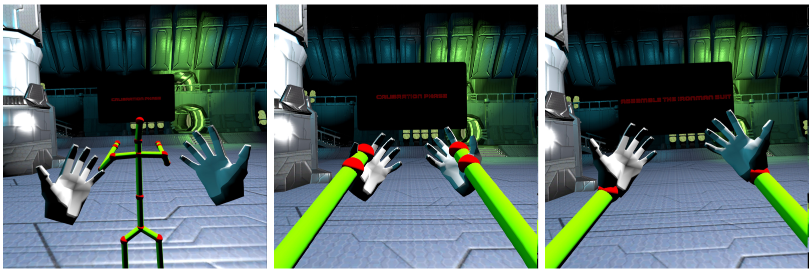
5

Exploring Full Body Embodiment in Virtual Reality

If in chapter 4, the interaction was the focus of our research, in the following chapter we delve into the analysis and the impact of a self-representation in 1PP of the user in VR.
Different technologies, such as cameras or IK to obtain FBT, were implemented to fully understand unique insight and development strategies.
FBT and self-representation in VR have the potential to significantly impact user perception, behaviour, and emotional response in a variety of contexts, from object interaction and navigation to skill learning.
Experiments are divided as follows:

- **Experiment 1 - Iron-man Task**: This experiment explores how users interact with objects in a VE, incorporating full body representation through an RGBD camera. Participants engaged in the Iron-man task, using Oculus Rift controllers, Leap Motion Controller, and Manus Prime haptic gloves. The focus was on evaluating the impact of full body representation on task performance and user experience.
- **Experiment 2 - Walk and Sit Task**: Here, we assess user behaviour in basic navigational tasks, such as walking and sitting, in both RE, MR and Mixed Reality with Avatar (A). The experiment compares user behavior with and without full body representation, achieved through six-point tracking and IK using Final IK plugin, with the real world counterpart.
- **Experiment 3 - Tai Chi Task**: This experiment investigates the effects of synchronous (real-time) and asynchronous (delayed) embodiment on learning a simple movement sequence, specifically Tai Chi. Utilizing the QuickVR package for environment development and FBT, the study examines the role of agency and the impact of illusory agency.
- **Experiment 4 - Walking again Task**: This experiment explores the potential of VR to simulate walking for individuals confined to a wheelchair. By employing full body VR representation and joystick-controlled navigation, the study aimed to provide a semblance of walking. However, the experiment was halted due to instances of motion sickness, highlighting the challenges and considerations in designing VR experiences for physically impaired users.

Through these experiments, we aim to further refine the current knowledge



(A) (B) (C)

FIGURE 5.1 Reference frame alignment. (A) The body and the hands' representations are in their own reference frames (different also with respect to the first person view). (B) The head, body and hand reference frames are aligned. (C) The head, body and hand reference frames are aligned and residual errors are corrected. (Figure is taken from [169])

about embodiment and how it affects user behaviour in different scenarios.

5.1 Iron-man Task

This experiment was conducted at the same time with respect to section 4.1, but it is reported here to maintain a coherent structure of the thesis.

5.1.1 Materials and Methods

Visualization Devices

The same visualization device of section 4.1 was used in this experiment. An RGBD camera was used togheter with the HMD to acquire information about the joints of the user body to create a full body representation in VR in 1PP that coherently move as the user.

Interaction Devices

The same interaction devices of section 4.1 were used in this experiment. However, compatibility issues emerged while using the Manus gloves with the RGBD camera. The gloves are not stable if used with an RGBD camera based on infrared light. The problem is caused by the IR light of the RGBD camera that interferes with the Vive trackers on the gloves. Therefore, the calibration leads to a bad alignment of the avatar and it is hard to complete the task. Thus, we decided not to take into consideration the Manus gloves with a self-avatar condition.

Implementation Details

The same tools and plugin of section 4.1 were used in this experiment to implement interaction. Moreover, we explored the integration of a full body representation in VR, leveraging sensor fusion and reference frame alignments to create a cohesive self-representation of the user. Our focus was on ensuring that the avatar's movements were perceived from a 1PP, enhancing the sense of presence and immersion in the VE.
To construct a cohesive self-representation, we employed a two-step process involving rigid transformation and live correction. Before these two steps, sensor data were localized to their respective reference frames, leading to a lack of 1PP alignment as in Figure 5.1(A). We chose a simplified avatar model, prioritizing the accurate alignment of reference frames over complex graphical representation, ensuring that the effectiveness of VR interaction remained our primary focus.
To align the data of all sensors, the alignment phase is divided into two steps:

- **Rigid transformation**: It is computed just one time at the beginning, among common points from the sensors.
- **Live correction**: After the Rigid transformation, it tries to overcome the residual offset present between the avatar body and the hands' module.

The rigid transformation uses the least-square rigid motion with Singular Values Decomposition (SVD) to align data from different sensors. This process involved calculating the optimal rotation matrix and translation vector to minimize the distance between two sets of points (Eq. 5.1).

$$(\overline{R}, \overline{t}) = \underset{R,t}{\operatorname{argmin}} \sum_{i=1}^{n} |(Rp_i + t) - q_i|^2 \qquad (5.1)$$

where:

- R is the rotation matrix between the two sets of points, called P and Q, and $\overline{R}$ is the computed estimate.
- t is the translation vector between the centers of mass of the two sets of points, called P and Q, and $\overline{t}$ is the computed estimate.
- $P = \{p_1, p_2, \ldots, p_n\}$ are the VR system samples, acquired by the HMD and the hand detection device.
- $Q = \{q_1, q_2, \ldots, q_n\}$ are the RGBD camera samples.
- n is the number of samples.

To properly align the different reference frames of the sensors (i.e. "to move" P towards Q), several correspondences between them are required. In our case, we have some common joints tracked by both the RGBD camera and the HMD with one of the technologies for the hands and fingers detection: i.e. the head, the palms and the wrists. Nevertheless, the result of the rigid transformation carried out for a single set of common points often leads to

a visually incorrect alignment. This means that the user does not perceive the avatar as superimposed on their body. This can be due to multiple factors, such as co-planar points among the common joints selected and noise on the points detected by the sensors.
To address this, we increased robustness by considering multiple samples over time and instructing users to move their arms in a specific pattern to ensure comprehensive tracking. After this step, the result is a partial alignment of the reference frames (i.e. the avatar with the real body of the user), as shown in Figure 5.1(B).

The Live Correction step involves a real-time correction to refine the alignment between the avatar and the user's real body. We focused on ensuring a natural continuity between the hands (tracked by Controllers, Leap Motion Controller or Manus glove) and the rest of the body (tracked by the RGBD camera). In particular, The wrists' positions, obtained from the hand detection technologies, were used for this purpose, offering precision in aligning the forearm with the hand. The outcome of this step was a more accurate alignment, as shown in Figure 5.1(C)

5.1.2 Experiments

Participants

The same 6 participants from section 4.1 were involved. Indeed they were 4 males, 2 females ranging in age from 20 to 55 (average 38.5 ± 16.7), all with normal or corrected-to-normal vision and no prior experience with VR. To mitigate learning or habituation effects, each participant engaged with the five experimental conditions in a randomized sequence.

Task

The experiment was performed at the same time of section 4.1. Thus the task was explained and performed in the same way with the five conditions. A snapshot of the experiments can be seen in Figure 5.2.

Data Acquisition

The same data as in section 4.1 were acquired in order to being able to compare interactions with and without the self-avatar. Thus TTC and the number of instances when a suit piece was dropped as an error rate durign the grasping. Post to the completition of each condition, participants filled out the UEQ and the IPQ. More details respectively in User Experience Questionnaire and Igroup Presence Questionnaire.

