2024 IEEE International Conference on
Advanced Robotics and Its Social Impacts (ARSO)
Hong Kong, China, May 20-22, 2024

2024 IEEE International Conference on Advanced Robotics and Its Social Impacts (ARSO) | 979-8-3503-4463-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/ARSO60199.2024.10557821

Comparison and Analysis of Human Comfort in Virtual Reality (VR)-based and Reality-based Human-Robot Collaboration Tasks

Yuchen Yan, Kexuan Zhai and Yunyi Jia

Abstract— **Virtual Reality (VR) has been used in robotics fields due to its convenience and cost-efficiency compared to actual reality. Whether the VR application can truly simulate the actual reality and offer a similar immersive experience has always been a research question. Most existing studies mainly focus on the usability of VR compared to actual reality. In addition to usability, whether VR can reproduce the human comfort feeling, which is different from VR motion sickness but instead the comfort while interacting with a virtual robot compared to a real robot, still remains unanswered. Therefore, this paper aims to explore this issue with a focus on human comfort through experimental studies in both VR-based and reality-based human-robot collaborations. The experiments require human subjects to collaborate with a real Yumi robot with a VR-based virtual Yumi robot to accomplish a series of tasks. A comprehensive analysis of the results is performed, including the effectiveness of the VR in reproducing human comfort feeling and the cases when VR could not do it well.**

Keywords: virtual reality, human comfort, human-robot collaboration

I. INTRODUCTION

The Human-Robot Collaboration (HRC) is defined as "the state of a purposely designed robotic system and operator working in a collaborative workspace [1]". HRC has become a hot topic of research and application in recent years. The comfort of humans plays a very critical role in their production. It is also more challenging due to the unpredictability of human feelings. The comfort level of humans affects the efficiency of manufacturing, which has become an important issue [2], [3], [4].

In recent years, there has been some latest research on human comfort during HRC manufacturing tasks. For instance, Wang et al. [5] proposed a computational Human Comfort Model (HuCoM) approach to model and quantify human comfort during human-robot collaborative manufacturing. Ross et al. [6] found that human comfort has a direct and immediate influence on the collaboration quality between the robot and its human partner, which is also a significant factor for the robot to be aware of. Przemyslaw et al. [7] examined human response to motion-level robot adaptation to determine its effect on team fluency, human satisfaction, and perceived safety and comfort.

While most of the current research on human comfort uses robots to conduct experiments in a real laboratory environment, they are also costly and time-consuming. Moreover, under some special circumstances such as a pandemic, such traditional on-site experimental methods may also introduce safety risks and concerns. In order to deal with these issues, remote experiments using virtual reality can be an alternative. A VR device can be given to the experimenters, and they can complete the experiments at some remote or safe locations. It will thus have a lot of unique benefits, including more cost savings, more convenience, better time efficiency, and even better safety.

Although virtual reality technology has emerged for decades, it has only been widely adopted and acknowledged in the manufacturing field in recent years [8], [9], [10], [11], [12] An increasing number of manufacturing companies are leveraging VR technologies to help their new-recruited employees to get their hands on their new positions in a shorter period, for the vividness and sense of presence brought by the VR technology makes it the best alternative solution for staff training [13], [14]. The advantages of adopting VR for staff training in manufacturing include but are not limited to lower cost, no risk of danger or injuries, a highly tunable environment and setups, and a higher tolerance for operating mistakes.

Despite the benefits that VR provides, there remains one question which is whether the VR application can truly simulate the actual environment and offer a similar immersive experience. In recent years, some research about the evaluation of the immersive experience for VR-simulated scenarios has been conducted since greater levels of immersive quality elicit higher levels of presence, in turn enhancing the effectiveness of a mediated experience [15], [16]. Marc et al. [17] investigated and compared the differences in terms of presence between virtual reality and actual reality environments via usability studies. Kuowei et al. [18] used the think-aloud protocols, Questionnaire for User Interaction Satisfaction (QUIS), and User Experience Questionnaire (UEQ) to understand the user's thoughts on the UI and UX of VR E-commerce. Rui et al. [19] studied the differences between actual reality and VR with a focus on proxemic preferences in combination with exploring the effects of visual familiarity and spatial sound while using the robot. Sportillo et al. [20] developed a VR platform to train participants driving skills with a virtual vehicle and then transfer and compare the training effects with real vehicle driving scenarios.

