Czech Technical University in Prague
Faculty of Biomedical Engineering
Department of Natural Sciences

DISSERTATION THESIS STATEMENT

Czech Technical University in Prague
Faculty of Biomedical Engineering
Department of Natural Sciences

Modular Motor Rehabilitation System Using Computer Vision, Augmented and Virtual Reality

by

Ing. Jindřich Adolf

Ph.D. Programme: Biomedical and Clinical Technology
Branch of study: Biomedical and Clinical Technology

Dissertation thesis statement for obtaining
the academic title of "Doctor" abbreviated to "Ph.D."

Prague, June 2024

The dissertation thesis was written during full-time doctoral study at the Department of Natural Sciences, Faculty of Biomedical Engineeringof the Czech Technical University in Prague.

Ph.D. Candidate: **Ing. Jindřich Adolf**
Department of Natural Sciences
Faculty of Biomedical Engineering
Czech Technical University in Prague
nám. Sítná 3105
272 01 Kladno 2
Czech Republic
jindrich.adolf@cvut.cz

Supervisor: **Doc. Ing. Lenka Lhotská, Ph.D.**
Department of Natural Sciences
Faculty of Biomedical Engineering
Czech Technical University in Prague
nám. Sítná 3105
272 01 Kladno 2
Czech Republic
lenka.lhotska@cvut.cz

Reviewers: ____________________________

____

____

The dissertation thesis statement was distributed on ....

The defence of the dissertation thesis will be held before the Committee for the presentation and defence of the dissertation thesis in the doctoral degree study program Biomedical and Clinical Technology on .... at .... in the meeting room No. ....

....

Chairman of the Board for the Defence of the Doctoral Thesis in the branch
of study Biomedical and Clinical Technology
Department of Natural Sciences
Faculty of Biomedical Engineering
Czech Technical University in Prague

Contents

1 Introduction and related work

In the contemporary world, constantly and rapidly evolving, we witness a significant shift from manual labor to professions predominantly requiring a sedentary lifestyle. This trend is a direct consequence of technological advancements over the past decades, which have led to the replacement of physical labor with automated and robotic systems. Since physical activity is no longer an inherent part of many job roles, it is imperative for individuals to actively make an effort to maintain their physical fitness outside of the work sphere. Otherwise, we risk developing musculoskeletal disorders. These impacts are elaborated in the study titled 'Global Burden of Musculoskeletal Disorders and Attributable Factors' [1] highlights the increase in these problems on a global scale.

The increasing number of people needing physical therapy, combined with higher treatment costs, puts significant pressure on the medical community. This scenario underscores the imperative to develop innovative solutions, as underscored by the studies [2] and [1]. This change requires us to include physical activity in our daily routine, which is vital for keeping us healthy.

However, this "sedentary" [3] era is also witnessing exponential growth in technology. In the last decade, we have witnessed a surge in computing power and the development of technologies such as virtual reality, augmented reality, and advanced computer vision models that recognize the human posture with unprecedented accuracy.

It is therefore logical to ask: can these technologies be used to address health problems associated with increased sedentary behavior? Can telerehabilitation become a tool that bridges the gap between modern lifestyles and the need for physical rehabilitation? Research has shown that one of the reasons why patients do not exercise at home is the lack of feedback and control [4].

For the patient to receive accurate and personalized feedback, the use of a motion capture system that can reliably describe the patient's movement is essential.

If this technology could be used well enough to capture patient movement in the home environment, it would greatly improve the efficiency of the system for treating movement disorders. This is primarily because such sensing is based on a single RGB camera, which is currently available on almost every device at a price so low that anyone can afford it. Thus, the motivation for this research is to describe the current methods, define them, verify their advantages and shortcomings through practical experiments and studies, and thus develop a methodology for modern motion capture using any RGB camera.

My goal is thus to approach the problem from a completely new perspective, to build and investigate a system that would solve the problems described above. I believe that the combination of current computer vision methods and current knowledge in physiotherapy can lead to better outcomes in the field of physical rehabilitation, which is the main motivation of this research.

In this chapter, it is essential to address the current trends in home rehabilitation. This involves discussing which methods are effectively in use and showing practical applicability. Additionally, reviewing today's advanced motion capture systems is necessary. A dedicated subsection will also explore the current state of Computer Vision systems.

1.1 Physical Telerehabilitation

Telerehabilitation can be defined as the service of the delivery of rehabilitation services over telecommunication networks and the Internet[5]. This method gained popularity, especially during the global COVID-19 pandemic [6], which lasted from January 30, 2020, to May 5, 2023. Saaei's study [7] conducted with practical physiotherapists and patients shows that new modern approaches are needed. There's no doubt about the advantages and effectiveness of remote physical rehabilitation. In their systematic review, Seron et al.[8] considered fifty-three reviews. They concluded that telerehabilitation is as effective as in-person rehabilitation or even better in the absence of any rehabilitation for conditions such as osteoarthritis, low-back pain, hip and knee replacements, and multiple sclerosis.

Currently, telerehabilitation is still conducted mostly with the remote presence of a therapist, often through video calls [9] alternatively, they function as systems that are capable of playing personalized videos with a trainer[10].

1.2 Current Challenges of Physical Telerehabilitation

1.2.1 Technology Barriers

The common problem of widespread telerehabilitation is a lack of technical knowledge. In a nationwide survey in 2020 [11], only 58.8% of physiotherapists reported having sufficient knowledge about telerehabilitation. Despite the potential advantages of telerehabilitation, its actual implementation and usage in physical therapy settings remained limited. The primary barriers identified were technical issues, staff skills, and the associated high costs.

Similarly, patients also face challenges when it comes to technological proficiency. Many find it difficult to navigate and use state-of-the-art technological approaches for their rehabilitation. This further exacerbates the problem, as not only do therapists face barriers in implementing telerehabilitation, but patients themselves also encounter hurdles in accessing and effectively using these platforms.

For telerehabilitation to reach its full potential and benefit a broader spectrum of patients, the design of future systems must prioritize user-friendliness. These platforms should be as intuitive and straightforward as possible, minimizing the technological barriers for both therapists and patients alike. This would ensure a smoother transition to digital platforms, enhancing patient engagement and optimizing the benefits of telerehabilitation.