(A)

(B)

(C)

FIGURE 5.2 Snapshots of 3 experimental conditions, ControllersAvatar (A), LeapAvatar (B) and ManusNoAvatar (C). For each figure, on the left is the first person view of the virtual reality scene, and on the right is the external view of the user in the real environment. (Figure is taken from [169])

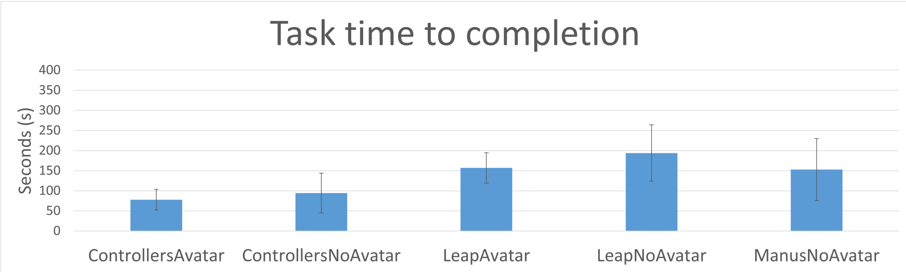


FIGURE 5.3 Total time to completion TTC for the five experimental conditions. (Figure is taken from [169])

5.1.3 Results

In Figures 5.3 and 5.4 the bar graphs representing the mean values of the TTC and the error rates (and the related standard deviations), for the 5 experimental conditions, are shown. The results show that the Controllers are the easiest interaction device (mean TTC with avatar 77.93 ± 25.57 seconds and 0.33 ± 0.82 errors), while the Leap Motion Controller (mean TTC without avatar 193.87 ± 70.24 seconds and 5.00 ± 2.19 errors) is the hardest and the Manus Prime haptic gloves are the middle ground (mean TTC without avatar 152.65 ± 77.39 seconds and 2.50 ± 1.76 errors).
Figure 5.5 shows the results of the UEQ. The average value of each scale (range between -3 and 3) and the associated standard deviations are shown for the 5 experimental conditions. Unfortunately, no appreciable differences can be drawn from it.
Figure 5.6 shows the results of the IPQ, the mean values of each category (range between 1 and 7) and the associated standard deviations, for the 5 experimental conditions, are reported. The answers of the subjects show that the Manus Prime haptic gloves allow us to achieve a higher General sense of "being there" (6.50 ± 0.55) and Spatial Presence (6.37 ± 0.57) with respect to, in particular, the Leap Motion Controller cases, in which the worst type of interactions with complex objects reduces these two aspects (6.17 ± 0.98 and 4.47 ± 1.43, respectively, with the avatar). While the values for the Involvement and the Realism are very close one from the other. For what concerns the comparison between the avatar and no-avatar solution while using the same technology, the results show that the use of avatar is slightly better in all the categories of the IPQ.

5.1.4 Discussion and Limitations

The main objective of this work was to understand the importance of an avatar in representing the user for interaction proposes. The comparison between interactions with and without the self-avatar provided insights into the utility of full body representation. Notably, even with a limited number of subjects, there was a trend towards improved interaction, presence, and user experience,

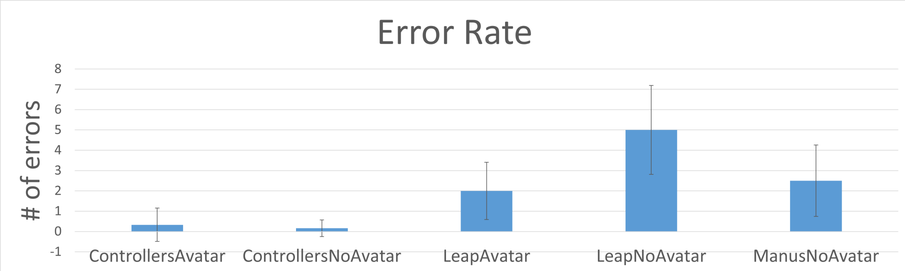


FIGURE 5.4 Error rate for the five experimental conditions. (Figure is taken from [169])

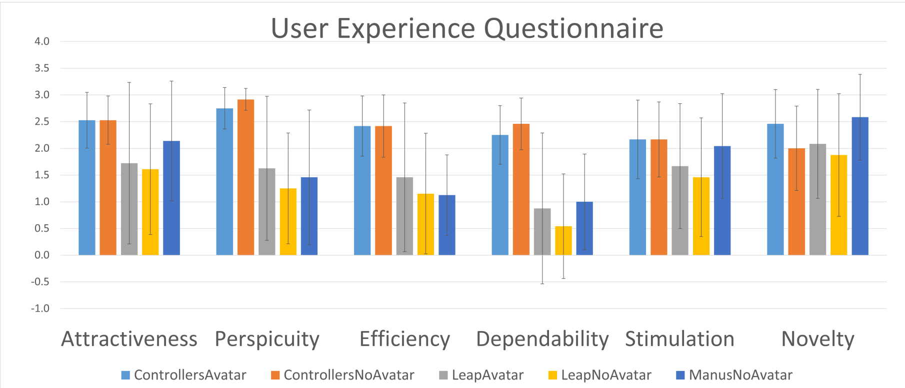


FIGURE 5.5 Results of the UEQ: mean values and standard deviations on a scale from -3 to 3. (Figure is taken from [169])

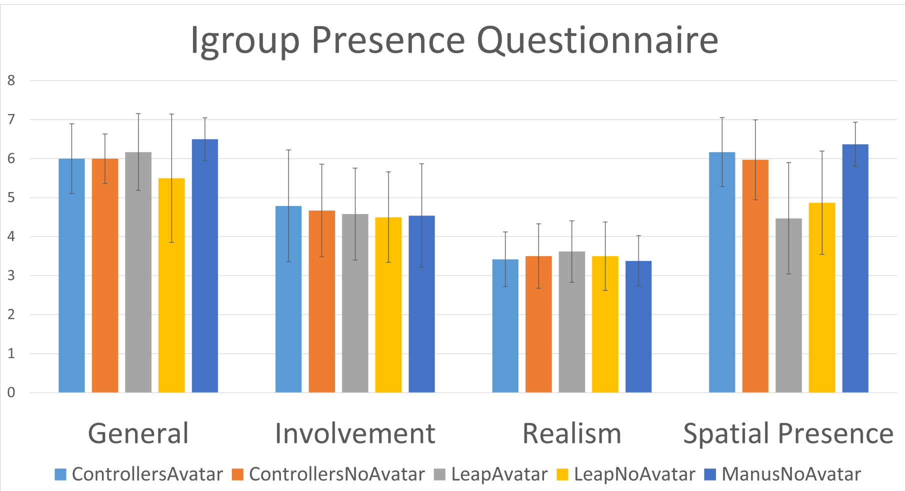


FIGURE 5.6 Results of the IPQ: mean values and standard deviations on a scale from 1 to 7. (Figure is taken from [169])

particularly with the Leap Motion Controller.
Even if some limitations are present such as a small sample size due to covid restriction and the fact that the avatar is a simple sick figure, the presence of a user body representation seems to positively affects the user during interaction even if there are no significance differences in the acquired measurement among the avatar and non-avatar conditions.
Future works could try to fix the interference issues between the gloves and the RGBD camera and also use a real mesh body instead of a stick figure. Moreover we should also increment the number of subjects.

5.2 Walk and Sit Task

5.2.1 Materials and Methods

Visualization Devices

The Walk and Sit task was conducted using the HTC Vive Pro eye described in Visualization Devices. We used a machine with the following specifications NVIDIA GeForce 3080 graphics card, AMD Ryzen 9 5900x processor, 32 GB of RAM, and Windows 10 Home 64-bit, ensuring smooth handling of the VR simulation and device integration.

Interaction Devices

To interact with the environment the participants use the Vive controllers described in Controllers. The FBT is achieved using Final IK plugin [1] which utilizes IK to deduce the positions of all bones from six key points (head, hands, pelvis, feet). These points were tracked by the HMD, the HTC Vive Controllers and 3 Vive trackers.