Despite these efforts, most existing studies studied human feelings mainly from the usability perspective of VR compared to actual reality in different application fields. Human comfort while working with a robot is a very important

This work was supported by the National Science Foundation under Grant IIS-1845779. Yuchen Yan, Kexuan Zhai, Yunyi Jia are with the Department of Automotive Engineering, Clemson University, Greenville, SC 29607, USA. (e-mails: yucheny@clemson.edu; kzhai@clemson.edu; yunyij@clemson.edu)

issue to the user acceptance of human-robot collaboration. However, whether VR can reproduce a similar human comfort feeling while interacting with a virtual robot compared to a real robot still remains unanswered. The mentioned comfort above is different from the motion sickness caused by VR, but instead focuses on the human comfort feeling while closely working with a robot. This will determine if VR can be used to study human comfort in human-robot collaboration research in addition to the usability experience. Therefore, the contribution of this paper is to explore human comfort feelings in VR-based and real human-robot collaborations under different robot motion behaviors and find out how these different robot motion factors will affect the comfort feelings of humans between VR-based and real human-robot interactions.

II. HUMAN COMFORT STUDIES IN HUMAN-ROBOT COLLABORATION

A. Actual Reality-based Human-Robot Collaboration

The reality-based experiment platform is shown in Fig. 1. The Yumi robot is placed on one side of the experimental platform. The human subject stands on the other side of the experimental workbench and will interact and collaborate with the robot in manufacturing tasks. We choose the most common collaborative tasks in manufacturing in the study, i.e., robots delivering parts to human.

The Yumi robot is controlled by our built control system in ROS. The higher-level Yumi motions for both arms are generated and executed in ROS. For example, there are two cube parts placed on the left and right sides of the workbench. Given a deliver task, e.g., delivering the right cube to the left hand of the human, the ROS control system will first generate the action plan to pick up the cube, move the cube and then deliver the cube. Since the focus of this study is not robot autonomy but human comfort, we have structured the working environment where all object positions are known. Based on the positions, the control system will generate the motions in terms of trajectories of the end-effector, and then the Yumi motion controller is used to generate and execute joint motions to drive the robot to follow these trajectories. The same ROS Yumi control system will be used to control the virtual Yumi robot arms' motion in the VR experiment later.

The human wears marker gloves on both hands so that the motions of his/her hands can be precisely tracked by a Vicon motion tracking system. The human can use his hands to trigger the robot part delivery motions. For example, when the left hand is raised, it triggers the robot to deliver a part to his left hand. A variety of robot part delivery solutions will be created and executed to evaluate human comfort changes. The creation of delivery solutions will be introduced in a later section.

B. Virtual Reality (VR) based Human-Robot Collaboration

The setups of the VR-based human-robot collaboration are shown in Fig. 1. The virtual reality interactive environment is constructed by bridging the Robot Operating System (ROS) and the Unity Real-time Development Platform, allowing each platform to fully utilize their respective advantages. Unity is responsible for the visualization and all other interactive activities during the VR experiment process. The virtual scenes, including all 3D models (e.g., workbench, parts, walls, etc.) except for the Yumi robot, are constructed with the help of Blender and Unity's built-in modeling tools. The Yumi 3D model is then imported into Unity. Some refinements were taken in Unity to make the graphics more realistic and vivid, thus enhancing the sense of immersion and presence, such as adjusting the environment lighting conditions and reflections, and using high-resolution texture materials, etc. It is worth noting that although Unity is also capable of controlling the robot's joint motions, it is however insufficient for our tasks because we need task-level planning and controls and transfer the task-level motions to joint-level motions using the kinematic model of the robot. The ROS control system we built in reality-based human-robot collaboration is utilized here and is responsible for the planning and control of the virtual Yumi in Unity.

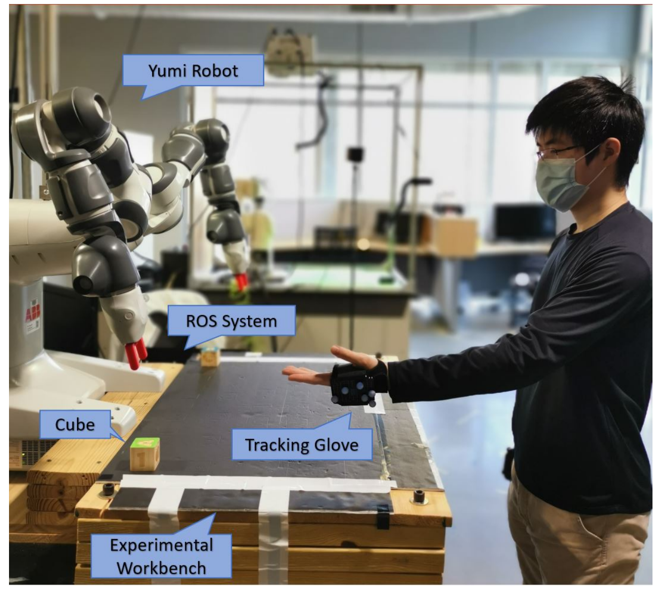

Fig. 1. Reality-based Human-robot collaboration with Tracking System.

