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User Embodiment Comparison of Semi-Autonomous and Fully-Captured Avatar Movements in Virtual Reality

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Abstract—We describe in this paper a user study in the context of animated virtual human to compare the user self-perception of well known semi-autonomous Avatar and full-body tracked Avatar. We aim at highlighting the advantages and limitations of those methods during various walking phases. The participants walked inside 4 simulated environments with different obstacles. Those results are quantified through a virtual reality sickness questionnaire and a new questionnaire specialized on user perception and enjoyment of his avatar lower part. This study shows positive results for the semi-autonomous Avatar especially in a cluttered environment. The users maintain the same efficiency with both methods, they have no sickness issues after more than 45 minutes inside the simulation and they present better enjoyment results for environment with complex obstacles.

I. INTRODUCTION

Avatars, also referred as Virtual humans (VH) are the representation of the user inside a simulation. They are used in the manufacturing field as a tool for design, maintenance studies, operator training or ergonomics studies [1], [2]. For real time applications, avatars may be animated by replicating the movements of an operator using an optical motion-capture system. We refer to this method as full-body tracking method. This strategy offers quite accurate tracking of the operator and is usually applied when real and simulated environments are similar. However, when the real and simulated environments are mismatched, the full-body tracked method has limitations whereas a semi-autonomous method offers new opportunities :

- On one hand, if the user encounters real obstacles which are not simulated, such as another user or a workbench like in Figure 1, the motion-capture sensors may be obstructed from cameras. Thus, the full-body method fails. On the other hand, the semi-autonomous method requires fewer sensors to track the user, which avoids the problem of having lower-body sensors obstructed by the environment, making the application more robust. Reducing the number of sensors also facilitate the use of VR for industries.

- If the avatar encounters simulated obstacles which are not physically present, the full-body method can be improved with three strategies [3], [4]. The first one is to move the obstacle away from the avatar, so that the avatar follows the user command. The second one is to move the avatar away from the obstacle, like elevating the whole avatar when it encounters a step. The third one is to apply a contact between the obstacle and the avatar, thus forcing the user to overcome the virtual obstacle through his own movements. Each of these solutions has limitations. The first one does not allow fixed obstacles in the environment. The second one can greatly increase the motion sickness of the user since the elevation of the head of the avatar differs from its own. Finally, the third one is exhausting for the user and does not support physical consistency, since the avatar could trip when hitting an obstacle.

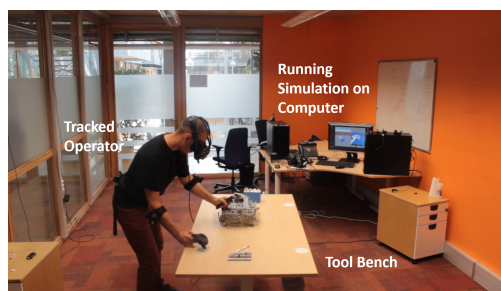


Fig. 1. The user is experiencing a VR simulation with an obstructed environment.

Semi-autonomous avatar is a good candidate to overcome these limitations. The semi-autonomous method is based on the positions of the tracked sensors from the upper body of the avatar, such as the head, hands and waist. A three points method of semi-autonomous avatar is proposed in [5] but the experiment shows a loss of information without waist tracking. The tracked positions are then used as inputs to generate the

positions of the avatar lower body, through a walking pattern generator. Then, tracked upper body and generated lower body positions are combined to compute the avatar.

In this paper, our contribution is the comparison of the user's movements perception between a full-body tracked avatar and a semi-autonomous avatar in a virtual obstructed environment. Full-body methods are sensitive to real obstacles. Non-tracked limbs of the user can lead to bad performance where the avatar is not synchronised with the user. This is why we propose to compare those methods with only simulated obstacles, where both methods can generate positions at all times. We aim at demonstrating that the semi-autonomous method can maintain the user's feeling of immersion and enjoyment despite experiencing differences between the avatar and the user's movements in rich simulated environments. The paper consists of four parts:

Section II describes the control strategies for animating the avatar in the the full-body tracked and the semi-autonomous modes. We introduce related work on avatar control to define existing solutions including the advantages and limitations of those solutions. We compare the full-body tracked and semi-autonomous motion control. In the simulation, the avatar waist uses a floating base model, with upper and lower limbs moving by using an Inverse Kinematics (IK) controller.

In section III, we introduce among the many walking pattern generators, the one we used. We recall the state of the art of capturability-based locomotion control and explain which algorithm we selected, based on reactivity and human-like stance. With this approach the avatar can better adapt to the obstacles in the simulated environment. This specificity helped us to design the user experience.

The section IV describes the environments of the user study and the questionnaires we applied. There are four simulated environments which vary with obstacles on the ground. These obstacles are here to highlight the specificity of the semi-autonomous avatar to adapt to its environment. The main objective of the experiment is to highlight differences between the two methods, quantified through sickness, time efficiency and enjoyment results.