Implementation Details

This project delves into the dynamics of human behaviour in a MR setting, with a particular focus on the actions of walking and sitting. Our objective was to discern whether our actions in VR mimic those in the real world. We hypothesize that if a sufficiently immersive and present VE is provided, behaviour in VR should closely resemble that in reality.
In particular our questions were if we behave similarly in VR with and without avatar with respect to the real worlds, and if having a avatar infuence in some ways the behaviour of the user in VR.
Our hypothesis are:

> *We will behave similarly in RE, MR and A if we can provide a good enough sense of presence and immersion in the VE.*

[1] http://root-motion.com

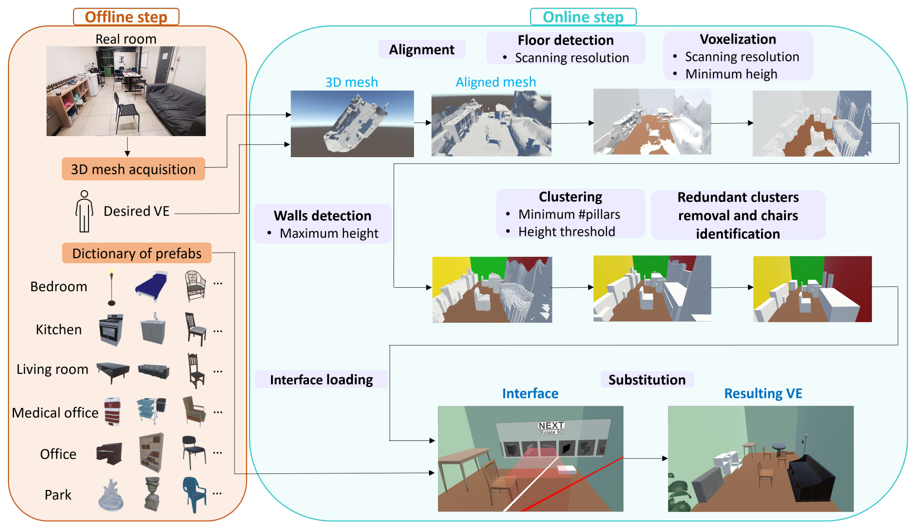


FIGURE 5.7 SwitchToVirtual's pipeline, with offline steps in orange and online steps in blue. User-adjustable parameters are listed under each step. Notably, user intervention is mainly needed for "3D Mesh Acquisition" and "Substitution" using the interface and controller to select prefabs. The system features a prefab dictionary for immediate use or expansion. Prefabs are categorized by six virtual environments, including standard and chair variants. (Figure is taken from [117])

The presence of a self-representation will impact positively the behaviour of the user resulting in a higher IPQ and SUSP values and a smilar biomechanical data with respect to the RE

Our methodology involves the use of SwitchToVirtual, a system we designed to generate interactive VEs mapped onto real-world spaces. The system is based on the prior work described in [164] and further developed to suit our needs in [117].

The pipeline, illustrated in Figure 5.7, encompasses both offline and online steps. Among the online procedures, a key focus lies on recovering real world geometry information, which serves as a constraint for subsequent stages. We use our laboratory as input of the pipeline described above, to recreate an outdoor environment where the participants can walk around and sit on a chair. The real and the correspondent VR environment where experiments were performed are shown in Figure 5.8.

5.2.2 Experiments

Participants

Considering some preliminary results and the design of the experiment (within-group), we determined the *Cohen's d* to compute the effect size for our experiment. Having a Cohen's d around 0.800, looking at tables in [77], we determined that the optimal sample size for our experiment was 24 subjects.

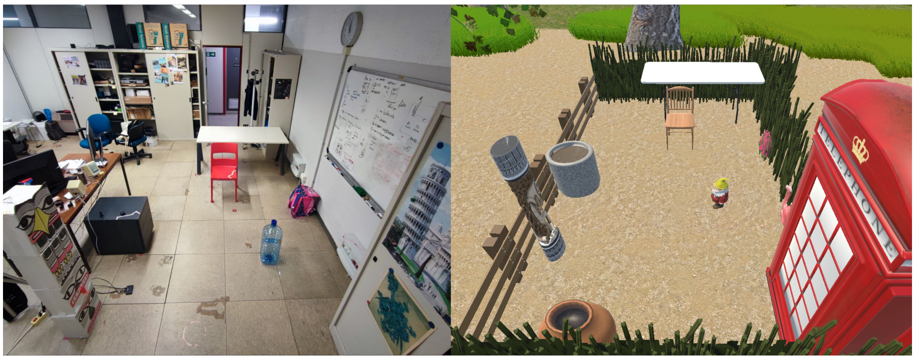


FIGURE 5.8 The first image represents the real environment where experiments were performed, thus our laboratory. The second image shows the corresponding MR environment that participants saw during the experiment in the MR conditions. (Figure is taken from [117])

We had a total of 24 participants, but in the end, we reported results only for 22 subjects (11 females and 11 males, mean age 26.4 years, range 21-41) due to corrupted data for two participants. Participants, both male and female, were matched with gender-congruent avatars. Also we ensure that each participant experienced the three conditions, RE, MR and A, in a randomized order to minimize the carry over effect.

Task

In each of the three conditions, participants were asked to start from a resting position in front of the closet (seen as a telephone cabin in MR and A), and then the experiment followed this scheme:

1. Stand still for 10 seconds at the starting position;
2. Walk straight-line to the chair;
3. Sit on the chair for 10 seconds;
4. Return to the starting position.

This sequence has to be repeated five times in each condition (RE, MR and A). The instructions for when to perform each step were provided by pre-recorded audio through the HMD headphones in the MR and A cases and through a speaker in the RE.
It is worth noting that, during the experiment, the chair's virtual counterpart had a similar visual appearance with respect to the real chair. The real chair was always physically present. Moreover, before executing the experiment, participants were instructed to perform this task.
We designed this task taking into strong consideration the Time Up and Go (TUG) test [2], which is used to evaluate overall functional mobility in older

[2] https://www.sralab.org/rehabilitation-measures/timed-and-go

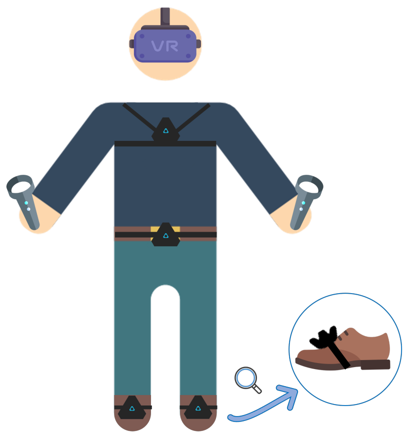


FIGURE 5.9 Configuration of the trackers on the user.

adults or people with Parkinson's disease. In the TUG test, subjects are asked to stand up from a standard chair, walk a distance of 3 meters at a comfortable pace, turn, walk back and sit down.

Data Acquisition

The main objective of this project was to investigate human behaviour in a MR environment, specifically focusing on walking and sitting. The experiment aimed to answer two key questions: whether individuals behave similarly in VR compared to reality, and whether having a FBT system and a self-avatar that mimics real movement would influence behaviour and performance.
Participants were asked to hold the controllers in their hands and to wear four Vive trackers, on the chest, on the pelvis, and on the feet, as shown in Figure 5.9, to collect biomechanics data during the experiments with a sampling frequency of 100Hz. Also, these trackers were used in the A condition to synchronize the avatar. Moreover TTC, IPQ and SUSP were acquired during and after the experiment. More details for each questionnaires can be found respectively in Igroup Presence Questionnaire and Slater-Usoh-Steed Questionnaire.

5.2.3 Results

The results of the study provided valuable insights into these research questions. Firstly, the analysis of the TTC, in Figure 5.10, indicated significant differences between RE - MR and RE - A conditions, but there are no differences between MR and A. According to that, the analysis suggests that the presence of an avatar had a similar effect on participants' completion time as not having an avatar at all.