After the virtual Yumi robot and virtual working environment are created, a virtual human is also added in Unity. The human is equipped with a full set of VR devices, including one head-mounted display (HMD) device, two controllers, and two base stations (lighthouses) for device tracking. He/she will immersively observe the VR environment and hold the controllers on his/her left and right hands to control the virtual left and right hands in VR, respectively in order to interact with the VR Yumi robot.

ROS and Unity are connected through ROS Rosbridge, and Unity's plug-in tool named ROS# developed by Siemens. ROS publishes the joint motions of the Yumi robot as a topic message while Unity's interface connector ROS# node will subscribe to it and synchronize the robot arm motions in the VR scene in real time. ROS# not only enables Unity to

Fig. 2. The Framework of the VR-based human-robot collaboration.

receive the command from ROS but also enables Unity to publish topic messages back to the ROS environment so that ROS can make further reactions based on Unity's events.

The same robot-to-human part delivery task in a reality-based experiment is used in the VR-based setup. The same cube parts are created in VR, and the robot needs to pick up the parts and deliver them to humans in different ways. As illustrated in Fig.2, The human hand motions in the VR scene are tracked by the VR controllers in their left and right hands, which will be used to not only control the virtual hands but also trigger the robot part delivery motions, e.g., raising the left-hand controller triggers the robot to deliver a part to the human left hand. A variety of robot part delivery solutions will be created and executed to evaluate human comfort changes.

C. Comfort Studies in Human-Robot Collaboration

In order to study the differences between human comfort in reality and VR-based human-robot collaboration, we need to create scenarios that can result in different human comfort levels. In this study, robot part delivery tasks are used and the robot motion factors are employed as the trigger to change human comfort. Based on the results of our prior study [5], we have selected the following key motion factors as variations in robot part delivery motions, including the robot delay time (i.e., delay of robot response after the human asks for a part), robot moving speed, delivery distance, delivery height and the use of robot left or right arm, due to the fact that these factors have been proved to have great impacts on human comfort. The delivery distance refers to the shortest horizontal distance between the tip of the robot tool center point (TCP) and the human subject, and the delivery height refers to the vertical distance between the robot TCP and the working platform. A special factor is the use of the left or right arm of the Yumi robot for the delivery task because it can also be an impact on human comfort level. The variations of motion factors are shown in Table 1. Each factor has seven different levels to choose from, except for the robot arm choice which has only left or right option. One robot delivery solution can be generated by using a combination of different values of the factors. With this setup, we have selected 58 robot part delivery solutions which can produce distinct human comfort feelings and implemented them in both the VR-based and reality-based experiments.

Before the experimental process starts, a thorough training session will be carried out. The human subjects will get familiar with the VR setup, real robot setup, and human-robot collaborative tasks in both setups. These training tasks are similar to the tasks in the experiments but will not appear in the experiments. The height of the human subject in the VR scene will be appropriately adjusted offline before experiments so as to make the subject have the same relative height with respect to the robot and the working platform. During the training session, subjects will also experience some extreme scenarios such as the fastest robot speed and highest delivery height to calibrate their expectations of the most uncomfortable feelings. This training stage carries on repeatedly until the subject confirms that he/she feels fully prepared, and then the human subject's proficiency in the operations will be double-confirmed before starting the experiments.

During the experiments, the scenario tasks will be carried out in a random sequence between VR-based and Reality-based experiments. The total experimental time for each subject is about 2 hours. In each task, a virtual/real Yumi robot will pick one part and deliver it to the subject with a specific motion behavior, and the subject needs to grab the part from the robot and then place it in an assigned area. At the same time, the subject needs to report his/her comfort level using a 5-point Likert scale by speech which is recognized by our speech recognition APP, in which 5 indicates the highest comfort and 1 indicates the highest discomfort.

