Embodied Augmented Reality for Lower Limb Rehabilitation

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Abstract

Immersive platforms have emerged as valuable tools in rehabilitation, with potential to enhance patient engagement and recovery outcomes. Addressing the limitations of traditional Virtual Reality (VR) setups that restrict physical movement, this paper presents the system architecture of a novel, head-worn, Augmented Reality (AR) system for lower limb rehabilitation. The rehabilitation experience is enhanced by embodying avatars that replicate patients' movements. The system integrates varied avatar perspectives, such as mirror and follow modes, based on an avatar centered interface. The proposed system architecture supports seated and standing exercises, expanding the scope of rehabilitation beyond just gait. Computer vision-based 3D pose estimation captures patients' movement, mapped onto the avatar in real-time, accurately estimating the co-ordinates of 3D body landmarks. Wearable sensors evaluate patients' movements by utilizing deep learning to discern movement patterns. Feedback to patients is provided based on visual cues indicating limb areas for exercise adjustment so that exercise execution is improved. Embodiment has the potential to improve exercise understanding and assists patients' rehabilitation recovery.

CCS Concepts
• General and reference → Design; • Human-centered computing → Mixed / augmented reality;

1. Introduction

Immersive platforms offer engaging rehabilitation by aiding re-learning of motor skills through interactive, tailored experiences facilitating recovery following injury or surgery [EDM*22], [DZF*23]. Concerns are raised about safety of Virtual Reality (VR) [GRNL23], as it excludes patients' physical surroundings [KAS*19]. In contrast, Augmented Reality (AR) seamlessly integrates digital elements in the real world [CSC22]. While most AR platforms for lower limb rehabilitation predominantly target gait [WHY*22], rehabilitation requires a broader range of exercises.

Going beyond gait, this paper introduces the system architecture of a novel, embodied, lower limb rehabilitation system employing head-worn AR, depicting and analyzing bodily movement in three rehabilitation setups while the patient is either sitting, standing, or walking. These exercises, often for non-immersive devices, [KRA*23, KCP*20], are re-imagined in interactive AR promoting the role of a 3D body in enhancing patient engagement. First-person view avatars in a mirrored stance reduce the disparity between real and virtual bodies [GFPMSS10], compensating for the absence of body view within the devices' field of view. While

avatars have been explored in non-immersive settings [SPF*22], avatars in a real world context offer engaging rehabilitation.

In this paper, the patient wears an AR head-worn device, offered leg flexion and extension exercises while seated, as well as squats and gait exercises. For seated and squats, an avatar in a mirrored stance appears in front of the patient, while during gait, patients view an avatar from the back in follow mode. The avatar replicates patients' 3D poses in real-time as captured by an RGB camera. Eight Inertial Measurement Units (IMU) + surface Electromyography (sEMG) sensors placed on the patient's legs gather muscle activation and kinematic data, enabling assessment of execution in real-time. Observing the avatar from the rear during the gait regimen encourages patients to follow movement trajectories without mirroring their actions. Therapists monitor exercise execution without standing in the patient's path. This setup is deployed for gait aligning with the forward movement of walking, while seated or standing exercises benefit more from a mirrored stance, for accurate replication of static movements. Our contributions include:

- The architecture of a novel AR-based rehabilitation system occurring in real-world settings, overcoming occlusion of the physical environment and movement constraints of past VR systems.

Unlike VR that confines patients to treadmills for simulated gait exercises, our system encompasses the unaltered feedback of natural walking for efficient as well as safe rehabilitation.

- An embodied AR system that combines diverse avatar viewpoints, including mirror and follow modes, with an avatar centered interface, supporting a range of exercises beyond gait.
- Full-body pose estimation accurately depicting movement, enabling real-time motion analysis while offering valuable feedback to patients. Compared to standard gait analysis provided by infrared cameras and markers studying only straight trajectories, our system studies curved trajectories up to walking in a circle.

