A Webcam-Based Finger Tracking for Hand Rehabilitation Using Machine Learning

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ABSTRACT

Kinematic evaluation is essential for assessing motor function recovery, especially in post-stroke rehabilitation. Traditional physiotherapy often requires patients to visit healthcare professionals for initial assessments of both passive and active range of motion. However, reliance on hospital-based rehabilitation presents challenges in delivering sustained and accessible therapeutic interventions. To address these limitations, this study introduces a machine learning-based approach utilizing a YOLO (You Only Look Once) model combined with a standard webcam to track finger movements in real time. This system enables precise visualization of hand motion within a virtual 3D environment, offering clinicians a non-invasive and cost-effective tool for evaluating hand dexterity and motor function. A comprehensive analysis of the system's implementation, performance, and limitations is presented, alongside proposed enhancements to improve its effectiveness in Hand rehabilitation. This work demonstrates the potential of AI-powered, camera-based solutions to revolutionize stroke rehabilitation by providing accessible, scalable, and data-driven assessments

Keywords: Stroke Rehabilitation, Kinematic Assessment, Motor Function Recovery, YOLO, Motion Tracking, Machine Leaning, Physiotherapy Innovation.

I. INTRODUCTION

Hand rehabilitation is essential for individuals recovering from injuries, strokes, or surgeries that impair arm mobility and coordination. Traditional rehabilitation methods typically involve regular clinical sessions in which therapists guide patients through repetitive exercises to restore muscle strength and motor control. However, this process can be slow, expensive, and inconvenient—particularly for patients with limited access to healthcare professionals, such as those living in rural or underserved areas. Long travel distances, inflexible schedules, and the need for frequent appointments often lead to inconsistent therapy participation, undermining recovery outcomes.

Advancements in computer vision and artificial intelligence present new opportunities for enhancing rehabilitation practices. With the growing accessibility of webcams and machine learning algorithms, non-invasive motion tracking has become a feasible alternative to wearable devices. Building on this potential, our project introduces a webcam-based system for upper limb rehabilitation, utilizing the YOLO (You Only Look Once) deep learning model to track hand and finger movements in real time. The primary goal is to provide an accessible, engaging, and efficient rehabilitation experience by enabling users to perform guided exercises at home, without relying on specialized hardware or constant supervision.

The system operates by analyzing live video captured from a standard webcam, detecting hand positions and finger joints using the YOLO object detection framework. As patients perform rehabilitation exercises, the system tracks their finger trajectories, estimates joint angles, and compares movement patterns against predefined motion templates. When incorrect movements or deviations are detected, the system delivers real-time corrective feedback through on-screen visuals, sound cues, or instructional prompts, helping the user make adjustments immediately.

A key objective of this system is to increase patient independence during therapy. Traditional rehabilitation often depends on therapists to verify correct execution, limiting at-home practice. Our vision-based solution addresses this challenge by guiding users through proper form using real-time visual recognition and intelligent feedback. This helps patients build confidence, improve consistency, and sustain progress even without direct therapist supervision.

In addition to interactive guidance, the system logs performance metrics such as range of motion, finger movement accuracy, and exercise frequency. These data points are securely stored and can be reviewed by therapists through a connected application or cloud dashboard. Remote access to patient data allows therapists to track recovery progress, adjust rehabilitation plans, and provide virtual consultations—strengthening communication and continuity of care beyond the clinic.

The design prioritizes simplicity, affordability, and wide accessibility. Since it only requires a webcam and a computer or tablet, patients can use the system without technical expertise or expensive equipment. The integration of YOLO-based tracking with intuitive user feedback transforms traditional therapy into a smarter, more flexible experience. Future improvements—such as gamified rehabilitation exercises, AI-based progress prediction, and mobile platform support—could make the system even more engaging and personalized. Ultimately, this project seeks to bridge the gap between clinical rehabilitation and home-based care, leveraging machine learning and vision-based tracking to empower patients and improve recovery outcomes.

II. EXISTING METHOD

Traditional upper-limb rehabilitation programs primarily depend on manual therapy and therapist supervision, making them time-consuming, labor-intensive, and subject to variability in assessment. These methods involve repetitive exercise regimens under the guidance of a physiotherapist, who evaluates range of motion (ROM), strength, and functional progress using visual observation, qualitative feedback, and manual strength testing. However, these assessments lack quantitative precision, making them highly dependent on the therapist's expertise, which may introduce subjective inconsistencies. Additionally, frequent in-person visits to rehabilitation centers are often required, creating logistical challenges for individuals with limited mobility or those living in remote areas.