In section V, we gather the results of the user study. Combining the 19 users data from the questionnaires gives us the differences between the two algorithms and the four environments. Then, we suggest a conclusion on the user perception of the two control strategies.

II. RELATED WORK

A. Avatars in Virtual Reality

The feeling of body ownership in VR is called Embodiment [6], [7]. The avatar is a tool to increase the user immersion in VR [8]. However, incorrect poses decrease embodiment such as revealed by Steed et al [9]. It is important to describe which avatar is best suited for our application and which controller should be applied.

Nowadays, avatars may be a full body representation of the user, or a simplification of the body with only the main limbs (like the hands) displayed. To better represent the full

body, one can use expensive capture systems [10], [11]. This solution does not suit our objectives which tend to simplify VR application. Another way to represent the full body avatar is to generate the non-tracked limbs with an Inverse Kinematic (IK) controller [12]–[14]. The study from [15] shows that users prefer having an avatar with full limbs rather than only their extremities, on the condition that the generated limbs are adequate. Another survey from [16] shows that full-body avatar increases the user's presence feeling. Finally, the works of [17] compare three different locomotion techniques and conclude that these techniques have low impacts on the sensation of embodiment. All those studies consider that the avatar simulated environment is little to no different from the user environment. What we propose in this paper is to determine which method is the best suited for the user to track his movements when the simulated environment changes and when the avatar has to avoid obstacles. The first method is a well-known full-body tracked avatar with Inverse Kinematics that we will use as reference. The second method is a semi-autonomous avatar with tracked sensors on the upper body and a walking pattern generator to obtain lower body limbs positions.

B. Walking Pattern Generator

Many walking patter generators are present in the literature. They are well-known topics in robotics [18], [19] and animation [20], [21]. They are all based on the dynamics of the Inverted Pendulum or its variations. They tend to give an estimation of the future state in order to anticipate the next optimal feet positions like in [22], [23]. The original inverse pendulum allows applications where the user's center of mass (CoM) exhibits significant dynamical height variations. This is the case for stair climbing, squat action or obstacle avoidance. However, locomotion with pendulum mode has three variables: the period of the step, the length of the step and the CoM height variation. In general, walking pattern generators are good to optimize only two out of three of these parameters, while the third one remains constant, such as in [24]–[26]. Since we do not have significantly strong variations of the CoM for our application, we prefer to use a Linear Inverse Pundulum Mode (LIPM) algorithm with variation of length and period of step, such as in [27], [28]. Finally, we recall that our walking pattern generator needs to compute feet positions in real time, for any user size and any movements. Therefore, we cannot use offline algorithms such as in [29], [30].

III. CONTROLS ALGORITHM

A. Avatar Control

The avatar control is the algorithm that handles the desired positions to move the avatar. Those are captured positions for the upper body, and lower body if we use the capture control (C1) or walking pattern generated positions if we use the semi-autonomous control (C2). The avatar control consists of an avatar following a tracked user reference for the upper-body and the walking pattern generator for the feet. The limbs are controlled by using Inverse Kinematics, like in Figure 2, where

the root of the kinematic tree is the floating base attached to the waist link. The avatar has 53 degrees of freedom with joints limits. Its geometry and inertial properties are automatically tuned depending on the size and mass of the user using the calibration tool from ¹. This method is detailed in [31].

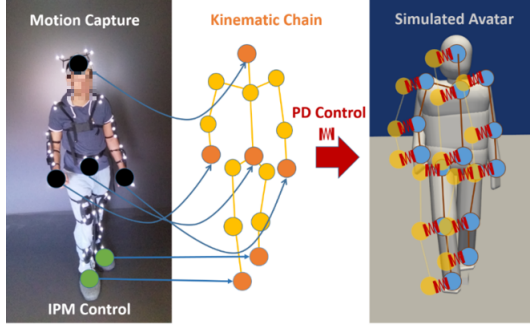


Fig. 2. The avatar follows the desired positions from the walking pattern generator and motion capture with a Proportional Derivative control and a closed kinematic chain.

In order to prevent leg auto-collisions, we add an offset to the final feet position to maintain a minimum distance between the two feet. We also have an intention step detector to allow the avatar to rest when the user has almost static motion. Both methods are based from our previous work [32]. In that case, the avatar must cancel the next step if the future generated step is inside the support area ascertain by the feet. The avatar control algorithm runs at 33Hz in order to compute the generated positions but the frame-rate of the simulation is maintained at 90Hz to give to the user a fluid animation.