1.2.2 Assessment Limitations

One of the challenges of telerehabilitation is the difficulty in assessment and the inability to observe certain aspects up close or physically interact with the patient [12]. While remote technology cannot replace physical contact, it can, thanks to the objective measurement of certain movements, technically enable at least a partial evaluation of quality.

1.2.3 Patient Engagement and Adherence

Whether it's rehabilitation or telerehabilitation, a common problem is the lack of motivation [13]. The study [14] suggests that feedback and progress monitoring can boost motivation. Unlike traditional rehabilitation, telerehabilitation offers much broader possibilities, primarily due to the integration of technology. Therefore, systems can be designed to track a patient's progress, and provide stronger feedback.

1.3 Markerless Systems

In the rapidly evolving field of motion capture technology, markerless systems have gained significant attention. Prominent examples include the Microsoft Kinect[1], Leap Motion[2], and Intel's RealSense[3]. While it is essential to acknowledge these systems as potential alternatives to our approach, their reliance on specialized hardware does not fully align with the specific requirements of our application. This discrepancy underscores the need for a solution that balances technical capability with practical applicability in diverse settings.

1.4 Virtual Reality Motion Capture Systems

Virtual reality motion capture systems employ a combination of inertial sensors, optical markers, and sophisticated algorithms to accurately capture and interpret human motion [15]. Inertial sensors, such as accelerometers and gyroscopes, are often embedded in wearable devices to track movement and orientation without the need for external cameras. Optical systems, on the other hand, use cameras to detect specially designed markers placed on the user's body, providing precise spatial data by triangulating the positions of these markers. The collected data is processed using advanced algorithms that filter noise and compute the kinematics of the human body. This allows the system

[1] `https://learn.microsoft.com/en-us/windows/apps/design/devices/kinect-for-windows`
[2] `https://www.ultraleap.com/`
[3] `https://www.intelrealsense.com/`

to deliver real-time feedback and interaction within the virtual environment, making it essential for creating fluid and realistic user experiences in VR. These technical solutions collectively ensure high fidelity in motion capture, crucial for applications demanding accurate and responsive movement replication. One of the most commonly utilized systems today is the HTC Vive[4], which operates with base stations. The HTC Vive's base stations, known as Lighthouse stations, employ a combination of infrared LEDs and rotating laser emitters for precise room-scale tracking. Each base station issues a synchronization flash from its LEDs, followed by sequential horizontal and vertical laser sweeps. Sensors on the Vive headset and controllers capture the exact timing of these laser hits relative to the LED flash, enabling the system to accurately triangulate their positions within the play area. For motion capture, we utilize a set of Vive Trackers[5] placed on the human body and reconstruct the full body using inverse kinematics [16].

The Voxs study [17] compares a commercial VR tracking sensor system (HTC Vive tracker combined with an inverse kinematic model, Final IK [6]) with a marker-based optical motion capture system Qualisys[7], the gold standard for motion analysis, to evaluate their accuracy in measuring joint angles for ergonomic assessments. Results indicate that while the HTC Vive system has potential for mapping joint angles, it shows significant deviations in accuracy ($\pm 6°$ to $\pm 42°$) compared to Qualisys, highlighting the need for improvements to reduce systematic errors in ergonomic evaluations.

1.4.1 RGB-Depth Sensors

The Microsoft Kinect, launched in 2010, was a pioneer in using RGB-Depth (RGB-D) technology for motion capture. It combined a standard camera with an infrared (IR) depth sensor to track 3D space and movement without needing physical markers, marking a big step forward for computer vision. Kinect measured depth by shining a pattern of IR light and then analyzing how this pattern changed when it bounced off objects. This method allowed it to figure out how far away things were, helping to turn flat images into 3D models. This technology was important not just for games but also for physical therapy, as it helped track movements in a non-invasive way, crucial for rehab exercises. Research, like the studies reviewed by Hondori[18], showed Kinect's value in healthcare, proving it was useful and impactful in various settings.

While Kinect's implementation of RGB-D technology represented a significant leap forward, its reliance on specialized hardware, including an infrared (IR) depth sensor and structured light projector, poses limitations for scalability and universal application. With the discontinuation of Kinect in 2017 and the desire for more versatile and widely deployable solutions, the focus has shifted towards leveraging standard cameras, which are more ubiquitous and can be integrated into a vast array of devices, from smartphones to conventional computing systems.

The transition to using standard cameras for motion capture and depth sensing reflects a broader trend in computer vision towards software-based solutions that can interpret depth and motion from conventional RGB video feeds.

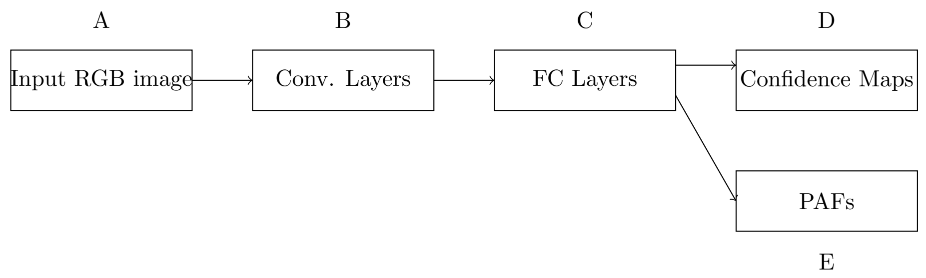
1.4.2 Pose Estimation

By identifying and analyzing the structure of an object (like a human body), computer vision techniques can estimate its pose. This involves determining the position of each body part relative to others. This work is primarily based on the concept published in[19], introduced alongside a GitHub repository releasing open-source code for developers. This software utilizes two datasets for training: MPII [20] and COCO [21]. This software is widely used globally for human skeleton detection in various applications such as people counting, human detection from autonomous vehicles, and more. Another widely adopted practical tool is Google's MediaPipe [22], which is also based on the COCO dataset.

