A Survey of Computer Vision and Augmented Reality Applications in Medical Rehabilitation and Healthcare Technology

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Abstract

This survey paper provides a comprehensive examination of the integration of computer vision and augmented reality (AR) technologies within medical rehabilitation and healthcare technology. It explores the transformative potential of these technologies in modern healthcare practices, highlighting their applications in medical imaging, diagnostics, patient monitoring, and rehabilitation. The paper discusses the role of AR in enhancing surgical precision, physical therapy, and patient education, demonstrating its benefits in reducing task completion time and error rates. It also delves into human pose estimation and motion analysis, underscoring their significance in developing personalized rehabilitation programs and sports medicine. Furthermore, the survey addresses the challenges and future directions in integrating these technologies, including technical limitations, cost, user acceptance, and ethical considerations. Key findings emphasize the need for continued research and development to overcome these challenges and fully realize the potential of computer vision and AR in improving healthcare outcomes. The paper concludes by reiterating the importance of interdisciplinary collaboration and the establishment of measurable criteria to evaluate progress and advance these transformative technologies in healthcare.

1 Introduction

1.1 Structure of the Survey

This survey comprehensively explores the integration of computer vision and augmented reality (AR) technologies in medical rehabilitation and healthcare. It begins with an introduction that outlines significant advancements in AR and its transformative potential in healthcare practices, emphasizing applications such as remote surgery, telemedicine, and enhanced diagnostic tools, while also addressing current challenges and future research directions [1, 2, 3, 4]. Section 2 provides background definitions of key concepts, including computer vision, AR, human pose estimation, medical rehabilitation, healthcare technology, virtual reality, and motion analysis, establishing foundational knowledge of these technologies and their interconnections.

Section 3 focuses on the applications of computer vision in healthcare, particularly in medical imaging, diagnostics, and patient monitoring, demonstrating how visual data interpretation enhances healthcare services. Section 4 comprehensively analyzes AR's role in medical rehabilitation, highlighting its transformative applications in physical therapy, surgical training, and patient education. It illustrates how AR improves rehabilitation outcomes by overlaying digital information onto the real world, enhancing patient engagement and accuracy in home exercises, facilitating remote medical education, and aiding in the mastery of complex anatomical structures. Additionally, it discusses AR's potential in optimizing prosthetic training, enabling amputees to practice motor skills pre- and post-prosthesis fitting, resulting in significant improvements in functional outcomes and motor learning [5, 6, 7, 8].

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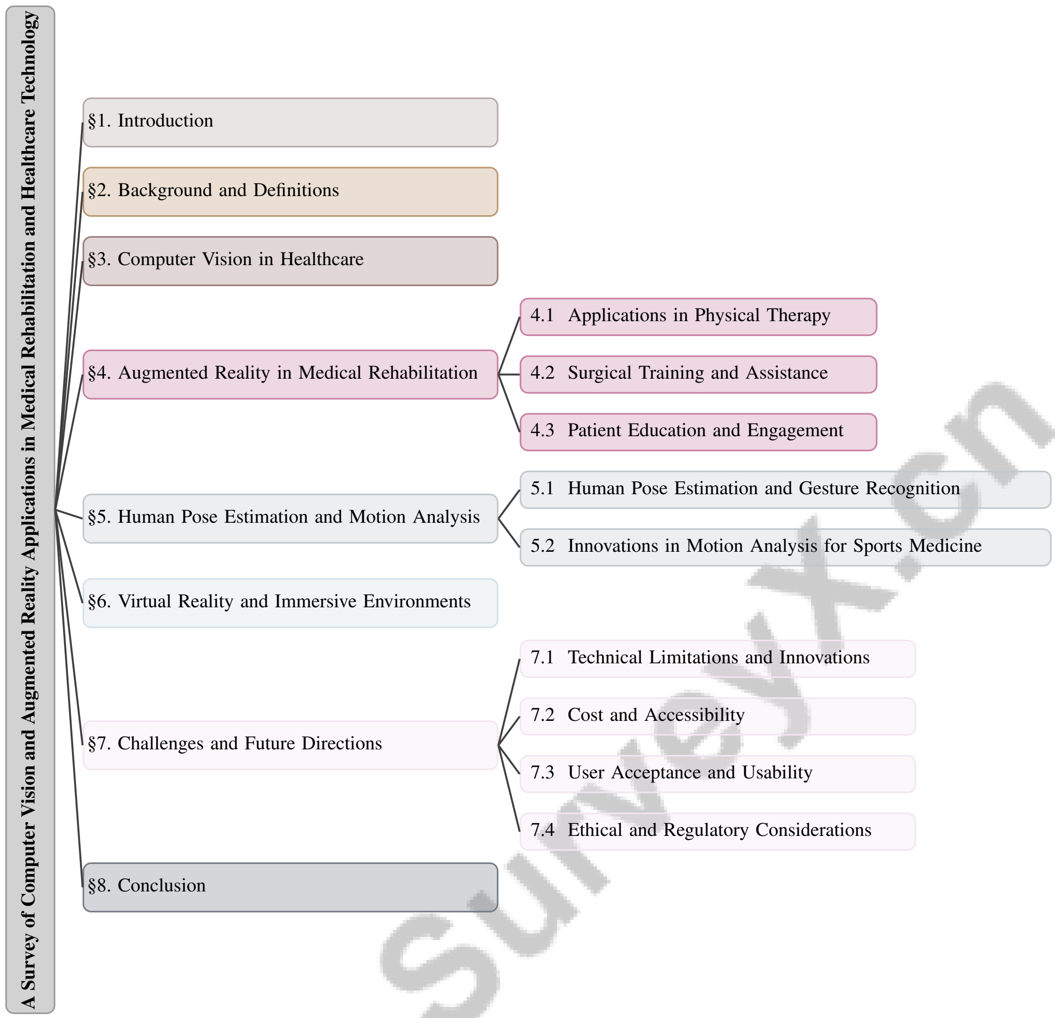

Figure 1: chapter structure

Section 5 highlights human pose estimation and motion analysis, emphasizing their importance in monitoring patient movements and contributing to personalized rehabilitation programs and sports medicine. Section 6 analyzes virtual reality's role in creating immersive environments for healthcare applications, such as pain management, mental health therapy, and medical training, emphasizing VR's advantages in providing controlled and engaging therapeutic experiences.