To assess the similarity of sitting behaviours in the MR and A condition compared to the standard behaviour in the RE, various metrics were analyzed. The linear velocity of the user's pelvis, angular velocity of the user's trunk in

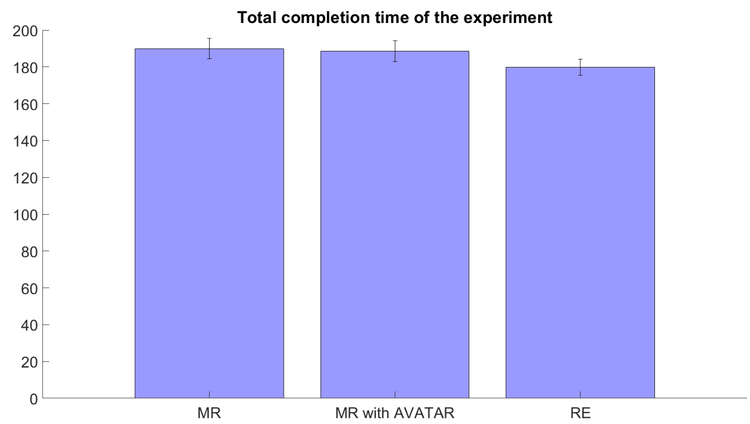


FIGURE 5.10 Total time to complete the task.

the sagittal plane, and trunk angle in the sagittal plane were considered. The mean profiles of these quantities during the sitting phase are shown in Figure 5.11. The results showed a repeated pattern across all three conditions in all the above considered variables, suggesting that a natural walking and sitting behaviour was achieved in MR and A cases.
One notable difference from the graph shown is the peak of velocity during the act of bending down to sit. Indeed, participants had a slightly slower velocity in MR and A with respect to RE. The same can be said also for the angular velocity of the trunk.
This finding supports the hypothesis that providing a good enough sense of presence and immersion in VR can lead to behaviour similar to reality.
To evaluate the degree of similarity of the virtual biomechanical performances with respect to the real one, we formulated a cost functional:

$$\text{cost} = \sum_{j=1}^{N \text{ tot bin}} (LVP_{j,a_m} - LVP_{j,b_n})^2 + \\ + \sum_{j=1}^{N \text{ tot bin}} 1/\sigma (AVT_{j,a_m} - AVT_{j,b_n})^2 \qquad \forall m, n$$

where:

- a, b: are two among the three conditions of the experiment which we are considering, thus RE, A and MR.
- j: different temporal bins related to the sitting phase;
- m, n: different subjects that performed the experiment;
- Linear Velocity of Pelvis (LVP);
- Angular Velocity of Trunk (AVT);
- $1/\sigma$: weight for the angular velocity, this weight was introduced to ensure that angular velocity and linear velocity had the same weight within the

cost functional.

In comparing different time sequences, it's crucial to ensure that each trial is resampled to have an equal number of bins. While it's true that the bins may have varying lengths across trials, the essence lies in preserving the inherent characteristics of the trajectories under consideration. This is achieved through resampling taking care of aligning the phases of sitting and standing up. By resampling with such arrangement, we effectively maintain the integrity of the information. This attention in the alignment ensures that when averaging across the various resampled trajectories, there's no loss of information. This loss of information would have otherwise occurred if resampling were performed without taking into acount this arrangement.
The main objective of the analysis is to assess how similar the virtual biomechanical performances, represented by LVP and AVT, are to the real ones under the three experimental conditions, during the sitting phase.
To measure the similarity between virtual and real performances, the difference between the corresponding LVP and AVT variables for each temporal bin, denoted as 'j' within the sitting phase, is calculated. The sum of the squared differences for each temporal bin is employed as a measure of disparity, yielding a numerical value: the higher this value, the greater the difference between the conditions.
The cost function is utilized to compute confusion matrices. These matrices are statistical tools that allow for evaluating the agreement between virtual and real performances, both within the same subject and among subjects under different experimental conditions. In this sense, confusion matrices can be employed to analyze the interaction in the virtual world versus reality. Furthermore, they enable us to assess differences among various subjects within the same experimental condition, considering either RE, A or MR.
The cost functional is calculated for each combination of subjects (m and n) and conditions (RE-RE, A-A, RE-A, MR-MR, MR-A, RE-MR). This implies that:

- In RE-RE, MR-MR, A-A, the biomechanical performances are compared among different subjects.
- In RE-A, MR-A, RE-MR , the virtual and real biomechanical performances are compared within the same subject under the two conditions (diagonal of the matrix) and among different subjects.

Of course, this analysis allows us to thoroughly evaluate the differences and similarities among subjects and conditions in the context of biomechanical performance. The resulting confusion matrices are shown in Figure 5.14. From the plot emerges that most of the subjects perform similarly to other subjects in all conditions and also among different conditions.
Regarding the analysis of the questionnaires, unfortunately, even if there is a visual difference in the evaluation of users' sense of presence using the IPQ 5.12 and SUSP 5.13 there is not a significant difference between the A and MR conditions according to ANOVA test.