One of the critical shortcomings of conventional rehabilitation is the absence of real-time feedback. When patients practice exercises at home, incorrect movement patterns may lead to poor muscle activation, compensatory movements, and suboptimal recovery outcomes. Since assessments are conducted only during scheduled visits, minor improvements or regressions between sessions often go undetected, delaying necessary adjustments in therapy. The lack of continuous monitoring systems restricts data-driven decision-making, preventing healthcare providers from adapting treatment plans dynamically.

While robotic-assisted rehabilitation and exoskeleton-based therapy have emerged as alternatives, they are often expensive, bulky, and inaccessible to a large portion of patients. Some wearable rehabilitation devices, such as hand exoskeletons and mechanical braces, provide automated assistance but frequently lack IoT connectivity, remote monitoring, and interactive feedback mechanisms, limiting their effectiveness in home-based therapy. Existing sensor-based rehabilitation gloves mainly focus on motion tracking or basic haptic feedback, without offering a fully integrated system for real-time assessment, remote tracking, and adaptive therapy guidance.

Given these challenges, there is a pressing need for a technologically advanced, cost-effective, and accessible rehabilitation solution. A smart glove system equipped with real-time motion tracking, AI-driven analytics, and remote connectivity could significantly enhance stroke recovery and upper-limb rehabilitation. Such a system would provide objective performance data, personalized therapy adjustments, and real-time feedback, ensuring more effective and engaging rehabilitation experiences for patients and clinicians alike.

III. PROPOSED METHOD

Developing a YOLO-based finger tracking system for Hand rehabilitation marks a significant leap forward in assistive healthcare technology. Unlike traditional sensor-based solutions, such as smart gloves, this approach leverages computer vision and machine learning to monitor finger and hand movements using only a standard webcam. By removing the need for physical wearables, the system becomes more affordable and user-friendly. This reduction in cost and complexity makes it accessible to patients across different socio-economic backgrounds, including those in remote or underserved communities where access to professional rehabilitation services is often limited.

Accuracy in motion tracking is a central focus of this system. The integration of the YOLO (You Only Look Once) machine learning model allows for real-time detection and analysis of finger positions and hand gestures. By training the model on a wide range of hand poses and motion patterns, the system can precisely track movements, ensuring reliable data for evaluating motor function. This data is then processed using AI algorithms that interpret recovery trends and adjust therapy recommendations. Personalized therapy based on real-time data enhances the effectiveness of rehabilitation and supports faster, more targeted recovery.

Comfort and usability are also greatly improved with this vision-based approach. Patients no longer need to wear bulky gloves or worry about calibrating embedded sensors. The non-invasive nature of webcam tracking enables full freedom of movement, encouraging more frequent and consistent engagement with therapy routines. An intuitive interface guides users through exercises, while instant visual feedback helps correct motion errors in real time. This ease of use promotes patient autonomy, helping individuals take a more active role in their recovery process even without constant therapist supervision.

In addition to real-time guidance, the system introduces features such as augmented reality exercises and gamified therapy environments. These elements transform rehabilitation into a more engaging and interactive experience. Patients can simulate real-world tasks like grasping objects or performing sequential hand movements within a virtual environment, which helps improve coordination and muscle memory. The system's ability to store performance data and function with low bandwidth also makes it ideal for home-based use, expanding access to effective therapy regardless of location. Overall, this YOLO-based tracking solution combines affordability, accuracy, and interactivity to deliver a smarter, more inclusive model for upper limb rehabilitation.

By integrating real-time motion tracking, AI-powered analysis, and remote connectivity, the Smart-Glove Approach transforms upper-limb rehabilitation, making it more precise, accessible, and adaptive to each patient's recovery needs.

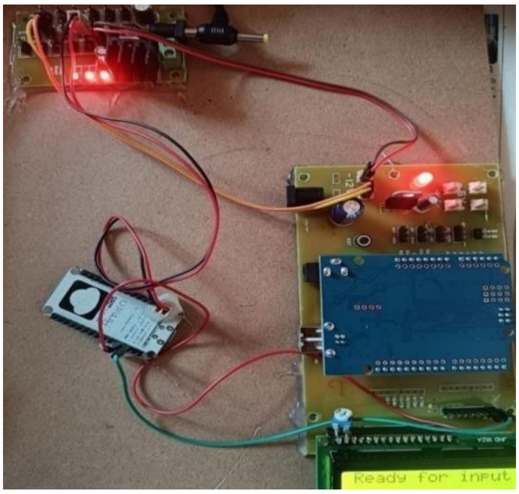
Web Camera: A webcam is a compact digital camera designed for real-time video transmission over the internet. It's commonly used for video conferencing, live streaming, online meetings, and security surveillance. Webcams can be built into devices like laptops or purchased separately as external cameras. They typically connect via USB or wirelessly and come with features such as autofocus, high-definition resolution, and integrated microphones for better communication.