To avoid other factors which may affect the human comfort feelings, especially the motion sickness of VR, the subjects have been instructed to evaluate their comfort feelings only based on the motion behaviors of the robot delivery rather than others. To minimize the VR motion sickness effects, VR has been divided into different sessions, and each session will be no more than 15 minutes. In addition, the subjects were asked to report their feelings about the task during both training and experiments. Whenever motion sickness symptoms occur, the study will be stopped, and the data will not be used. In total, 15-subject data were used between the age of 25 and 32, including 13 males and two females.

TABLE I
THE FACTOR COMBINATION SET TABLE

Factors /Levels	Delay Period(s)	Robot Speed	Distance (cm)	Height (cm)	Robot Arm
1	0	0.1	25	15	Left/Right
2	1	0.2	35	20	
3	2	0.3	45	25	
4	3	0.4	55	30	
5	4	0.5	65	35	
6	5	0.6	75	40	
7	6	0.7	85	45	

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Results and Analysis of Overall Comfort Evaluations by Individuals

We calculated the average and variance values of the comfort levels among all the experiment scenarios for each participant in both reality-based experiments and VR-based experiments. The average and variance data are listed in Table 2 and Table 3, respectively. The curve plots are also shown in Fig. 4, respectively.

From the results in Table 2 and Fig. 4, it can be seen that the orange curve which represents the reality-based experiment results, has almost the same trend and magnitude as the blue curve which represents the VR-based experiment results. This indicates that the comfort in VR-based experiments can be generally well reproduced in reality-based experiments.

TABLE II
THE AVERAGE COMFORT LEVEL THROUGHOUT THE ENTIRE EXPERIMENT OF EACH PARTICIPANT

Subject#	1	2	3	4	5	6	7
Reality	3.36	2.74	2.93	4.17	2.75	2.81	2.27
VR	2.93	2.65	2.82	3.98	2.87	2.5	2.39

Subject#	8	9	10	11	12	13	14	15
Reality	2.5	2.58	2.94	3.20	2.93	2.48	3.31	2.68
VR	2.75	2.27	2.89	3.01	3.20	2.74	3.34	2.58

Based on the results in Table 3 and Fig. 4, the comfort variance in reality-based experiments is slightly and generally higher than the comfort variance in VR-based experiments. Such a higher variance indicates that the reality-based experiment data are more widely dispersed within the comfort level interval and fluctuate more drastically. Based on each participant's individual evaluation data and post-interviews, we found that human subjects tend to feel safer in the VR environment and have a little higher sensitivity to the factor changes in robot motions. Human subjects provided more widely dispersed results due to the fact that they felt stronger in terms of discomfort changes in reality-based experiments. By looking into the data of individuals, it is found that almost all the extreme comfort data (i.e., very high or very low comfort ratings) for an individual are directly related to extreme factor values (i.e., very high or very low factor values) and the variance of comfort in such situations tends to be larger because they have high comfort or discomfort. In contrast, the virtual environment has alleviated human stress to some extent and weakened human feelings of comfort changes to a certain extent.

TABLE III
THE VARIANCE OF COMFORT LEVEL THROUGHOUT THE ENTIRE EXPERIMENT OF EACH PARTICIPANT

Subject#	1	2	3	4	5	6	7
Reality	1.00	0.93	1.18	1.02	1.16	0.96	0.55
VR	0.83	0.68	0.88	1.06	1.16	0.60	0.48

Subject#	8	9	10	11	12	13	14	15
Reality	1.13	0.91	0.47	1.18	1.01	0.74	1.34	0.91
VR	1.06	0.58	0.33	1.14	0.79	0.68	1.00	0.87

In addition, the correlation coefficient, which describes the degree to which a pair of variables are linearly related to each other in the data, is employed as the metric to measure the degree of relation in human comfort transition between reality-based experiments and VR-based experiments. The correlation coefficient can take the value within a range [-1, 1], where a correlation value of 1 indicates the perfect positive correlation and vice versa. As shown in Fig. 4, the average comfort ratings and the curve trends of real and VR-based experiments for all 58 scenarios are highly overlapped. The correlation of these two sets of data is 0.924 with a t-test p-value of 0.53e-25, thus indicating an extremely good correlation [21]. The correlation value indicates that the VR-based HRC tasks provide similar comfort level transitions as the reality-based experiment and thus further imply that, in general, human subjects tend to have similar comfort level evaluations in reality-based experiments and VR-based experiments.

Therefore, the results and analysis above suggest that VR-based experiments are able to reproduce the comfort feelings and transition of comfort feelings for humans similarly to the reality-based experiments in a general sense. In addition, VR-based experiments tend to result in a relatively small comfort variance of humans compared to reality-based experiments.