B. Motion Capture

Motion Capture is a tool we use to define the user's position in space. To track this positions we use sensors placed on the user's main limbs. The one we use is an HTC Vive tracking system to detect those movements. The main body parts are, for the upper body, the head and hands, and for the lower body, the waist and feet. We reduced the tracked limbs to six only, meaning that we need the previously explained IK control to generate the rest of the body movements. The output positions of motion capture sensors are used as inputs for both control algorithms. For the first method, the full-body is following all the sensors positions. For the semi-autonomous method, the avatar is following only the hands and head positions.

C. Walking Pattern generator

1) *Inverse Pendulum Mode*: The full-body avatar has many bodies and articulations. Therefore, the equation of the dynamics is too complex to be simulated in real time. Consequently, the bipedal dynamic model is simplified. The two most common ones are the linear [33] (LIPM) and non-linear inverted pendulum models [34] (IPM). The equation of motion of the IPM is:

$$\ddot{c}(t) = \lambda(t)(c(t) - r(t)) + g \quad (1)$$

¹http://tools.openlab.psu.edu/tools/proportionality_constants.htm

The equation of the LIPM is the same except for λ which remains constant. t denotes time, $c(t)$ is the center of mass (CoM) of the avatar, g is the gravity vector, also written $g = -ge_z$ with g the gravitational constant and e_z the upright vertical of the inertial frame. $\lambda = \omega^2$, with $\omega = \sqrt{\frac{c_z}{g}}$, is the natural frequency of the pendulum. The control input of the system is r , the Center of Pressure (CoP) under the contact or Zero-Tilting Moment Point (ZMP) in case of multiple contacts. Since we do not have significantly strong variations of the CoM for our application, we rather use a LIPM algorithm with variation of length and period of step, such as in [27], [28].

2) *Locomotion with Variable ZMP, length and period of Step*: The algorithm from [27], [28] solves a Quadratic Problem (QP) to obtain time and length of steps and to maintain physical consistency over an infinite horizon of steps. We summarize here this algorithm through its most important equations. If you seek to completely understand this method, we invite you to look at those documents first to know how feet positions are generated. With this method we can define a Quadratic Problem (QP) to obtain time and length of steps to reach the desired velocity and to respect the boundness condition. The Quadratic Problem is defined as:

$$\begin{aligned} \text{minimize}_{u_{T,x}, u_{T,y}, \tau, b_x, b_y} & \alpha_1 \|u_{T,x} - L_{nom}\| + \alpha_2 \|u_{T,y} - W_{nom}\| \\ & + \alpha_3 \|\tau - \tau_{nom}\| + \alpha_4 \|b_x - b_{xnom}\| \\ & + \alpha_5 \|b_y - b_{ynom}\| \end{aligned}$$

$$\text{subject to } u_{T,x} - \tau(\xi_{mea} - u_0)e^{-\omega_0 T_{max}} + b_x = u_{0,x},$$

$$u_{T,y} - \tau(\xi_{mea} - u_0)e^{-\omega_0 T_{max}} + b_y = u_{0,y},$$

$$u_{T,x} \leq L_{max},$$

$$u_{T,x} \geq L_{min},$$

$$u_{T,y} \leq W_{max},$$

$$u_{T,y} \geq W_{min},$$

$$b_x \leq e^{\omega_0 T_{max}},$$

$$b_y \geq e^{\omega_0 T_{min}}$$

With L_{nom} the desired length of step, W_{nom} the desired width, τ_{nom} the desired ZMP, b_{nom} the desired value of the boundness condition and ξ_{mea} the measured capture point. α are the weights giving priority to the constraints. The most important one is the one on the Divergent Component of Motion (DCM) offset b , then L and W then τ . The last three constraints define the velocity of walk. We would rather have variable time steps than steps lengths for more human-like locomotion. In the continuity of [27], a new method has been proposed in [28] to apply the Walking Pattern Generator with variation of length and time of step, but with variation of the ZMP under the supporting foot during the step. This method

is more efficient to react to perturbations since the trajectory, and mostly orientation, of the CoM can vary during the step. This is not the case of fixed ZMP algorithm which have a fixed trajectory. This is very useful for our application since the human operator has unpredictable movements and needs a very reactive algorithm to follow his/her positions. This new method takes the form of a Proportional Derivative (PD) control based on the variation of ZMP during the step such as:

$$\mathbf{r}_{t,cZMP} = -\frac{e^{\omega(T-t)}}{1 - e^{\omega(T-t)}} \xi_{t,err} \quad (2)$$

Where, $\mathbf{r}_{t,cZMP}$ is the ZMP control value. This value is the instantaneous variation of ZMP we apply in order to follow the variation of DCM $\xi_{t,err}$ that occurs during the step.

Now that we have explained how we generate avatar movements for both methods, we compare them through user experiments in the next section.