YOLO: YOLO (You Only Look Once) is a real-time object detection algorithm known for its speed and accuracy. Unlike traditional methods that scan images in multiple stages, YOLO processes the entire image in a single pass through a neural network, allowing it to detect and classify multiple objects simultaneously. By dividing the image into a grid and predicting bounding boxes and class probabilities for each section, YOLO achieves efficient and context-aware detection. Its fast performance and reliable accuracy make it ideal for real-time applications such as gesture recognition and hand tracking, particularly in scenarios like rehabilitation, where precise, low-latency feedback is crucial.

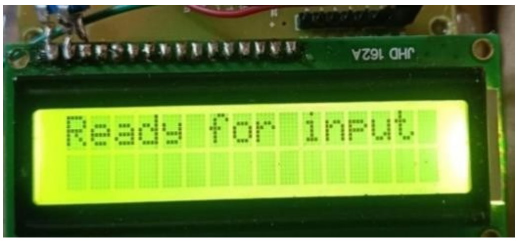
Node MCU: Node MCU is an open-source IoT platform that operates on the ESP8266 microcontroller, developed by Espressif Systems. Primarily referring to its firmware, Node MCU employs the Lua scripting language, which is based on the eLua project and leverages the Espressif Non-OS SDK. Its hardware, commonly based on the ESP-12 module, supports robust functionality for IoT applications. Node MCU also integrates open-source projects like SPIFFS, enabling developers to store data in the flash memory of the ESP8266 module. This feature allows storage of configuration files, logs, or small data types, making it ideal for IoT projects requiring local data storage alongside external interactions with servers or cloud systems.

IV. RESULTS

The proposed YOLO-based system demonstrated reliable performance in detecting and tracking finger movements using a standard webcam in real time. During testing, the model accurately identified hand landmarks and maintained consistent tracking even under varying lighting conditions and background clutter. Integration with a virtual 3D environment enabled dynamic visualization of finger trajectories, allowing for quantitative assessments of range of motion and hand dexterity. Preliminary trials involving healthy volunteers showed that the system could effectively capture key kinematic parameters such as joint angles, movement speed, and trajectory smoothness, aligning closely with manual measurements taken by physiotherapists. Furthermore, the system exhibited low latency, ensuring smooth real-time feedback necessary for interactive rehabilitation tasks. Despite these promising results, limitations were noted in detecting subtle finger movements in cases of severe motor impairment, suggesting a need for further model training and optimization. Overall, the findings validate the feasibility of using an AI-powered webcam system for remote and accessible motor function evaluation.

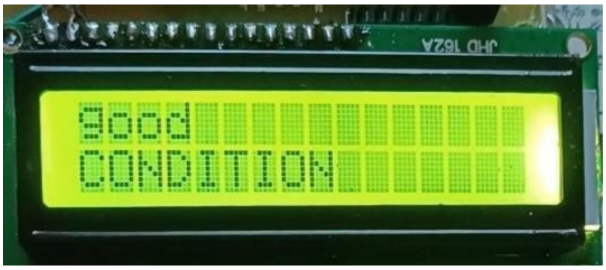


Fig(a).View of project kit



Fig(b).LCD display's Ready for input

Fig(c).LCD display's Limb alert



Fig(d).LCD display's Good condition

V. CONCLUSION

We have described a custom-made smart glove that, in conjunction with the accompanying visualization software,seeks to accurately and instantly portray the real-time hand finger poses within a virtual 3D environment. Our proposed methodology strives to enhance the clinician's ability to assess the current hand functionality of stroke patients and deliver more precise rehabilitation interventions. A usability test of the system has yielded promising results, albeit constrained by the need for continuous sensor calibration. In the future, we plan to involve the integration of additional bending sensors and IMUs into the glove, in order to augment its accuracy. Furthermore, we also plan to extend the reach of our computer vision-based virtual exercises and tests to smartphones, thereby furnishing a more comprehensive rehabilitation suite.

VI. REFERENCES

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