Inverse kinematics for full-body self representation in VR-based cognitive rehabilitation

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***Abstract*—Being self-represented through an avatar increases embodiment and the feeling of presence in virtual reality. Nevertheless, currently users in VR are typically represented only by their hands, as not enough tracking data is available for full body self-representation. In our use case of VR-based diagnostics and cognitive rehabilitation of stroke patients, we aim for full body self-representation in order to increase therapeutic effectivity of the treatment. To solve this problem, Inverse Kinematics (IK) can be used for pose estimation, where no tracking data is available. IK allows to minimize the use of hardware and efforts of patients and clinical staff and, at the same time, provides a full-body representation based only on positions of the VR-HMD and users hands as input. In some use cases tracking data from additional, visual full body tracking sensors can be used to estimate the position of the lower body joints. In this study, we evaluate existing IK-based pose estimators; find that VRIK from Final IK is the most suitable approach for the given use case; integrate VRIK in our VR-rehabilitation system; adapt VRIK to meet the use case requirements and conduct subjective tests to validate a significantly increased notion of embodiment and presence through full-body over hands-only self-representation.**

Keywords—self-representation, virtual reality, inverse kinematics, embodiment, avatar

I. Introduction

A key aspect in immersive Virtual Reality is to feel present in the virtual world: The illusion of being in the virtual environment is called “presence”. This illusion consists of two aspects: the illusion of being in this place ("place illusion") and the illusion that the scenario is really happening ("plausibility illusion"). A self-representation through an avatar influences both aspects. Being able to look at your own body evokes the feeling of really being in the virtual place (place illusion) and synchronous movements of the avatar can increase the plausibility illusion, a feeling of embodiment can arise. [1]

This feeling of embodiment is a combination of the sense of self-location, agency and body ownership [2]. Botvnick and Cohen demonstrated that a feeling of body ownership can be generated for a rubber hand by synchronous tactile stimulation of the hidden real hand and a visible rubber hand [3]. This effect has been reproduced for the arm in a virtual environment [4]. Furthermore, it was shown that the same effect happens with synchronous movements of the hand instead of tactile simulations [5]. These studies show that a sense of body ownership for virtual limbs can be developed rather easily. However, the feeling of body ownership is higher, when the avatar moves in sync to the movements of the user [6]. Moreover, the sense of body ownership can be developed for avatars that differ in appearance or even morphology from their user, for example for avatars with a larger belly or a tail [7]–[10].

Proprioceptive manipulations through adaptations of the self-representation in VR can even affect the user’s behavior. A prominent example is the Proteus effect [11] that shows that users tend to behave like they expect the avatar to behave. This causes users to be more confident if they are embodied in a tall avatar. This powerful effect can also influence the biases of users, for example by embodying a person in an avatar with a different skin color or age [12]–[14]. Even the cognitive abilities can be improved by a self-representation through an avatar [16]. Steed et al. [15] showed that users with a self-avatar could better memorize letters.

Users represented through full-body avatar can better judge physical properties of the virtual world [17]–[20]. For example, they can better estimate if they can step off a ledge or over a pole [20]. In VR without the self-representation through an avatar, users tend to perceive distances as shorter than they are [21]. Furthermore, users behave more realistic with an avatar, i.e. they are less likely to walk through walls [22].

These findings suggest that adequate full body proprioception has the potential to support the therapeutic efficiency in cognitive rehabilitation. The application of VR for the diagnosis and treatment of neurological diseases like stroke and dementia is investigated in the *VReha* project [23], [24]. One of the tools developed in VReha is the immersive Virtual Supermarket Task. This virtual environment, illustrated in Fig. 1, can be used to test and train executive functions by confronting the patient with the task to navigate through a supermarket, find all the products on a shopping list and to place them into the shopping cart. There is a standing version in which the user pushes a virtual shopping trolley and a sitting version in which the user steers a virtual electric scooter. Navigation is based on a real handle bar (shown in the right image of Fig. 1) that is mapped to the respective handlebar in VR [25].

