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AI-based Pose Estimation System for Exercise Error Detection and Telerehabilitation Support in Resource-Constrained Settings

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***Abstract*— Nowadays, many people learn physical exercises from video tutorials on the internet, but tend to do exercises incorrectly by bending or stretching too much. This is more problematic in low-resource environments such as rural India, where access to physiotherapists is limited, and clinic visits may be costly. This paper describes the development of an AI-based system for estimating poses by tracking joints during home-based exercises with a single camera and providing an end-session report to both the individual and physiotherapists on errors in exercises and deviation from the standard poses. The AI-based system compares the poses of the individual with standard poses by tracking joints and estimates deviation in each repetition. A 2D pose estimation model has been proposed to test the feasibility of providing real-time support and summary analysis in telerehabilitation in low-resource environments.**

***Index Terms*— Pose estimation, error detection in exercises, telerehabilitation, physiotherapy, computer vision.**

I. Introduction

There has been a large number of online exercises and home-based rehabilitation programs that have increased significantly with increased access to smartphones and internet connectivity. But the factor that has dealt a setback to these online exercises is that they can easily lead to improper exercises being performed and can even result in injuries and improper clinical outcomes, as they lack the supervision of a trained professional. This problem is even more significant in India since access to a physiotherapist is relatively low compared to the population.

Telerehabilitation systems aim to introduce therapeutic approaches to patients' homes via digital technology to remotely monitor and assist patients in physical therapy sessions with physiotherapists. Recent breakthroughs in human pose analysis and computer vision algorithms make it possible for computers to analyses joints in the body by means of a common camera and judge the quality of exercise in fitness or physiotherapeutic videos. Such technologies open opportunities to create inexpensive tools that will assist viewers in exercising safely while also allowing therapists to interpret results objectively. This study puts forward a proposal for an AI-enabled pose estimation system that helps identify errors in physical exercise, such as insufficient stretching or bending, performed by a patient during home rehabilitation and telerehabilitation sessions.

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This proposed solution focuses on environments with limited resources where professional motion capture systems are not feasible, utilizing low-cost cameras instead. By extracting skeletal joint coordinates from video streams, pose estimation techniques make it possible to evaluate posture and movement quality. Exercise errors can be identified and categorized by comparing a user's posture to ideal reference poses. Users can receive instant feedback from such automated analysis, and therapists can receive structured performance.

An AI-based pose estimation system created especially for low-resource settings is proposed in this paper. The system generates session-level feedback and detects exercise performance errors using a single RGB camera and lightweight models.

The main goal is to improve home-based physiotherapy and telerehabilitation's efficacy, safety, and accuracy without using costly motion capture equipment or a lot of processing power. The study aims to provide both patients with basic feedback on incorrect physical exercise performance and practitioners with a report to modify their plan of action accordingly.

II. Related Work

Pose estimation in human bodies is an area of immense research in the fields of computer vision, health, and fitness. Traditionally, pose estimation was done using marker-based systems in motion capture. This method is quite precise but involves the use of costly infrastructure, resulting in it being non-applicable in rural health settings [1].

Currently, studies on pose estimation based on deep learning with RGB images or videos have been prevalent. OpenPose, PoseNet, and MediaPipe tools have displayed good performance on real-time 2D human skeletal keypoint estimation tasks. These tools have found applications in posture correction, activity analysis, and fitness tracking systems [2] [3]. Regarding the use of telerehabilitation applications, many studies have focused on using AI-powered systems for the distant supervision of patients and analysis of their exercise. These applications have greatly enhanced the availability of rehabilitation care.

However, many of these applications are dependent on GPUs, cloud computation capabilities, and/or reliable internet connectivity. These are actually restraining factors in developing these applications in resource-limited settings due to connectivity barriers and cost constraints of internet access. To overcome these shortcomings, there have been recent developments in the use of light-weight architectures for neural networks and edge computing solutions.

These models that have been optimized using methods like quantization and pruning can run efficiently on low-power systems like smartphones and single-board computers. Although these developments exist, surprisingly not much work has been done on the combination of light-weight pose estimation with error detection in exercise patterns with telerehabilitation feedback, especially in low-resource environments. This is what is addressed in the proposed research.

III. Physiotherapy Background and Standards

Exercise regimens for physiotherapy are created using functional anatomy, biomechanical principles, and therapeutic objectives. To guarantee successful rehabilitation, each recommended exercise is linked to particular joint movements, muscle activation patterns, and ranges of motion (ROM). If these recommended movements are not followed, the therapeutic benefits may be diminished or harm may result.

Traditionally, manual goniometry, visual observation, and therapist knowledge have been used in clinical evaluation of exercise performance. Improper execution, such as inadequate joint movement, compensatory techniques, or excessive loading, can have a detrimental effect on recovery outcomes, according to standard physiotherapy literature. In unsupervised home-based rehabilitation programs, these problems are especially common.