[4] `https://www.vive.com/us/`
[5] `https://www.vive.com/eu/accessory/tracker3/`
[6] https://assetstore.unity.com/packages/tools/animation/final-ik-14290
[7] https://www.qualisys.com/

Recently, there has been a surge in the development of similar libraries and modified models. Examples include FastNet [23], AlphaPose[24], YOLO-Pose[25] and others. A comparison of these current solutions is presented in the study by Zheng [26]. Various benchmarks, such as PoseTrack[27], are often used for this comparison.

OpenPose [28] uses Convolutional Neural Networks (CNNs) to predict confidence maps S and Part Affinity Fields [29] L. The confidence maps represent the location of key points, while PAFs represent the degree of association between parts.



Where:

A: Represents the input image to the network, this is a color single RGB image in a video stream. The image is preprocessed [30], resized, and normalized.

B: Represents the convolutional layers[31] that learn spatial hierarchies of features. These layers capture low-level features like edges and textures initially and progressively extract higher-level features.

C: Represents the fully connected layers that make predictions based on the features learned[32].

D: Outputs the confidence map of the keypoint in the image for each body part, see fig. 1

E: Outputs the Part Affinity Fields (PAFs), see fig. 2

Confidence Heatmaps For generating confidence heatmaps [33] in human pose estimation, each model-predicted 2D heatmap corresponds to a specific keypoint. Within this heatmap, every pixel represents the probability of the associated keypoint being at that specific location in the original image. Due to convolutional operations like pooling or striding, these heatmaps usually possess a lower spatial resolution than the input image. For example, a heatmap of 32x32 pixels would represent an original image of 256x256 pixels, with each pixel in the heatmap accounting for an 8x8 region in the image. The pixel with the highest value in this heatmap pinpoints the most probable position of the respective keypoint.

Part Affinity Fields It is a novel representation introduced by the authors of OpenPose [28] to effectively detect the orientation and location of limbs (pairs of joints) in an image, even when the image contains multiple people in close proximity or with overlapping body parts. A Part Affinity Field is a 2D vector field for each limb, where each vector points from one joint of the limb to the other. The magnitude of the vector indicates the confidence that a limb exists in that particular position, see image 2

The final pose estimation is then obtained by parsing the detected keypoints and using the PAFs to associate these keypoints with individual human figures in the image.

2 Aims of the doctoral thesis

Integrating camera systems into homes for health and fitness tracking has become more popular. These advanced systems, capable of real-time movement and exercise assessment, hold potential in domains such as personalized training, rehabilitation, and preventive measures against injuries. Despite their emerging popularity, critical inquiries persist: How accurately do these systems detect movements?

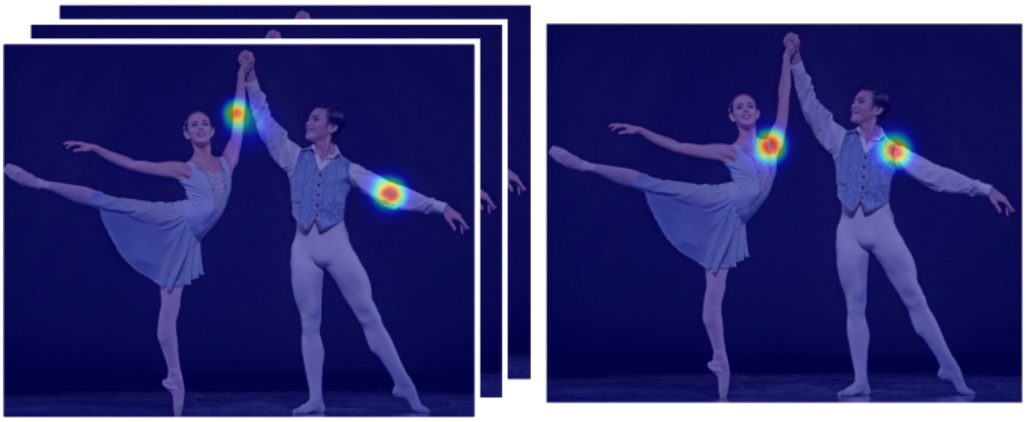


Figure 1: Confidence maps for keypoint "right shoulder", taken from the original OpenPose publication[28].

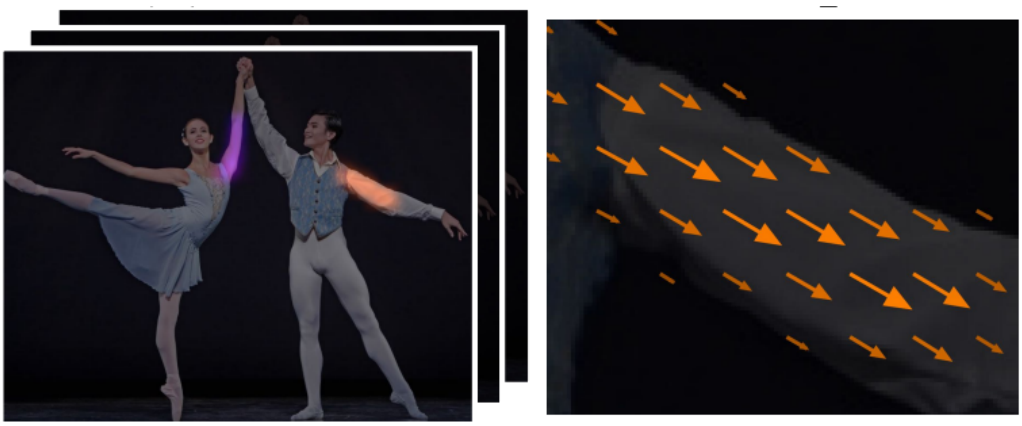


Figure 2: Affinity filed for keypoints "right shoulder" and "right elbow", taken from the original OpenPose publication[28].

Which exercises align optimally with this technology? What are the inherent limitations in their sensing capabilities? How computationally intensive are they? And, of overarching clinical significance, what are their potential applications within a home environment for health monitoring? What advantage do these systems have over virtual reality systems? This thesis outlines six key research questions to understand the complex nature of these systems.