Section 7 discusses current challenges and future directions for integrating AR technologies into healthcare, addressing key technical limitations such as security and privacy concerns, high implementation costs, and the necessity for user acceptance. It also considers ethical and regulatory issues that must be navigated to ensure successful adoption, ultimately aiming to improve patient care, enhance operational efficiency, and reduce overall healthcare costs [9, 4]. The conclusion in Section 8 synthesizes the key points, reaffirming the transformative potential of computer vision and AR in medical rehabilitation and healthcare technology, and underscores the importance of ongoing research and development to enhance healthcare outcomes.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Interrelation of Technologies

The integration of computer vision, augmented reality (AR), and virtual reality (VR) in healthcare creates a synergistic framework that enhances medical practices through innovative solutions and

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augmentation of existing capabilities. Computer vision is pivotal for interpreting visual data, crucial for medical diagnostics and motion analysis, thereby improving precision in healthcare applications. This precision is augmented by integrating motion priors for 3D pose tracking and ensemble modeling for 2D pose estimation [10].

AR enhances spatial tracking by overlaying digital information onto the real world, benefiting surgical procedures requiring precise, non-invasive tracking. The UXAR-CT questionnaire underscores the significance of user experience in AR applications, highlighting the interconnectedness of AR, user experience, and training technologies. Conversely, VR creates immersive environments for mental health therapy and medical training, offering therapeutic pathways beyond traditional methods [11]. However, limitations in the human visual system's ability to detect changes in visual scenes, as discussed in [12], present challenges in VR and AR environments that need addressing to prevent significant oversights.

These technologies' interconnectedness is exemplified in developing cost-effective solutions for motion analysis and human pose estimation. Integrating pose estimation with deep learning significantly enhances exercise tracking and performance feedback, enabling real-time analysis of movement accuracy and repetition counting, essential for optimizing rehabilitation protocols and improving sports medicine outcomes. This advancement allows clinicians to conduct quantitative assessments in patients' homes, researchers to analyze movement kinematics using everyday video recordings, and coaches to evaluate athlete performance directly on the field, making human movement measurement more accessible across various health and performance applications [13, 14, 15]. Furthermore, AR and computer vision applications extend to human development and performance optimization, such as tracking motor skills and optimizing athletic performance.

Accurately modeling organ deformations during surgery underscores the critical need for reliable navigation systems that dynamically align preoperative models with evolving intraoperative anatomy. Traditional preoperative models often inadequately represent the actual anatomical landscape due to significant changes during surgical procedures. This necessitates advanced techniques for modeling intraoperative deformations, essential for precise integration of AR systems into surgical workflows. Recent reviews highlight methodologies enhancing organ deformation modeling accuracy, thereby improving AR-guided surgical navigation and patient outcomes [16, 17, 2, 18]. The integration of machine learning algorithms in medical diagnosis enhances diagnostic accuracy and efficiency, demonstrating these technologies' transformative potential. The introduction of multimodal datasets supports various rehabilitation movements, showcasing these technologies' potential in healthcare.

Finally, the limitations of existing marker-based optical motion capture systems highlight the need for breakthroughs in markerless approaches to improve accessibility and accuracy in healthcare applications. The survey by [19] emphasizes the necessity for empirical studies and cost-benefit analyses to better understand AR/VR adoption, highlighting the economic and practical considerations in implementing these technologies. This interconnected framework of computer vision, AR, VR, and healthcare technologies continues to evolve, offering promising avenues for future research and development in medical practices.

In recent years, the field of computer vision has made significant strides, particularly within the healthcare sector. This advancement is largely attributed to the integration of sophisticated algorithms and technologies that enhance medical imaging and diagnostics, as well as patient monitoring and motion analysis. To elucidate this hierarchical structure of computer vision applications in healthcare, Figure 2 provides a comprehensive illustration. The figure highlights key areas such as deep learning algorithms, augmented reality (AR) and virtual reality (VR) integration, 3D human pose estimation, remote health coaching systems, and innovative tracking technologies. By visualizing these components, we can better understand the interplay between various applications and their implications for improving patient outcomes.

3 Computer Vision in Healthcare

3.1 Medical Imaging and Diagnostics

Computer vision has revolutionized medical imaging and diagnostics by providing precise solutions for complex medical challenges. Deep learning algorithms, such as those used for liver segmentation from CT scans, enhance diagnostic accuracy and speed [20]. The CARDIACAR system exemplifies