2. Related Work

2.1. Augmented Reality Rehabilitation

AR rehabilitation focuses on gait recovery [WHY*22], exploiting the ambulation activities of physiological walking on the floor, preserving natural feedback provided by ground surfaces. Virtual obstacles and barriers overlaid onto the ground cause patients to perform leg movements with real-time visual and auditory feedback [HYP*20]. Moreover, integrating virtual indication of movement in the real world through AR improves walking in patients by providing augmented feedback while adapting 3D objects' appearance in response to patients' walking speed [EDM*22, GBOD20]. This way, patients controlled their walking speed. The impact of virtual objects on patients' walking speed was explored while 3D objects moved within a patient's peripheral vision [KSK23], resulting in reduction of a virtual object's speed as well as perceived walking speed. Virtual cueing via visual footprints were displayed on the ground and on eye level, with a consistent distance between each footprint [RGP*24]. Participants scaled their step length consistently to the footprints. The results indicated that users altered stride length accordingly.

Although past research confirms the effectiveness of AR intervention, lack of embodiment in the form of abstract 3D shapes limits patient engagement with physiotherapy. VR adoption indicated that avatars improves the representation of the patient's effort level enhancing rehabilitation awareness [MMS*22, dSB18]. Avatar mirroring encourages patients' movements to follow, e.g., mirror an avatar and, thus, promotes symmetrical movement patterns [WAN*22, MMS*22]. The use of avatars in AR rehabilitation, across exercises beyond gait, remains under-explored. Our system employs an avatar in multiple exercise setups beyond gait, including seated and standing exercises, simulating real-world exercise execution, enhancing engagement.

2.2. Realistic Avatar Production for Embodiment

Realistic avatars have seen an increasing attraction in line with the ever increasing developments in the area of immersive platforms in a wide variety of domains including rehabilitation [FAA*23, BMD*20]. Automatic and scalable mass production of realistic avatars is a complex process comprising a series of singular steps that each impose their own unique technical challenges. The key steps can be summarized to i) Data Acquisition, ii) Human body shape reconstruction, iii) Human body models for template fitting, iv) Rigging and skinning, v) Facial animations, vi) Hair, vii) Clothing and finally, viii) Asset packaging for compatibility and interoperability. Once the 3D model of the avatar is complete, it is imported in modern games engines for vertical domains including rehabilitation. Previous research has shown promising results for embodiment, since it increased patient engagement with the rehabilitation protocol and, thus, overall performance, albeit focusing on VR without using the patient's realistic avatar [BMD*20]. Realistic avatars have been shown great potential for social interaction in VR [RBB*22] and, specifically, for VR rehabilitation [FAA*23]. A review of virtual embodiment and realistic avatars in AR concludes that in-depth research is needed on how we perceive self-avatars replacing our real bodies, on the influence of 'avatarization' on the medical field as well as on multisensory AR embodiment and generally on AR avatars as vehicles of the self. [GLH21] In this paper, we address such issues by exploring avatars as low latency virtual mirrors in the medical field in conjunction with the real body tracked by sensors and pose estimation methods.

2.3. 3D Pose Estimation via RGB Input

3D human pose estimation estimates the location of body joints and bones in 3D space via images or sequences of images as input, applied in sports, autonomous driving and human-computer interaction [WTZ*21]. There has been interest in deep learning, advancing estimation of 3D poses from RGB video by extracting rich spatio-temporal features from video frames. One popular 3D human pose estimation method that outputs 33 3D pose landmarks is integrated into Google's Mediapipe. The method employs a convolutional neural network (CNN) architecture similar to MobileNetV2, designed to have enhanced performance in real-time [SHZ*18]. It is a variant of BlazePose [BGR*20] which uses Generative 3D Human Shape and Articulated Pose Models (GHUM) [XBZ*20] to predict the full 3D body pose of a person in visual inputs. Other methods proposed for 3D pose estimation are the Video Inference for Human Body Pose and Shape Estimation (VIBE) [KAB20] and the 3D Human Motion Model for Robust Pose Estimation (HuMoR) [RBH*21]. There has been limited past research integrating computer vision-based 3D human pose estimation in rehabilitation dealing with input not restricted solely to the RGB visual channel. Such methods assess rehabilitation in lying patients and diagnose infants with early cerebral palsy [WXZ*20]. The RGB input in this method is complemented by depth information to predict the human 3D pose. A single camera framework for pose estimation in tele-rehabilitation demonstrated performance comparable to Kinect [PIO*19]. A comparative study of state-of-the-art human pose estimation (3D-based and Mediapipe), using RGB data assessed their performance in rehabilitation exercises [AOBSJV*23]. For exercises in standing positions, Mediapipe performed best, whereas for supine and sitting, an image-based, not directly receiving video input and hybrid analytical-neural inverse kinematics method named HybrIK performed best [LXC*21]. A technical challenge in 3D pose estimation using only RGB input is accurately estimating the depth coordinates of the 3D body landmarks, required for tracking non-lateral movements. Our module tackles this shortcoming by implementing deep learning for accurate and stable 3D body landmark detection in challenging AR. We test varied post-processing methods, e.g. correction methods based on statistics, appropriate

landmarks' filtering, to refine the output of MediaPipe's deep neural network and rectify irregularities in the estimated skeleton.