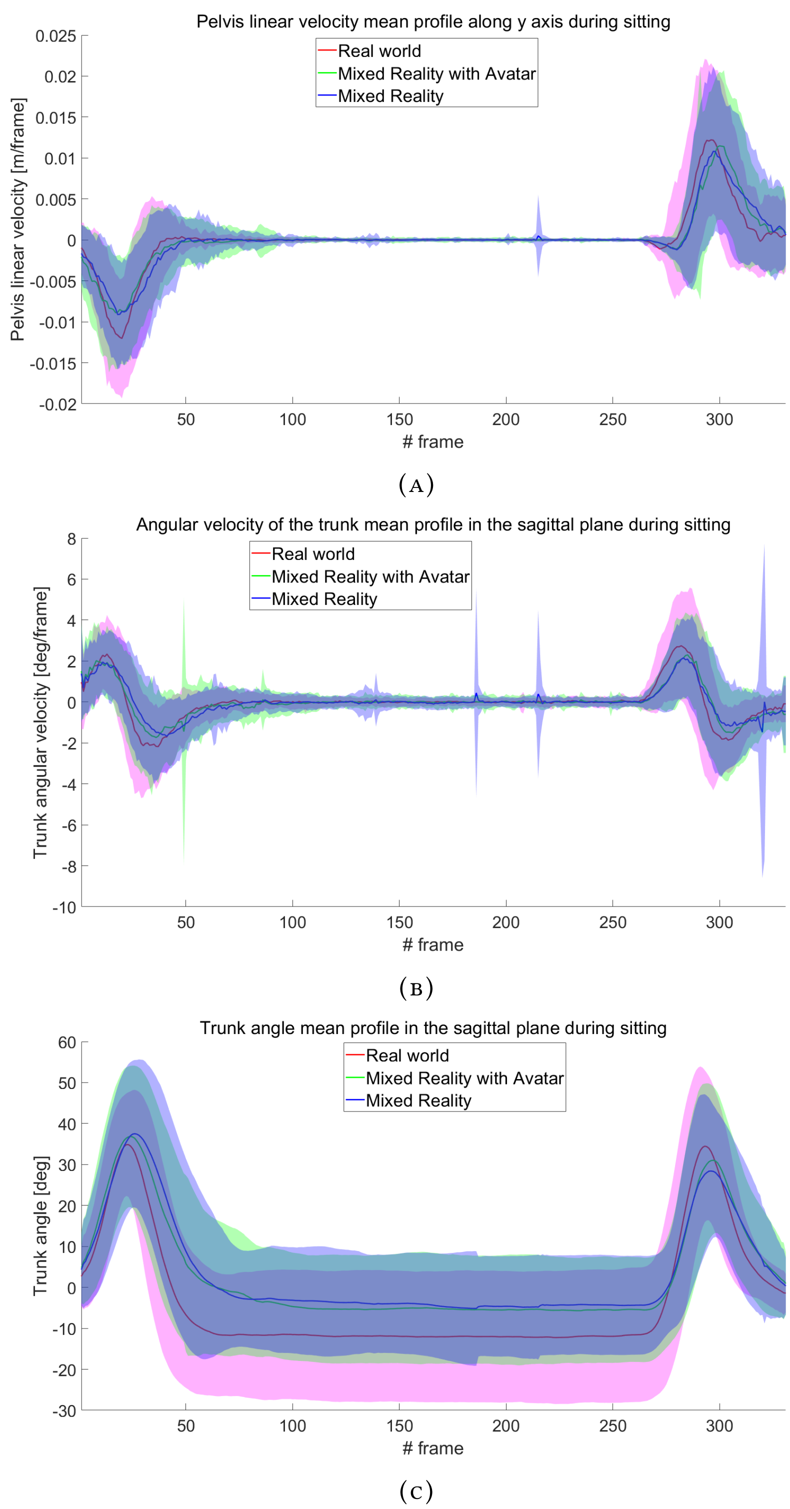


FIGURE 5.11 (A) Comparison of mean pelvis velocity profile among the three conditions during the sitting, thus from the moment the participant begins to sit down to the moment they stand up again. (B) Comparison of mean trunk angular velocity profile among the three conditions during the sitting, thus from the moment the participant begins to sit down to the moment they stand up again. (C) Comparison of mean trunk angle profile among the three conditions during the sitting, thus from the moment the participant begins to sit down to the moment they stand up again.

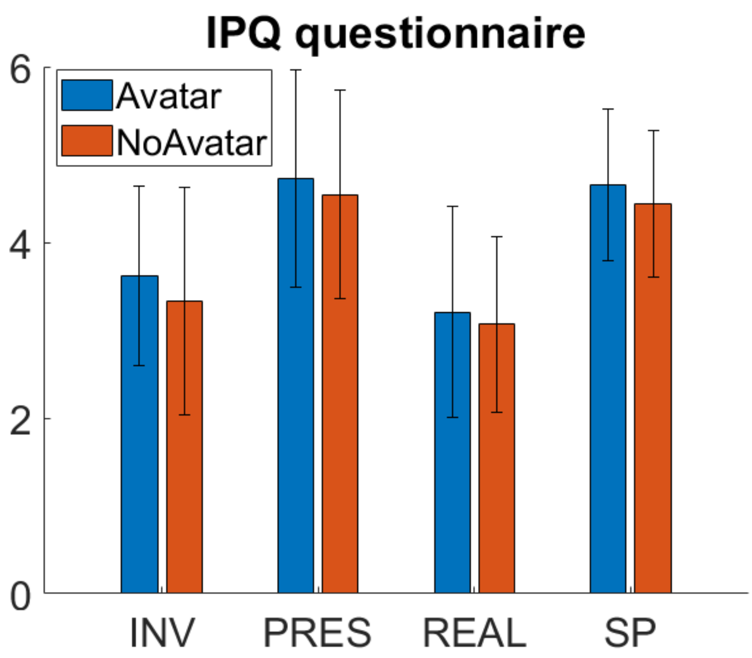


FIGURE 5.12 IPQ questionnaire results.

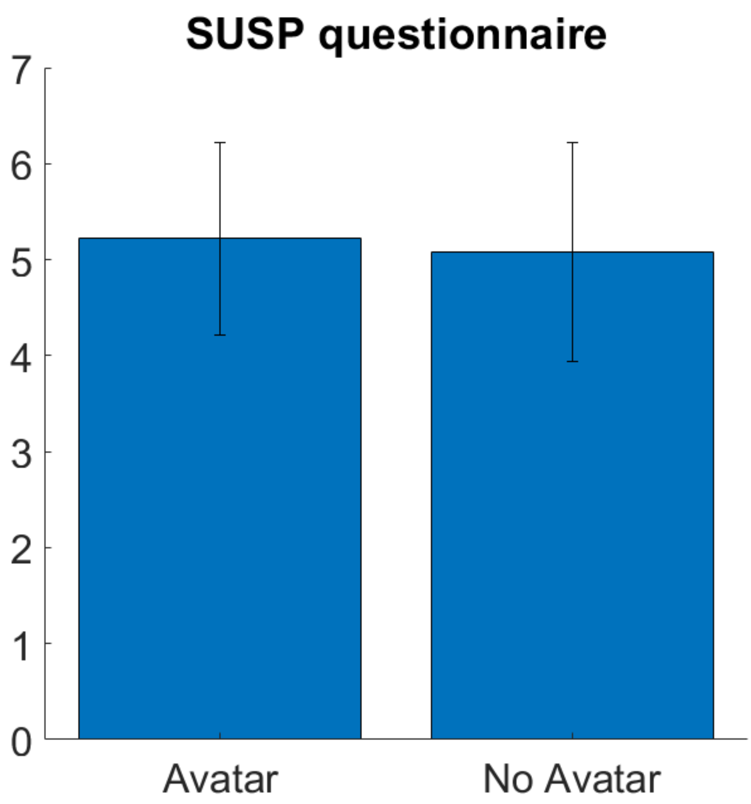


FIGURE 5.13 SUSP questionnaire results.

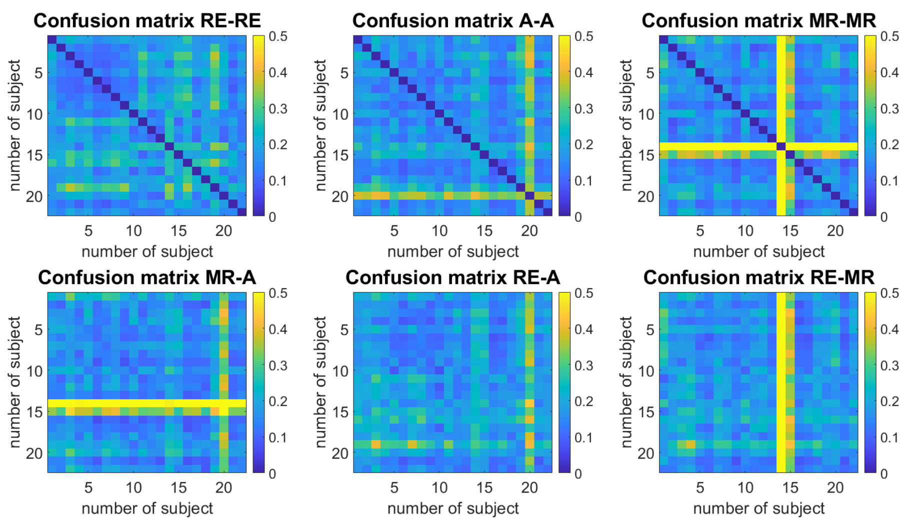


FIGURE 5.14 Matrices to compare between and within subjects and conditions based on the cost function.

Overall, the results of the experiment support the hypothesis that individuals can behave similarly in a VE if a good sense of presence and immersion is provided. The presence of an avatar that tracks real movements slightly influenced participants' behaviour, but not in a meaningful way. Moreover, the inclusion of an avatar did not have a significant impact on the similarity of biomechanical performances compared to the VE without an avatar. These findings contribute to our understanding of human behaviour and performance in VE, emphasizing the importance of presence and immersion for a more realistic and engaging user experience.