IV. HUMAN PERCEPTION COMPARISON

A. Experiment

In order to compare the full-body motion-capture method (C1) and the semi-autonomous method (C2), we propose to measure the user's feedback on three parameters over four environments. The first parameter is the sickness of the user, which will be quantified with a state-of-the-art questionnaire. The second parameter is the efficiency of the user, which will be measured via a time evaluation of a simple guided-walk. The last parameter is the enjoyment of the user, which will be evaluated through another questionnaire, adapted to our experiment. Based on those questionnaires, we deduce which method is best suited to which environment.

B. Environments

The four environments are equal in size, $4\text{m} \times 4\text{m}$. In addition to the first person point of view in VR, the user always has a mirror on one edge of the room to look at his avatar and the environment. In order to highlight the differences between both methods (C1 and C2), variations among the four environments are localized on the floors. One can see the scene on 3. Collisions between the avatar and the ground and the obstacles are detected but the real environment does not feature these obstacles. The first room, R1, is empty. The second room, R2, has 4 obstacles of 30 cm height, forming a cross with a hole at the center of the cross. The third room, R3, has three separated obstacles of 30 cm height. Finally, the fourth room, R4 has a stair composed of 3 steps with a height of approximately 10 cm for each step. Using these environments, we want to see if the variation of ground height with obstacles can have an impact on the user's experience. We believe that an obstacle free environment is better suited for our study, to compare the two working methods. Doing so, we will maintain consistency between the avatar and its owner, no matter which method we use.

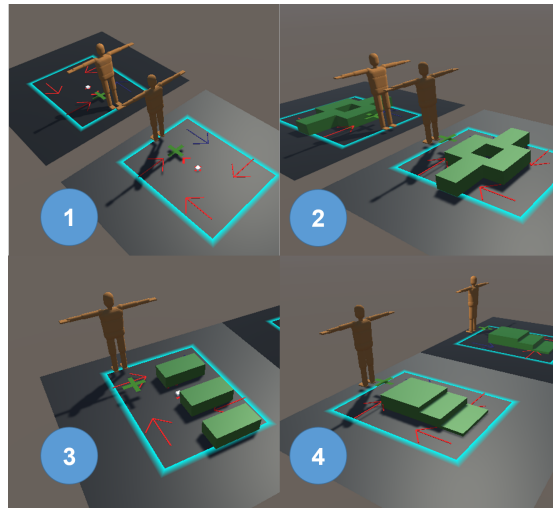


Fig. 3. VR Scenes of the experiment

C. Protocol

We ask questions about the user personal information and describe the task he will have to execute. The user is tracked with six sensors: one HTC Vive VR Headset, one controller in each hand, one tracker on the back of the waist and on each foot. Once the user is tracked, we can tune his avatar to have the same size and follow the positions defined by the control algorithm. The user must walk freely for two or three minutes in the simulated room. He has to interact with obstacles present in the room. Afterwards, the user has to follow a guided walk defined by arrows on the ground. The experiment stops on the end of the walk. After each experiment, we submit one questionnaire to the user to measure his enjoyment. The simulation is then restarted with the same environment but with the other control algorithm, repeating the procedure with free walk, guided walk and questionnaire. This process is repeated four times in total in order to test all the environments. At the end of the whole experiment, the user must answer a sickness questionnaire. The sickness questionnaire is longer than our enjoyment questionnaire and it would be too long to ask it eight times. If the results showed high sickness values, we would need to check after each variation of environment or control algorithm to see what parameters induced the sickness. Otherwise, if we do not detect any issues, we can safely say that none of those parameters affect the health of the user. The experiment is randomized: the order of rooms and algorithms is generated for each user. The user is not informed of the variation of algorithms, but he is encouraged to pay attention to the movements of his legs.

D. Detailed Questionnaires

In order to quantify the user's perception, we submit three questionnaires at the beginning, during and at the end of the experiment. The first questionnaire harvests various personal information on the user such as age, sex, approximate size and

weight (for avatar initialisation), previous VR experience and use of eyeglasses. During the experiment, after each test of an algorithm, the user must answer an enjoyment questionnaire of six questions evaluated on a scale of one to seven. Immersion and enjoyment are well-known subjects from the VR field like in [35], [36]. We propose to apply an adapted questionnaire from [37], each questions are answered on a scale from one to seven where one strongly disagree and seven strongly agree to the question. That leads to:

- 1) Which score would you give to your avatar?
- 2) Do you think this method made your experience comfortable?
- 3) Do you think this method made your experience appreciable?
- 4) Would you like to apply this method for future experiences?
- 5) Do you think the avatar leg movements were realistic?
- 6) Do you think the avatar leg movements matched your own?

We use the Kennedy Lane Simulator Sickness Questionnaire from [38] as Virtual reality sickness questionnaires (VRSQ).

