The Importance of Virtual Hands and Feet for Virtual Reality Climbing

Figure 1: First person view of the climber's virtual hands and feet.

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Abstract

Virtual reality (VR) climbing systems registering physical climbing walls with immersive virtual environments (IVEs) have been a focus of past research. Such systems can provide physical user experiences similar to climbing in (extreme) outdoor environments. While in the real world, climbers can always see their hands and feet, virtual representations of limbs need to be spatially tracked and accurately rendered in VR, which increases system complexity. In this work, we investigated the importance of integrating virtual representations of the climber's hands and/or feet in VR climbing systems. We present a basic solution to track, calibrate and represent the climber's hands and feet, and report the results of a user study, comparing the importance of virtual limb representations in terms of perceived hand and feet movement accuracy, and enjoyability of the VR climbing experience. Our study suggests that the inclusion of feet is more important than having a hand visualization.

Author Keywords

Virtual reality; passive haptic feedback; hand tracking; foot tracking; rock climbing; user study.

CCS Concepts

•**Human-centered computing** → **Virtual reality;** *User studies; Visualization techniques;*

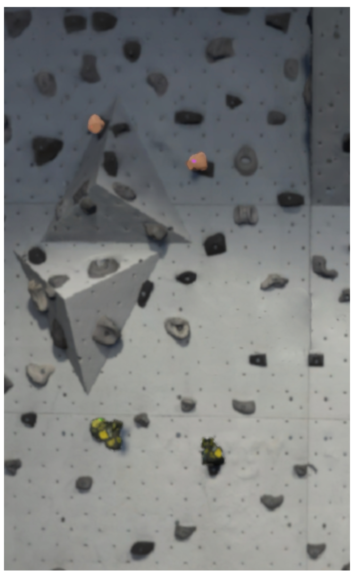

Figure 2: Third person view of the climber's virtual hands and feet. In the other three conditions, the hands or feet were not visualized.

Introduction

Climbing is a sport gaining increasing popularity, be it outdoors on a rock or indoors on artificial climbing walls. As a very physical activity that requires the climber to be highly concentrated on the planning and execution of movements, sufficient practice is key to reduce the risk of injuries. However, as practice comes with repetition, gaining sufficient experience to master dangerous situations, for example in outdoor climbing, can be cumbersome due to the required amount of traveling or unforeseeable weather conditions.

Climbing systems that combine physical climbing with the feeling of presence that can ensue in immersive virtual environments (IVEs), promise to be suitable instruments for climbing preparations and have been a focus of past research [11, 15, 17]. With such virtual reality (VR) systems, users can climb on a physical wall while being immersed visually in a virtual scene through head-mounted displays (HMDs). VR climbing allows users to experience arbitrary climbing heights while practicing in a physically safe environment, e.g. at very low height. As such, VR climbing systems can be used to train dangerous situations such as falling rocks or suddenly appearing wildlife, or as part of acrophobia treatment to overcome the fear of heights. Apart from that, such augmented climbing experiences enable entirely novel types of entertainment, enriching the climbing experience through games.

To achieve a high degree of presence, VR climbing systems aim to provide a visual and physical (i.e. haptic) stimulation close to real life. This involves realistic graphics and the ability of VR climbers to grasp grips. While HMDs track the user's head in the IVE, tracking of the hands and feet, however, is not a standard feature of today's VR systems. As climbers in the real world can always see their hands and feet, it is necessary to integrate an accurate tracking of the hands and feet, as well as a suitable virtual representation to allow for the same visual reference points in VR climbing.

This work is motivated by previous observations showing that users could successfully climb in VR without seeing any representations of their hands and/or feet [11], just relying on their proprioception. To investigate the importance of integrating virtual representations of hands and feet in VR climbing systems, we propose a basic method to track, calibrate, and represent hands and feet in VR. Based on this integration, we conducted a user study to assess and compare the effect that the presence and absence of virtual hand and foot representations have on perceived VR climbing accuracy and the enjoyability of the VR climbing experience. To gain further insights, we invited novice-level, as well as intermediate-level climbers to participate in our experiment.