B. Results and Analysis of Comfort Evaluations by Factors

After finishing the general comparison of human comfort level between VR and reality-based experiments, the impacts of each factor are also investigated in order to find out under which conditions the VR technology will have good/bad performance in simulating reality. The results of the factors are presented into two groups named ”left arm,” representing using the robot's left arm to deliver the part to humans, and ”right arm,” representing using the robot's right arm to deliver the part to humans.

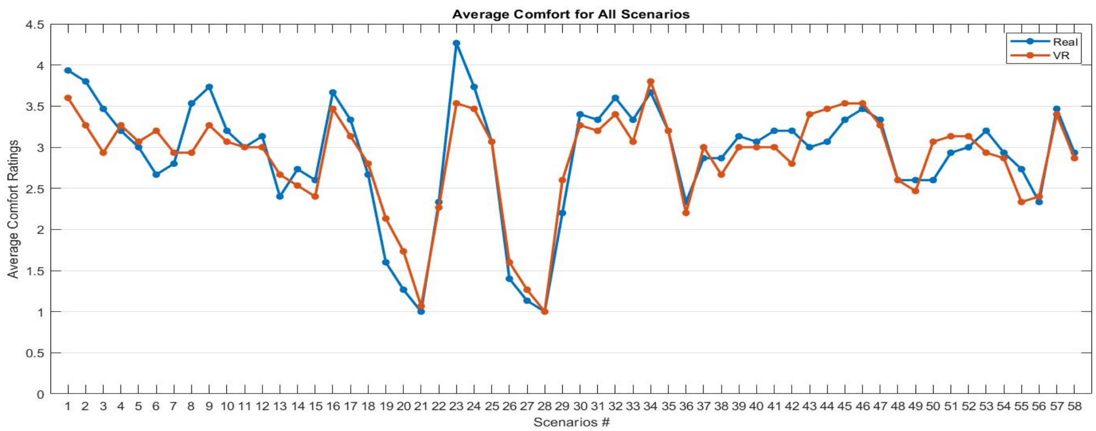

Fig. 3. Comfort Ratings of All Cases.

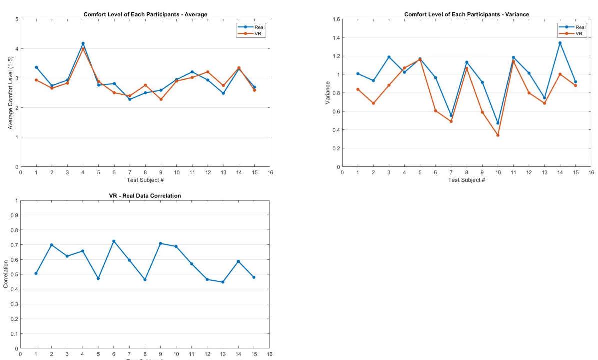

Fig. 4. The Average, Variance of Comfort Level of Each participant and VR-Real Correlation

The comfort evaluations to robot delay changes in both reality-based and VR-based experiments are shown in Fig. 5, which show the average comfort levels of all 15 subjects to different robot delays in the left arm and right arm scenarios, respectively. It can be seen that the comfort level decreases as the delay time increases in both reality and VR-based results. Although the shapes of these two curves are different, the maximum difference between the corresponding comfort levels has never exceeded 0.6. By a statistical calculation, the overall correlation coefficients are 0.594 with a t-test p-value of 0.16 and 0.821 with a t-test p-value of 0.024 for the left-arm and right-arm scenarios, respectively. The F-tests were also implemented; the p values were 0.048 and 0.083 for left/right arm scenarios, respectively, indicating that there is no difference in the variance of the right arm duration cases between the reality-based experiments and VR-based experiments. These results indicate that the VR-based experiment is reasonably good for simulating human comfort to the delay of robot response in human-robot collaboration when the delay times are chosen at mid-range values. The average comfort rating gap between VR-based and reality-based experiments tends to get larger when extreme values are taken.

In addition, it is also observed that comfort for the left arm is slightly higher than the comfort for the right arm in reality, and such change is also successfully reflected in the VR-based results. Furthermore, it is shown in both left-arm and right-arm results that VR curves tend to be slightly flatter than reality-based curves. This indicates a relatively low sensitivity to the robot delay changes in VR than reality.

From post-interviews, it is found that human subjects tend to be more patient with the robot in VR than in reality, which may have led to the relative sensitivity to delay time changes in VR.