E. Pool of Participants

We recruited 19 participants aged between 21 and 60 years with an average of 33.8 years. 16 of them already used VR. 8 of them had glasses but could not use them during the experiment. There were 2 women. All participants succeeded the experiment, with 40 min to 1h15 inside the simulation, with 20 min to 40 min with the avatar moving, and 20 min to 35 min to answer questionnaires.

V. RESULTS OF THE STUDY

A. Hypothesis

Previous studies have shown that semi-autonomous avatar can be a useful tool to display lower body positions when sensors are obstructed by obstacles. What we aim to study here is the user feeling of embodiment of his avatar when using this tool. We expect that the full-body tracked avatar gives overall better results with environment without obstacles, and that the semi-autonomous avatar provides better results in environments with obstacles. The hypotheses are the following ones:

- 1) The user does not experience any sickness issues with any methods, making both methods safe for VR applications (VRSQ questions).
- 2) The user is more efficient with the semi-autonomous avatar because he does not have to pay attention to his legs and the simulated obstacles (measured time).
- 3) The sense of embodiment is influenced by the avatar technique and the simulated environment. In particular, we expect the sense of embodiment to be higher for the tracked avatar without obstacles and the semi-autonomous avatar with heavy obstacles (enjoyment questionnaire).

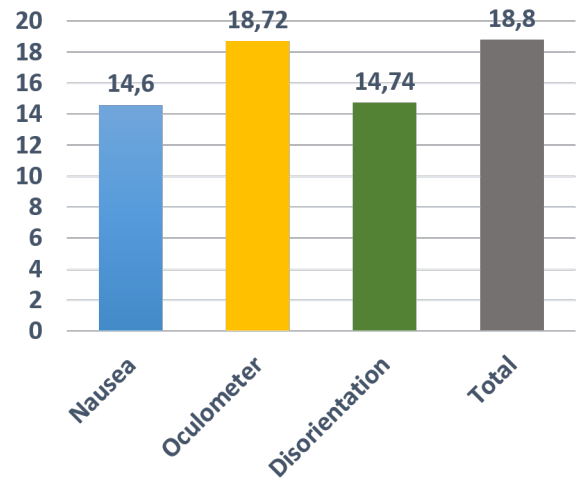


Fig. 4. Average value of the VRSQ

B. Results of the Sickness Hypothesis

The results of the VRSQ shown in figure 4 give the four following values for nausea (14.6), oculomotor (18.72), disorientation (14.74), and total score (18.8). Those values are low enough since the maximum is the oculomotor score of 18,8 on a scale of 160. We can say that both methods do not trigger significant sickness symptoms after an exposure of more than 40 minutes.

C. Results of the Time Hypothesis

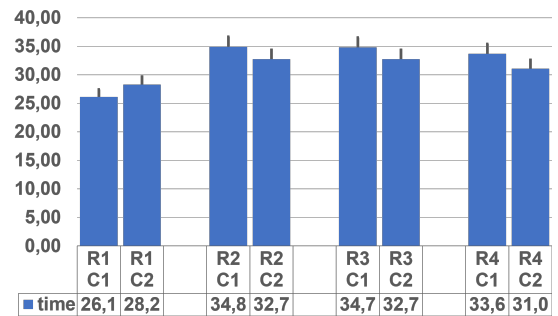


Fig. 5. Average time value of the guided-walk for each room and algorithm

D. Results of the Enjoyment and Embodiment Hypothesis

We used a two-way Anova with repetition to compare user guided-walk time results, with significant p value of 0.02. We computed for control variable $p = 0.52$, for room variable $p = 0.04$ and for interaction between the two variables $p = 0.36$. It is fair to say there is no significant variation of the results depending of both the chosen algorithm and the room. We use a graph of average values to better see those variations. Figure 5 shows that the best times are obtained with C1 for the empty room. With more obstacles, the user needs more time to finalise the guided-walk and C2 offers better results. This can be explained with the fact that the user does not have