1. What are the practical differences, advantages, and disadvantages between using virtual reality and a camera-based system for motion capture?

2. How well does the camera-based motion capture detection work?

3. What are the limits of capturing motion with this camera approach?

4. For which exercises or movements is this approach suitable?

5. How demanding is the camera-based system on computational performance?

6. What could be the clinical applications of this camera-based motion capture?

This thesis aims to provide a comprehensive view of the benefits, challenges, and potential of camera systems for home health and exercise monitoring.

The development of new technologies and tools often significantly changes how we solve problems and reach our goals. This is especially true in the fields of health and fitness. Employing camera systems and other technologies to monitor and enhance physical well-being at home can offer significant benefits to many.

However, it's crucial to recognize that it's not just about a technical solution. On the contrary, the successful deployment of these technologies necessitates the integration of expertise and experience from professionals in physiotherapy. They typically possess not only technical know-how but also a deeper understanding of anatomy and the musculoskeletal system, which is essential for the appropriate and efficient use of camera systems in a home environment.

Consequently, the advancement of these technologies necessitates the integration of physiotherapy professionals' expertise. By adopting this approach, the solution is optimized to genuinely enhance patient outcomes, facilitating improved exercise and rehabilitation results.

In my research and publications, I've emphasized collaboration with practicing physiotherapists and educators in the field of physiotherapy. I've structured our collaboration so that I provide all the technical and research resources, allowing them to focus exclusively on their expertise. Their role, therefore, was to define clinical criteria and assess the practical applicability of the measured parameters

Based on these questions, the following objectives were proposed:

1. Evaluate the advantages and challenges of using virtual reality for motion capture compared to camera-based systems. This investigation will explore how virtual reality can enhance motion capture with its immersive and interactive capabilities, offering potentially more precise and dynamic data collection in controlled environments. Conversely, it will also examine the limitations of virtual reality systems, such as potential technical complexities and user discomfort.

2. Describe the functional concept of telerehabilitation using a camera. Due to the ubiquity of cameras, this allows for capturing movement virtually anywhere using any device. This approach provides a versatile platform for rehabilitation and can be adapted to various environments, making it a flexible solution for diverse needs.

3. Verify detection functionality using a large video database. This will determine the optimal perspectives for the camera system, facilitating the establishment of the correct methodology for movement recording.

4. Assess the feasibility of building machine learning models with the gathered data. Expert evaluations by practicing physiotherapists will generate a dataset containing both comprehensive movement records and assessments of these movements. Such a dataset can then be used for more sophisticated data modeling.

5. A principal objective of the study is to integrate interdisciplinary insights from cybernetics, biomedical engineering, and physiotherapy, thereby enhancing the translational applicability of the research outcomes.

6. Develop an automated evaluation software tool, which will assist physiotherapists in facilitating and streamlining the diagnosis of exercise execution.

7. Create a functional application based on this system and define feedback elements for interactive exercises. To validate the entire concept in practice, it's essential to develop a working prototype for real-time exercise with an augmented reality mirror. Experimenting with this software will not only gauge the detection's success but more importantly, assess the user experience.

3 Working methods and selected results

3.1 Introduction

To address the research questions, I divided the work into individual parts and proceeded systematically, publishing each step in a peer-reviewed journal. The first task was to evaluate how well the system operates on a large database of videos, which I detailed in the article "Single Camera-Based Remote Physical Therapy: Verification on a Large Video Dataset"[34]. Next, I explored the capabilities of automatic error detection in functional testing in the article "Evaluation of Functional Tests Performance Using a Camera-based and Ma- chine Learning Approach"[35]. Finally, I published a user study in the article "Camera-based Real-time Feedback for Daily Stretching Exercises"[36], where I tested the software I developed for training with real-time feedback. In the dissertation, each paper is presented as a separate chapter. The dissertation also included initial experiments and numerous practical experiments that were published as conference contributions. The final chapter of the work is a methodology that references all the experiments, both conference and peer-reviewed publications and compiles a method for capturing human movement using a single camera in a home environment for physical rehabilitation.

3.2 Single Camera-Based Remote Physical Therapy: Verification on a Large Video Dataset

This chapter is primarily derived from the paper "Single Camera-Based Remote Physical Therapy: Verification on a Large Video Dataset," which has been adapted and expanded to fit the context of this dissertation. The focus of this chapter is to address three research questions that are central to understanding the efficacy and limitations of camera-based motion capture in physical therapy. These questions not only guide the structure of this chapter but also align with the broader objectives of this dissertation.

1. How well does the camera-based motion capture detection work?
2. What are the limits of capturing motion with this camera approach?
3. For which exercises or movements is this approach suitable?

The following sections delve into each of these questions, drawing upon the findings and discussions presented in the original paper [34]. The integration of this paper into the dissertation allows for a comprehensive exploration of the camera-based system's capabilities, its constraints, and its applicability to various physical therapy exercises and movements. All co-authors have provided their formal acknowledgments, confirming their contributions to the work and their agreement with the authorship as presented. They collectively acknowledge that the core results and findings primarily originate from my dedicated research and efforts.

3.3 Evaluation of Functional Tests Performance Using a Camera-based and Machine Learning Approach

The publication 'Evaluation of Functional Tests Performance Using a Camera-Based and Machine Learning Approach' is a vital part of my dissertation, expanding on the work of earlier experiments and publications. It focuses on the fifth research question of my study: 'What are the clinical applications of camera-based motion capture?' The goal is to show how this new method can be used in real situations, connecting expert insights with the use of machine learning algorithms for assessment purposes.

This chapter begins by outlining the methodology employed, emphasizing the integration of camera-based motion capture technology with machine learning algorithms. This approach not only advances our understanding of functional test performance but also highlights the ease of data acquisition compared to other systems, a crucial factor for the effectiveness of machine learning applications.

This research is important because it has the potential to change clinical practices using technology. It merges expert knowledge with sophisticated algorithmic analysis, leading to more precise, faster, and easily accessible clinical evaluations.

