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MediHopps: A novel approach to virtual rehabilitation sport
- Practice Track -

Tobias Gottschalk, Kevin Gisa, Nanna Dahlem, Lea Reichl, Tobias Greff, and Dirk Werth
[1] August-Wilhelm Scheer Institut für digitale Produkte und Prozesse gGmbH, Uni Campus Nord D 5 1, 66123 Saarbrücken

Abstract

Throughout Germany, there is an increasing demand for home-based rehabilitation sports, especially in rural areas. Although current systems already target location-independent remote sports, the practice of training is not possible in groups. Especially the aspect of collaborative rehabilitation sport is demonstrably decisive to strengthen the self-help character of the performance and to achieve positive group dynamic effects. Extended Reality represents a promising technology to provide location-independent effective group rehabilitation sports training. Therefore, the research project MediHopps aims to develop an intelligent full-body holoporation for stand-alone XR glasses, which makes it possible to precisely capture body postures and poses and transfer them to digital avatars in the virtual world just by wearing multisensory glasses. The purpose is to enable collaborative medically precise telerehabilitation in a virtual training room. The intelligent assistance system classifies the recognized movements and detects incorrectly performed exercises. MediHopps thus creates an easily accessible, supervised, qualitatively controlled and location-independent rehabilitation sports training including positive group dynamic effects. The research project solves thereby social challenges referring to limited access possibilities for rehabilitation sport and contributes to a human-centered Society 5.0.

1 Introduction

Rehabilitation sport is an important component to medically rehabilitate affected people after an illness promoting their reintegration into professional life and thus enabling them to participate in social and cultural life again. In Germany there were 1.4 million rehabilitation sport requests in 2020. In this context, costs totaled 6.9 billion euros in 2019 (in Germany) (Deutsche Rentenversicherung Bund, 2021). Rehabilitation sport aims to restore the physical and mental abilities of a patient. It is also used as a preventive measure to avoid damage to health and injuries. With an average age of 53.8 years (in Germany) (Deutsche Rentenversicherung Bund, 2021), most participants in rehabilitation sports are employed. Therefore, rehabilitation sport also is used for a gradual reintegration. Popular disease patterns are orthopedic diseases and complaints such as osteoarthritis, joint pain, back and knee pain. Rehab sport is performed only in groups of up to 15 people and the exercises are performed by a qualified specialist exercise instructor. Among other things practicing in groups aims bringing people together and enable an exchange. Which is, in addition to the medical aspect an essential part of rehabilitation sports. In this paper there is presented a new approach on how rehabilitation sport can be conducted digitally and in a virtual environment. MediHopps (Medical Full Body Holoportation in Virtual Collaboration Spaces) is a research project at the BMBF (Federal Ministry of Education and Research, Germany) in the funding initiative “KMU-Innovativ”. An expert in XR applications, a center for rehabilitation sports and a research institute for digitalisation and artificial intelligence are researching how rehabilitation sports can be carried out in a virtual space using only XR glasses. * Regarding to this central project objective, this paper will examine the question of how rehabilitation sports can be performed in a simulated 3-D environment using only one single device while preserving dynamic group effects and promoting social interactions.

For this purpose, first the underlying problem is described, followed by an analysis of the state of the art, related work and state of the market. Afterwards the vision and the technical realization of MediHopps are outlined and a conclusion is drawn.

2 Problem Statement

More and more people are suffering from chronic degenerative diseases and are dependent on continuous care. The supply bottlenecks in urban regions constitute a particular challenge. In addition, the length of stay of patients in inpatient facilities is being shortened to a minimum. This means that they enter aftercare and thus make use of rehabilitation sports as a treatment earlier. Demographic change is accompanied by an increase in working time. In combination with changes in the world of work, this requires an increasing demand for rehabilitation sports as a preventive health measurement (John, Einhaus, Klose, Kock, & Graßhoff, 2020; Dhein, 2020). Accordingly, there is an increasing need for medical rehabilitation sports in both aftercare and prevention. Location-based offers are associated with many further disadvantages. For people who are limited in their personal mobility due to physical or mental causes, or who have no access to services needed due to their place of living, regular participation in rehabilitation sports is not an option (Telemedizinische Assistenzsysteme in Rehabilitation und Nachsorge, 2022). This demonstrates the need for location-independent opportunities that prevent the exclusion of social groups from community resources (Dhein, 2020; Pfannstiel, 2019). Telemedicine solutions offer the potential to address the lack of care in rural areas and to overcome the physical and temporal distance between the participants (John, Einhaus, Klose, Kock, & Graßhoff, 2020). The challenge here is that rehabilitation sport exercises should be performed in groups. "Exercising together in fixed groups is namely a prerequisite to promote group dynamic effects, to support the exchange of experiences between affected persons and thus to strengthen the self-help character of the performance." (Rahmenvereinbarung über den Rehabilitationssport und das Funktionstraining, 2011). The feeling of being part of a group is a strong motivating factor in health sport. However, current telemedicine does either not allow qualitative control of exercises by the trainer or by the telemedicine software (e.g., apps like CASPAR). Multisensory systems, are expensive and not end-user friendly (teslasuit.io) or do not allow rehabilitation sports in socially motivating group settings (meine Reha, 2022). Extended reality (XR) applications show a variety of positive effects when