5.2.4 Discussion and Limitations

The main objective of this project was to investigate human behavior in a VE, specifically focusing on walking and sitting. The experiment aimed to answer two key questions: whether individuals behave similarly in VR compared to reality, and whether having a full body tracking system and a self-avatar that mimics real movement would influence behavior and performance.
The results showed a repeated pattern across all three conditions in the biomechanical analysis, suggesting that a similar walking and sitting behavior was achieved in the VE. This finding supports the hypothesis that providing a good enough sense of presence and immersion in VR can lead to behave similarly as in the real world.
Further analysis on the confusion matrices suggest that the inclusion of an avatar did not significantly affect the similarity of biomechanical performances compared to the real condition for this specific task. Furthermore, the evaluation of users' sense of presence using IPQ and SUSP revealed that there are not significant differences between MR and A conditions. Our explaination

for this phenomenon is because, normally, during a walk o sit task, we do not look at ourself, at our body. Same probably happens in VR, meaning that people are not influenced by it. Moreover, there is not an embodiment phase prior to the start of the task and no mirror is provided in the scene following guidelines from [12] where the mirror did not influence the results.

5.3 Tai Chi Task

This project further analyzes recent findings that the induction of body ownership through 1PP and visuomotor synchrony can result in illusory agency over an act carried out solely by the virtual body. By agency, we refer to the attribution of an act to the self [64, 50]. Body ownership and agency can be independently manipulated [75], although the agency is a component of body ownership as explained in the chapter 2.
Visuomotor synchrony, where the virtual body moves in real-time in synchrony and correspondence with the real body, is a powerful way to induce body ownership (assuming 1PP) and of course, also produces veridical agency [8]. The question that was considered in [10] is whether such veridical agency and body ownership can lead to illusory agency, specifically over an act of talking.
In this work, our goal is to test whether we can use this approach to enhance the acquisition of complex motor sequences, using Tai Chi as an example. We will follow a paradigm similar to the illusory speaking one, where participants are embodied in 1PP in a virtual body with visuomotor synchrony or asynchrony (the two condition of the experiment) during the first embodiment phase. The hypotheses are:

- Participants will have greater agency over the movements of the virtual body if they experience the embodiment phase in the synchronous embodiment condition than those in the asynchronous embodiment condition.
- At the end participants who had agency over their virtual body movements will have movements closer to the correct movements of the virtual Tai Chi teacher.

Following previous results in the literature, we expect that those in the embodiment who had the visuomotor synchrony will have agency over the movements of the virtual body and that this will be reflected in their movements and questionnaire answers. Those who had asynchronous movements in the embodiment will have less agency over the Tai Chi movements of the virtual body.

FIGURE 5.15 The tai chi teacher shows the movement to the participants.

5.3.1 Materials and Methods

Visualization Devices

The Tai Chi task was conducted using the HTC Vive Pro described in Visualization Devices. We used a machine with the following specifications NVIDIA GeForce 3080 graphics card, AMD Ryzen 9 5900x processor, 32 GB of RAM, and Windows 10 Home 64-bit, ensuring smooth handling of the VR simulation and device integration.

Interaction Devices

To interact with the environment the partecipants used the Vive controllers describe in Controllers. The FBT is achieved using QuickVR [3]. This package allows FBT based on IK and 6 key points on the user similarly as Final IK plugin. The QuickVR also offers a tool to easily create and manipulate the workflow of an application.

Implementation Details

The VR system was programmed to immerse the participants into a virtual room as in Fig. 5.15 with a virtual body that mirrored their movements either synchronously or asynchronously during the first stage. The participants could select their virtual representation on a pool of six avatars, 3 male and 3 female, of different races. For the entire time of the experiment, there will be a spatial audio that will explain to the partecipants the next step to do. Canvas and button are used to start, stop and continues the flow of the experiment. Animation clips and text are used to show what kind of movement the partecipants have to perform during the simulation.

[3]https://gitlab.com/eventlabprojects/quickvr.packages/com.quickvr.quickbase

5.3.2 Experiment

Participants

The study involved a between-groups design with 24 participants (6 females and 18 males, mean age 25.5 years, range 18-34) half assigned to the synchronous condition and the other half to the asynchronous condition in the embodiment phase. Participants, both male and female, with normal or corrected-to-normal vision, have all low to medium experience with VR.

Task

The experiment is performed in three phases. During the embodiment phase, participants performed five simple movements in front of a virtual mirror to establish a sense of body ownership and agency, based on the condition experienced (synchronous or asynchronous). This phase lasts 3 minutes and the following movements were asked to be performed: stretching out their arms, crouching down, without moving their feet at all turning their body to the right/left, raising their arms to the ceiling, and lifting one leg.
After that the learning phase starts. This phase si repeated three times and each time two things happen: firstly, the virtual Tai Chi teacher shows the correct movement to perform, and then the partecipants will see the same movement performed by their avatar in 1PP. During this time they are free to try to replicate the proposed movement or watch it on the mirror or in 1PP.
After that, they remove the HMD and compile the questionnaire. On completion, they go back in VR and attempt to replicate for five times the Tai Chi movement shown by the teacher, with their actual movements displayed and recorded. This last phase is called measurement phase.
At the end, the participants answer the following question "Write about your experience in virtual reality, for example, how you felt while watching your body move and while looking at it in the mirror during the three phases (embodiment, learning and measurement). Please write approximately 100 words".

Data Acquisition

The participants' movements were captured and recorded during the measurement phase using motion capture technology. The participants also answer to an open question at the end of the experiment to describe their feeling. Both of these will not be shown there. Additionally, participants completed a questionnaire detailing their experience and perception of body ownership and agency in the VE. More information of this questionnaire can be found in Virtual Reality Questionnaire.

5.3.3 Results

The questionnaire results are shown in Fig. 5.16. The asynchronous condition reported a Mean = 3.33 with Std = 1.40, while the synchronous condition a Mean = 4.28 with Std = 1.12. The t-test indicates that there is a significant difference between the two conditions (p = 1.26e-06).
Means and Stds of each question (with the inverted item already inverted) are a also provided in the following:

- Question 1: Mean = 3.92, Std = 1.16 (asynchronous) - Mean = 4.92, Std = 0.67 (synchronous)
- Question 2: Mean = 3.00, Std = 1.41 (asynchronous) - Mean = 4.08, Std = 1.38 (synchronous)
- Question 3: Mean = 2.83, Std = 1.75 (asynchronous) - Mean = 4.08, Std = 1.08 (synchronous)
- Question 4: Mean = 3.75, Std = 1.66 (asynchronous) - Mean = 5.00, Std = 0.74 (synchronous)
- Question 5: Mean = 3.33, Std = 1.72 (asynchronous) - Mean = 3.92, Std = 1.78 (synchronous)
- Question 6: Mean = 1.25, Std = 0.97 (asynchronous) - Mean = 3.67, Std = 0.98 (synchronous)
- Question 7: Mean = 3.17, Std = 1.34 (asynchronous) - Mean = 3.33, Std = 1.15 (synchronous)
- Question 8: Mean = 3.92, Std = 1.62 (asynchronous) - Mean = 5.17, Std = 0.72 (synchronous)
- Question 9: Mean = 3.25, Std = 1.60 (asynchronous) - Mean = 3.92, Std = 1.24 (synchronous)
- Question 10: Mean = 5.67, Std = 0.65 (asynchronous) - Mean = 5.67, Std = 0.89 (synchronous)
- Question 11: Mean = 2.58, Std = 1.51 (asynchronous) - Mean = 3.33, Std = 1.67 (synchronous)

5.3.4 Discussion and Limitations

The analysis of the questionnaire suggest that, the synchronous condition consistently shows higher mean scores across most questions compared to the asynchronous condition. This suggests that participants in the synchronous generally reported a better experience in VR, with higher scores indicating stronger agreement with positive statements about the VR experience.
The overall analysis reinforces these findings. The mean score for synchronous condition is higher (4.28) compared to asynchronous condition (3.33), and the lower standard deviation suggests more consistent experiences among participants.