Related Work

Climbing has been investigated in the context of human-computer interaction (HCI) in the past. Prior work has been focused on interactive climbing walls, interaction with climber and belayer [10, 13] and even environment-scale fabrication of artificial walls [18]. So far, only a few initial approaches to climbing in VR have been proposed.

Interactive Climbing Walls

In the past, rock climbing has been investigated in the context of HCI. Liljedahl et al. [12] presented *Digiwall*, a climbing wall that featured translucent, instrumented holds that incorporated LEDs and capacitive sensors, enabling different interaction models. Ouchi et al. also used sensor-embedded climbing holds to model play behavior on an instrumented climbing wall [14]. A similar system that augments the climbing wall by instrumentation was presented by Fiess and Hundhausen [4]. In their work, they built a

Figure 3: Wooden template to calibrate the climbers feet with the virtual shoe models.

Figure 4: Virtual representation of the wooden template.

climbing wall out of translucent material. A LED-wall placed behind the climbing wall surface acted as a display that covered the whole climbing wall. As in the work of Liljedahl et al. [12], the authors also included capacitive sensors to allow for interactive climbing games.

While the systems described above rely on heavy instrumentation of the climbing wall, including wiring or replacing the surface with translucent material, some research projects approach the augmentation of climbing walls. Daiber et al. [3] introduced BouldAR, a mobile augmented reality system to track climbing walls and augment route information in AR. *The Augmented Climbing Wall* by Kajastilla et al. [8, 7] combines a regular climbing wall, a depth camera, and a projector. With this, the authors implemented several interactive games and new ways to highlight custom routes which are usually indicated by the color of the holds. Similar to that, Wiehr et al. [19] proposed a mobile, self-calibrating camera-projection unit that could be placed in front of an arbitrary bouldering wall. Besides playing games and creating new routes via an augmented reality smartphone app, the system allows for the recording and playback of in-place video, projected directly on the climbing wall. In addition to projections on the climbing wall, Kosmalla et al. [9] investigated the use of augmented reality glasses to learn climbing movements.

In contrast to the direct instrumentation and the augmentation via projection, the system proposed in this work augments the climbing wall in three dimensions by utilizing the possibilities of current VR headsets. The use of VR entails a notable number of opportunities that go beyond the illumination of holds or projections on the climbing wall. The main reasons for that are that the augmentation is not only limited to the surface of the climbing wall but can span areas as far as the eye can reach. Furthermore, it allows altering the representation of the reality by removing elements like holds from the wall or adding new details like weather conditions, animals, or falling rocks in the IVE.

Climbing in VR

While VR climbing in the context of VR games exists (e.g. The Climb [2]), our approach involves actual climbing on a real wall and thus can be classified as an instance of substitutional reality [16, 20]. Substitutional reality relies on the concept of utilizing existing objects in the real surrounding as haptic proxies. Insko [6] showed that passive haptics can enhance the user's sense of presence. While not addressing a climbing context, Bruder et. al [1] demonstrated a camera-based approach to visualize the user extremities in VR which was reported to add a higher sense of presence to the IVE.

A first approach to VR climbing experiences have been proposed by Kosmalla et al. [11]. Their system consists of a real climbing wall, a head-mounted display, and a tracking system. The "Venga!" system by Tiator et al. [17] is a follow-up project that implemented both, hand and foot tracking and proposed a simple approach for hand and feet calibration. Their calibration approach requires the user's extremities to remain at a certain location during the calibration phase. Furthermore, the system has not been evaluated in an extensive user study. Recently, Schulz et al. [15] investigated the role of physical props on presence, stress, and anxiety in VR climbing. The results of their study suggest that the integration of physical props in VR climbing effectively simulates an induced sense of height. Gao et al. [5] investigated the sensory and perceptual factors in simulated climbing environments.