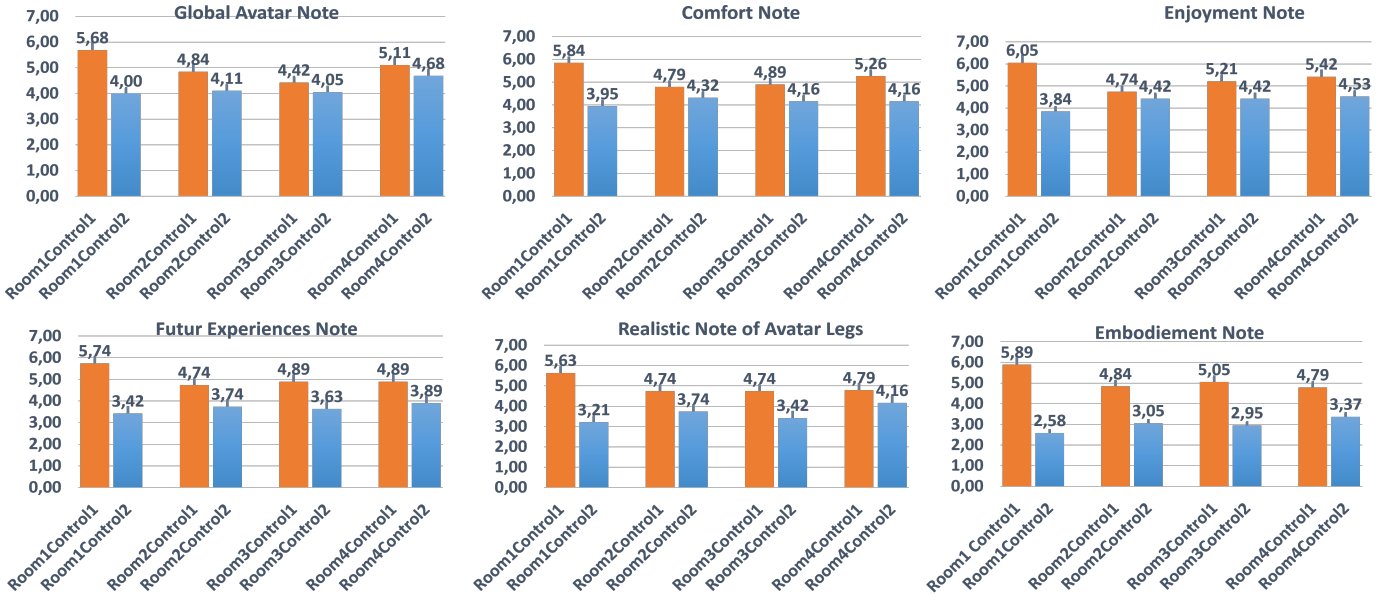


Fig. 6. User Study Results, regrouped with the six questions of our questionnaire. Here, R means room, the first one being the empty room, the second one the room with a hole, the third one the room with the separated obstacles and the fourth room the one with the stairs. C is the Control Algorithm used for the Avatar, the first one being the Full-Body Capture control and the second one being the Semi-autonomous control.

to pay attention to the ground anymore with C2 and can walk more freely in the rooms with obstacles.

We use a two-way Anova with repetition for each question of the enjoyment questionnaire, with significant p value of 0.02 in order to quantify the impact of the rooms and algorithm for each question.

For the six questions, we have $p < 10^{-4}$ for the algorithm variable, $p > 0.11$ for the room variable and $p > 0.03$ for the interaction between variables, beside question 6 which gives $p = 0.01$. We conclude that C1 and C2 results are not equal and are impacted by the environment. For a better comprehension, we regroup in graph 6 the average values of each question for C1 and C2 in the four rooms to quantify the impact of the room.

First of all, we have a global view from Figure 6 that shows C1 and C2 differences are reduced in obstructed environments, especially for room 4, the room with the stairs.

Then, we make a t-test analysis to compare only the algorithm in each room. We use the average value of our designed questionnaire to obtain this results. The empty room R1, the t-test gives, for $p < 0.02$, a t value of 5.23 with a value of $t_{max} = 2.06$. The average value of the full-body method is 5.87, while the average of C2 is 3.68. We conclude that C1 is significantly better than C2 for environments without obstacles.

For the room with a hole R2, and the obstacle room R3, we still have significant differences but fewer than the empty room. We have for R2, with $p < 0.02$, $t = 2.99$ for $t_{max} = 2.04$ and with means of 4.98 for C1 and 3.82 for C2. For R3, with $p < 0.02$, we have $t = 2.46$ and $t_{max} = 2.04$ and means of 4.98 and 3.82. We can explain this difference by the fact that the obstacles are small enough and the user can avoid most

of them if he raises the legs high enough, leading to better results with C1.

Finally, with the stairs room R4, with $p < 0.02$, we obtain $t = 1.96$ and $t_{max} = 2.03$: both methods give similar results. This can be explained by the fact that the stairs are composed of only one obstacle and that the user cannot avoid the obstacle anymore.

E. Summary of Results

The results show that the best case for the user is an empty room without obstacles and with the full-body tracking method, for which the avatar will almost perfectly match the user's movements. However, the increase of complexity in the room and its obstacles leads to close or equal results between the two control methods. This means that full-body capture is not perfectly suited for experiments where the simulated environment differs from the real one, and can be improved. The semi-autonomous and full-body tracked methods offer good results in terms of sickness symptoms (close to none). The semi autonomous algorithm gives slightly better results in efficiency (time performance) in rooms with obstacles. In term of enjoyment and embodiment, the full-body tracked method offers better results than the semi-autonomous method but this difference is greatly reduced, and sometimes not significant, when we use them in environments with obstacles. This implies that the semi-autonomous method is not suited for experiences where real and simulated environments are matched, but can be applied for scientific studies, or training purposes where training and ergonomic studies around obstacles are more important than the user's satisfaction.