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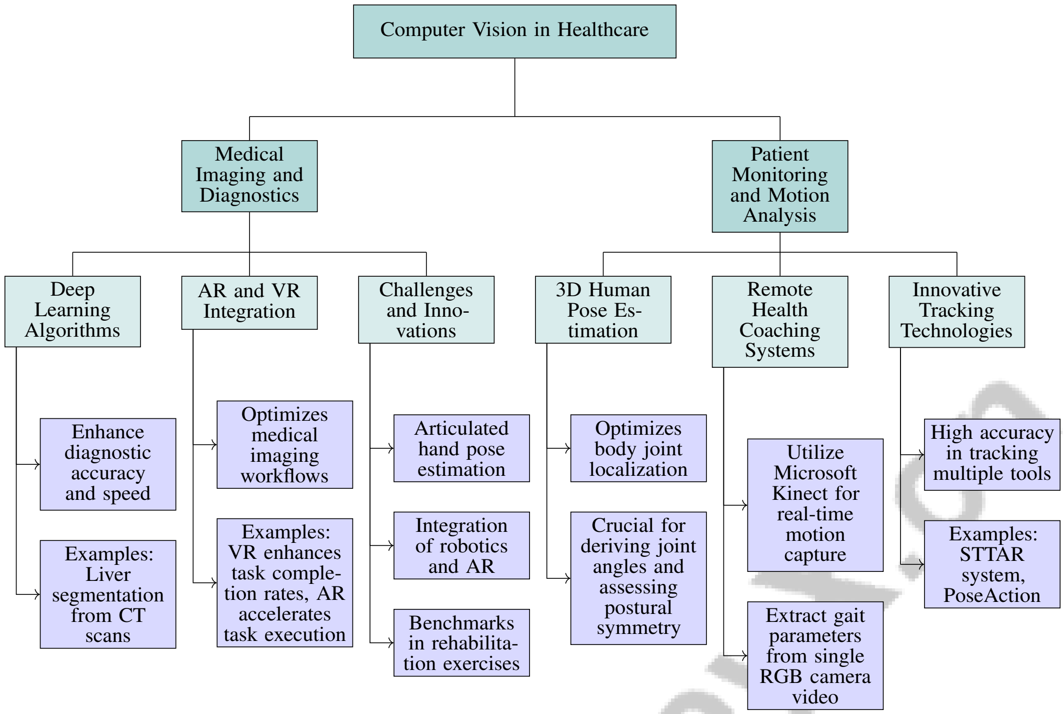

Figure 2: This figure illustrates the hierarchical structure of computer vision applications in healthcare, focusing on medical imaging and diagnostics as well as patient monitoring and motion analysis. Key areas include deep learning algorithms, AR and VR integration, 3D human pose estimation, remote health coaching systems, and innovative tracking technologies.

improvements in spatial understanding and interactive planning during cardiovascular surgeries, leading to enhanced surgical outcomes [21].

As illustrated in Figure 3, advancements in medical imaging and diagnostics can be hierarchically categorized, with a focus on deep learning, AR/VR integration, and robotics/AR applications. This figure highlights key contributions across various domains, including liver segmentation, cardiac planning, workflow optimization, surgical tool tracking, remote mentoring, and rehabilitation exercises.

The integration of AR and VR with computer vision further optimizes medical imaging workflows. VR enhances task completion rates and path efficiency, while AR accelerates task execution, demonstrating their complementary roles in diagnostics [7]. The STTAR system exemplifies real-time surgical tool localization through AR HMDs using retro-reflective markers for critical surgical support [17].

Challenges in articulated hand pose estimation, such as robust segmentation and real-time processing, require advanced computer vision algorithms. Datasets from CT and point clouds from devices like Microsoft HoloLens 2 propel deep learning advancements in medical imaging [22, 23]. The integration of robotics and AR, as seen in systems like the daVinci Si surgical robot and Microsoft HoloLens 2, enhances remote mentoring and training for surgical tasks, improving precision and fostering collaboration [24]. Benchmarks assessing algorithm performance in rehabilitation exercises underscore the importance of accurate exercise execution in patient care [25].

3.2 Patient Monitoring and Motion Analysis

Advancements in computer vision have significantly enhanced patient monitoring and motion analysis. The deployment of 3D human pose estimation methods optimizes body joint localization, addressing the limitations of traditional 2D techniques [26]. This capability is crucial for deriving joint angles and assessing bilateral postural symmetry [27].

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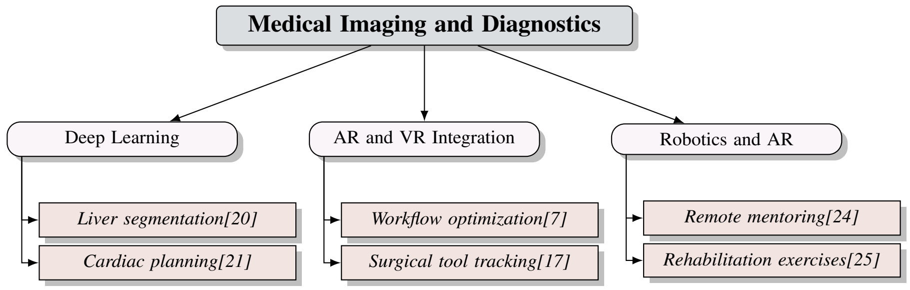

Figure 3: This figure illustrates the hierarchical categorization of advancements in medical imaging and diagnostics, focusing on deep learning, AR/VR integration, and robotics/AR applications. It highlights key contributions in liver segmentation, cardiac planning, workflow optimization, surgical tool tracking, remote mentoring, and rehabilitation exercises.

Innovations in remote health coaching systems, utilizing tools like Microsoft Kinect for real-time motion capture, demonstrate computer vision's potential in extracting gait parameters from single RGB camera video. These systems enable detailed assessments of patient movement, essential for identifying deviations in joint angle kinematics, supported by data-driven normative values [28].

In clinical contexts, especially for Autism Spectrum Disorder (ASD), computer vision tools tracking facial features and body poses enhance patient monitoring [29]. Multi-view information integration resolves depth ambiguities and occlusions, improving the robustness of motion capture systems [30].

Innovative tracking technologies, such as the STTAR system, achieve high accuracy in tracking multiple tools simultaneously without external components, benefiting surgical and medical environments [17]. Systems like PoseAction have achieved a mean Average Precision of 98.72

The 3D Pictorial Structures method significantly enhances clinician pose estimation in complex operating room environments, utilizing RGB-D data and 3D pairwise constraints [31]. Achieving 84

4 Augmented Reality in Medical Rehabilitation

4.1 Applications in Physical Therapy

Augmented Reality (AR) is revolutionizing physical therapy by creating immersive environments that enhance therapeutic outcomes through real-time motion tracking and information overlays. Systems like AR-PT and ARFit improve patient motivation and rehabilitation effectiveness by providing immediate feedback on body motion and enabling real-time exercise visualization and practice [8, 32]. Integrating deep learning into AR interfaces ensures precise feedback during exercises, vital for effective rehabilitation [33].