A straightforward approach to implement self-representation with synchronous movement would be a motion capture system. This could be either a marker- or wearable-based system or a marker-free system employing computer vision algorithms. Marker- or wearable-based systems typically exhibit higher accuracy but rely on more sophisticated technical setups and longer preparation time [26]. However, in VReha, the primary user group comprises of patients in a clinical setting during neurological or cognitive rehabilitation. For patients and clinicians, the VR-setup itself is new and challenging; users should not be restricted in their freedom of movements with

Fig. 1: The virtual supermarket in the VReha-project. User's first-person - perspective within the virtual environment with the handlebar of the virtual shopping cart (left), third-person perspective on the user in the virtual environment (middle), third-person perspective on the user in the physical world with the physical handlebar (right).

additional setups (e.g. a full body suit, markers or controllers) and potentially be able to perform VR training at their homes. Thus, the setup needs to be as simple as possible and the preparation time short. Therefore, we choose to implement a solution that is, apart from cabling of the HMD, wire- and wearables-free and mostly relies on computer vision algorithms. Obviously, this relative simplicity of the technical setup trades for less direct measurements of user's body joints. When not all joints of the skeleton are given, the missing joints can be derived by Inverse Kinematics (IK) [27]. There is no explicit solution for the position of the missing joints (e.g., elbow when hand and shoulder were given), but several existing software packages promise a plausible estimation.

This paper contributes to the understanding of the use of Inverse Kinematics for self-representation in various ways: In Sec. II we evaluate and compare existing IK-methods in order to find the optimal IK-solution for our system design. We then describe the application, implementation and adaptation of this optimal IK-approach for self-representation through a full body avatar in Sec. III. This optimized system is validated in terms of the degree of the feeling of embodiment and presence in extensive subjective tests. This evaluation of the possible improvement of the experience in VR is described in Sec. IV. Sec. V concludes the paper with a discussion of the overall results and future research directions.

II. Inverse Kinematics for pose estimation

A. State of the Art

In Inverse Kinematics, limbs are considered as a kinematic chain, for example, the arm can be represented as a kinematic chain with the joints shoulder, elbow and wrist. Based on the position and orientation of the last link of the chain (end effector), for example the hand, all links of the chain are brought into a suitable position [28][29]. There are various IK approaches available to solve limbs or the full body: Jiang et al. [30] developed an IK-solver for the upper body in combination with animation blending for the lower body. A solution to solve serial chains (e.g. arm, leg) is the Forward And Backward Reaching Inverse Kinematics (FABRIK) [31] algorithm. The open source solver SAFullBodyIK [32] and the commercial solver from FinalIK [33] offer a solution specifically for the human body. FinalIK also offers an additional solution for single limbs (e.g. the arm). VRArmIK is an IK solver specifically developed to solve the arms for VR applications [28]. Unity (game engine / development platform) itself provides two IK solvers: The Constraint Two Bone IK can be used to get the location of the elbow [34]. The other approach is made to solve the full body, hereinafter referred to as Unity IK. For full body pose estimation the feet positions are required, without them only the upper body pose can be estimated [35].

B. Comparison of current IK solutions

Parger et al. already compared five of the above mentioned IK arm solvers [28]: the FABRIK algorithm, the solver by Jiang et al., FinalIK, SAFullBodyIK and their own solution VRArmIK. They concluded that their own solution is the most suitable IK-arm-solver [28]. Building up on Parger's et. al evaluation we compared their VRArmIK (Version 1.0) solution, with three approaches that are not systemically evaluated yet: VRIK from Final IK (Version 1.0) [36] and the two solutions provided by Unity (Version 2019.4.2f1) (see Sec. II.A). As a baseline, motion capture data from the Carnegie Mellon University was used [37]–[39]. 100 animations with a total length of 25 minutes were chosen, containing varying movements especially of the arms. All solvers were used with their default settings, only settings regarding the avatar (e.g. head to neck distance) were adapted.