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performing remote sports. The transfer of what is learned in the virtual world has a positive impact on motor skills and physical activity in the real world (Kim, Schweighofer, & Finley, 2019). In rehabilitation sports, XR represents a promising solution to deliver an effective rehabilitation sports training program in a location-independent and interactive manner between physical therapists or certified trainers and patients. It is therefore imperative to develop a solution that precisely captures the entire body movements and poses, derives a body model from it and transfers it to a virtual 3D image (3D avatar) (full-body holoportation) to provide participants an attractive group sport experience in a virtual collaborative space.

3 State of the art

XR has many positive effects on motor skills, performance, motivation, liking, activity and fatigue in healthy and ill individuals (Basu, Ball, Manning, & Johnsen, 2016; Kim, Schweighofer, & Finley, 2019; de Melo, et al., 2018; Schmidt, et al., 2018; Tuveri, Macis, Sorrentino, Spano, & Scateni, 2016). A good transfer of motor skills learned in VR to real life has also been shown in the process (Kim, Schweighofer, & Finley, 2019). Black Box VR founded fitness studios, that effectively combine common equipment training with gamification elements and VR.

Subject of investigation	Scientifically sound statements	Implementation in the MediHopps project
XR in sports	• Positive effects on motor skills, performance, motivation, enjoyment and activity. (Kim, Schweighofer, & Finley, 2019) (Basu, Ball, Manning, & Johnsen, 2016; de Melo, et al., 2018; Schmidt, et al., 2018) • Good transfer of motor skills learned in VR to real life. (Kim, Schweighofer, & Finley, 2019) • Use of XR in physically demanding scenarios scientifically proved (BLACKBOX VR, 2022)	• Benefit of XR for individual physical benefit of patients. • Implementation of XR for rehabilitation sport
Sensor technology	• Different technologies such as motion capturing suits or wearable sensors already implemented • Frequent impracticality due to the need to wear complex and highly expensive systems (Mehta, et al., 2017) • Innovative approaches like head camera and IMU sensors with positive results for whole body tracking systems (Tan, Lui, & Chihara, 2020; Nagaraj, Schake, Leiner, & Werth, 2020; Ng, Xiang, Joo, & Grauman, 2020) • Accuracy and accessibility of the tracking system in the rehabilitation sport context of great importance.	• Combination, further development and optimization of IMU sensors and first-person camera • Enabling a full-body holoportation system by transmitting motion sequences and body postures to digital 3D avatars in real time • Only using built-in sensor technology in XR devices • No need to purchase expensive external sensors

Table 1. Comparison of XR in sport and sensors

This also shows that XR can be used in physically demanding scenarios, such as performing athletic exercises. This benefit also led to the creation of the Virtual Reality Institute of Health and Exercise, which aims to evaluate the effect of widespread VR games on the human body and scientifically determine their calorie consumption. However, no solution for supervised, social and collaborative implementation of rehabilitation sports exists yet. The Tracking as well as the transmission of movements in industry and science already is realized in several sectors using different technologies, such as motion-capturing suits or wearable sensors. However, such solutions are impractical due to the need to carry complex and highly expensive systems.