Physiotherapy guidelines acknowledge that variations in age, flexibility, degree of pain, and stage of recovery can all contribute to acceptable movement variability. As a result, rather than fixed positions, exercises are assessed within clinically acceptable joint angle ranges. This idea facilitates the creation of automated systems that use tolerance-based joint angle evaluation to evaluate the quality of movement.

One of the biggest obstacles to successful rehabilitation in settings with limited resources is the absence of ongoing professional supervision. An automated pose estimation system based on physiotherapy standards can help with early error detection, exercise quality monitoring, and helping therapists make well-informed clinical decisions.

VI. SYSTEM DESIGN AND ARCHITECTURE

This section contains details regarding the overall design of the proposed AI Exercise Monitoring System, including the four primary design elements (modules) that comprise the system (data acquisition, pose estimation, evaluation, and tele-rehabilitation feedback). Each module is designed to operate independently but use the same data as output to communicate with subsequent modules via a serial or sequential processing pipeline.

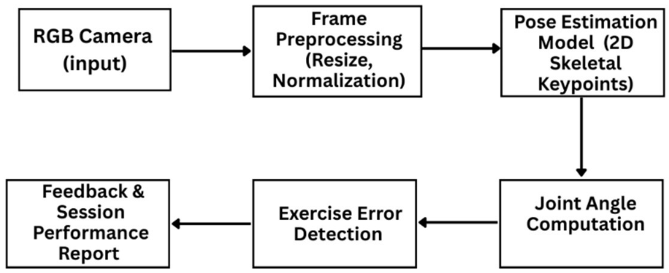

Fig 1. System Workflow of the Proposed Telerehabilitation Framework

A. Data Acquisition Module

The Data Acquisition Module captures video stream data from the physiotherapy user's performance of the physiotherapy exercises using one RGB camera. The placement of the camera will allow for complete viewing of the significant body joints during the performance of the exercise by the user. The camera captures frames from the video stream, which are then preprocessed (to eliminate any noise) and resized to meet the input size requirements of the Pose Estimation Module [4].

B. Pose Estimation Module

This module determines the locations of the major joints, such as the shoulder, elbow, hip, knee and ankle, and derives 2D joint keypoints from each frame of a video to create a skeletal model of a human body. The Pose Estimation Module has been designed for real-time processing on low-power devices, so that it can be applied in situations where power resources are limited [5].

The Exercise Evaluation Module bridges the gap between two key areas: pose estimation and clinical assessment. It will take the positions of the joints from the Pose Estimation Module and send those coordinates to the methodology layer for analysis of the angles of the joints and the quality of motion. The Evaluation Module also allows the user to set up different rules for evaluating different physiotherapy exercises as it is exercise-agnostic [6].

C. Telerehabilitation Feedback at end of session

The Feedback module provides a summary of the results including an analysis report of what was completed during the session and concise feedback about the user and structured performance reports for physiotherapists. In order to provide reliable information over an unstable network, all critical metrics were sent and compressed.

VII. METHODOLOGY: DEFINING IDEAL JOINT ANGLE

A. Joint Angle Selection Clinical Basis

The optimal joint angles for any exercise are determined from physiotherapy guidelines and therapeutic exercise procedures. The optimal angles are the clinically determined degrees of range of motion that are sufficient to provide for muscle activation and joint mobilization while avoiding excessive mechanical and physiological stress. Therefore, rather than specifying an absolute, unyielding posture, our system uses tolerance ranges that more accurately reflect clinical practices for the assessment of patients.

As an example, physiotherapy standards indicate that functional therapeutic movement typically occurs when a patient's knee is flexed within a specified amount of flexion. Therefore, if a patient does not have enough knee flexion to perform a particular exercise correctly and does not exhibit sufficient knee flexion during the exercise (i.e., does not activate the knee muscles), then the patient may be at risk of suffering knee ligament injury as a result of excessive knee flexion or may also experience excessive mechanical and/or physiological stress on the knee joint.

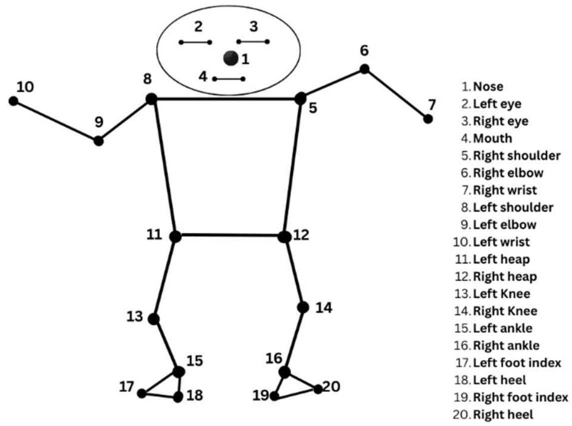

Fig 2. Visual placement

B. Calculation of Joint Angles

Using the identified skeletal key points, joint angles can be calculated based on vector geometry. The angle between each pair of adjacent limb segments (e.g. hip/knee/ankle for the body) is calculated for every frame during exercise repetitions.