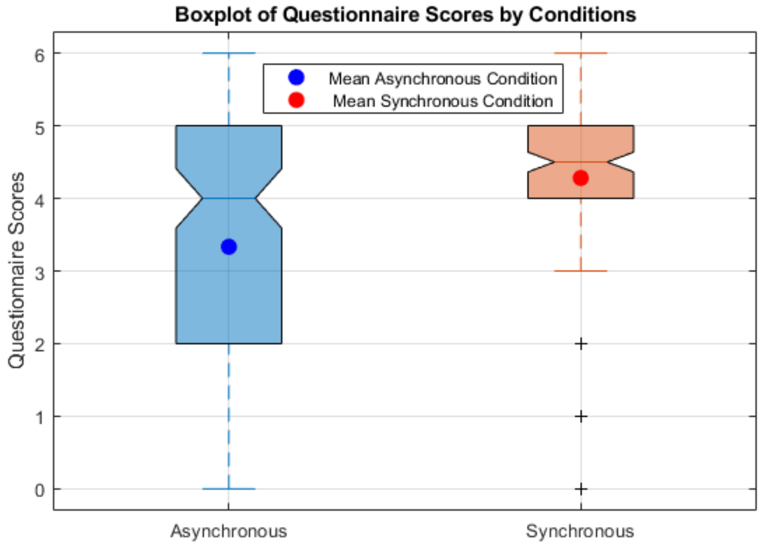


FIGURE 5.16 Boxplot showing questionnaire scores grouped by conditions.

The t-test result confirms that these differences are statistically significant, indicating a real difference in experiences between the two conditions rather than random variation.
However, some limitations were noted, including a small number of participants who struggled to remember the movements (subject number 17 that performed the experiment in the synchronous condition). Additionally, while participants did not report significant issues with the delay, several mentioned noticing it in their open-ended responses, but noone of them reported the issue during the experiment, as if they were thinking there was some bugs in the application. Further research is needed to explore the movement data coming from the partecipants and if embodiment and agancy could influence the learning of a sequence.

5.4 Walk again Task

5.4.1 Materials and Methods

Visualization Devices

The intervention utilized Pico and Oculus Quest for the VR experience. These HMDs were chosen for their compatibility with QuickVR for body tracking. More information on these HMDs can be found in Visualization Devices.

Interaction Devices

The primary interaction device was a controller that allowed the participant to initiate and halt the walking motion of their virtual avatar. The user was positioned in front of a virtual mirror within the VE, enabling them to see and control their avatar by pressing the controller's trigger.

Implementation Details

The virtual environment was designed to simulate walking through an outdoor setting, based on the recreation of the outdoor setting used in the study by Kokkinara et al. QuickVR was employed for body tracking to ensure accurate replication of the user's movements within the virtual avatar. The VR application aimed to provide a familiar and tested backdrop for the intervention, allowing for a controlled and user-driven experience. The walking was very slow and the environment a bit dark to try to reduced sickness that often happen when deling with such setup.

5.4.2 Experiment

Participants

The participant was a 14-year-old girl experiencing chronic leg pain and mobility issues due to complex regional pain syndrome. Despite the absence of physical abnormalities according to medical examinations, her condition restricted her to a wheelchair and precluded any contact with her legs. At the time of the intervention, she had been in this condition for five years. She twisted her ankle and this was a bodily hyper-reaction to that. Her legs are atrophied (very thin, wrong colour).

Task

The participant engaged with the VE by pressing the controller's trigger to initiate and halt the walking motion of her virtual avatar. The task was designed to be simple yet effective, allowing the participant to experience the sensation of walking in a controlled manner. The user-driven experience was intended to harness the illusion of body ownership and agency.

5.4.3 Results

Upon wearing the HMD and witnessing her virtual self "standing up," the participant expressed surprise and delight, suggesting a strong initial illusion of body ownership and agency. This positive reaction aligns with previous findings, indicating the potential of VR to elicit profound psychological and perceptual responses. However, the participant also experienced symptoms of dizziness and headaches, leading to the cessation of the VR sessions.

5.4.4 Discussion and Limitations

The initial positive reactions underscore the potential of VR interventions to provide psychological benefits through the illusion of body ownership and

FIGURE 5.17 Participant looking at their self and the mirror in the created environment

agency. However, the adverse physical effects experienced by the participant highlight the need for a cautious and personalized approach to VR therapy. The balance between the psychological benefits and the physical comfort of the participant is delicate and must be carefully managed. Future interventions should consider strategies to mitigate simulator sickness and enhance the overall comfort of the VR experience.

5.5 Conclusion

Summarizing the content of this chapter, I would like to firstly remind the limitations of the presented works that must be considered.
In the Iron-man Task with avatar (section section 5.1), as for section 4.1, the experiment soffer for a small sample size affecting the reliability and generalizability of the results and as a consequence, they are tentative.
In the Tai Chi Task (section section 5.3) only the results of the questionnaire are presented and analyzed.
In the Walk again Task (section 5.4), the application was designed for only one person. Our research on VR body tracking and self-representation has explored both technical and experimental aspects. Our analysis delves into various methods of FBT and representation, shedding light on the balance between technological capabilities, user comfort, and the psychological impact of embodying a virtual avatar.
From a technical standpoint, our work has navigated through two technologies: RGBD cameras and Vive trackers, each bringing its own set of advantages and challenges such as occlusion issues and precision in the case of RGBD cameras, and the physical encumbrance of wearing tracking devices for rehabilitation purposes in case of Vive trackers.

Software solutions like Rigid Transformation have been pivotal in aligning reference frames when using RGBD camera, while tools like Final IK and QuickVR have been used to solved IK based on six key points, ensuring that the virtual embodiment closely mirrors the user's actual movements.
Our diverse array of use cases, including object interaction, walk-and-sit tasks and movement Learning has provided a rich landscape for understanding user behaviour in VR and better insight into the impact of a self-avatar on enhancing presence, immersion, and embodiment within the VE.
In particular, from what emerges from the studies, the use of a self-representation in VR is not always a game changer. For example, in the small sample size study about object interaction, seems to give interesting results into this direction, even if more experiment with a bigger sample size should be carried out. Moreover embodiment and agency seems higher in the Tai Chi experiment in the synchronous condition.
On the contrary, it seems that in the walk and sit use case, the self-avatar seems to not affect the movement of the subjects and the level of presence in the VE. This could be coused by the fact that while walking or sitting we usually do not look at our body, even in reality, thus its precence in VR is not necessary. Future works should try to better characterize when a self-representation is needed to really improve the users VR experiences.
The Walk Again experiment also remind us that even with the adnvaced developed technologies, sickness is still a major problem when developing specific application that have "different" requirements. Future works should also work on solving this issue to increase VR audience. Moreover, future work of this research area should pivot towards the social aspects of VR, where the use of a self-representation is fundamental to provide the others all the means to understand my behaviours.

6

Conclusion

This thesis has explored problems and limitations of interaction, full-body tracking and self-representation in VR, emphasizing the importance of these elements in enhancing user experience and presence. Considering the wide range of hand interaction techniques available in consumer VR applications (from controllers and vision-based techniques, to haptic gloves), we devised the following research questions:

- **RQ1:** How do different interaction devices (controllers, sensor-based gloves, vision-based systems) compare in terms of user performance and experience in VR tasks?
- **RQ2:** How does audio, visual and haptic feedback impact hands/finger positions and performance in VR?

Moreover, analyzing the problem of full-body representation, which is extensively considered in the literature and now available in most consumer devices for immersive VR, we formulated an additional research question, focusing on the role of body tracking in achieving a good sense of presence, important in many applications:

- **RQ3:** To what extent can full-body representation in VR enhance the sense of presence and immersion for users?

In this thesis, we addressed the research questions with specific use cases and developed a framework to facilitate the creation of full body representation in VR.