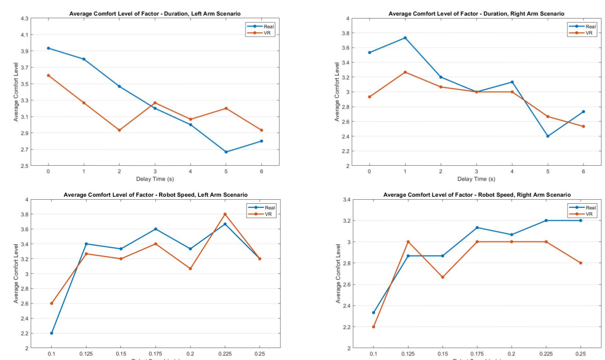

Fig. 5. The Average Comfort Level of Each participant in Delay and Speed

The comfort evaluations of robot speed changes in both reality-based and VR-based experiments are shown in Fig. 5, which show the average comfort levels of all 15 subjects to different robot speeds in the left-arm and right-arm scenarios, respectively. The results show that the comfort level increases quickly as the robot's speed increases to 0.125 m/s at the beginning, and afterward when the speed is more than 0.15 m/s, the comfort level increases slowly as the robot's speed increases and even drops when the robot speed is high.

This makes sense as the human subjects feel impatient when the robot moves too slow and some human subjects could feel stressed or nervous when the robot moves too fast. It can be clearly seen that both the reality-based and VR-based comfort curves capture this trend with consistency.

By a statistical calculation, the overall correlation coefficients are 0.97 with a t-test p-value of 3.8e-4 and 0.987 with a t-test p-value of 3.77e-5 for the left-arm and right-arm scenarios, respectively. The p values from F-tests were 0.238 and 0.475 for left/right arm scenarios, respectively, indicating that there is no difference in the variance of both the left and right arm cases between the reality-based experiments and VR-based experiments. This indicates that VR reproduces reality very accurately under the impact of robot speed changes, especially when the delay times are non-extreme values.

It is also observed that comfort for the left arm is slightly higher than the comfort for the right arm in reality, and such change is also successfully reflected in the VR-based results. Furthermore, it is shown that the comfort levels change in a relatively larger range in reality than in VR, although the difference is not very distinct. It indicates a slightly low sensitivity to the robot speed changes in VR than in reality.

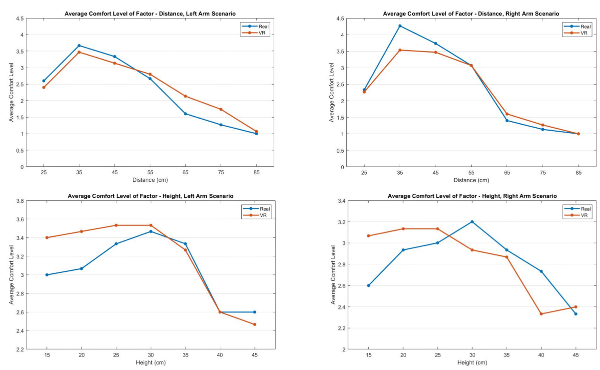

Fig. 6. The Average Comfort Level of Each participant in Distance and Height

The comfort evaluations of robot delivery distance changes in both reality-based and VR-based experiments are shown in Fig. 6. They show the average comfort levels of all 15 subjects to different robot delivery distances in the left-arm and right-arm scenarios, respectively. The results show that the comfort level increases quickly as the robot delivery distance increases between 25 cm and 35 cm at the beginning. As the distance keeps increasing after 35 cm, the comfort level starts to decrease consistently. This aligns with common sense as the human subjects feel stressed when the robot is too close and start to feel uncomfortable when the delivered part by the robot is too far to reach. It can be clearly seen that both the reality-based and VR-based comfort curves capture this trend very well. By a statistical calculation, the overall correlation coefficients are 0.897 with a t-test p-value of 0.0062 and 0.86 with a t-test p-value of 0.013 for the left-arm and right-arm scenarios, respectively. The p values from F-tests were 0.303 and 0.309 for left/right arm scenarios, respectively, indicating that there is no difference in the variance of both the left and right arm cases between the reality-based experiments and VR-based experiments. This indicates that VR-based experiments can well reproduce human comfort with the robot delivery distance in human-robot collaboration, even if the distances are chosen at extreme values. In addition, it is seen that comfort for the right arm changes in a bigger range than the comfort for the left robot arm in reality, and such range difference is also successfully reflected in the VR-based results. Furthermore, it is also shown in both left-arm and right-arm results that VR curves tend to be slightly flatter than reality-based curves. This indicates a relatively low sensitivity to the robot delivery distance changes in VR compared to reality in human-robot collaboration.