In the next sections, I'll explain the specific goals, methods, findings, and implications of this study, always connecting them to the wider objectives and questions of my dissertation. This chapter adds value to the field of telerehabilitation by offering practical solutions and showcases how technological progress can be applied in clinical environments. This method was developed within the framework of the international project TAČR LTAIZ19008. As discussed in the following chapter, the full details of this study can be found in the original paper, please see the list of publications 4.

I conducted this study in collaboration with colleagues from Charles University, who supported me with an expert design of the study, and together we carried out all measurements.

3.4 OffiStretch: Camera-based Real-time Feedback for Daily Stretching Exercises

One of the defined goals was to create applications with real-time feedback. I developed such an application and named it Offistretch. This application utilizes a camera-based system, making it accessible for a wide range of users in a home environment. I submitted an overview of the application and the results of a user study as an article to the Visual Computer journal, published by Springer, under the title "OffiStretch: Camera-Based Real-Time Feedback for Daily Stretching Exercises." This article was officially published on May 28, 2024. This paper was submitted with me as the lead author and primary contributor. All co-authors have signed an Acknowledgment of Contribution and Authorship form, thereby confirming that the main results and findings of the paper are derived from my research and work.

3.5 Methodology for a Single Camera-based Human Motion Capture in Physical Telerehabilitation

The final chapter of the thesis presents the methodology itself. Based on all the conducted experiments and published results, I have developed a method of using cameras in home environments for physical telerehabilitation. This methodology provides an overview of the exercises that can benefit from this approach and the technical requirements for these systems. It discusses when to use real-time feedback and when remote evaluation is appropriate. The basic concept is illustrated in Figure 3, which shows the workflow for designing such systems in a block diagram format.

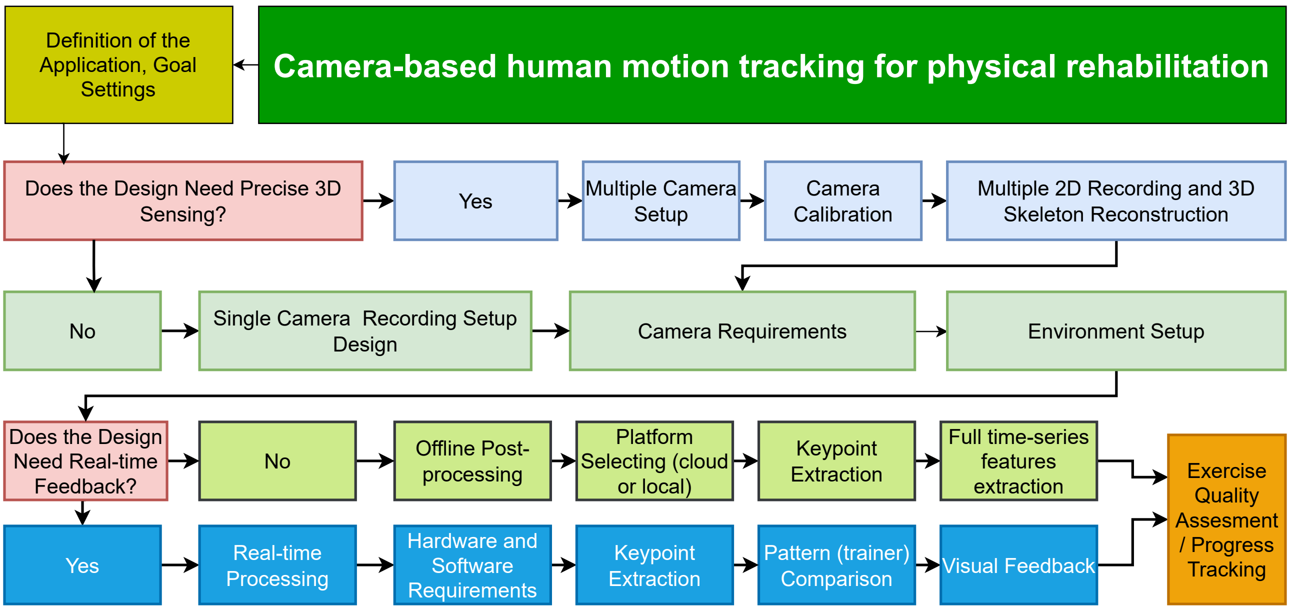


Figure 3: Workflow of Camera-Based Motion Capture System for rehabilitation.

The methodology guides future camera system designers, offering a comprehensive perspective on the entire subject. It discusses when it is appropriate to use a single-camera system and when multiple cameras are necessary for better depth perception. Furthermore, it examines the requirements for the recording environment and the technical specifications of the cameras. Another section is dedicated to the technical requirements for video processing. Additionally, it addresses considerations for real-time processing versus remote processing. For readers seeking a deeper understanding, the work references my publications, where each aspect is explored in greater detail.

4 Conclusion

This dissertation aimed to explore the potential of using a single camera as a sensing device for physical rehabilitation, emphasizing its applicability in telerehabilitation due to the simplicity of capturing exercises with any device with an integrated camera. Initially, the research explored the limits of using virtual reality in telerehabilitation as one of the options. However, it was found that a camera-based system offered greater practicality and accessibility for both therapists and patients. Consequently, the focus shifted to maximizing the effectiveness of single-camera solutions. Central to this investigation were the application of computer vision algorithms and the processing of digital video recordings, addressing questions about the efficacy, limitations, and suitability of camera-based motion capture in physical therapy.

The work is based on the following three studies: the verification of camera-based motion capture using a large video dataset, the evaluation of functional test performance through a camera-based and machine-learning approach, and the development of OffiStretch, a real-time application for daily stretching exercises. These studies collectively addressed key research questions, ranging from the technical performance of camera-based detection to its practical clinical applications.

The first study, "Single Camera-Based Remote Physical Therapy: Verification on a Large Video Dataset," extensively examined the OpenPose algorithm's capability to detect anatomical landmarks under varied conditions, providing foundational insights into the operational parameters and limitations of such systems. This study highlighted how the participant's location and the camera's angle affect detection quality, providing a detailed view of the system's effectiveness.