Fig. 2 shows which positions have been measured and which ones have been estimated by the IK solver. For VRArmIK and VRIK the hand and head positions are measured by standard VR hardware or tracking cameras. To estimate elbow positions, Two Bone IK requires two input positions below the neck in addition to the hand positions. The neck positions are not provided by standard VR HMD equipment. In order to consider Two Bone for the comparison of elbow position error, we had to provide these positions from another source. After preliminary evaluations, we decided to use the reliable position of the lower neck estimated by VRIK as the corresponding input position for Two Bone. Unity IK requires the center-eye position and the body center of mass position in addition to the hand location.

To evaluate the solvers, the error between the joint ground truth and the joint given by the IK solution was calculated. This was done for the elbow and, if solved, also for the upper arm joint.

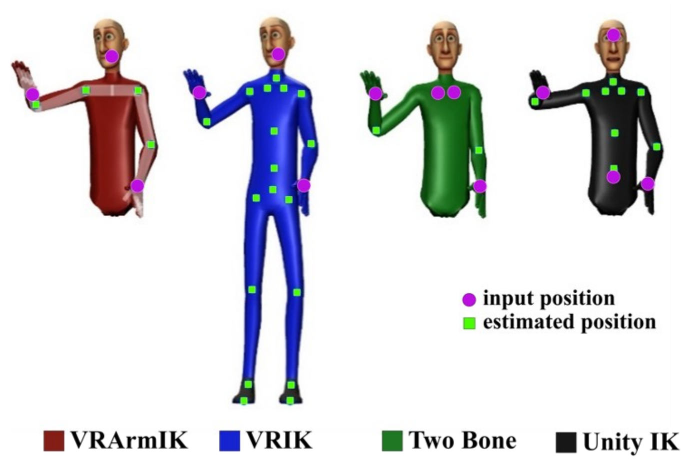

Fig. 2: Visualization of joint positions as estimated by different IK-models and corresponding input positions

C. *Results of the current IK comparison*

The results are presented in Fig. 3. Comparing the elbow positioning error, Two Bone IK provides the best result with a mean error of 4.7 cm. However, as Two Bone IK is not able to solve the whole chain from the head to the hands like the other solvers, it is not a suitable solution for our use case. VRIK is the second-best solution with a mean error of 5.3 cm.

The upper arm error is difficult to compare. As Unity IK is provided with the correct position of the center of mass, the solver has an advantage compared to the other solvers. This results in the lowest mean error of 4.3 cm for the upper arm positioning. The mean error of VRIK is 5.7 cm. For Two Bone IK there is no upper arm positioning error measured, as the location was given.

In conclusion, VRIK appears to be the best IK-solver with a low elbow and upper arm positioning error. As the hand and head locations are sufficient as input, it is an adequate solution for VR applications. In most cases the head position is given by the VR-HMD; the hand positions are estimated from the camera image from the Kinect and Leap Motion or determined by the position of the controller. Both IK solvers from Unity are not suitable: the upper arm error of Unity IK is too high, and Two Bone IK can only solve the elbow position. Additionally, they require position information, which is not available in most VR-setups (e.g. the center of mass). VRArmIK would be also a suitable solution in principle, but as the positioning errors are higher than from VRIK, we choose to use VRIK in the following.