AR systems offer adaptive exercise feedback, enhancing performance and engagement while allowing therapists to monitor patient progress [34]. The combination of AR with intelligent assistive systems, such as smart glasses, promotes patient independence by providing contextual information during therapy sessions [35]. AR frameworks initially developed for minimally invasive surgery (MIS) are applicable to physical therapy, offering enhanced guidance by delivering relevant cues based on exercise phases [36, 37]. The ConFusing Image Quality Assessment (CFIQA) model enhances visual quality in AR applications, ensuring clarity during therapy [38], while ARPOV aids in tracking rehabilitation progress through improved visualization [39].

AR's integration into physical therapy enhances interaction with the real world, improving situational awareness. Recent advancements in AR, including immersive experiences and low-latency feedback, are being incorporated into applications like remote surgery and telemedicine to enhance patient outcomes [3, 40, 41, 4].

As shown in Figure 4, AR is enhancing medical rehabilitation in physical therapy by improving traditional practices with advanced technology. Motion analysis workflows assess patient movements, providing insights into gait and motion patterns, while feedback surveys capture patient experiences related to exercise accuracy and adherence. AR human-machine interfaces, such as those using

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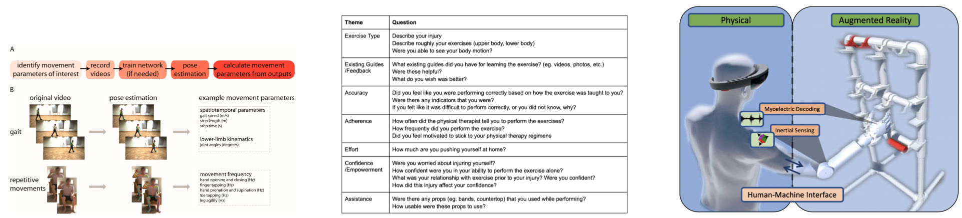

Theme	Question
Exercise Type	Describe your injury Describe roughly your exercises (upper body, lower body) Were you able to see your body motion?
Existing Guides /Feedback	What existing guides did you have for learning the exercise? (eg. videos, photos, etc.) Were these helpful? What do you wish was better?
Accuracy	Did you feel like you were performing correctly based on how the exercise was taught to you? Were there any indicators that you were? If you felt like it was difficult to perform correctly, or you did not know, why?
Adherence	How often did the physical therapist tell you to perform the exercises? How frequently did you perform the exercise? Did you feel motivated to stick to your physical therapy regimens
Effort	How much are you pushing yourself at home?
Confidence /Empowerment	Were you worried about injuring yourself? How confident were you in your ability to perform the exercise alone? What was your relationship with exercise prior to your injury? Were you confident? How did this injury affect your confidence?
Assistance	Were there any props (eg. bands, countertop) that you used while performing? How usable were these props to use?

(a) An Overview of a Motion Analysis Workflow[14]

(b) Physical Therapy Exercise Feedback Survey[8]

(c) Augmented Reality Human-Machine Interface[42]

Figure 4: Examples of Applications in Physical Therapy

VR headsets, enable intuitive control of robotic arms, enhancing rehabilitation through immersive environments [14, 8, 42].

4.2 Surgical Training and Assistance

AR is significantly advancing surgical training and assistance by improving precision and educational outcomes. The CARDIACAR system exemplifies this by enhancing visualization of cardiac anatomy through real-time omni-directional slicing, benefiting both training and intraoperative assistance [21]. Head-mounted displays (HMDs) guide surgical arm setups, aligning robotic arms with planned virtual models to reduce cognitive load and enhance workflow efficiency [43]. Integrating ultrasound imaging with navigation data on HoloLens 2 improves biopsy needle guidance, merging imaging with spatial navigation for better procedural outcomes [44].

AR's photorealism and immersive environments overcome traditional video conferencing limitations, offering engaging experiences for remote surgical training and collaboration [45]. Visimarkers ensure precise alignment of surgical plans with patient anatomy through automatic registration in AR-assisted navigation [16]. Innovations like the Anatomy Experience enhance medical students' understanding of anatomy through immersive learning, and AR supports remote mentoring in robotic surgery, allowing experienced surgeons to guide trainees in real-time [6, 24].

4.3 Patient Education and Engagement

AR is advancing patient education and engagement by providing interactive experiences that enhance understanding of medical information. By visualizing complex health data, AR allows patients to interact with digital content, improving comprehension and retention, as demonstrated in collaborative settings [46]. AR's capacity for immediate content placement without extensive calibration is beneficial in clinical environments where accuracy is critical [47]. AR Object Labeling (AROL) systems provide directional cues, aiding patients in identifying objects and improving spatial relationship understanding [48].

Ensuring accessibility for diverse patient populations is vital for AR technologies [49]. Personalized AR interfaces enhance task competency and reduce errors, crucial for patient empowerment [50]. Ethical considerations, including privacy and transparency, are essential in AR application design to maintain patient trust [51]. Combining physical models with digital content enriches learning experiences, enhancing engagement and understanding of medical concepts [6]. AR's spatial awareness capabilities improve interaction with surgical data, significantly enhancing user experience [2].

Despite its advantages, AR devices face limitations such as restricted fields of view, which can hinder user experience. Expanding the field of view in AR head-mounted displays (HMDs) is crucial for improving patient interaction [40]. Ensuring positional synchrony in AR environments supports effective communication and collaboration, enhancing patient engagement [52].