The comfort evaluations of robot delivery height changes in both reality-based and VR-based experiments are shown in Fig. 6. They show the average comfort levels of all 15 subjects to different robot delivery heights in the left-arm and right-arm scenarios, respectively. The results show that the comfort level first increases when the delivery height increases till 30 cm. After 30 cm, the comfort level starts to decrease as the delivery height keeps increasing. The results also obey common sense as humans will tend to feel uncomfortable when the delivered part by the robot is either too low or too high to reach. It can be clearly seen that both the reality-based and VR-based comfort curves capture this trend very well. By a statistical calculation, the overall correlation coefficients are 0.886 with a t-test p-value of 0.00785 and 0.572 with a t-test p-value of 0.18 for the left-arm and right-arm scenarios, respectively. The p values from F-tests were 0.276 and 0.353 for left/right arm scenarios, respectively, indicating that there is no difference in the variance of both the left and right arm cases between the reality-based experiments and VR-based experiments. This indicates that VR-based experiments can well reasonably reproduce the human comfort to the robot delivery height in human-robot collaboration. However, the simulation performance is not satisfying when the heights are chosen at small values due to the big comfort rating gaps between VR-based and reality-based experiments.

In addition, it is seen that comfort levels for the left arm are higher than the right arm for the same delivery height in reality, and this difference is also successfully reflected in the VR-based results. Furthermore, it is also shown in both left-arm and right-arm results that VR curves tend to be slightly flatter than reality-based curves. This indicates a relatively low sensitivity to the robot delivery height changes in VR compared to reality in human-robot collaboration.

It is also worth noticing that the maximum comfort value differences between reality and VR take place at the smallest height scenario at the beginning, in which the VR-based experiment provides higher comfort ratings. The reason for this is that in reality-based experiments, human subjects' hands have to get extremely close to the experiment platform with even almost collisions, thus making the clearance distance between the robot arm end-effector and the platform very small, which makes the subject feel very uncomfortable. However, such a situation could not be very well reproduced in the VR environment because human subjects could not well feel the almost collision case in VR, and they also have fewer concerns about a virtual robot colliding with their hands. This result suggests that VR technology still has some weaknesses in reproducing high-fidelity feelings of collisions, and some extra development such as an integration of force/haptic feedback into VR, may be able to help enhance the capability of VR in simulating some extremely close human-robot interaction scenarios.

Therefore, from these results, it has been seen that although the VR-based experiment can well reproduce human comfort feelings in most conditions, it is also found that there are still some comfort rating gaps between VR and reality under some factor conditions. Table 4 provides a detailed list of all the scenarios where relatively large comfort rating gaps are generated. Suppose it is found that VR-based experiments may have relatively low sensitivity to some robot motion factor changes compared to reality-based experiments. Human subjects tend to feel safer in VR-based experiments than in reality-based experiments. The reproduction of collisions or almost collisions in VR-based experiments is not as good as in reality-based experiments. Their findings provide some guidelines for appropriately conducting human-robot collaboration research in virtual reality in the future.

TABLE IV
SCENARIOS OF RELATIVELY LARGE COMFORT RATING GAPS

Ranks	Scenarios	Max Average Comfort Gap
1	Low Robot Delay	0.467
2	Low Delivery Height	0.433
3	High Robot Delay	0.4
4	Low Robot Speed	0.267
5	High Robot Speed	0.2

IV. CONCLUSION

This paper investigates the differences in human comfort in VR-based and reality-based human-robot collaborations through experimental studies. A set of HRC tasks are designed and implemented with VR-based and reality-based experiments to collect human comfort level feedback. The similarities and differences are analyzed based on human subject studies. It is found that, in general, the subjects tend to have similar comfort evaluations in the VR-based and the reality-based experiments. There are also some factor sensitivity variances and gaps between the VR-based and reality-based experiments, which have been discussed in the paper as a guideline for using VR to conduct human-robot collaboration research appropriately. As for future work, we plan to integrate force/haptic feedback into VR in order to reproduce more high-fidelity feelings of human comfort in tightly physical human-robot interactions.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation under Grant IIS-1845779.