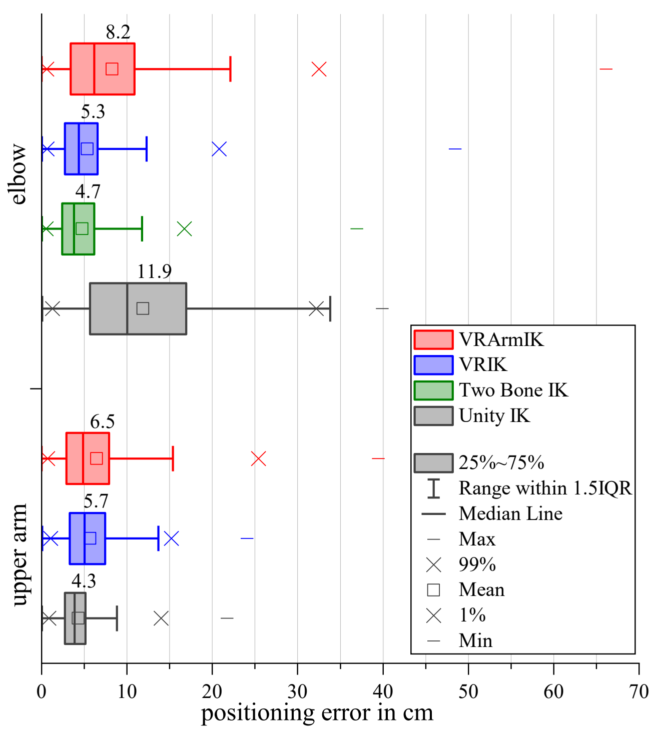

Fig. 3: Distribution of the Euclidean geometric error of the elbow and upper arm position as estimated by different IK-models.

III. Implementation

A. *Technical Setup*

The Technical setup is shown in Fig. 4. The VR applications are implemented using the Unity game engine and displayed on an Oculus Rift HMD. The position of the HMD is tracked by two sensors. A Leap Motion, mounted at the HMD, is used for hand tracking. While the Leap Motion is addressed directly via Unity, there are separate applications for the full body tracking sensors (we support Azure Kinect, Microsoft Kinect 2 and Intel RealSense), which send the body data in a common JSON format. Our simple to use HHI middleware is used for data transmission between the VR applications and the various sensors via WebSockets. All components are running on a single PC (Xeon E51650v3, 16 GB RAM, nvidia GTX 1080).

The HMD and the extern sensors Leap Motion or Kinect have different coordinate systems. To fuse the positions of the joints measured by the different sensors the coordinate systems have to be calibrated. For the calibration of an HMD and Leap motion a default calibration is used even if the position of the Leap Motion on the HMD is not exactly given. For extern sensors as Kinect this is not possible. For calibration we used the position of the hand controllers of the VR system and the position of the estimated hands from Kinect. Depending on the device (Kinect 2 and Azure Kinect) and the distance to the device, the position of the hands is not given or inaccurate. In this case we estimate the hand position from elbow and wrist position. To overcome the latency difference between the position of the hand controllers and the position of the external sensors, we only collected the position when the hands are not moving. Using around 20 calibration points for each hand in a RANSAC algorithm and Iterative Closed Point algorithm by Umeyama leads to a calibration accuracy of less than 50 mm.

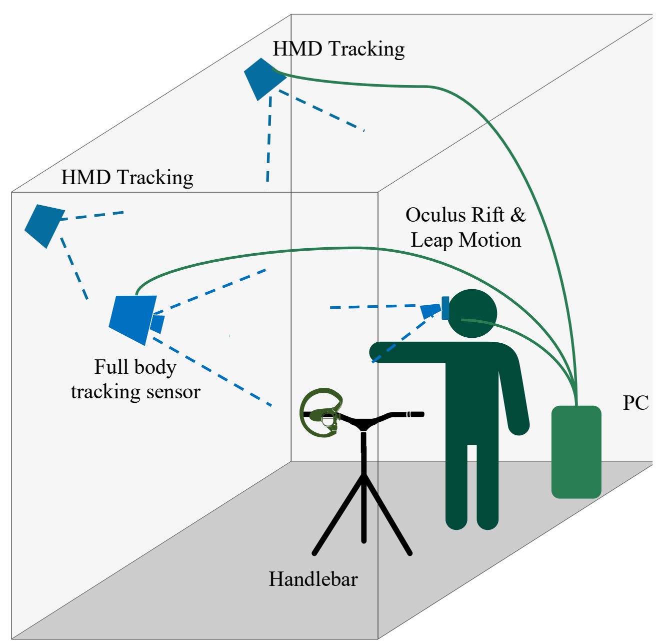

Fig. 4: Technical setup of our system.

