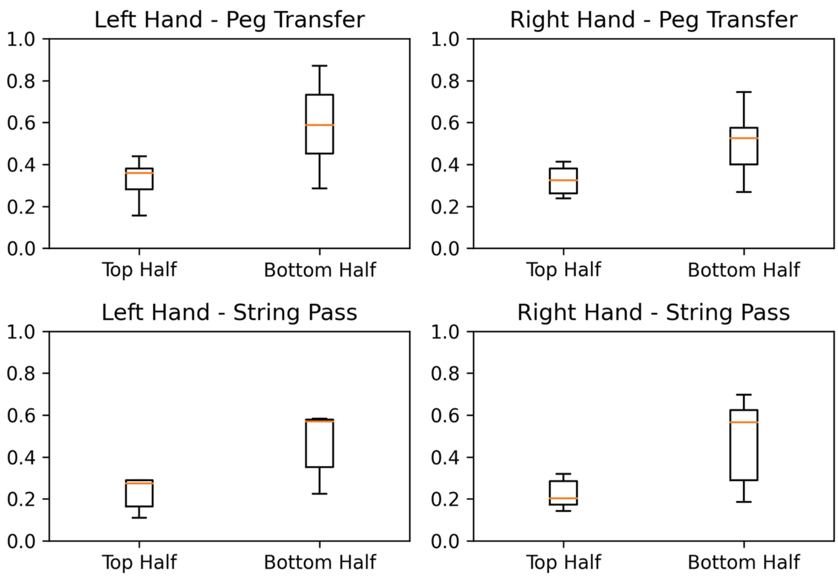

Fig. 4. Distribution of mean jerk (m/s^3) of each hand of the users for both tasks.

3.3 ECG Analysis

The heart rate of the participants is investigated to understand the physical response to doing the procedure in a VR environment. The mean heart rates of the participants are significantly less in resting than during the play according to the one-sided t-test. However, there is no significant difference is found between successful and unsuccessful groups in terms of heart rate for both tasks while playing. Furthermore, the mean distance between normal RR peaks (MeanNN) is also significantly decreased between resting and playing states as shown in Table 2. However, the frequency domain features of HRV; low-frequency component of the signal 0.04 Hz and 0.15 Hz (LF), the high-frequency component of the signal 0.15 Hz to 0.4 Hz (HF), and the ratio of LF and HF (LF/HF), did not show any significant difference between rest and playing.

Table 2. Descriptive statistics of mean HR and mean distance between normal RR peaks (MeanNN) of the participants for each task between resting and playing states.

		Mean	SD	*t*	*p*	*df*
Heart Rate (bpm)						
Peg Transfer	Resting	84.78	10.4	–3.87	< 0.001	13
	Playing	89.11	9.94			
String Pass	Resting	86.88	11.55	–2.18	< 0.025	13
	Playing	89.22	10.70			
MeanNN (ms)						
Peg Transfer	Resting	717.64	84.42	4.50	< 0.006	13
	Playing	681.58	79.71			
String Pass	Resting	702.08	91.88	2.44	< 0.030	13
	Playing	682.61	87.91			

4 Discussion

In the developed VR application, post-procedure questionnaires showed that the second version with haptic feedback and tutorials made the application more usable. The first version was "not good" in terms of usability whereas the second version is acceptable according to SUS. Moreover, significant improvements in acceptance scores are observed in the second version compared to the first. Haptic feedback is an important tool for VR environments in laparoscopy training because of the lack of real graspers and their interaction with solid objects. It is used in the study to mimic the force feedback and is seen to improve user experience along with the other changes done in the second version. Moreover, even though the participants were briefed about the task and the required motion to accomplish the tasks verbally, tutorials still improved the usability according to the questionnaires and free text responses. It can be said that using the advantages of virtual reality by integrating the methods that are commonly used in games can improve the experience of the users in VR-based laparoscopy training.

The motion analysis is thoroughly used for predicting or evaluating the skill level of the trainees in literature both in box trainers and computer-based simulations with physical graspers. The analysis shows that the same pattern of motion exists even without the need for a physical device. Mean velocity and jerk are distinguishing factors between the top half and the bottom half of the participants according to their finish times in both tasks, where the mean jerk inversely related to the smoothness of the motion is significantly less in the more successful group. Showing the parallel between the kinematics of training with physical devices and training in VR paves the way for automatic skill evaluation, personalized training, and other benefits of immersive environments.

HR and HRV comparison between resting state and during training can provide insight into the mental workload (MWL) of the trainee. Estimating MWL is important for proper training because studies showed that mental MWL is inversely correlated with task performance in laparoscopy training and experienced surgeons can perform the tasks with less MWL [24, 25]. Thus, MWL is both a differential factor and a parameter to reckon with to design a training procedure. We found out that HR increased and HRV decreased significantly during the training. The mean HR increase between rest and training was about 4% and is not sufficient to suggest physical load. However, an increase in HR and a decrease in HRV combined suggest increased MWL in participants during the training. However, the LF, HF, and LF/HF indices of HRV did not show significant differences, therefore our results did not indicate MWL difference between the top and bottom half groups. This might be due to a lack of practice and familiarity between both groups since we cannot distinguish them as experts and novices as in previous studies. The HR and HRV can be measured with wearable devices and estimations on MWL can be integrated into training in real time.

5 Conclusions and Future Work

Ours is a preliminary work for immersive psychomotor training in various fields. Laparoscopy is an important way of minimally invasive surgery and making its training more accessible with customer-grade products, more scenarios and personalized training is important for achieving broader adaptation. Our work shows the parallels between currently used methods and VR-based training and suggests ways to understand physiological responses during training and analysis of kinematic behavior in an automatic fashion.

We intend to increase the sample size of the participants and study the differences between groups with different levels of virtual reality experience and familiarity with games. Also, we are planning to conduct experiments with surgeons with various levels of expertise to understand if the real-life skills are translating into immersive VR performance. The kinematic analysis can be done in real-time during the training and the effects of personalized learning performance tasks can be investigated.

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