In contrast to prior work, to the best of our knowledge, the effect of accurate virtual hand and feet visualization on climbing in VR has not been investigated in depth before.

This work in progress makes an initial yet important step towards a better understanding of how the visualization of virtual extremities affects proprioception in VR climbing and other full-body activities in VR.

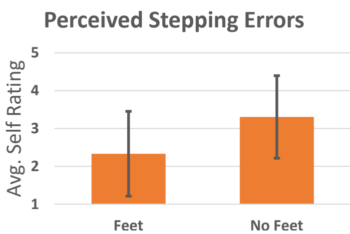

Figure 5: Avg. agreement with the statement "*I often missed a grip while using my feet*" on a scale from 1 (= I totally disagree) to 5 (= I totally agree).

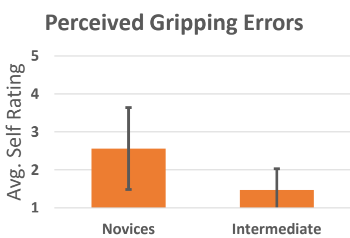

Figure 6: Avg. agreement with the statement "*I often missed a grip while using my hands*" on a scale from 1 (= I totally disagree) to 5 (= I totally agree).

User Study

To conduct a pilot user study to investigate the importance of integrating hands and feet into a VR climbing experience, we extended the system described by [11]. The following sections describe the technical realization, the study design and the gathered results in detail. Our setup consisted of a physical climbing wall measuring four by three meters. To catch the climber in case of a sudden fall, a thick mat covers the floor in front of the climbing wall. A 3D model of the climbing wall was created utilizing the Microsoft Kinect v1 and Skanect[1], which resulted in a model that was dimensionally correct and textured like the physical counterpart. As output device, we chose the HTC Vive because of their free-roaming capabilities. The virtual climbing wall was placed in an empty space to keep the focus of the user on the climbing wall. For the calibration and integration of hands and feet in VR, we used HTC Vive trackers as described in the following section.

Calibration

Concerning the calibration of the physical climbing wall, we used the same method as proposed in previous work [11] and defined four distinct points that were easily perceivable on both the physical and the virtual climbing wall, i.e. tips of climbing holds or features of the wall. These real-virtual pairs of reference points were used to calculate the optimal rotation and translation to match the visual climbing wall with its physical counterpart.

[1] https://skanect.occipital.com/download/

We extended the setup by Kosmalla et al. [11] by adding HTC Vive trackers to the top of the climber's feet and the back of their hands to track them. To ensure a realistic virtual representation, we created a virtual model of a pair of climbing shoes using photogrammetry[2].

To calibrate the climber's shoes with their virtual counterparts, we crafted a wooden template utilizing a laser cutter and MDF panels as depicted in 3. We designed the template so that we could line up both the virtual, as well as the physical shoes with the horizontal and vertical panels as shown in Figure 3. In addition to that, we added a mount for an HTC Vive tracker. This provided us with the position and rotation of the template at all times, allowing for a flexible calibration. Prior to the calibration, the virtual shoes are attached as children in the scene hierarchy to the template so that the sides and tips of the shoes would line up as described above. While wearing climbing shoes fitted with individual Vive trackers, the climbers would be asked to step onto the template, lining up their physical shoes as closely to the virtual representation as possible. A press of a button completed the calibration and changed the parent of the virtual shoes in the scene hierarchy to the Vive trackers, resulting in a visualization of the climbers' feet in the IVE.

The calibration of the hands followed a similar pattern. We attached Vive trackers to the back of the hands of the climbers with velcro straps. Rigged and animated hands were placed palm down and extended onto the same wooden template so that the tip of the middle finger as also the tip of the thumb lined up with the horizontal, respectively the vertical panel. A button press changed the parent of the virtual hands in the scene hierarchy after placing the physical hands onto the template.