B. Avatar Models

We use the Rocketbox Avatars from Microsoft [40] for this project, as they provide numerous and diverse rigged avatar models. To fix the issue that the mesh of the arm is twisted, when the wrist is rotated, we added two Twist Bones. Additionally, we slightly changed how the rotation of the bones influences the mesh (e.g. for more realistic bending of the thumb). Furthermore, the models got adapted, so that the user can choose the shape (small, medium and large), the skin color and the shirt color. This way the users will get a matching avatar to their appearance.

In the next step the avatar is scaled according to the body dimensions of the user. Otherwise, the limbs of the avatar would be for example bent, if they are longer than the actual limbs. Therefore, the user has to first stand straight and extend arms forward. Secondly, the user has to position the hands at the height of the hips. This way the height, arm length and hips height can be measured, and the avatar can be scaled accordingly. For later usage the scaling values are stored. The scaling poses are visualized in Fig. 5.

C. Placement of the effectors

To use VRIK the effectors (head, hand et al.) have to be placed and rotated accordingly. The orientation of the effectors has to match the joint orientation of the avatar.

The head effector is placed based on the center-eye anchor provided by the VR-HMD (Oculus Rift / Oculus Quest). The hand effectors are placed depending on the availability of the tracking data: If tracking data from the Leap Motion or Oculus Quest is available, this data will be used. In case this data is not available, e.g. if the hands are outside of the field of view, the tracking data of a full body tracking sensor (Azure Kinect, Kinect 2, RealSense) is used. As this data is less accurate, it will only be used in this case. Switching between data sources is filtered by a hysteresis to filter short term tracking errors, which occur for example when the user is clapping. For the elbow effectors the principle is the same as for the hand effectors. The lower body effectors (pelvis and feet effectors) are placed by a full body tracking sensor.

First, we evaluated the Azure Kinect as full body tracking sensor, but the latency is too high. Based on reversal points during hand movement, a latency of 200 ms was determined, when using no smoothing. The smoothing factor has an influence on the latency, the higher the smoothing factor, the higher the latency. Additional latency occurs when the VR application and the Azure Kinect sensor are running on the same PC (technical data see above). This has for example the effect that when walking in place the wrong leg is lifted because of the latency. Therefore, we switched to the Kinect 2, which has an acceptable latency. Additionally, we developed an own solution using the RealSense D435.

To place the feet effectors, the rotation data of the leg joints is used to calculate the feet position starting at the pelvis position. This has the advantage, that the legs bend correctly even if the avatar and the user have different sized legs. Additionally, the toes get bent if necessary.

The lower body effectors are optional. If no tracking data is available, the lower body pose is estimated by VRIK. The legs get bended, and the pelvis gets positioned under the head. The feet are always on the ground and a step gets triggered if necessary. A comparison between the avatar with and without the usage of lower body effectors is shown in Fig. 6.

D. Adapt IK to Seated Pose

In our setting we have to offer the possibility for the user / avatar to sit (see Sec.I). Since VRIK aligns the avatar based on its center of gravity, if the user is sitting and only head and hand effectors are given, the avatar will crouch. Full body tracking data are not available because joint positions are not recognized well for seated people. If hip and foot effectors are given, VRIK can position the avatar correctly seated. These effectors are now determined by the position of the head: To calculate the position of the effectors, the user must be sitting up straight. With the upper body height determined during scaling, the hip effector is positioned under the avatar's neck. Then the hip joints are placed as an aid for the foot effector positioning. The foot effectors are created as child elements. Starting from the hip joint, these are moved forward by the thigh length and the foot length. The height of the foot effectors is set according to the distance from the toes to the floor. This was determined before the initialization of VRIK so that the feet were on the ground at that time. In addition, the rotation of the toes in the avatar's T-pose is applied to the effectors so that the feet are facing forward. All calculations are done with local transformation values to position the effectors correctly even with a rotated parent element. A seated avatar is shown in Fig 7. For our application we choose to place the effectors on click of a button, when the user is seated.