Advancements in AR are reshaping patient education and engagement by providing applications that improve understanding of health conditions and treatment options. This technology supports remote medical training and interactive learning experiences, empowering patients with knowledge and tools that lead to better healthcare outcomes and reduced costs [6, 1, 53, 41, 4].

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5 Human Pose Estimation and Motion Analysis

Category	Feature	Method
Human Pose Estimation and Gesture Recognition	Attention and Analysis Methods	ACRNet[54], RERC[13]
	Integration Techniques	PEML[15], HPE-MPEM[55], PDA-PE[56]
Innovations in Motion Analysis for Sports Medicine	3D Pose Techniques	DCP-3D-HPE[26], PP[57], OFCM[30], MV3DPE[58]
	Motion Data Processing	KFA[59], ITR-MMC[60]
	Sensor and Hardware Optimization	DSE[61]

Table 1: This table provides a comprehensive summary of recent methodologies in human pose estimation, gesture recognition, and motion analysis for sports medicine. It categorizes various techniques under human pose estimation and gesture recognition, highlighting attention and analysis methods as well as integration techniques. Additionally, it outlines innovations in motion analysis for sports medicine, including 3D pose techniques, motion data processing, and sensor and hardware optimization.

Human pose estimation technologies have revolutionized healthcare by enhancing the understanding of human movement, enabling personalized rehabilitation programs, and improving patient outcomes. Table 1 presents an organized overview of the latest advancements in human pose estimation and motion analysis, crucial for enhancing rehabilitation strategies and sports medicine practices. Additionally, Table 4 offers a comparative overview of recent advancements in human pose estimation and motion analysis, emphasizing their applications and challenges in healthcare and sports medicine. This section examines advancements in human pose estimation and gesture recognition, focusing on their roles in refining rehabilitation strategies and monitoring patient progress. By analyzing methodologies and applications, we underscore their significance in modern healthcare, particularly in clinical settings.

5.1 Human Pose Estimation and Gesture Recognition

Method Name	**Technological Integration**	**Clinical Applications**	**Challenges and Solutions**
MV3DPE[58]	2D Pose Detector	Movement Disorders Diagnosis	Occlusion Complexity
PP[57]	2D Keypoint Detection	Gait Analysis	Open-source Pipeline
PEML[15]	Pose Estimation	Rehabilitation Assessment Analysis	Algorithm Complexity Occlusion
HPE-MPEM[55]	Ensemble Modeling	Motor Development Assessment	Algorithm Complexity
DSE[61]	Imu Sensors	Health Applications	Sensor Configurations
ACRNet[54]	Attention Mechanisms	Remote Rehabilitation Services	Occlusions
PDA-PE[56]	Openpose Rotations	-	Data Augmentation
RERC[13]	Pose Tracker	Motor Development Assessment	Occlusion

Table 2: Overview of Human Pose Estimation Methods, Their Technological Integrations, Clinical Applications, and Associated Challenges. This table summarizes various methodologies utilized in human pose estimation, highlighting their technological integration, clinical applications, and the challenges they address. It provides a comprehensive comparison of the methods, illustrating their strengths and limitations in the context of healthcare applications.

Human pose estimation and gesture recognition are pivotal in healthcare for providing insights into human movement, which are essential for personalized rehabilitation and improved patient care. These technologies facilitate precise monitoring and evaluation of physical activities, crucial for optimizing rehabilitation outcomes. Advanced techniques, such as integrating 2D pose detectors with 3D limb constraints through belief propagation, enhance multi-view pose estimation accuracy [58]. This comprehensive approach improves reliability in clinical environments. Table 2 presents a detailed comparison of various human pose estimation methods, their technological integrations, clinical applications, and the challenges they address, providing valuable insights into their role and effectiveness in healthcare settings.

Occlusion is a significant challenge, especially in scenarios like in-bed pose estimation where body poses may be obscured [62]. Addressing occlusions is vital for accurate pose detection and analysis. The complexity and rapid evolution of algorithms add further challenges [57]. The PosePipe open-source pipeline mitigates this complexity by managing data and computational workflows, simplifying clinical video analysis [57].

Incorporating pose estimation data into user video feeds alongside trainer videos enhances movement learning, aiding rehabilitation by improving the accuracy of therapeutic exercise replication [15]. The

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combination of motion priors for dynamic tracking and ensemble methods for static pose estimation has led to enhanced performance [55].

Applications of human pose estimation span motor development assessment, neuromuscular rehabilitation, and gait analysis [63]. Using a limited number of IMU sensors with Design Space Exploration (DSE) methodology allows for evaluating sensor configurations to achieve precise pose estimation with minimal hardware [61].

Innovations like the Attention Cube Regression Network (ACRNet) employing an attention cube to regress 3D joint positions enhance pose estimation [54]. Expanding the Pictorial Structures framework with color and depth images and using 3D pairwise constraints significantly improve accuracy [31].

The Post-Data Augmentation for Pose Estimation (PDA-PE) method enhances accuracy for extreme motions by applying multiple rotations to video frames and selecting the most consistent pose [56]. This addresses the challenge of accurately estimating poses during extreme movements.

A key innovation is recognizing and reporting correct and incorrect exercise repetitions, crucial for feedback and effective rehabilitation [13].

These advancements in human pose estimation and gesture recognition are transforming healthcare, offering solutions for monitoring patient movements and assessing physical conditions. Technologies like augmented reality (AR) enhance personalized rehabilitation and sports medicine practices by facilitating immersive experiences. AR addresses challenges such as therapy adherence and exercise accuracy, extending its applications to telemedicine, remote surgeries, and diagnostic support, thus improving patient outcomes and reducing costs [4, 8].