4 Related Work

At SIGGRAPH conference 2017 there was presented the VNect approach (Mehta, et al., 2017) which shows a prototypical full-body tracking system through a single RBG camera aimed at the user. However, this requires external computing units as well as an optimally positioned external camera. Other methods include multiple IMU sensors for a full-body pose estimation (Nagaraj, Schake, Leiner, & Werth, 2020; McGrath & Stirling, 2020). First innovative approaches show positive results in whole body tracking system using a single ego camera. By attaching one camera to the chest, full-body pose estimation is successfully carried out (Ng, Xiang, Joo, & Grauman, 2020; Jiang & Grauman, 2017). Rhodin et al. (Rhodin, et al., 2016) use two helmet cameras for the same purpose. The Mo²Cap² system performs real-time 3D human body pose estimation based on a single cap-mounted fisheye camera (Xu, et al., 2019). However, all these systems require extra cameras or sensors. Since the full-body holoportation in Medihopps aims to develop a solution for stand-alone XR glasses, these approaches are not suitable. The video frames recorded by XR devices, which are located just a few cm away from the user's face, generate thereby a unique perspective. The upper and lower body parts suffer from high distortion. In addition, lower parts are often not visible due to self-occlusion. These characteristics make the task of full-body pose estimation using video streams only from VR devices particularly challenging. Early models are based on imitation learning and constrain the results to humanly possible poses (Yuan & Kitani, 2018). To learn these constraints, exact data for the allowed humanoid movement within different poses is necessary. For broader application scenarios, this is usually not the case and the usage of body models such as SMPL (Loper, Mahmood, Romero, Pons-Moll, & Black, 2015) is preferred. Recent approaches integrate these models in their predictions (Dittadi, et al., 2021). Since head and hand poses can be detected very reliably (Cao, Zhang, Wu, Lu, & Cheng, 2017; Li & Kitani, 2013; Li, Fathi, & Rehg, 2013), Dittadi et al. (Dittadi, et al., 2021) present a generative approach based on the SMPL data of head and hand poses. They use a variational autoencoder estimating full-body poses together with the commonly used ResNet (He, Zhang, Ren, & Sun, 2016) architecture. By integrating head and hand poses from older frames, the accuracy of the model for full-body pose estimation is even improved. Overall, this generative approach works well but suffers from some limitations. The lower parts of the body are not always determined exactly and it is also assumed that hand and head poses are always available. Since hands are not always within the field of view, this circumstance can lead to problems in certain applications. In addition, hand and head poses are calculated beforehand and the approach performs its prediction afterward. This leads to an increased computational effort which makes real-time use harder. Tome et al. (Tome, Peluse, Agapito, & Badido, 2019) create a fully labeled XR-EgoPose dataset with video frames from a fisheye camera of an XR device. Instead of directly train a 3D model, 2D heatmaps are generated to capture uncertainty information. A ResNet101 structure (He, Zhang, Ren, & Sun, 2016) translates an input image to 15 heatmaps, which are used to train a dual-branch autoencoder. The encoder structure consists of fully connected layers generating a compressed representation. The decoder is separated in two branches. One branch aims to reconstruct the heatmaps, while the other estimates 3D poses. The loss function of the dual branch autoencoder comprises the reconstruction error of the 3D pose and of the heatmaps. This dual-branch approach yields stable results on the XR-EgoPose dataset with the special perspective of a unique fisheye camera. It outperforms other approaches such as Mo^2Cap^2 on the corresponding Mo^2Cap^2 dataset. The described dual-branch approach is refined by including a third branch to capture rotations and by replacing ResNet with UNet (Ronneberger, Fischer, & Brox, 2015) for the heatmap extraction. The resulting SelfPose model (Tome, et al., 2020) performs excellent for ego camera perspectives and also for front facing cameras. The authors claim that their model constructs accurate full-body 3D poses from a single frame of one egocentric camera and demonstrate a direct construction of virtual avatars based on the estimations of the network. Similar to the generative approach (Dittadi, et al., 2021), failures are reported for hand movement and lower body parts, when these are completely out of sight.

In summary, recent approaches show that full-body pose estimation based on data from a single VR device is possible. Problems occur mainly due to hands or lower body parts, which are out of the field of view. The transfer to digital avatars based on estimations is also examined but not integrated in any real-time system or transferred into a virtual room. Combinations of data streams from different built-in sensors is not investigated so far.

In the project Medihopps, the insights from the latest research is integrated and the combination of image data along with IMU sensor data to refine recent approaches for full-body pose estimation is evaluated. By implementing the project, not only will a supervised, assisted and thus safe digital solution for the collaborative performance of rehabilitation sports be created for the first time, but a technological possibility will be developed to enable a stand-alone XR solution for accurate full-body holoportation in real-time. Since no high-priced external hardware is necessary, one of the biggest problems of previous XR systems is eliminated. Thus the market position and acceptance of the technology will be significantly increased and will help to establish XR in other sectors of the economy and society.

5 State of the market

MediHopps goes beyond existing projects such as meinereha, VReha, Rehago or eRehamobil. Particularly the aspect of collaborative training as well as the precision of movement and body pose detection using XR glasses represents an innovative advance. The existing projects and systems only enable training, guided by a digitally animated trainer. The practice of rehabilitation sports in a group, as a condition for the generation of positive group-dynamic effects, led by a real trainer is not possible. MediHopps therefore represents a further development of these systems, using XR technology, a virtual joint training with interaction in real time via virtual avatars. For the trainer, the possibility arises to continue to care for a whole group of patients at the same time, which is not possible with existing systems. The advantages of avatars compared to transmitting a video image via web meetings is that the entire body can be captured and virtually imaged, allowing a qualitative control for the trainer.

Complementing the advantages of the mentioned projects with the possibility of collaborative training, the precision of movement and body detection by means of XR glasses, as well as the virtual representation of the trainer and the patients via avatars, and thus the possibility of detection of the whole body as a qualitative control option for the trainer, MediHopps goes far beyond existing systems and improves methods already in use.