Furthering the application of camera-based systems, "Evaluation of Functional Tests Performance Using a Camera-based and Machine Learning Approach" ventured into the clinical realm, demonstrating how the integration of machine learning with camera-based systems could perform functional test assessments. This study showed how these systems could be useful in medical settings, providing a method that combines expert opinions with precise algorithms for better medical assessments.

Lastly, the development of OffiStretch showcased the practical application of camera-based systems in promoting physical activity and correcting exercise postures with real-time feedback as an augmented mirror. This initiative highlighted the potential of digital tools to motivate and guide users in their exercise routines, emphasizing the importance of accurate, accessible, and user-friendly technological solutions in addressing the challenges of physical inactivity and sedentary lifestyles.

Collectively, these studies underscore the dissertation's contribution to advancing the field of physical rehabilitation through technological innovation.

In conclusion, this dissertation successfully demonstrated the feasibility, challenges, and clinical relevance of using a single camera for motion capture in rehabilitation contexts. The knowledge and methods developed here provide a valuable roadmap for future system development, ensuring goals are met and setting the stage for ongoing progress in the field.

References

[1] B. Putsa, W. Jalayondeja, K. Mekhora, P. Bhuanantanondh, and C. Jalayondeja, "Factors associated with reduced risk of musculoskeletal disorders among office workers: A cross-sectional study 2017 to 2020", *BMC Public Health*, vol. 22, no. 1, Aug. 2022. DOI: `10.1186/s12889-022-13940-0`. [Online]. Available: `https://doi.org/10.1186/s12889-022-13940-0`.

[2] C. Tersa-Miralles, C. Bravo, F. Bellon, R. Pastells-Peiró, E. R. Arnaldo, and F. Rubí-Carnacea, "Effectiveness of workplace exercise interventions in the treatment of musculoskeletal disorders in office workers: A systematic review", *BMJ Open*, vol. 12, no. 1, e054288, Jan. 2022. DOI: 10.1136/bmjopen-2021-054288. [Online]. Available: https://doi.org/10.1136/bmjopen-2021-054288.

[3] L. J. McGowan, R. Powell, and D. P. French, "Older adults' construal of sedentary behaviour: Implications for reducing sedentary behaviour in older adult populations", *Journal of Health Psychology*, vol. 26, no. 12, pp. 2186–2199, Mar. 2020. DOI: 10.1177/1359105320909870. [Online]. Available: https://doi.org/10.1177/1359105320909870.

[4] B. Chen, N. Hu, and J.-H. Tan, "Efficacy of home-based exercise programme on physical function after hip fracture: A systematic review and meta-analysis of randomised controlled trials", *International Wound Journal*, vol. 17, no. 1, pp. 45–54, Nov. 2019. DOI: 10.1111/iwj.13230. [Online]. Available: https://doi.org/10.1111/iwj.13230.

[5] A. Peretti, F. Amenta, S. K. Tayebati, G. Nittari, and S. S. Mahdi, "Telerehabilitation: Review of the state-of-the-art and areas of application", *JMIR Rehabilitation and Assistive Technologies*, vol. 4, no. 2, e7, Jul. 2017, ISSN: 2369-2529. DOI: 10.2196/rehab.7511. [Online]. Available: http://dx.doi.org/10.2196/rehab.7511.

[6] J. P. Bettger and L. J. Resnik, "Telerehabilitation in the age of COVID-19: An opportunity for learning health system research", *Physical Therapy*, vol. 100, no. 11, pp. 1913–1916, Aug. 2020. DOI: 10.1093/ptj/pzaa151. [Online]. Available: https://doi.org/10.1093/ptj/pzaa151.

[7] F. Saaei and S. G. Klappa, "Rethinking telerehabilitation: Attitudes of physical therapists and patients", *Journal of Patient Experience*, vol. 8, p. 237 437 352 110 343, Jan. 2021. DOI: 10.1177/23743735211034335. [Online]. Available: https://doi.org/10.1177/23743735211034335.

[8] P. Seron, M.-J. Oliveros, R. Gutierrez-Arias, *et al.*, "Effectiveness of telerehabilitation in physical therapy: A rapid overview", *Physical Therapy*, vol. 101, no. 6, Feb. 2021. DOI: 10.1093/ptj/pzab053. [Online]. Available: https://doi.org/10.1093/ptj/pzab053.

[9] A. J. Buabbas, S. E. Albahrouh, H. N. Alrowayeh, and H. Alshawaf, "Telerehabilitation during the COVID-19 pandemic: Patients and physical therapists' experiences", *Medical Principles and Practice*, vol. 31, no. 2, pp. 156–164, 2022. DOI: 10.1159/000523775. [Online]. Available: https://doi.org/10.1159/000523775.

[10] C. Wei and J. Finkelstein, "Comparison of alexa voice and audio video interfaces for home-based physical telerehabilitation", in *AMIA Annual Symposium Proceedings*, American Medical Informatics Association, vol. 2022, 2022, p. 496.

[11] S. Aloyuni, R. Alharbi, F. Kashoo, *et al.*, "Knowledge, attitude, and barriers to telerehabilitation-based physical therapy practice in saudi arabia", *Healthcare*, vol. 8, no. 4, p. 460, Nov. 2020. DOI: 10.3390/healthcare8040460. [Online]. Available: https://doi.org/10.3390/healthcare8040460.

[12] W. S. Bjorbækmo and A. M. Mengshoel, ""a touch of physiotherapy" — the significance and meaning of touch in the practice of physiotherapy", *Physiotherapy Theory and Practice*, vol. 32, no. 1, pp. 10–19, Jan. 2016. DOI: 10.3109/09593985.2015.1071449. [Online]. Available: https://doi.org/10.3109/09593985.2015.1071449.

[13] V. Hein and A. Koka, *Perceived feedback and motivation in physical education and physical activity*, 2007. DOI: 10.5040/9781718206632.ch-008. [Online]. Available: https://doi.org/10.5040/9781718206632.ch-008.

[14] R. Essery, A. W. A. Geraghty, S. Kirby, and L. Yardley, "Predictors of adherence to home-based physical therapies: A systematic review", *Disability and Rehabilitation*, vol. 39, no. 6, pp. 519–534, Apr. 2016. DOI: 10.3109/09638288.2016.1153160. [Online]. Available: https://doi.org/10.3109/09638288.2016.1153160.