For every exercise:

- A physiotherapy reference angle is created with an acceptable margin of tolerance to account for differences between individuals.
- All angles outside of the defined range are flagged as a deviation from the acceptable range.

C. Classification of Deviations

The deviations detected are grouped into clinically relevant types as indicated below:

- Insufficient range of motion (underperforming)
- Excessive joint extension or flexion (over-exertion)
- Poor alignment or asymmetry (compensatory movements)

This mimics the clinical reasoning used by physiotherapists during the visual evaluation process and enables the feedback provided by the system to be meaningful and usable.

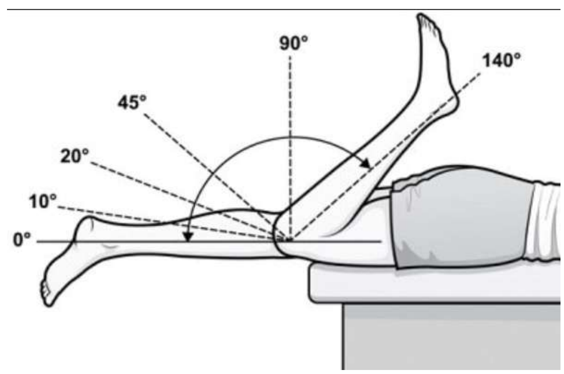

Fig 3. Knee range of motion. [7]

VIII. Discussion: Clinical Relevance of Detected Errors

The clinical relevance of the exercise error(s) detected affects treatment, as well as physiotherapy, in the physiotherapy and rehabilitation environments. The presence of insufficient joint motion may indicate muscle weakness, pain avoidance behaviour, or low understanding/awareness of the exercises; all of these factors impede or slow down the rehabilitation process. On the other hand, an excessive range of motion at the joint or malalignment of the joint increases the risk of stress on the joint, possible injury to the soft tissue and the potential to lead to an aggravation of symptoms.

The proposed system will allow the user to obtain objective evidence of inaccurate movement by the quantification of deviations from the normal clinical range of angles for movement of a joint, which has been gained through personal supervision in the past. This objective data will assist therapists in recognising patterns of incorrectly completed movements across multiple treatment sessions that can be used to make evidence-based changes to their rehabilitation plans.

The report produced at the end of a session will provide a means for asynchronous telerehabilitation, thereby allowing physiotherapists to evaluate the performance of their patients without requiring them to be available for real-time visual observation. This is particularly relevant in low-resource settings, where there is limited access to physiotherapists.

The proposed system does not replace a healthcare provider's professional opinion, but it enhances the safety of exercising, enhances compliance to therapeutic guidelines, and ultimately enhances the effectiveness of the rehabilitation process.

IX. CONCLUSION

In this paper, an AI-powered pose estimation system designed for the identification of errors in the execution of exercises as well as telerehabilitation in a resource-limited setup has been discussed. By leveraging a simple RGB camera and a 2D pose estimation model, the proposal has made it possible to monitor physiotherapy exercises in real time without the need for any dedicated hardware infrastructure. Through joint angles and their measurement against particular thresholds, errors in exercises have been determined.

The experimental results have shown that the system can achieve acceptable accuracy in pose estimation and exercise error detection while operating at an economical cost on low-power devices. The proposed solution can prove to be an efficient trade-off between cost, accuracy, and practicality.

The next area of research will focus on the expansion of support exercises, the personalization of the results, in addition to the integration of long-term tracking functionalities to improve tele-rehabilitation results.

REFERENCES

[1] F. e. a. Roggio, "A comprehensive analysis of the machine learning pose estimation models used in human movement and posture analyses: A narrative review.," Heliyon, p. 21, 2024.

[2] V. a. S. M. Arya, "Enhancing human pose estimation: A data-driven approach with mediapipe blazepose and feature engineering analysing," in nternational Conference on Pioneering Developments in Computer Science & Digital Technologies (IC2SDT), Delhi , 2024.

[3] J.-L. L.-Y. O. a. M.-C. L. Chung, "Comparative analysis of skeleton-based human pose estimation," Future internet , vol. 14, no. 12, p. 380, 2022.

[4] G. e. a. Beges, "Data acquisition module with large number of inputs.," in IMTC/2002. Proceedings of the 19th IEEE Instrumentation and Measurement Technology Conference (IEEE Cat. No. 00CH37276). , Delhi, 2002.

[5] J. F. L. G. F. Z. K. Q. R. H. &. L. J. Gong, "Diffpose: Toward more reliable 3d pose estimation," in IEEE/CVF Conference on Computer Vision and Pattern Recognition, Vancouver, Canada, 2023.

[6] L. A. C. Carolyn Kisner, Therapeutic Excercise, F.A.Davis Company, 2012.

[7] L. S. R. E. L. B. J. L. Pereiralow, "The knee smartphone-application goniometer is a more reliable tool than the standard goniometer in acute orthopaedic settings," Physiotherapy, vol. 101, pp. 1192-e1193., 2015.