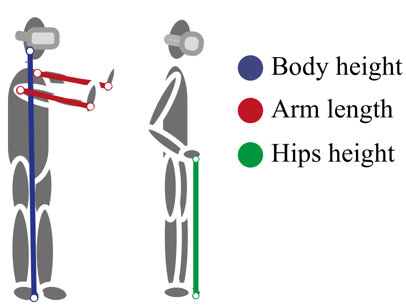

Fig. 5: Scaling poses used for calibrating the IK-models for a specific user.

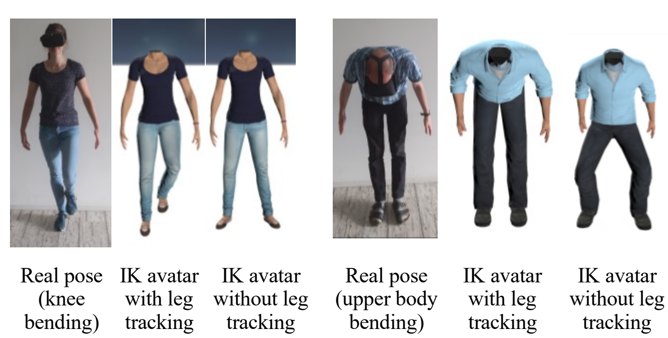

Fig. 6: Impact of leg tracking on the estimated pose.

Fig. 7: Self-representation of a user in the seated scenario (left); third-person perspective on a user in the seated scenario (right).

IV. User Study

To determine how the self-representation influences the feeling of embodiment and the feeling of physical presence, we conducted a user study. We formulate the following three hypotheses:

H1 Self-representation through an avatar leads to a higher feeling of embodiment compared to hands-only.

H2 Self-representation through an avatar leads to a higher feeling of physical presence compared to hands-only.

H3 Users prefer a self-representation through an avatar with leg tracking over the self-representation through hands-only and through an avatar without leg tracking.

A. Study Design

In order to test our hypotheses, we conducted a user study with three types of self-representation (see Fig. 8):

- Hands-only
- Avatar without leg tracking
- Avatar with leg tracking

We choose to use our VReha application for the study to have the results directly related to our application. For each condition the participant has to go shopping in the virtual supermarket for 5 minutes. They can move forward by walking in place and steer with a handlebar. We used the technical setup shown in Fig. 4.

The order of conditions is randomized. After each round the participants are asked to fill out the questionnaire. Participants had a break between rounds to avoid cybersickness affecting the results. In the end the participants had to fill out a general questionnaire.

a) Hand-only — b) avatar without leg-tracking — c) avatar with leg-tracking

Fig. 8: Different types of self-representation

We used the questionnaire from Gonzales-Franco et.al. [41] for the level of embodiment and the German translation of the Multimodal Presence Scale [42]. The questions regarding the embodiment were asked related to the hands and additionally to the body. From the Multimodal Presence Scale we only used the questions regarding the Physical Presence. The questions were in a random order.

B. Results

10 persons participated in our study. 40% of the participants were female. 60% of the participants rarely to never use VR applications, while 40% use them frequently. The average age was 37 years. To evaluate the results the provided formulas from the questionnaires were used [41], [42]. To determine the statistical significance, we used the Robust Paired Samples T-test, since the conditions necessary for other T-tests, such as a normal distribution or homoscedasticity, did not apply to the data.

The data shows that there is a significant difference for the embodiment related to the hands, the embodiment when represented through an avatar is significantly higher ($p < 0.05$). This confirms H1. For the physical presence (H2) there is only a tendency. Comparing the data for the avatar with leg tracking with the avatar without leg tracking a tendency for a higher feeling of embodiment when represented with an avatar with leg tracking is shown.

One interesting point is that the results for agency and location of the body tend to be more positive when represented through an avatar, although the hands are tracked and positioned in the same way for all conditions. The data is visualized in Fig. 9.