Projects	Advantages	Differentiation to MediHopps
eReha mobil (Richter, 2022)		
Rehabilitation and prevention solution using a virtual personal coach based on 3D sensors	• Location/time independence • Real-time feedback • Motivating setting through combination with game elements	• Concept of Rehabilitation: Rehabilitation towards a monitor, not via XR glasses • Sensors: 3D Sensors
Meine Reha (meine Reha, 2022)		
Rehabilitation training solution based on 3D and continuous acquisition of vital data.	• Location/time independence • Medically validated algorithms • User friendly	• Concept of Rehabilitation: Rehabilitation towards a monitor, not via XR glasses • Sensors: 3D sensors
Rehago [20] (Rehago, 2022)		
Digital rehabilitation solution using mirror therapy in a virtual environment	• Location/time independence • Motivating setting through combination with game elements	• Concept of Rehabilitation: using mirror therapy via VR • Field of Application: Rehabilitation after stroke
MediHopps		
easily accessible, supervised, quality-controlled, collaborative and location-independent telerehabilitation in a virtual training room	• Location/time independence • Real-time feedback • Motivating setting through combination with game elements • medically validated algorithms • User friendly • Possibility of collaborative training • Precision of movement and body detection by means of XR glasses • Virtual representation of the trainer and the patients via avatars • possibility of detection of the whole body as a qualitative control option for the trainer	• Concept of Rehabilitation: representation of the trainer and the patients via avatars • Sensors: Connection of IMU sensors and ego camera, built in sensors • Field of Application: Rehabilitation sports

Table 2. Comparison of MediHopps to other solutions

6 MediHopps

The MediHopps research project is the first to realize full-body holoportation for XR glasses, which enables precise tracking of the entire body in XR without the need for high-priced external hardware. An XR platform will be developed that supports the collaborative execution of re-habilitation sport units, through the qualitative supervision of a trainer, and to enable an intelligent assistance system in XR (see Figure 1). Due to their effectiveness, the project will initially focus on dynamic rehabilitation sport exercises in the application fields "mobilization" and "strengthening" from the established rehabilitation sport courses "spinal gymnastics", "shoulder-neck gymnastics" and "Pilates". However, the solution can be used for all equipment-free exercises, e.g. also in stretching or balance exercises. The aim of the MediHopps project is to develop an intelligent full-body holoporta-tion system for stand-alone XR glasses, which makes it possible to precisely record postures and body movements and transfer them to digital avatars. In combination with an AI-supported rehabilitation sports assistance system, rehabilitation exercises are classified in terms of correct exercise and the assessment is returned to the user as real-time feedback. In addition, value-added services for medically precise XR group collaboration will be developed. To implement the project, training data will be collected and processed by performing rehabilitation sports sessions with appropriate XR sensor technology. Existing XR glasses have several integrated, cleverly placed cameras that capture the entire front of the wearer's body in the field of view and are thus very well suited for the realization of a full-body holoportation system. This data, consisting of movements and body poses, is used for the training of an artificial intelligence. By evaluating visual information (viewing angle, visible body parts), IMU information (acceleration, velocity and angle information) and time series analysis (change over defined time axes), body pose and movement can be derived in real-time. Based on the latest approaches of 3D human body model or 3D human mesh regression (Osman, Bolkart, & Black, 2020; Loper, Mahmood, Romero, Pons-Moll, & Black, 2015), an essential innovation module of the holoportation system is developed for anatomically correct and precise transfer of body postures and movements to 3D avatars. This enables a collaborative, virtual and controlled rehabilitation sport in XR training roomsAs a value-added service, a rapid content creation module is being developed that offers the low-threshold creation of new virtual rehabilitation exercises by the trainer in the system.

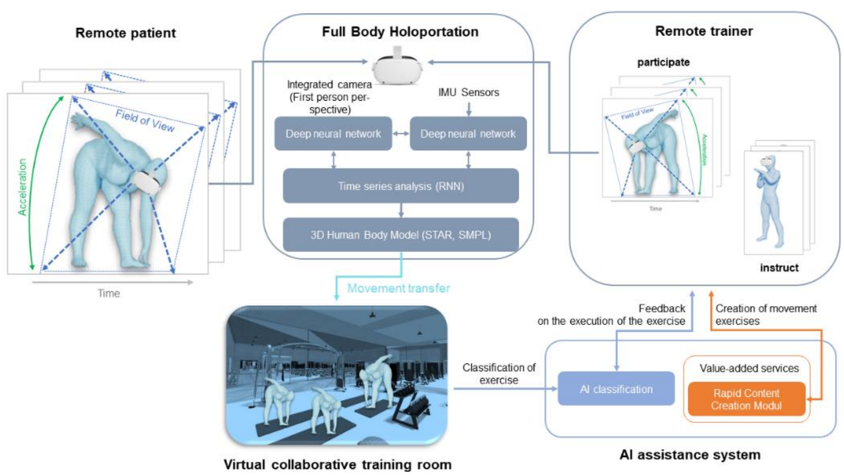

Figure 1: Overview

6.1 Realization

At the beginning of the project, a data set is generated containing the movement patterns necessary to train the AI. The data collection is conducted with an associated partner of the research project. The partner is an association that offers rehabilitation sports and has access to a large number of participants. Participants from rehabilitation sports are accompanied during a regular training session. Each participant wears XR glasses and the movement sequences are recorded by one external RGB camera aimed at the user and the built-in sensors of the XR device. This includes acceleration, speed and angle data as well as visual information from the ego camera. The data is saved in a database together with labels corresponding to the executed exercise and 3D body poses, retrieved by applying accurate models (Mehta, et al., 2017) on the image data from the external camera.