[15] V. Omowonuola, Z. Ridgeway, B. Vandeput, Y. Yamashiro, and S. Kher, "Virtual reality and motion capture training", in *Lecture Notes in Networks and Systems*. Springer International Publishing, Oct. 2021, 792–803, ISBN: 9783030899127. DOI: 10.1007/978-3-030-89912-7_60. [Online]. Available: http://dx.doi.org/10.1007/978-3-030-89912-7_60.

[16] P. Caserman, P. Achenbach, and S. Göbel, "Analysis of inverse kinematics solutions for full-body reconstruction in virtual reality", in *2019 IEEE 7th International Conference on Serious Games and Applications for Health (SeGAH)*, 2019, pp. 1–8. DOI: 10.1109/SeGAH.2019.8882429.

[17] J. P. Vox, A. Weber, K. I. Wolf, *et al.*, "An evaluation of motion trackers with virtual reality sensor technology in comparison to a marker-based motion capture system based on joint angles for ergonomic risk assessment", *Sensors*, vol. 21, no. 9, p. 3145, May 2021, ISSN: 1424-8220. DOI: 10.3390/s21093145. [Online]. Available: http://dx.doi.org/10.3390/s21093145.

[18] H. M. Hondori and M. Khademi, "A review on technical and clinical impact of microsoft kinect on physical therapy and rehabilitation", *Journal of Medical Engineering*, vol. 2014, pp. 1–16, Dec. 2014. DOI: 10.1155/2014/846514. [Online]. Available: https://doi.org/10.1155/2014/846514.

[19] Z. Cao, T. Simon, S.-E. Wei, and Y. Sheikh, *Realtime multi-person 2d pose estimation using part affinity fields*, 2017. DOI: 10.1109/TPAMI.2017.2720083. arXiv: 1611.08050 [cs.CV]. [Online]. Available: https://arxiv.org/abs/1611.08050.

[20] M. Andriluka, L. Pishchulin, P. Gehler, and B. Schiele, "2d human pose estimation: New benchmark and state of the art analysis", in *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2014.

[21] T.-Y. Lin, M. Maire, S. Belongie, *et al.*, *Microsoft coco: Common objects in context*, 2014. [Online]. Available: http://arxiv.org/abs/1405.0312.

[22] Google. "Mediapipe: Pose landmarker". Accessed: 24.8.2023. (2019), [Online]. Available: https://developers.google.com/mediapipe/solutions/vision/pose_landmarker/.

[23] Y. Luo, Z. Ou, T. Wan, and J.-M. Guo, "FastNet: Fast high-resolution network for human pose estimation", *Image and Vision Computing*, vol. 119, p. 104 390, Mar. 2022. DOI: 10.1016/j.imavis.2022.104390. [Online]. Available: https://doi.org/10.1016/j.imavis.2022.104390.

[24] H.-S. Fang, S. Xie, Y.-W. Tai, and C. Lu, "RMPE: Regional multi-person pose estimation", IEEE, Oct. 2017. DOI: 10.1109/iccv.2017.256. [Online]. Available: https://doi.org/10.1109/iccv.2017.256.

[25] D. Maji, S. Nagori, M. Mathew, and D. Poddar, "Yolo-pose: Enhancing yolo for multi person pose estimation using object keypoint similarity loss", in *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) Workshops*, 2022, pp. 2637–2646.

[26] C. Zheng, W. Wu, C. Chen, *et al.*, "Deep learning-based human pose estimation: A survey", *ACM Computing Surveys*, vol. 56, no. 1, pp. 1–37, Aug. 2023. DOI: 10.1145/3603618. [Online]. Available: https://doi.org/10.1145/3603618.

[27] M. Andriluka, U. Iqbal, E. Insafutdinov, *et al.*, "PoseTrack: A benchmark for human pose estimation and tracking", in *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition*, IEEE, Jun. 2018. DOI: 10.1109/cvpr.2018.00542. [Online]. Available: https://doi.org/10.1109/cvpr.2018.00542.

[28] Z. Cao, G. Hidalgo Martinez, T. Simon, S. Wei, and Y. A. Sheikh, "Openpose: Realtime multi-person 2d pose estimation using part affinity fields", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2019.

[29] Z. Cao, T. Simon, S.-E. Wei, and Y. Sheikh, "Realtime multi-person 2d pose estimation using part affinity fields", in *CVPR*, 2017.

[30] S. Bhattacharyya, "A brief survey of color image preprocessing and segmentation techniques", *Journal of Pattern Recognition Research*, vol. 1, no. 1, pp. 120–129, 2011.

[31] S. Albawi, T. A. Mohammed, and S. Al-Zawi, "Understanding of a convolutional neural network", in *2017 International Conference on Engineering and Technology (ICET)*, 2017, pp. 1–6. DOI: `10.1109/ICEngTechnol.2017.8308186`.

[32] S. S. Basha, S. R. Dubey, V. Pulabaigari, and S. Mukherjee, "Impact of fully connected layers on performance of convolutional neural networks for image classification", *Neurocomputing*, vol. 378, pp. 112–119, Feb. 2020. DOI: `10.1016/j.neucom.2019.10.008`. [Online]. Available: `https://doi.org/10.1016/j.neucom.2019.10.008`.

[33] E. Tjoa, H. J. Khok, T. Chouhan, and G. Cuntai, *Improving deep neural network classification confidence using heatmap-based explainable ai*, 2022. DOI: `10.48550/ARXIV.2201.00009`. [Online]. Available: `https://arxiv.org/abs/2201.00009`.