2.4. Wearable Sensors for Rehabilitation Assessment

Wearable-based sensing enable ubiquitous and continuous monitoring of body motions in VR/AR rehabilitation [ZLC*22]. Compared to video-based tracking, wearables do not suffer from occlusion or poor lighting. Two inertial sensors and sEMG sensors have been integrated to monitor upper and lower-limb exercises, using statistical and time domain features for classification with decision trees (DT), k-nearest neighbors (KNN), support vector machines (SVM), and random forests (RF) achieving a 92% accuracy [PFCS19]. Gait assessment was conducted using seven IMUs and lumbar sensors, applying linear discriminant analysis (LDA), principal component analysis (PCA), and naive Bayes (NB), obtaining accuracies of 100%, 86%, and 100% respectively in classifying healthy and unhealthy individuals [AMP17]. Moreover, seven exercises were assessed using four IMUs and time domain features with SVM yielding the highest accuracy (98–99%), compared to RF, KNN, and neural networks [dVPM*21]. A two-stage machine learning approach evaluated leg, gait and arm exercises [dVCPJMGD22]. Using SVM and time domain features, the approach reaches 96% accuracy for exercise recognition (first stage) whereas exercise evaluation varied between 93.6% and 100.0% (second stage). Current data-driven wearable-based posture assessment either rely on handcrafted features or utilize limited sensor modalities, e.g., only IMUs [dVCPJMGD22]. Our solution goes further by incorporating deep learning for automated feature extraction and exploit, apart from IMU, sEMG sensors to capture, also, muscular activation.

3. System Overview

This paper proposes the architecture and initial prototype of a head-worn AR rehabilitation system. Targeting lower limb recovery through clinical protocols incorporating sitting exercises with knee flexion and extension, squat and gait exercises, our design supports these tasks via avatars that reflect patients' movements, accompanied by intuitive AR interfaces. The patient's 3D body pose and movement is derived in real-time via external camera RGB input, and reflected onto the patient's avatar (Figure 1b). Wearable sensor data assesses exercise correctness, visually presented to the patient through real-time augmented feedback. The head-worn AR setup aims to present 3D avatars, UIs and performance feedback within the AR device's field of view, supporting hands-free interaction so that patients effortlessly focus on performing exercises.

3.1. System Architecture

The AR rehabilitation system has been developed in Unity for Microsoft's Hololens 2, employing the Mixed Reality Toolkit (MRTK). The proposed architecture is seen in Figure 2. Trigno Avanti sensors capture and transmit sEMG+IMU data to the base station which forwards it to a Windows PC and used as input for the posture assessement component in the information layer. RGB input is fed in the pose estimation component. Data outputs of those components are transmitted in real time via a publish/subscribe (pub/sub) communication framework, facilitated us-
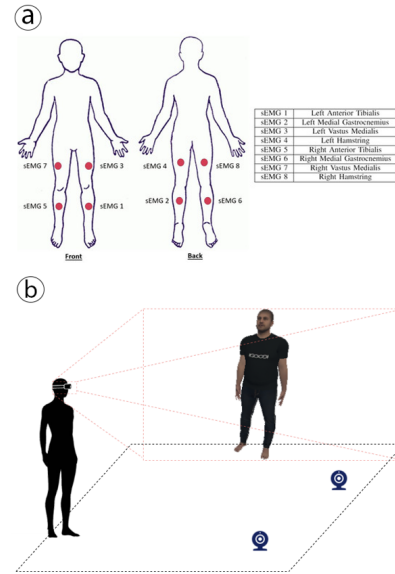
Figure 1: *(a): Sensor placement on the patients (Image from [GSE*20]), (b): Concept image of the setup.*