[2] https://www.autodesk.de/products/recap/overview

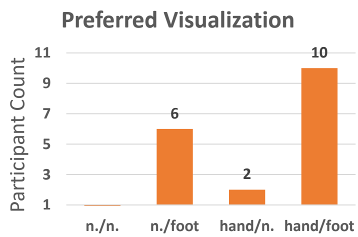

Figure 7: Histogram of the preferred visualization method.

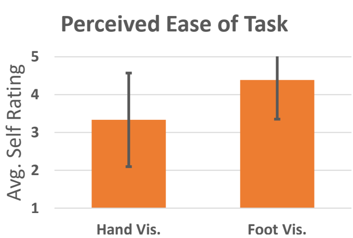

Figure 8: Avg. agreement with the statement "*The task was easier to accomplish while climbing with {Hand, Foot} Visualization*" on a scale from 1 (= I totally disagree) to 5 (= I totally agree).

Since the use of Vive trackers alone does not allow for sensing individual finger movements, we triggered a closing-hand animation as soon as the hand of the climber came in close range of a climbing hold. Although we recognize that this is just an approximation of the real world, we chose this option over wearing VR gloves to a) preserve the sensory experience while touching climbing holds and b) come closer to reality since climbing with gloves is rather uncommon. The resulting first-person view of the climber can be seen in Figure 9.

Guiding System
To obtain comparable results during the study, all participants had to use the same foot and handholds. This was ensured by the implementation of a guiding system. Spotlights were used to illuminate holds that were allowed to grab, respectively stepped on. In total four different routes were implemented which had to be climbed by each participant. After reaching an illuminated hold, a sound signal was played and the next hold was illuminated. Each route consisted of 20 holds.

As mentioned before, the goal of the study was to investigate how the visualization of hands and feet affects the climbers perceived precision in grabbing and stepping, as well as their experience during climbing. Although it would be technically feasible to measure the actual precision of gripping and stepping we deliberately postponed this analysis for future work. One reason for that is the need for a precise mesh of the individual climbing holds as also a detailed representation of hands and shoes. Both are necessary to detect not only the ballistic phase of the grabbing/stepping movements but also finer movements when adjusting the grip of the hand/foot. As a result, in this late-breaking work, we only regard the perceived precision of the participants.

Participants
18 participants volunteered in the pilot-study. The participants' age reached from 19 to 40 years (AVG=25, SD=4.86). Ten participants had prior climbing experience (regularly climbing more than once a week) while the rest had no significant climbing experience. Four participants stated that they already had experience with VR.

Design
The study followed a within-subjects design. All participants had to climb four different routes with four different visualization modes: 1) neither hands nor feet, 2) only hands, 3) only feet, and 4) both, hands and feet. A 4×4 Latin square design was used to counterbalance the order of route and visualization.

Procedure
After signing an informed consent form, participants were interviewed about their age, climbing and VR experience. Participants were given time to warm up on the climbing wall. After this, the Vive Trackers were attached to the participants' hands and feet, followed by a calibration as described above. Depending on the order defined by the latin square, the corresponding visualization was set. The participants were asked to climb four routes in total. After each climb, the participants filled out a questionnaire to assess their perception concerning the specific visualization. This included questions about the perceived number of missed hand and footholds and workload. At the end of the experiment, we asked the participants about their preferred visualization method.

Results
During this pilot study, we found four main findings. All tests of significance were done by utilizing the Wilcoxon signed-rank test. Significance was assumed when $p < 0.05$.

Missing Feet Visualization Increases Perceived Stepping Errors – When looking at both, novices and intermediate climbers, we found that participants who were not provided with a visualization of their feet made significantly more stepping errors than those who had a visualization (see Figure 5). This significant difference could not be found when looking at gripping errors and the corresponding visualization of hands.