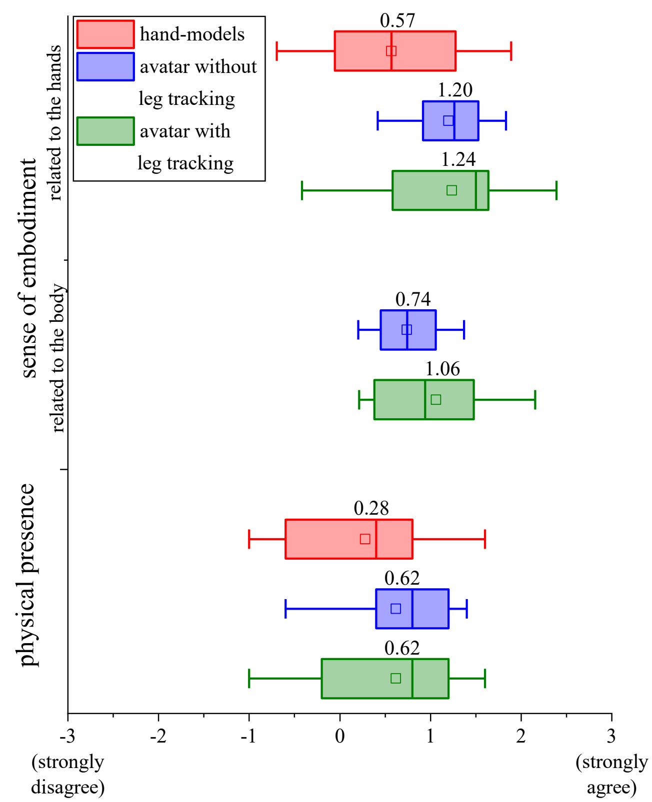

Fig. 9: Distribution of reported sense of embodiment and feeling of *physical presence for different models of self-representation.*

When asked which condition they prefer, 100% chose the representation through an avatar. 90% chose the avatar with leg tracking. Only 10 % choose the avatar without leg tracking, stating that the gripping worked best in that condition. On the other hand, the participant mentioned that the avatar with leg tracking felt most similar to him. This confirms H3. The participants stated some positive aspects of the representation through an avatar: They said, that with avatar the experience felt more realistic and immersive. The hand-models felt "unreal – like floating gloves".

C. *Summary and Discussion*

Through the user study we showed that H1 and H3 are fully supported. H2 is only partly supported, only a tendency and not a significant difference between the conditions was shown. A user study with more participants could lead to clearer results.

Another aspect we explored on the side in the user study is cybersickness for each condition. Here, we could not find any relations between cybersickness and the kind of self-representation. But some participants stated, they felt less sick when represented through an avatar. For example, one said: "I became less sick because I could see myself and my movements matched those of the avatar." This is an interesting factor, which we want to further research. A large-scaled user study might bring clearer results.

For the embodiment questionnaire we used there is now an improved version available [43].

V. Conclusion

In this work we compared current and most promising IK packages. We showed that with a suitable inverse kinematic solution, a self-representation can be created by tracking hands and the head (HMD) only. Nevertheless, in some use cases tracking the user´s feet can improve the self-representation. We described in which functionalities and how existing solutions should be improved for proper application in real world scenarios. Here especially the hand to arm connection of avatars, scaling of avatars, calibration of external devices to HMD and the latency of tracking data has to be addressed by application developers. We can also report that our approach is feasible to mobile VR headsets. An Oculus Quest with integrated cameras for hand tracking can be used as an alternative for the Oculus Rift with Leap Motion as well. This opens opportunities for home usage of VR training applications including real-time self-representation avatars to enhance treatment.

Our evaluation shows that self-representation increases embodiment in a VR environment. All users preferred the self-representation through an avatar to the representation with hand-models. The hypothesis that the feeling of presence increases is only partly supported, as there is no significant difference.

Acknowledgment

This research was supported by the German Federal Ministry for Research and Education (Project VReha, FKZ 13GW0206A). We thank our colleagues from the VReha consortium who provided insight and expertise. We also thank all participants of the user study.

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