VI. CONCLUSION

We compared a motion capture method with an on-the-shelf method from the robotics field to generate lower-body positions of an avatar. We have separated both methods (full-body capture and semi-autonomous control) in order to better analyse them, but we can easily imagine a better control approach which would switch from one method to the other depending on the environment and obstacles. We could also implement an algorithm which would compute average value between the semi-autonomous control and the full-body capture, with an output that would give more importance to one or another algorithm depending on the obstacles on the ground. Adaptation of the avatar to obstacles on the ground or to the variation of the ground height is a useful tool for VR applications, especially for task design or ergonomics studies. In our future work, we would like to apply a full-body torque control instead of an Inverse Kinematics control in order to move the avatar. This would lead to a next step for ergonomics studies in real time.

REFERENCES

- [1] J. Salini, V. Padois, and P. Bidaud, "Synthesis of complex humanoid whole-body behavior: a focus on sequencing and tasks transitions," in *IEEE International Conference on Robotics and Automation*, 2011, pp. 1283–1290.
- [2] M. Liu, "Personnage virtuel: contrôleur hybride couplant commande dynamique multi-objectifs et mouvements capturés," Ph.D. dissertation, Paris 6, 2012.
- [3] T. M. Takala, C. C. Hsin, and T. Kawai, "Stand-alone, wearable system for full body vr avatars: Towards physics-based 3d interaction," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2019, pp. 1398–1398.
- [4] V. Kamboj, T. Bhuyan, and J. S. Pillai, "Vertical locomotion in vr using full body gestures," in *25th ACM Symposium on Virtual Reality Software and Technology*, 2019, pp. 1–2.
- [5] D. Yang, D. Kim, and S.-H. Lee, "Real-time lower-body pose prediction from sparse upper-body tracking signals," *arXiv preprint arXiv:2103.01500*, 2021.
- [6] F. Biocca, "The cyborg's dilemma: Progressive embodiment in virtual environments," *Journal of computer-mediated communication*, vol. 3, no. 2, p. JCMC324, 1997.
- [7] K. Kilteni, R. Groten, and M. Slater, "The sense of embodiment in virtual reality," *Presence: Teleoperators and Virtual Environments*, vol. 21, no. 4, pp. 373–387, 2012.
- [8] E. Kokkinara and M. Slater, "Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion," *Perception*, vol. 43, no. 1, pp. 43–58, 2014.
- [9] A. Steed, S. Frlston, M. M. Lopez, J. Drummond, Y. Pan, and D. Swapp, "An 'in the wild' experiment on presence and embodiment using consumer virtual reality equipment," *IEEE transactions on visualization and computer graphics*, vol. 22, no. 4, pp. 1406–1414, 2016.
- [10] B. Spanlang, J.-M. Normand, D. Borland, K. Kilteni, E. Giannopoulos, A. Pomés, M. González-Franco, D. Perez-Marcos, J. Arroyo-Palacios, X. N. Muncunill *et al.*, "How to build an embodiment lab: achieving body representation illusions in virtual reality," *Frontiers in Robotics and AI*, vol. 1, p. 9, 2014.
- [11] B. Spanlang, J.-M. Normand, E. Giannopoulos, and M. Slater, "A first person avatar system with haptic feedback," in *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology*, 2010, pp. 47–50.
- [12] F. Jiang, X. Yang, and L. Feng, "Real-time full-body motion reconstruction and recognition for off-the-shelf vr devices," in *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1*, 2016, pp. 309–318.
- [13] D. Roth, J.-L. Lugin, J. Büser, G. Bente, A. Fuhrmann, and M. E. Latoschik, "A simplified inverse kinematic approach for embodied vr applications," in *2016 IEEE Virtual Reality (VR)*. IEEE, 2016, pp. 275–276.
- [14] Z. Tan, Y. Hu, and K. Xu, "Virtual reality based immersive telepresence system for remote conversation and collaboration," in *International Workshop on Next Generation Computer Animation Techniques*. Springer, 2017, pp. 234–247.
- [15] M. Parger, J. H. Mueller, D. Schmalstieg, and M. Steinberger, "Human upper-body inverse kinematics for increased embodiment in consumer-grade virtual reality," in *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, 2018, pp. 1–10.
- [16] P. Caserman, A. Garcia-Agundez, and S. Göbel, "A survey of full-body motion reconstruction in immersive virtual reality applications," *IEEE transactions on visualization and computer graphics*, vol. 26, no. 10, pp. 3089–3108, 2019.
- [17] D. Dewez, L. Hoyet, A. Lécuyer, and F. Argelaguet, "Studying the inter-relation between locomotion techniques and embodiment in virtual reality," in *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 2020, pp. 452–461.