ing the MQTT protocol. The application handles the communication from the client side using the M2MQTT library by subscribing to predefined topics facilitated by a desktop broker. Data streams consist of: a) the patient's whole body 3D pose estimation reflected on the avatar as 3D animations, and b) the processed sensor data evaluating the patient's performance based on muscular activation and recorded kinematics acting as input for augmented feedback in the form of visual cues guiding the patient to correct their posture.
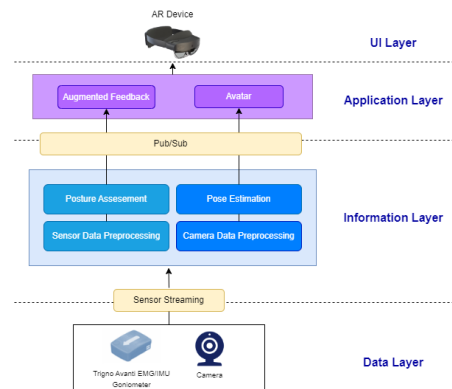
Figure 2: *System Architecture*

3.2. Rehabilitation Protocol

The proposed observational prospective pilot study is centered on knee joint pathology applicable due to high probability of knee problems, from osteoarthritis and patellofemoral pain to knee replacement and knee traumatic conditions, while the joint muscles are easily accessible with superficial location of measuring sites [HAG*23]. The protocol includes types of exercises that involve

knee bending and straightening combined with open and closed kinetic chain movements: seated, where the patient flexes and extends their leg in a sitting position, standing, in which the patient performs squats and walking for gait analysis. In sitting position patients perform a series of open kinetic chain knee flexion and extension exercises following the avatar performing the same movement. The goal is to increase the range of motion to full extension and hyperextension and full flexion as well as the muscles' strength by maximum muscle activation and the pain reduction as recorded by a 10-point VAS scale. In standing position, the patients will perform squats starting from upright position performing a series of closed-kinetic chain knee flexion and extension movements until seated. The aim is: to stimulate normal and efficient co-contractions of knee extensors and flexors, to increase the muscles' strength using the most often movement of the lower limbs which is the closed kinetic chain and to increase endurance by performing multiple repetitions. During walking, the patient follows the naturally moving avatar, viewed from the back, following avatar movement trajectories and stimulating the recovery of a symmetrical path between the healthy and affected limbs which is significant for physiological gait recovery. The aim is to educate/re-educate the kinetic control system to normal movement, by using visual, auditory and haptic feedback. Safety is assessed by recording eventual adverse effect and the patients' willingness to continue the exercise procedure; feasibility by measuring the adherence to the treatment (adherent: the percentage of patients who complete at least 80 percent of sessions), reducing pain and increasing muscle activation, Range-of-Motion and functionality; acceptability by self-report on a ten items Likert scale (1 to 5, agree to disagree). The effectiveness and functionality will be assessed by Oxford Knee Score (OKS) [DF98], and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) [SLC*03], used before and after treatment together with kinesiological metrics provided by the device. Each subject will perform 5 rehabilitative sessions per week lasting 30 minutes, for 3 weeks. The protocol is planned to be launched in a Rehabilitation Department where a set up for standard VR rehabilitation has already shown feasibility. Here, we go further by deploying embodied AR through 3D avatars.

3.3. Realistic Interoperable Avatar

This module represents the avatar as a cross-platform, interoperable asset produced a priori, utilising an automatic and scalable pipeline compatible with major engines, i.e. Unity, Unreal, three.js etc. The avatar asset is imported in the application layer and contains the elements to realise lower limb motor rehabilitation. It contains the 3D model fitted in a standardised template with a number of triangles compatible with the engine as well as the application's and device's computational limitations. For optimal fps (above 90) whilst maintaining a visual result without visible tessellation, the avatar model is optimised to below 20K triangles. It comprises of rigging and skinning for both face and body, as well as clothing, ready to use. Motion data captured in the information layer as in pose estimation and pose assessment components are transformed into applicable data types for orientation representation in 3D space e.g. quaternions applied directly on the avatar's rig. The initialisation of motion mapping considers a T-Pose as the initial pose so as to calibrate motion data on the avatar and map 1-to-1 real to virtual motion.