Intermediate Climbers Are Less Dependent on Hand Visualization – When comparing the statements of the novices to the intermediate climbers who did not have a hand visualization, we found that the perceived number of missed grips was significantly less for the intermediate climbers (see Figure 6).

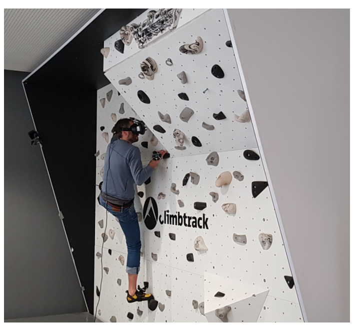

Figure 9: A climber wearing a head-mounted display with trackers attached to hands and feet.

Showing Hands and Feet Is the Preferred Visualization Method – When asking about their preferred visualization method after climbing all routes, 55% of the participants chose the combined visualization of feet and hands (see Figure 7). The second preferred visualization just included the feet (33%), followed by just the hands. No participants preferred the visualization which neither showed hands nor feet.

Visualizing of the Feet Is More Important Than the Hands
When asking about the perceived ease of tasks, the participants claimed that having a visualization of the hands did not make the task as easy as when adding feet as visual feedback (see Figure 8). The difference in perceived ease between these two modalities was significant.

Discussion
One factor for the missing significance when looking at the perceived number of grips (Figure 6) based on the hand visualization could be related to muscle memory. Since most people use their hands for tasks that require more coordination than walking or running, their eye-hand coordination is more evolved than their eye-foot coordination. Since intermediate climbers can draw on experience from prior training sessions, their eye-hand coordination is superior to the ones of novices (see Figure 6). Although one would assume that having both hands and feet visualized during a VR climbing experience, only a little more than half the participants stated that this would be their preferred visualization, closely followed by the visualization that just included the feet.

This could be the case since the representation of the virtual hands did not completely match the reality as described above. In general, this suggests that for the use case of climbing in VR having a visualization of feet is more important than a visualization of hands.

Conclusion and Future Work
In this work, we explored the importance of having visual feedback of hands and feet in a VR climbing scenario. For this we implemented a system that supports the tracking of hands in feet in VR and thus, allows physical climbing on a virtual climbing wall. While we did not report the actual difference of precision in climbing with visual representations of hands and feet, we investigated the perception of errors and ease of climbing. The results of this pilot study suggest that having a visual representation of feet is more important than having the visualization of hands when climbing in virtual reality. In future work, this tendency needs to strengthened with a more elaborate user study. As mentioned before, a precise description of gripping and stepping precision needs to be defined and implemented. This entails having a more precise tracking of individual fingers and the use of a more detailed mesh of the individual climbing holds.

REFERENCES

[1] Gerd Bruder, Frank Steinicke, Kai Rothaus, and Klaus Hinrichs. 2009. Enhancing presence in head-mounted display environments by visual body feedback using head-mounted cameras. In *2009 International Conference on CyberWorlds*. IEEE, 43–50.

[2] Crytek. 2016. *The Climb*. Game [Oculus VR]. (28 April 2016).

[3] Florian Daiber, Felix Kosmalla, and Antonio Krüger. 2013. BouldAR: Using Augmented Reality to Support Collaborative Boulder Training. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems (CHI EA '13)*. Association for Computing Machinery, New York, NY, USA, 949–954. DOI: http://dx.doi.org/10.1145/2468356.2468526

[4] Fabian Fiess and Felix Hundhausen. 2015. Interaktive Kletterwand. (2015), 429–432.

[5] BoYu Gao, Jee-In Kim, and HyungSeok Kim. 2018. Sensory and Perceptual Consistency for Believable Response in Action Feedback Loop. In *Proceedings of Computer Graphics International 2018*. 201–210.