5.2 Innovations in Motion Analysis for Sports Medicine

Method Name	Technological Advancements	Application Areas	Data Processing Techniques
DCP-3D-HPE[26]	Differentiable Camera Projections	Surgical Environment	3D Localization Heatmaps
KFA[59]	Kinematic Filtering Algorithm	Physical Therapy	Unscented Kalman Filter
ITR-MMC[60]	Implicit Functions	Rehabilitation Settings	Trajectory Reconstruction
OFCM[30]	3D Pose Estimation	Motion Capture Quality	Trajectory Reconstruction
MV3DPE[58]	Multi-view Methodologies	Injury Prevention	Trajectory Reconstruction
PP[57]	3D Joint Locations	Clinical Research	Kinematic Filtering
DSE[61]	Deep Learning Model	Sports, Rehabilitation	Kinematic Filtering

Table 3: This table provides a comprehensive overview of various methodologies and technological advancements in motion analysis pertinent to sports medicine. It highlights the application areas and data processing techniques employed by each method, illustrating their contributions to enhancing accuracy and efficiency in motion capture and analysis.

Advancements in motion analysis have significantly impacted sports medicine, providing solutions for assessing athletic performance and enhancing rehabilitation protocols. Table 3 presents a detailed examination of contemporary methods in motion analysis, underscoring their technological innovations, application domains, and data processing strategies, which are pivotal for advancing sports medicine practices. The use of 3D human pose estimation improves accuracy and handles limited data effectively through advanced data augmentation [26], crucial for refining motion capture and developing personalized training regimens.

Kinematic filtering algorithms, like those based on the Unscented Kalman Filter, enhance kinematic parameter extraction from noisy data, offering insights into athlete movements [59]. This is beneficial for injury prevention and performance optimization.

The evolution from single-view to multi-view methodologies in motion capture, categorized into single-person and multi-person approaches, allows comprehensive analysis of athletic movements [64]. Advancements in implicit trajectory reconstruction yield smoother and anatomically consistent marker trajectories compared to sparse keypoint methods [60].

Future research focuses on enhancing method robustness against viewpoint similarities and improving 2D pose estimator accuracy, crucial for refining motion capture results from internet videos and dynamic environments [30]. Synchronized multi-camera video footage, as seen in datasets like TUM Campus and Shelf, is instrumental in evaluating 3D pose estimation accuracy [58].

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In clinical settings, the PosePipe open-source pipeline has been effective in tracking and estimating human movement across numerous videos [57]. This pipeline simplifies complex motion data analysis, aiding sports medicine professionals in optimizing athlete performance and rehabilitation strategies.

Recent studies emphasize sensor placement for accurate motion tracking, highlighting the benefits of optimizing configurations to minimize hardware complexity while maintaining high accuracy [61]. Upper-body sensor placement is critical for accurate full-body pose estimation, essential for comprehensive motion analysis in sports medicine [61].

These advancements in motion analysis continue to transform sports medicine, offering tools and methodologies that enhance performance, prevent injuries, and support effective rehabilitation. The development of sophisticated algorithms and data-driven methodologies underscores the transformative potential of motion analysis technologies in revolutionizing sports medicine practices. These technologies enable clinicians to conduct quantitative motor assessments remotely, allow researchers to analyze movement kinematics using everyday devices, and empower coaches to evaluate player performance in real-time, thus enhancing injury prevention, performance optimization, and rehabilitation outcomes across diverse populations [59, 14, 60].

Feature	Human Pose Estimation and Gesture Recognition	Innovations in Motion Analysis for Sports Medicine
Technological Integration	2d-3D Integration	3D Pose Estimation
Application Domain	Rehabilitation, Healthcare	Sports Medicine
Challenge Addressed	Occlusion Issues	Data Noise Reduction

Table 4: This table provides a comparative analysis of two advanced methodologies in human movement analysis: Human Pose Estimation and Gesture Recognition, and Innovations in Motion Analysis for Sports Medicine. Key features such as technological integration, application domains, and challenges addressed are outlined to highlight their distinct contributions to healthcare and sports medicine.

6 Virtual Reality and Immersive Environments

6.1 Cognitive and Mental Health Rehabilitation

Virtual Reality (VR) is a transformative tool in cognitive and mental health rehabilitation, providing immersive environments that facilitate therapeutic interventions and enhance mental well-being. VR's role in cognitive rehabilitation is particularly notable, offering engaging environments for individualized cognitive tasks, thereby improving rehabilitation efficacy [12]. In mental health therapy, VR's controlled exposure to distressing stimuli aids in treating anxiety, depression, and PTSD, significantly reducing symptoms and improving outcomes [11]. By simulating real-world scenarios without inherent risks, therapists can tailor interventions to patient-specific needs, enhancing therapeutic efficacy.

VR's multisensory experiences engage various cognitive domains, promoting neuroplasticity and cognitive recovery, crucial for patients with neurological injuries [11]. Additionally, VR technology facilitates objective assessments of cognitive and mental health, allowing clinicians to monitor patient progress and adjust therapeutic strategies based on data-driven insights [12]. However, challenges such as user acceptance and accessibility remain, necessitating ongoing research to refine VR technologies and broaden their therapeutic applications [11].

The evolution of extended reality (XR) technologies, including VR, augmented reality (AR), and mixed reality (MR), is poised to enhance mental health interventions significantly. These technologies offer new recovery avenues, with studies showing substantial symptom reductions in anxiety and depression. XR applications extend to virtual companionship and palliative care, enhancing social connectivity and psychological support for individuals facing mental health challenges [65, 66, 67].

6.2 Psychological and Emotional Benefits

Virtual Reality (VR) offers significant psychological and emotional benefits in healthcare by enabling immersive therapeutic interventions that enhance patient well-being. VR's realistic simulations facilitate psychological healing and emotional resilience, particularly for anxiety, depression, and

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PTSD, by allowing safe confrontation of fears [11]. The immersive nature of VR supports emotional regulation and stress reduction, providing distraction from real-world stressors, which is crucial for mental health treatment adherence and outcomes [11].