3.4. 3D pose estimation via RGB input

The 3D pose estimation module is based on computer vision detecting in real-time 3D poses for rehabilitation assessment. The module receives input from external RGB cameras set to one or two combined and supports the creation of animations of the depicted users in order to have realistic visualization of movement in AR, facilitating monitoring by the physiotherapist providing feedback. In both one- and two-camera setups, the camera(s) must be static. It is essential to ensure that the entire body of the subject remains visible during the exercise. In the two-camera setup, the optimal angle between them should be determined based on the size of the installation space, ranging from 30 to 60 degrees. Two processes are executed in this module: fristly, the extraction of 3D body landmarks, e.g. points on a human body identifying the human pose, implementation based on Mediapipe. An example knee exercise is illustrated in Figure 3. The second process is the mapping of the landmarks onto the target 3D avatar described in subsection 3.3.

Figure 3: *Example body landmarks extracted from an RGB image frame by Mediapipe. Input source: https://www.youtube.com/watch?v=G0EdB5vwmJY*

3.5. Wearable-based Posture Assessment

This module decides, in real-time, whether the patient correctly executes the rehabilitation exercises based on muscular activation and recorded kinematics, exploiting the sEMG and IMU recordings. A multi-task approach is embraced, where a lightweight and quantized deep learning (DL) model, consisting of three 1D dilated convolutions, followed by a multi-head cross-attention module similar to [KTB*23], is trained from scratch in order to recognize the performed activity, e.g., squat, evaluate its correctness and estimate the joint angle of the knees. This is unlike past work in [dVCPJMGD22] proposing a two-stage approach leading to two inferences and, consequently, more latency. In addition to this, the DL model provides the joint angle of the knees as an explainable metric compared to the black box evaluation used in [dVCPJMGD22]. Finally, the DL model is deployed on a GPU-accelerated edge device, e.g., laptop, to further increase its throughput.

3.6. Design of the AR Experience

The avatar is the reference for interaction in AR. Once the patient is fitted with sensors (Figure 1a), they wear the Hololens 2 and select one of three exercise protocols. The avatar is displayed on a mirrored stance in the seated and standing exercises, whereas for the gait, is viewed from behind. Building upon pervasive AR, aware of the user's context and allowing for continued use [GLZR16],

the UIs are oriented around the avatar, expanding at the desired level of information based on user input, without obstructing the user's central view (Figure 4) to avoid hindering physical tasks. Utilizing the device's eye tracking, gaze input is incorporated in the interaction for a hands-free experience, while compensating for the distance between the user and the avatar. The following functionalities are available via the UIs: a) patients adjust the avatar's position for a comfortable view, b) in order to ensure safe spatial requirements for each exercise protocol, virtual annotations, such as a virtual corridor on the ground, are displayed providing adequate space for gait c) before they perform the exercise, patients witness the correct exercise execution by the avatar through predefined animations. During exercise performance, their movement is reflected on the avatar via the pose estimator. Utilizing the outcome of posture assessment, the system displays intuitive digital visual cues referencing specific limb areas where exercise execution should be improved. While textual instructions are available to the user, visual indication regarding situated information about exercises or patients' performance are available during idle states.

Figure 4: *Avatar-Oriented Interface. Information is expanded upon user input away from the central view*

4. Conclusions

This paper proposes the architecture of a work-in-progress lower limb rehabilitation system designed for a head-word AR device, capable of real-time patient movement replication, as well as real time avatar-referenced error visualization. Scalable, mass production of realistic avatars facilitates use within AR rehabilitation enhancing users' experience and adherence to the clinical protocol. Moreover, 3D human pose estimation facilitates rehabilitation monitoring by continuously tracking the body poses using RGB cameras. The posture assessment module detects, in real-time, inconsistencies regarding the execution of lower limb rehabilitation exercises. Improving 3D body landmark detection focusing on depth coordinates, and developing an automated process to map its output onto the 3D avatar, brings forward accurate and time-efficient movement transfer. Next steps will include developing an explainable solution, also providing data on which sensor activated the neurons of the DL model, to detect inaccurate exercise execution, exploiting an attention module. This data will be displayed as color-based or dynamically-shaped visual cues around the referenced avatar area, informing patients to make adjustments to their posture and technique. It is an open research question how far the use of modern realistic avatars in rehabilitation improves rehabilitation efficacy.

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