List of candidate's work related to the thesis

Journals (Impact)

- J. Adolf, J. Dolezal, P. Kutilek, *et al.*, "Single camera-based remote physical therapy: Verification on a large video dataset", *Applied Sciences*, vol. 12, no. 2, p. 799, 2022. DOI: `10.3390/app12020799`. [Online]. Available: `https://doi.org/10.3390/app12020799` , Q2, Impact Factor = 2.7

- J. Adolf, Y. Segal, M. Turna, *et al.*, "Evaluation of functional tests performance using a camera-based and machine learning approach", *PLOS ONE*, vol. 18, no. 11, Z. Mehmood, Ed., e0288279, Nov. 2023. DOI: `10.1371/journal.pone.0288279`. [Online]. Available: `https://doi.org/10.1371/journal.pone.0288279` , Q2, Impact Factor = 3.7

- J. Adolf, P. Kán, T. Feuchtner, *et al.*, "Offistretch: Camera-based real-time feedback for daily stretching exercises", *The Visual Computer*, May 2024, ISSN: 1432-2315. DOI: `10.1007/s00371-024-03450-y`. [Online]. Available: `http://dx.doi.org/10.1007/s00371-024-03450-y` , Q2, Impact Factor = 3.5

Conferences

- J. Adolf, J. Dolezal, and L. Lhotska, "Affordable personalized, immersive vr motor rehabilitation system with full body tracking", *Studies in health technology and informatics*, vol. 261, pp. 75–81, Jan. 2019

- J. Adolf, P. Kán, B. Outram, *et al.*, "Juggling in VR: Advantages of immersive virtual reality in juggling learning", in *25th ACM Symposium on Virtual Reality Software and Technology*, ACM, Nov. 2019. DOI: `10.1145/3359996.3364246`. [Online]. Available: `https://doi.org/10.1145/3359996.3364246`

- J. Adolf, J. Dolezal, P. Kutilek, *et al.*, "Automatic telerehabilitation system in a home environment using computer vision", *Studies in Health Technology and Informatics*, vol. 273, no. pHealth 2020, 142–148, 2020, ISSN: 0926-9630. DOI: `10.3233/SHTI200629`. [Online]. Available: `https://doi.org/10.3233/SHTI200629`

- P. Kutilek, J. Hejda, L. Lhotska, *et al.*, "Camera system for efficient non-contact measurement in distance medicine", in *2020 19th International Conference on Mechatronics - Mechatronika (ME)*, IEEE, Dec. 2020. DOI: `10.1109/me49197.2020.9286647`. [Online]. Available: `https://doi.org/10.1109/me49197.2020.9286647`

- Y. Segal, Y. Yona, O. Danan, *et al.*, "Camera setup and OpenPose software without GPU for calibration and recording in telerehabilitation use", in *2021 International Conference on e-Health and Bioengineering (EHB)*, IEEE, Nov. 2021. DOI: `10.1109/ehb52898.2021.9657743`. [Online]. Available: `https://doi.org/10.1109/ehb52898.2021.9657743`

- J. Adolf, J. Dolezal, M. Macas, *et al.*, "Remote physical therapy: Requirements for a single rgb camera motion sensing", in *2021 International Conference on Applied Electronics (AE)*, 2021, pp. 1–4. DOI: `10.23919/AE51540.2021.9542912`

- J. A. et al., "Upper limb range of motion evaluation by a camera-based system", *IUPESM World Congres On Medical Physic And Biomedical Enginering*, vol. 11, no. 5, pp. 13–13, Dec. 2022

Applied results

- J. Hejda, J. Doležal, J. Adolf, *et al.*, *Software for quantitative evaluation of motion activity and treatment effectiveness by telemedicine tools enabling distant patient rehabilitation*, English, RIV/68407700:21460/22:00344887, 2022

List of candidate's work non-related to the thesis

Conferences

- M. Macik, K. Prazakova, A. Kutikova, *et al.*, "Breathing friend: Tackling stress through portable tangible breathing artifact", in *Lecture Notes in Computer Science*. Springer International Publishing, 2017, 106–115, ISBN: 9783319680590. DOI: `10.1007/978-3-319-68059-0_6`. [Online]. Available: `http://dx.doi.org/10.1007/978-3-319-68059-0_6`

- J. Adolf, M. Macas, L. Lhotska, *et al.*, "Deep neural network based body posture recognitions and fall detection from low resolution infrared array sensor", in *2018 IEEE International Conference on Bioinformatics and Biomedicine (BIBM)*, IEEE, Dec. 2018. DOI: `10.1109/bibm.2018.8621582`. [Online]. Available: `http://dx.doi.org/10.1109/BIBM.2018.8621582`

- J. Petnik, L. Lhotska, J. Dolezal, *et al.*, "Behavioural data modeling: A case study in iot", in *Proceedings of the 12th International Joint Conference on Biomedical Engineering Systems and Technologies*, SCITEPRESS - Science and Technology Publications, 2019. DOI: `10.5220/0007691902590264`. [Online]. Available: `http://dx.doi.org/10.5220/0007691902590264`

- P. Kutilek, J. Kacer, L. Cicmanec, *et al.*, "Non-contact measurement systems for physiological data monitoring of military pilots during training on simulators: Review and application", in *2019 International Conference on Military Technologies (ICMT)*, IEEE, May 2019. DOI: `10.1109/miltechs.2019.8870115`. [Online]. Available: `http://dx.doi.org/10.1109/MILTECHS.2019.8870115`

- L. Lhotska, J. Adolf, and J. Dolezal, "Virtual reality in research and education: A case study", in *2019 29th Annual Conference of the European Association for Education in Electrical and Information Engineering (EAEEIE)*, IEEE, Sep. 2019. DOI: `10.1109/eaeeie46886.2019.9000435`. [Online]. Available: `http://dx.doi.org/10.1109/EAEEIE46886.2019.9000435`

- L. Lhotska, J. Dolezal, J. Adolf, *et al.*, "Personalized monitoring and assistive systems: Case study of efficient home solutions", *Studies in health technology and informatics*, vol. 249, pp. 19–28, Jan. 2018

- L. Lhotska, J. Husák, J. Stejskal, *et al.*, "Role of virtual reality in the life of ageing population", *Neural Network World*, vol. 32, no. 5, 253–267, 2022, ISSN: 2336-4335. DOI: `10.14311/nnw.2022.32.015`. [Online]. Available: `http://dx.doi.org/10.14311/NNW.2022.32.015`