Figure 2 shows the construction of the architecture and the components. To participate in the virtual rehabilitation sport, only XR glasses are needed. The glasses work independently, i.e. do not require a connection to a PC, and provide the AI as well as the necessary data. The AI is responsible for pose estimation, oriented towards the recent approaches in research such as multi-branch autoencoder, and initially pretrained with public training data sets based on ego-centric image data (Tome, Peluse, Agapito, & Badido, 2019). The training combines the pose predictions from the pretrained estimator with time series analysis and IMU data to get an advanced pose estimation. One example is the mobilization of the cervical vertebrae. This exercise aims to relax neck and back muscles. The head is rotated alternately to the left and the right. The pretrained estimator can perform pose estimation based on the image data from the ego camera and improve its prediction using acceleration and rotation rate sensor data. Along with the time series analysis from recent poses, the final pose estimation can be improved. Next, the advanced pose estimation is transferred to a digital avatar using the Fully-Body Holoporation module. Innovative methods of 3D Body and Shape Model or 3D Human Mesh Regression are applied by the anatomically correct transfer of individual joint positions to the 3D Body Model and the exact pose as well as the body shape are calculated. For this purpose, methods such as SMPL (Skinned Multi-Person Linear model) and STAR (Sparse Trained Articulated Human Body Regressor) are used. The result is a digital avatar. The digital avatar is then transferred to the XR collaboration platform. This modular and cloud-based platform provides the virtual training room. The platform represents an essential basic building block. The rehab environment as well as the social component, which is important for rehab sports, will be simulated and realized in the platform. It includes voice chats to allow participants to communicate using the XR glasses without additional devices. The proven OpenXR standard is integrated to realize the collaborative XR training room. This is compatible with common development environments for XR such as Unity or Unreal Engine 4/5 and thus enables the implementation of an XR platform compatible with all common XR glasses (Oculus Quest 2, NReal, HoloLens 1/2). This allows the use, control and interaction with the XR training room independent of the worn XR glasses. Participants can see and hear all other participants present in the room. To enable a conversation, the volume of a participant, who is currently in the field of view, is automatically increased. Likewise, the volume is turned up when getting closer to another participant. Also, other social interactions and a lobbying system will be developed and integrated. The lobby system allows participants to join a special room before and after the training. Here, again, the participants can interact socially with each other. The platform additionally provides feedback to the trainer and the participant. The trainer receives an indication of which student is not performing the exercise correctly. For this purpose, the movement patterns are sent to another AI.

The AI is trained based on the poses stored in the database. It first analyzes and classifies the avatar's movement patterns. It then validates whether the exercise is performed correctly and generates feedback accompanied by a recommendation on how to improve the exercise. The feedback is sent to the XR collaboration platform where it is displayed in the participant's and trainer's XR glasses. It is given to the participant via audio and visual indications, visualizing how the exercise is carried out currently followed by the correct execution with a human 3D model which highlights the differences. At the same time the trainer receives a visual indicator showing which participant is performing incorrectly so that he can provide targeted and individualized support.

The Rapid Content Creation module is used by the trainers to create low-threshold sports exercises themselves. The exercises are generated by the trainer in a simple and intuitive user interface. It does not require any programming knowledge. The trainer first enters the necessary meta information. He demonstrates the exercise afterwards, assisted by an intelligent assistant. Optionally, other trainers can perform the exercises. The resulting movement patterns are aggregated. The number of repetitions for the exercise may differ. The patterns are stored together with the meta information in the database and are integrated in the training of the AI.