6.1 Technical Advances and Findings

The main technical advancement achieved through this research is the development of the IMMERSE framework, which integrates interaction features with body tracking technologies to facilitate the prototyping of VR systems. This framework, specifically developed for Unity3D, is based upon the existing assets to integrate HMDs and tracking methods inside VR and has the main aim of creating a uniform interface towards the different SDKs. Its main features are: (1) to track the user's body, combining the tracked points (e.g., using the Vive trackers) with an Inverse Kinematic solver to estimate the main body joints; (2) to provide the flexibility to choose between different interaction mediums, such as hand tracking and controllers; (3) to incorporate a recording system capable of creating animation clips and CSV files of the user's movements within the VE.

The primary findings of this research can be summarized as follows:

1. **User Preferences and Performance**: The studies reported in chapter 3 (Iron-man Task and Meccano Task), focusing on hand grasping, showed that while advanced interaction technologies such as haptic gloves and hand tracking offer new possibilities, users still show a preference for traditional motion controllers due to their simplicity and familiarity. Indeed, the use of controllers allowed the user to finish the grasping and positioning task in less time and with fewer errors.
2. **Feedback Analysis**: The study on feedback (Wooden Brick Task) shows that they do not influence the user in positioning the fingers, in particular, the distance between the thumb and the index finger.
3. **Behavioral Analysis**: The investigation into walking and sitting (Walk and Sit Task) behaviors in VR compared to reality indicated that providing a good sense of presence and immersion in VR can lead to behaviors similar to those in the real world. However, the use of an avatar did not significantly affect the presence in VE and the similarity of biomechanical performances compared to conditions without an avatar.
4. **Impact on Agency and Embodiment**: In tasks involving learning sequences of movements, such as the Tai Chi Task, the research found that participants who experienced synchronous visuomotor synchrony during the embodiment phase showed greater agency over their movements.

The results obtained from this thesis further confirm the importance of interaction and user representation inside VEs. However, our results highlight how many aspects still remain unsolved, especially when focusing on the use of consumer off-the-shelf devices.

The developed framework provides a solid foundation for future VR applications, with the twofold aim of developing better use cases to analyze interaction by considering different modalities and tasks and helping people to develop immersive, engaging, and useful applications across various domains, including gaming, simulation, therapeutic interventions, and professional training.

6.2 Critical Examination

Reflecting on the journey and outcomes of this research, several lessons emerge that could shape future approaches:

1. **Integration and Communication**: One of the initial realizations was the lack of communication between interaction techniques and body tracking

technologies. The IMMERSE frameworks could be a valid starting point to ensure a more integrated approach from the outset, developing systems that seamlessly combine these functionalities to enhance user experience.

2. **Sample Size and Diversity**: The studies were often limited by small sample sizes, affecting the results' reliability and generalizability. This is partially motivated by the consequences of the COVID19 pandemic and by the fact that the development of trials to validate the developed systems was not the main focus of this thesis, more devoted towards the investigation of software techniques for VR. Future research should aim for larger, more diverse participant pools to validate findings and ensure broader applicability.

3. **Task complexity**: By integrating the knowledge and software advancement reached at the end of the thesis, future works should focus on rethinking tasks already addressed (e.g., the Meccano Task) and finding more complex tasks to be performed in VR. This would also help in highlighting the effective contribution of user representation in performing VR tasks (e.g., by considering more complex tasks than the Walking and sitting ones).

6.3 Future Work

Looking ahead, several avenues for future research are apparent:

1. **Grasp taxonomy in VR**: Through the years, the complexity of grasping actions was studied to comprehend, recognize, and understand common usage patterns during interaction [22, 45, 46]. Indeed, the interplay between the visual appearance of objects, the planning of actions and how we actually grasp them is extremely complicated (see Fig. 6.1).
Results shown by this thesis (Wooden bricks Task) and by previous research [32] confirm that such variability is not still present when interacting in VR. However, to obtain VE where embodiment and agency are really achieved and where users can manipulate objects in sophisticated manners would require the possibility of complex hand interaction in VR.

2. **Immersive Feedback Systems**: The development of haptic feedback devices integrated into body suits could significantly enhance the sense of embodiment by providing realistic tactile sensations, thereby enriching the VR experience beyond visual and auditory stimuli. The preliminary results with the use of haptic gloves in this thesis (Iron-man Task and Wooden bricks Task) were not satisfying, though new technologies have been developed, also including other feedbacks such as the temperature (see for example, the TouchDIVER haptic glove, by WEART [1]). Future development should perform a comprehensive analysis of the available solutions to integrate feedback systems in immersive VR.

[1] https://weart.it/haptic-vr-products/touchdiver-haptic-glove/

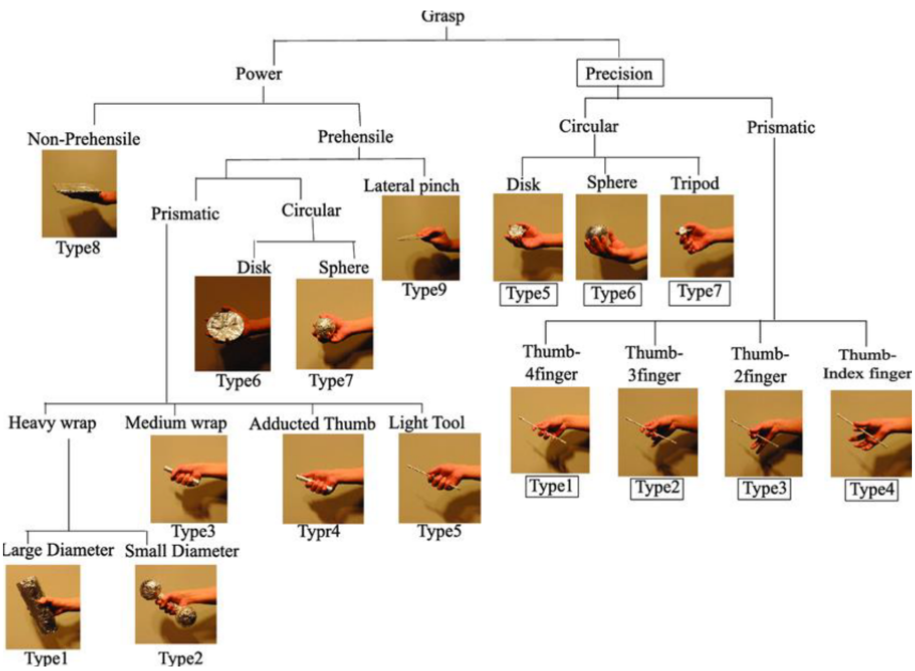


FIGURE 6.1 From Cutkosky, M. R. (1989). On grasp choice, grasp models, and the design of hands for manufacturing tasks. IEEE Transactions on robotics and automation, 5(3),269-279.

3. **User Experience Optimization**: Further research should explore ways to optimize the balance between realistic representation and smooth VR experiences. This includes studying the impact of different and newer interaction devices on user performance and comfort over extended periods.

4. **Broader Applications and Accessibility**: As the technology becomes more accessible and affordable, expanding its use in various fields such as education, healthcare, and professional training will be crucial. Future studies should also consider the potential of VR in social applications, where accurate body representation could enhance virtual gatherings and collaborations.

5. **Self-representation in VR**: An interesting approach to this would be to better describe when the self-representation is actually useful, as according to our consideration, it does not always improve all VR factors, nor the user experience and behaviors. Moreover, it seems really important that the VR community would work toward the definition of a standard about avatar models and rigging. Having a standard avatar description could help during the development of VR frameworks, like IMMERSE, to support the vast majority of avatars, but also for the interconnection among different visualization and tracking systems.

6. **Learning in VR**: Further research is needed in this area, beyond the

specific use case of learning a sequence (like the one in te Tai-chi Task). Both simple and complex movements should be analyzed, comparing different setups such as self-avatar/no avatar, 1PP/3PP or realistic/non realistic avatar.

In conclusion, while significant strides have been made in the field of VR through this research, there remains much to explore and improve. By addressing the identified limitations and pursuing the proposed future work, the potential for VR to revolutionize various aspects of our interaction with digital content and with each other in virtual spaces is immense.

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