REFERENCES

[1] Standard, I. Iso 10218-1: 2011 robots and robotic devices—safety requirements for industrial robots—part 1: Robots. *International Organization For Standardization*. (2011)

[2] Wang, H., Xu, M. & Bian, C. Experimental comparison of local direct heating to improve thermal comfort of workers. *Building And Environment*. **177** pp. 106884 (2020)

[3] Lan, L., Wargocki, P. & Lian, Z. Optimal thermal environment improves performance of office work. *REHVA Journal*. **49**, 12-17 (2012)

[4] Ye, X., Chen, H. & Lian, Z. Thermal Environment and Productivity in the Factory.. *Ashrae Transactions*. **116** (2010)

[5] Wang, W., Liu, N., Li, R., Chen, Y. & Jia, Y. HUCOM: A model for human comfort estimation in personalized human-robot collaboration. *Dynamic Systems And Control Conference*. **51906** pp. V002T23A006 (2018)

[6] Mead, R. & Matarić, M. Proxemics and performance: Subjective human evaluations of autonomous sociable robot distance and social signal understanding. *2015 IEEE/RSJ International Conference On Intelligent Robots And Systems (IROS)*. pp. 5984-5991 (2015)

[7] Lasota, P. & Shah, J. Analyzing the effects of human-aware motion planning on close-proximity human–robot collaboration. *Human Factors*. **57**, 21-33 (2015)

[8] Siedler, C., Glatt, M., Weber, P., Ebert, A. & Aurich, J. Engineering changes in manufacturing systems supported by AR/VR collaboration. *Procedia CIRP*. **96** pp. 307-312 (2021)

[9] Galambos, P., Csapó, Á., Zentay, P., Fülöp, I., Haidegger, T., Baranyi, P. & Rudas, I. Design, programming and orchestration of heterogeneous manufacturing systems through VR-powered remote collaboration. *Robotics And Computer-Integrated Manufacturing*. **33** pp. 68-77 (2015)

[10] Hitch, J. VR becoming manufacturing reality — machine design. , https://www.machinedesign.com/automation-iiot/article/21836703/vr-becoming-manufacturing-reality

[11] Schwarz, M., Lenz, C., Memmesheimer, R., Pätzold, B., Rochow, A., Schreiber, M. & Behnke, S. Robust immersive telepresence and mobile telemanipulation: Nimbro wins ana avatar xprize finals. *2023 IEEE-RAS 22nd International Conference On Humanoid Robots (Humanoids)*. pp. 1-8 (2023)

[12] Zhu, Y., Jiang, B., Chen, Q., Aoyama, T. & Hasegawa, Y. A shared control framework for enhanced grasping performance in teleoperation. *IEEE Access*. (2023)

[13] Hegy, S. AR and VR are transforming training in manufacturing: Augmented reality (VR) and virtual reality (VR) technologies are improving training programs in plant facilities and bridging the skills gap with more efficient training for the incoming workforce–training new workers at 30

[14] Andaluz, V., Amaquiña, J., Quevedo, W., Mora-Aguilar, J., Castillo-Carrión, D., Miranda, R. & Pérez, M. Oil processes VR training. *International Symposium On Visual Computing*. pp. 712-724 (2018)

[15] Cummings, J. & Bailenson, J. How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. *Media Psychology*. **19**, 272-309 (2016)

[16] Paes, D., Arantes, E. & Irizarry, J. Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. *Automation In Construction*. **84** pp. 292-303 (2017)

[17] Busch, M., Lorenz, M., Tscheligi, M., Hochleitner, C. & Schulz, T. Being there for real: presence in real and virtual environments and its relation to usability. *Proceedings Of The 8th Nordic Conference On Human-computer Interaction: Fun, Fast, Foundational*. pp. 117-126 (2014)

[18] Su, K., Chen, S., Lin, P. & Hsieh, C. Evaluating the user interface and experience of VR in the electronic commerce environment: a hybrid approach. *Virtual Reality*. **24**, 241-254 (2020)

[19] Li, R., Almkerk, M., Waveren, S., Carter, E. & Leite, I. Comparing human-robot proxemics between virtual reality and the real world. *2019 14th ACM/IEEE International Conference On Human-robot Interaction (HRI)*. pp. 431-439 (2019)

[20] Sportillo, D., Paljic, A. & Ojeda, L. On-road evaluation of autonomous driving training. *2019 14th ACM/IEEE International Conference On Human-Robot Interaction (HRI)*. pp. 182-190 (2019)

[21] Benesty, J., Chen, J., Huang, Y. & Cohen, I. Pearson correlation coefficient. *Noise Reduction In Speech Processing*. pp. 1-4 (2009)