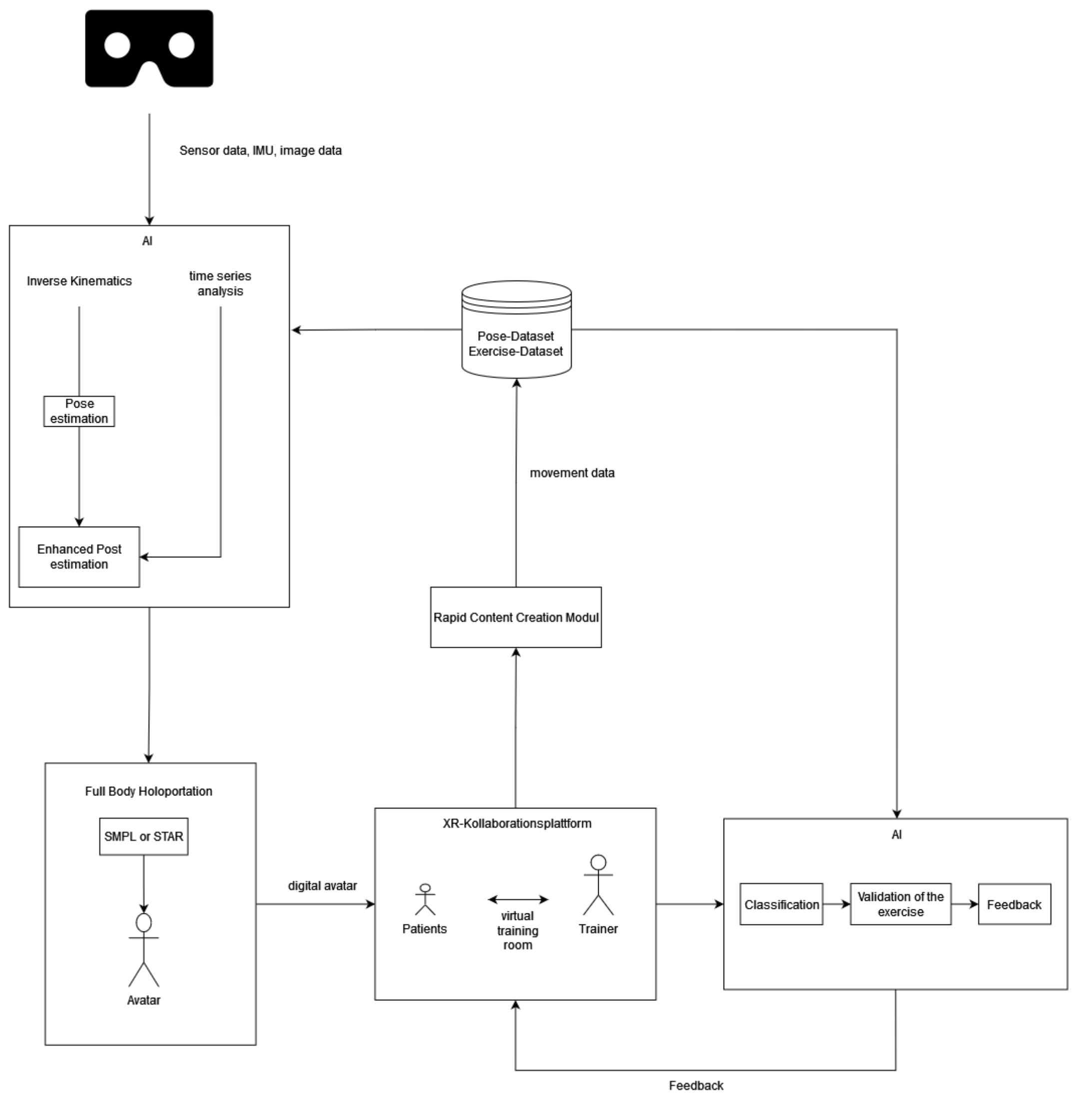

Figure 2: Architecture of MediHopps

6.2 Challenges

To reach a usable solution for location-independent, supervisable rehabilitation sport in a virtual environment, there are challenges which need to be addressed. On the technical side, the artificial intelligence needs to be able to produce accurate full-body tracking results with sensors from common stand-alone XR glasses. The projection of these tracking results on virtual avatars needs to be precise and immersive enough to reach the desirable group-dynamic effect known from collaborative sports in non-virtual environments. The problem of Motion Sickness, which is common for virtual reality and especially present when there is a sensory mismatch in the human body, needs to be addressed. As an example, motion sickness arises, when the user needs to press a button on a controller to move in a virtual environment but the real body isn't moving. To reduce motion sickness to a minimum, interactions with buttons or controller will be not necessary to move through the virtual environment. Users can either move with their own body or, in the case of a space-limitation in the real world, can move through teleportation in the virtual environment.

7 Conclusion

In this paper the MediHopps research project is presented. The described state of research show that the scientific possibilities to perform full-body pose estimation based on a stand-alone XR device exist, but are not coupled with a real-time transfer of 3D avatars into a virtual room. The combination of IMU and image data for full-body pose estimation to refine recent approaches is not examined so far. The analysis of existing solutions for rehabilitation sports reveals, that there are currently no systems available allowing interaction with other participants. Overall, this demonstrates that there is currently no application for monitored and digital collaborative rehabilitation sports in a remote scenario. Here MediHopps pursues a new approach to perform a virtual and assisted rehabilitation sport for the first time, which only requires XR glasses. During the development, the social components are taken into account in order to maintain the group-dynamic effects and the self-help character also via VR. By intelligently linking the sensor technology of the glasses and the image data of the ego-camera, full-body holoportation is used to create a digital avatar that accurately mirrors body posture. This results in a leap forward innovation, especially on a technical level, because a full-body tracking without additional costs for external hardware enables XR to be used and transferred to new areas of application. Another AI classifies and validates the movement patterns and indicates incorrectly performed exercises. This helps the trainer to monitor correct execution, especially in larger groups and realizes a safe training supporting each participant with a virtual trainer.