VR's capacity to simulate social interactions provides a controlled environment for practicing social skills, benefiting individuals with social anxiety or autism spectrum disorders by allowing them to build confidence without real-world pressures [11]. Beyond therapeutic applications, VR serves as a medium for emotional expression and exploration, enhancing self-awareness and emotional insight through immersive experiences that promote personal reflection [65, 68, 66, 67].

Integrating VR into healthcare enables personalized therapy, tailoring interventions to individual patient needs and preferences, thus improving therapeutic outcomes [11]. As VR technology advances, its healthcare applications are expected to expand, offering innovative support for psychological and emotional well-being. Studies highlight VR's potential to reduce anxiety and depression symptoms, enhance communication with loved ones in challenging times, and increase engagement in therapeutic practices, fostering recovery and resilience. The integration of XR technologies, including VR, AR, and MR, is transforming traditional mental health care approaches by providing personalized solutions that address the global prevalence of mental health disorders [66, 8, 65, 9, 67].

7 Challenges and Future Directions

The integration of augmented reality (AR) and virtual reality (VR) in healthcare presents several challenges that must be addressed to enhance their efficacy and accessibility. Key challenges include technical limitations, cost and accessibility issues, user acceptance, and ethical considerations, all of which shape the landscape of AR and VR in healthcare.

7.1 Technical Limitations and Innovations

AR in healthcare faces technical challenges requiring innovative solutions. Key issues include the complexity and cost of volumetric capturing and limitations of head-mounted displays (HMDs), such as restricted field of view (FoV), which reduce user immersion [45]. Advances in HMD technology are necessary to enhance AR user experience. Additionally, integrating AR with technologies like ChatGPT poses challenges that must be overcome to expand its application [69]. Future research should explore combining AR with advanced feedback mechanisms to enrich training experiences [70].

Quality concerns, including intensity and texture corrections, arise from potential inaccuracies in semantic segmentation, affecting the overall experience [71]. Improving semantic recognition algorithms is essential for reliable AR applications [72]. The lack of comprehensive datasets for rehabilitation evaluation also impedes effective assessment algorithm development [25]. Industry limitations, such as budget constraints and insufficient understanding of AR/VR technologies, further hinder adoption [19]. Addressing these challenges requires educational initiatives and strategic investments to build expertise and infrastructure.

Future research should examine long-term skill retention from AR training, explore avatar representations, and apply AR in non-medical training contexts [41]. Enhancing visualization of object detection model outputs in AR environments by providing broader spatial context and temporal continuity is crucial for application effectiveness [39]. Developing faster and more accurate registration methods, especially in conditions with limited point correspondences, is another key innovation area [16]. Addressing these limitations through continuous research is vital, as recent AR advancements show potential to enhance patient care, streamline processes like remote surgery and telemedicine, and support medical training. Machine learning integration has also led to innovative AR solutions, such as assistive technologies for individuals with disabilities and tools for older adults using smartphones. Overcoming these challenges promises to expand AR capabilities, transforming healthcare delivery and accessibility [73, 74, 9, 3, 4].

7.2 Cost and Accessibility

Cost and accessibility remain significant barriers to AR and VR integration in healthcare. High initial investment for AR/VR infrastructure, including advanced HMDs and supporting hardware, poses

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financial challenges for healthcare institutions. This is compounded by the need for ongoing updates and maintenance, which can be prohibitive for smaller organizations. Reliance on specific devices, such as those supporting ARCore, limits accessibility and user base, as not all potential users have compatible hardware [75].

Technical expertise required to implement and utilize AR/VR systems also influences accessibility. A lack of trained personnel to manage these technologies can hinder their integration into healthcare. Developing customized applications tailored to specific healthcare needs often requires specialized knowledge not widely available across institutions. Despite challenges, AR has shown potential in enhancing patient care, improving operational efficiency, and reducing costs in domains like remote surgery and telemedicine. As healthcare systems adopt AR solutions, demand for expertise in developing and implementing these technologies becomes critical, underscoring the need for targeted training and collaboration among healthcare professionals [6, 4].

Cybersecurity concerns add complexity to AR/VR deployment. Potential threats to sensitive patient data necessitate robust security measures, increasing overall adoption cost. Nevertheless, AR offers opportunities for real-time monitoring of security issues, providing valuable tools for addressing cybersecurity threats in healthcare [76].

Strategic investments in education and training are essential for building expertise and infrastructure. Developing cost-effective solutions and exploring alternative funding models could alleviate financial constraints and facilitate broader access to AR/VR technologies. Addressing these challenges will enable healthcare to leverage these innovations to enhance patient care and outcomes. Recent AR advancements showcase its transformative potential in applications like remote surgery, telemedicine, and emergency diagnostics, aimed at improving efficiency and reducing expenses. AR technologies are vital for bridging accessibility gaps for individuals with disabilities, providing real-time assistance that significantly improves interaction with the healthcare system. Addressing these challenges fosters inclusivity and leads to better health outcomes for diverse patient populations [9, 4].

7.3 User Acceptance and Usability

User acceptance and usability are critical for successful AR and VR integration in healthcare. These technologies must meet the diverse needs of healthcare professionals and patients for widespread adoption. Ensuring AR systems provide immersive feedback and simulate real-world interactions is crucial for user engagement and satisfaction [45]. Limitations of 2D video representations, which may restrict user perspective, can negatively impact the immersive experience and user acceptance.

Usability depends on AR and VR systems' reliability in uncontrolled environments, providing accurate performance that enhances user experience [16]. This reliability is essential for seamless clinical workflow integration, minimizing disruptions and reducing the need for extensive user adjustments. Intuitive interfaces that allow rapid prototyping and flexibility further enhance user acceptance by lowering barriers for new users.

Future research should prioritize enhancing methodologies for real-time pose estimation technology applications, examining sensor positioning effects on human motion. This focus will facilitate effective monitoring and analysis of human movement, benefiting fields like physical therapy and rehabilitation [47, 14, 77, 15, 78]. Addressing potential visual clutter when displaying complex data in pose estimation applications is also essential for maintaining user focus and minimizing cognitive load.