[6] Brent Edward Insko. 2001. *Passive haptics significantly enhances virtual environments*. Ph.D. Dissertation. University of North Carolina at Chapel Hill, USA. http://www.cs.unc.edu/techreports/01-017.pdf

[7] Raine Kajastila and Perttu Hämäläinen. 2014. Augmented climbing: testing prototypes in wizard of oz experiment. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*. 169–170.

[8] Raine Kajastila, Leo Holsti, and Perttu Hämäläinen. 2016. The Augmented Climbing Wall. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. ACM Press, New York, New York, USA, 758–769. DOI: http://dx.doi.org/10.1145/2858036.2858450

[9] Felix Kosmalla, Florian Daiber, Frederik Wiehr, and Antonio Krüger. 2017. ClimbVis: Investigating In-situ Visualizations for Understanding Climbing Movements by Demonstration. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ACM, 270–279.

[10] Felix Kosmalla, Frederik Wiehr, Florian Daiber, Antonio Krüger, and Markus Löchtefeld. 2016. Climbaware: Investigating perception and acceptance of wearables in rock climbing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1097–1108.

[11] Felix Kosmalla, André Zenner, Marco Speicher, Florian Daiber, Nico Herbig, and Antonio Krüger. 2017. Exploring Rock Climbing in Mixed Reality Environments. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 1787–1793. DOI: http://dx.doi.org/10.1145/3027063.3053110

[12] Mats Liljedahl, Stefan Lindberg, and Jan Berg. 2005. Digiwall - An Interactive Climbing Wall. In *Proceedings of the 2005 ACM SIGCHI International Conference on Advances in computer entertainment technology - ACE '05 (ACE '05)*. ACM, New York, NY, USA, 225–228. DOI: http://dx.doi.org/10.1145/1178477.1178513

[13] Eleonora Mencarini, Chiara Leonardi, Antonella De Angeli, and Massimo Zancanaro. 2016. Design opportunities for wearable devices in learning to climb. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. ACM, 48.

[14] Hisakazu Ouchi, Yoshifumi Nishida, Ilwoong Kim, Yoichi Motomura, and Hiroshi Mizoguchi. 2010. Detecting and modeling play behavior using sensor-embedded rock-climbing equipment. *Proceedings of the 9th International Conference on Interaction Design and Children - IDC '10* (2010), 118. DOI:http://dx.doi.org/10.1145/1810543.1810557

[15] Peter Schulz, Dmitry Alexandrovsky, Felix Putze, Rainer Malaka, and Johannes Schöning. 2019. The Role of Physical Props in VR Climbing Environments. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 183, 13 pages. DOI: http://dx.doi.org/10.1145/3290605.3300413

[16] Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proc. CHI*. ACM, New York, NY, USA, 3307–3316. DOI: http://dx.doi.org/10.1145/2702123.2702389

[17] Marcel Tiator, Christian Geiger, Bastian Dewitz, Ben Fischer, Laurin Gerhardt, David Nowottnik, and Hendrik Preu. 2018. Venga!: climbing in mixed reality. In *Proceedings of the First Superhuman Sports Design Challenge: First International Symposium on Amplifying Capabilities and Competing in Mixed Realities*. ACM, 9.

[18] Emily Whiting, Nada Ouf, Liane Makatura, Christos Mousas, Zhenyu Shu, and Ladislav Kavan. 2017. Environment-scale fabrication: Replicating outdoor climbing experiences. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 1794–1804.

[19] Frederik Wiehr, Felix Kosmalla, Florian Daiber, and Antonio Krüger. 2016. betaCube: Enhancing Training for Climbing by a Self-Calibrating Camera-Projection Unit. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1998–2004.

[20] André Zenner, Felix Kosmalla, Marco Speicher, Florian Daiber, and Antonio Krüger. 2018. A Projection-Based Interface to Involve Semi-Immersed Users in Substitutional Realities. In *2018 IEEE 4th Workshop on Everyday Virtual Reality (WEVR)*. https://wevr.adalsimeone.me/2018/WEVR2018_Zenner.pdf