In summary the MediHopps approach reveals how virtual rehabilitation sport can be carried out in an controlled virtual 3-D environment with a single device while maintaining positive group effects as well as social interactions and incorporates thereby a solution to the initial research question of this paper. MediHopps will enable people to participate in rehabilitation sports, even with limited access possibilities. This includes inhabitants of rural areas, group sports under strict regulations like the COVID-19 pandemic or also employees with limited time resources. Towards a human-centered Society 5.0 such intelligent digitalized solutions for health offerings are decisive to address social challenges of modern life by ensuring its compatibility with health.

References

Basu, A., Ball, C., Manning, B., & Johnsen, K. (2016). Effects of user physical fitness on performance in virtual reality. In *(3DUI), IEEE symposium on 3D user interfaces.*

BLACKBOX VR. (2022). (black box VR) Retrieved february 2022, from https://www.blackbox-vr.com

Cao, C., Zhang, Y., Wu, Y., Lu, H., & Cheng, J. (2017). Egocentric Gesture Recognition Using Recurrent 3D Convolutional Neural Networks with Spatiotemporal Transformer Modules. In *Proceedings of IEEE International Conference on Computer Vision (ICCV).* IEEE.

de Melo, G. E., Kleiner, A. F., Lopes, J. B., Dumont, A. J., Lazzari, R. D., Galli, M., & Oliveira, C. S. (2018). Effect of virtual reality training on walking distance and physical fitness in individuals with Parkinson's diseasen. In *Neurorehabilitation* (Vol. 4, pp. 473-480). IOS Press.

Deutsche Rentenversicherung Bund. (2021, 11). *Reha-Bericht 2021.* Retrieved from https://www.deutsche-rentenversicherung.de/SharedDocs/Downloads/DE/Statistiken-und-Berichte/Berichte/rehabericht_2021.html

Dhein, Y. E. (Ed.). (2020). *Erfolgreiches Rehabilitationsmanagement. Ein Leitfaden für die Praxis.* (Vol. I). Kohlhammer.

Dittadi, A., Dziadzio, S., Cosker, D., Lundell, B., Cashman, T., & Shotton, J. (2021). Full-Body Motion from a Single Head-Mounted Device: Generating SMPL Poses from Partial Observations. In *Proceedings of International Conference on Computer Vision (ICCV).* IEEE/CVF.

He, K., Zhang, X., Ren, S., & Sun, J. (2016). Deep Residual Learning for Image Recognition. In *Proceedings of the IEEE Computer Vision and Pattern Recognition (CVPR).* IEEE.

Huang, Y. a.-M. (2017). Deep Inertial Poser Learning to Reconstruct Human Pose from Sparse Inertial Measurements in Real Time. In *Proceedings of the ACM Transition on Graphics (TOG).* IEEE.

Jiang, H., & Grauman, K. (2017). Seeing Invisible Poses: Estimating 3D Body Pose from Egocentric Video. In *Proceedings IEEE Conference on Computer Vision and Pattern Recognition (CVPR).* IEEE.

John, M., Einhaus, J., Klose, S., Kock, G., & Graßhoff, T. (2020). *Bericht Telerehabilitation 2015. Medizinische Assistenzsysteme in der Prävention, Rehabilitation und Nachsorge.* Retrieved april 2021, from Hg. v. Fraunhofer FOKUS: http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-3643763.pdf

Kim, A., Schweighofer, N., & Finley, J. (2019). Locomotor skill acquisition in virtual reality shows sustained transfer to the real world. In *Journal of neuroengineering and rehabilitation* (Vol. 16). BioMedCentral.

Li, C., & Kitani, K. M. (2013). Pixel-Level Hand Detection in Ego-centric Videos. In *Proceedings of the IEEE Computer Society Conference on Computer Vision and Patter Recognition.* IEEE.

Li, Y., Fathi, A., & Rehg, J. M. (2013). Learningt to Predict Gaze in Egocentric Video. In *Proceedings of the IEEE international Conference on Computer Vision.* IEEE.

Loper, M., Mahmood, N., Romero, J., Pons-Moll, G., & Black, M. J. (2015). SMPL: A Skinned Multi-Person Linear Model. In *ACM Transactions on Graphics (TOG)* (Vol. 6, pp. 1-16).

McGrath, T., & Stirling, L. (2020). Body-worn IMU human skeletal pose estimation using a factor graph-based optimization framework. In *Smart Sensors: Applications and Advances in Human Motion Analysis.* MDPI.