Security and privacy concerns significantly influence AR and VR technology user acceptance. To foster trust, developing standardized security protocols that address specific vulnerabilities and enhance user education on potential security risks is vital, empowering users to recognize and mitigate threats like data theft and identity fraud [79, 80, 76, 53, 81]. Exploring user acceptance in training and education contexts highlights the need to identify and address factors influencing acceptance, such as ease of use and perceived usefulness.

Flexibility of communication methods to adapt to evolving AR and VR technology impacts is vital for enhancing user acceptance and usability, particularly in training and education contexts where tailored interactions can improve learning outcomes [79, 74, 82]. Future research should focus on improving user interfaces, increasing participant capacity, and exploring applications in various fields like education and remote assistance to broaden AR/VR technology appeal.

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To maximize AR and VR technology effectiveness in healthcare, targeted research and development addressing key factors influencing user acceptance and usability is essential. Recent AR advances demonstrate its potential to transform healthcare, enhancing telemedicine, remote surgery, and medical training, while improving patient care and operational efficiency. Ensuring a high-quality user experience is critical for successful future AR head-mounted display adoption, requiring sophisticated interfaces catering to user needs. By concentrating on these areas, we can overcome current challenges and vulnerabilities, paving the way for innovative applications that significantly enhance patient care [40, 4].

7.4 Ethical and Regulatory Considerations

Integrating AR and VR technologies in healthcare necessitates examining ethical and regulatory considerations to ensure responsible and equitable implementation. A primary ethical concern involves ensuring accessibility for all users, including those with disabilities, requiring an inclusive design approach to AR technologies [83]. This approach is crucial to prevent exacerbating existing disparities in healthcare access and ensure technological advancements benefit all individuals equitably.

Data privacy and ownership are significant ethical issues that developers and healthcare providers must address. Concerns about data ownership generated by AR and VR applications and its utilization are paramount for maintaining consumer trust [1]. Transparency from manufacturers regarding data collection and usage is essential, particularly in the context of cybersecurity [76]. Establishing regulatory frameworks to ensure safe and effective AR and VR technology use in healthcare, including validating these systems through clinical pilot studies, is necessary to confirm their efficacy and safety in real-world scenarios [51].

The potential for sensory overload in AR applications, particularly for users with ADHD, underscores the importance of designing systems that consider user well-being and mental workload [84]. Future research should focus on developing standardized user experience (UX) evaluation frameworks for AR, exploring the interplay between UX and learning effectiveness, and integrating emerging technologies like generative AI to enhance UX research [81].

Addressing concerns about input detection accuracy and object tracking robustness, particularly in uncontrolled environments, is vital for maintaining user trust and achieving widespread adoption [85]. Ongoing AR and VR technology development in healthcare requires collaborative efforts among stakeholders to tackle these ethical and regulatory challenges. By prioritizing ethical considerations and regulatory compliance, the healthcare industry can harness AR and VR's full potential to improve patient care and outcomes, ensuring these transformative technologies are implemented responsibly and equitably. Future research should explore applying the OPPH operator in practical healthcare settings for monitoring inactivity and deterioration in various populations, such as the elderly and individuals recovering from surgery [86].

8 Conclusion

The integration of computer vision and augmented reality (AR) technologies into medical rehabilitation and healthcare signifies a pivotal advancement in modern healthcare practices. These technologies offer innovative solutions that significantly enhance precision, efficiency, and patient care. AR has demonstrated substantial potential in augmenting surgical precision through advanced guidance systems that improve phase recognition and deliver essential clinical cues. Furthermore, AR-based assistance systems have been instrumental in reducing task completion times and error rates, thereby enhancing learning and efficiency within healthcare environments.

Progress in human pose estimation and gesture recognition has revolutionized movement assessments, providing detailed insights crucial for personalized rehabilitation programs. A notable advancement is a gait analysis system that achieves remarkable accuracy in identifying key joint points, surpassing traditional rehabilitation systems in environmental understanding and movement precision. Additionally, AR applications in educational contexts have markedly improved the quality of exercise learning compared to conventional methods, underscoring AR's transformative potential in promoting physical activity.

The combination of AR with wearable technologies has effectively reduced cognitive load, empowering users with enhanced information and control. In educational settings, AR has been shown to

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improve spatial learning, demonstrated by enhanced user interactions with occluded environments in real-time. The potential of AR and computer vision to augment diagnostic capabilities through machine learning and improve monitoring and control processes in healthcare technology is further underscored.

Ongoing research and development in computer vision and AR are crucial for maximizing their impact on healthcare outcomes. Interdisciplinary collaboration and the establishment of measurable criteria, including large-scale clinical trials and user interface design considerations, are essential to evaluate progress and navigate these technologies' complexities. As these technologies evolve, they promise to deliver innovative solutions that will transform medical rehabilitation and healthcare, ultimately enhancing patient care and outcomes. The role of intuitive AR designs in fostering user trust and understanding is critical for advancing healthcare technologies. Platforms that improve the development and debugging of AR assistants through comprehensive visual analytics exemplify the ongoing advancements in this domain.

This study concludes that while both algorithms can assess rehabilitation exercises, the STGCN generally outperforms, particularly with larger datasets, highlighting the importance of high-quality labels for accurate assessments. The integration of advanced AI models with AR significantly enhances efficiency, accuracy, and user experience in operational and maintenance tasks, indicating its potential for broader applications. Moreover, systems designed to improve movement accuracy and user experience in training scenarios provide immediate feedback that enhances learning outcomes. Enhanced speed and accuracy in medical imaging registration techniques further demonstrate the potential of these technologies. Notably, there has been substantial growth in AR/VR utilization, with experts anticipating continued expansion and potential for improved communication and efficiency.

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