- [18] A. Herdt, N. Perrin, and P.-B. Wieber, "Walking without thinking about it," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010, pp. 190–195.
- [19] S. Coros, P. Beaudoin, and M. Van de Panne, "Generalized biped walking control," *ACM Transactions on Graphics (TOG)*, vol. 29, no. 4, pp. 1–9, 2010.
- [20] I. Mordatch, M. De Lasa, and A. Hertzmann, "Robust physics-based locomotion using low-dimensional planning," *ACM Transactions on Graphics*, vol. 29, no. 4, p. 71, 2010.
- [21] J. M. Wang, S. R. Hamner, S. L. Delp, and V. Koltun, "Optimizing locomotion controllers using biologically-based actuators and objectives," *ACM Transactions on Graphics (TOG)*, vol. 31, no. 4, pp. 1–11, 2012.
- [22] T. Koolen, T. De Boer, J. Rebula, A. Goswami, and J. Pratt, "Capturability-based analysis and control of legged locomotion, part 1: Theory and application to three simple gait models," *The International Journal of Robotics Research*, vol. 31, no. 9, pp. 1094–1113, 2012.
- [23] M. Morisawa, S. Kajita, F. Kanehiro, K. Kaneko, K. Miura, and K. Yokoi, "Balance control based on capture point error compensation for biped walking on uneven terrain," in *IEEE-RAS International Conference on Humanoid Robots*, 2012, pp. 734–740.
- [24] O. E. Ramos and K. Hauser, "Generalizations of the capture point to nonlinear center of mass paths and uneven terrain," in *IEEE-RAS International Conference on Humanoid Robots*, 2015, pp. 851–858.
- [25] T. Koolen, M. Posa, and R. Tedrake, "Balance control using center of mass height variation: limitations imposed by unilateral contact," in *IEEE-RAS International Conf. on Humanoid Robots*, 2016, pp. 8–15.
- [26] S. Caron, A. Escande, L. Lanari, and B. Mallein, "Capturability-based pattern generation for walking with variable height," 2018, submitted. [Online]. Available: <https://hal.archives-ouvertes.fr/hal-01689331>
- [27] M. Khadiv, A. Herzog, S. A. A. Moosavian, and L. Righetti, "A robust walking controller based on online step location and duration optimization for bipedal locomotion," *arXiv preprint arXiv:1704.01271*, 2017.
- [28] H. Jeong, I. Lee, O. Sim, K. Lee, and J.-H. Oh, "A robust walking controller optimizing step position and step time that exploit advantages of footed robot," *Robotics and Autonomous Systems*, vol. 113, pp. 10–22, 2019.
- [29] K. Lowrey, A. Rajeswaran, S. Kakade, E. Todorov, and I. Mordatch, "Plan online, learn offline: Efficient learning and exploration via model-based control," *arXiv preprint arXiv:1811.01848*, 2018.
- [30] I. Mordatch, K. Lowrey, G. Andrew, Z. Popovic, and E. V. Todorov, "Interactive control of diverse complex characters with neural networks," in *Advances in Neural Information Processing Systems*, 2015, pp. 3132–3140.
- [31] R. C. Fromuth and M. B. Parkinson, "Predicting 5th and 95th percentile anthropometric segment lengths from population stature," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 43253, 2008, pp. 581–588.
- [32] V. Thomasset, S. Caron, and V. Weistroffer, "Lower body control of a semi-autonomous avatar in virtual reality: Balance and locomotion of a 3d bipedal model," in *25th ACM Symposium on Virtual Reality Software and Technology*, 2019, pp. 1–11.

- [33] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, and H. Hirukawa, "The 3d linear inverted pendulum mode: A simple modeling for a biped walking pattern generation," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 1, 2001, pp. 239–246.
- [34] J. E. Pratt and S. V. Drakunov, "Derivation and application of a conserved orbital energy for the inverted pendulum bipedal walking model," in *IEEE International Conference on Robotics and Automation*, 2007, pp. 4653–4660.
- [35] A. S. Fernandes and S. K. Feiner, "Combating vr sickness through subtle dynamic field-of-view modification," in *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 2016, pp. 201–210.
- [36] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte, "Leveraging change blindness for redirection in virtual environments," in *2011 IEEE Virtual Reality Conference*. IEEE, 2011, pp. 159–166.
- [37] J. Bhandari, S. Tregillus, and E. Folmer, "Legomotion: scalable walking-based virtual locomotion," in *Proceedings of the 23rd ACM symposium on virtual reality software and technology*, 2017, pp. 1–8.
- [38] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *The international journal of aviation psychology*, vol. 3, no. 3, pp. 203–220, 1993.