Mehta, D., Sridhar, S., Sotnychenko, O., Rhodin, H., Shafiei, M., Seidel, H.-P., . . . Theobalt, C. (2017). Vnect: Real-time 3d human pose estimation with a single rgb camera. In ". A. (TOG) (Ed.), *ACM Transaction on Graphics (TOG)* (Vol. 4). IEEE.

meine Reha. (2022, 02 05). (D. F.-I. Kommunikationssysteme, Producer, & Fokus) Retrieved february 2022, from https://www.meinereha.de/

Nagaraj, D., Schake, E., Leiner, P., & Werth, D. (2020). An RNN-ensemble approach for real time human pose estimation from sparse IMUs. In *Proceedings of the 3rd International Conference on Applications of Intelligent Systems* (pp. 1-6).

Ng, E., Xiang, D., Joo, H., & Grauman, K. (2020). You2me: Inferring body pose in egocentric video via first and second person interactions. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (pp. 9890-9900.).

Osman, A. A., Bolkart, T., & Black, M. J. (2020). *STAR: Sparse Trained Articulated Human Body Regressor Computer vision* (Vol. 123). (A. Vedaldi, Ed.) European Conference on Computer Vision. Springer.

Pfannstiel, M. D.-C. (Ed.). (2019). *Digitale Transformation von Dienstleistungen im Gesundheitswesen V. Impulse für die Rehabilitation.* Springer.

Rahmenvereinbarung über den Rehabilitationssport und das Funktionstraining. (2011). Retrieved april 2021, from http://www.kbv.de/media/sp/Rahmenvereinbarung_Rehasport.pdf

Rehago. (2022, 02 09). *Spiegeltherapie: Mentales Training nach einem Schlaganfall*. Retrieved february 2022, from https://rehago.eu/spiegeltherapie

Rhodin, H., Richardt, C., Casas, D., Insafutdinov, E., Shafiei, M., Seidel, H.-P., . . . Theobalt, C. (2016). EgoCap: Egocentric Marker-less Motion Capture with Two Fisheye Cameras. In *Proceedings of SIGGRAPH ASIA 2016.* ACM Transactions on Graphics.

Richter, S. (2022, 02 05). *eReha mobil*. (Bundesministerium für Bildung und Forschung.) Retrieved february 2022, from https://www.interaktive-technologien.de/projekte/erehamobil

Ronneberger, O., Fischer, P., & Brox, T. (2015). U-Net: Convolutional Networks for Biomedical Image Segmentation. In *Medical Image Computing and Computer-Assisted Intervention -- MICCAI 2015.* Springer International Publishing.

Schmidt, S., Ehrenbrink, P., Weiss, B., Voigt-Antons, J.-N., Kojic, T. J., & Moller, S. (2018). Impact of virtual environments on motivation and engagement during exergames. In *Procedings of the Tenth international conference on quality of multimedia experience (qoMEX)*. IEEE.

Tan, J. K., Lui, Z., & Chihara, T. (2020). Ego-Posture Estimation for a Pedestrian Using a Monocular Wearable Camera,. In *5th International Conference on Computer and Communication Systems (ICCCS)* (pp. 409-412).

Telemedizinische Assistenzsysteme in Rehabilitation und Nachsorge. (2022). Retrieved march 2022, from https://www.zeitschrift-sportmedizin.de/telemedizinische-assistenzsysteme-in-rehabilitation-und-nachsorge/

Tome, D., Alldieck, T., Peluse, P., Pons-Moll, G., Agapito, L., & Torres, F. (2020). SelfPose: 3D Egocentric Pose Estimation from a Headset Mounted Camera. In *Proceedings of IEEE transactions on pattern analysis and machine intelligence.* IEEE.

Tome, D., Peluse, P., Agapito, L., & Badido, H. (2019). xR-EgoPose: Egocentric 3D Human Pose from an HMD Camera. In *International Conference on Computer Vision.* IEE/CVF.

Tuveri, E., Macis, L., Sorrentino, F., Spano, L. D., & Scateni, R. (2016). Fitmersive Games. In M. Costabile, P. Buono, M. Matera, R. Lanzilotti, & t. I. Conference (Ed.), *Proceedings of the International Working Conference on Advanced Visual Interfaces* (pp. 212-215). New York.

Xu, W., Chatterjee, A., Zollhöfer, M., Rhodin, H., Fua, P., Seidel, H.-P., & Theobalt, C. (2019). Mo2Cap2: Real-time Mobile 3D Motion Capture with a Cap-mounted Fisheye Camera. In *IEEE Transactions on Visualization and Computer Graphics* (pp. 2093-2101). IEEE.

Yuan, Y., & Kitani, K. (2018). 3D Ego-Pose Estimation via Imitation Learning. In *Computer Vision.* ECCV.