REAL-TIME 3D BIOMECHANICAL ANALYSIS AND AI PERSONAL TRAINER FOR STRENGTH AND CONDITIONING EXERCISES USING MARKERLESS MOTION CAPTURE

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Introduction

Biomechanical analysis plays a crucial role in enhancing athletic performance and ensuring safety during physical activities [1]. However, conventional 3D motion capture systems are costly, require specialized environments, and are largely confined to laboratory use [2]. To overcome these limitations, this study presents a real-time, markerless 3D motion capture system using multi-angle 2D video and pose estimation models to provide accessible, low-cost biomechanical feedback during common strength and conditioning exercises. By addressing the underexplored integration of 2D pose estimation into real-time 3D reconstruction, this research aims to broaden access to high-quality biomechanical feedback in both training and rehabilitation contexts.

Methods

The system was developed using the SU-EMD dataset [3], which includes multi-angle video and corresponding 3D Vicon motion data of seven common strength and conditioning exercises, captured through multi-angle video. Five leading 2D pose estimation models—OpenPose, OpenPifPaf, AlphaPose, DCPose, and YOLOv8-pose—were evaluated for suitability in real-time 3D reconstruction. For each model, 2D keypoints were triangulated using stereo calibration parameters to generate 3D pose estimations. Accuracy was assessed against ground truth Vicon data using metrics such as mean error, precision, and percentage of correct keypoints (PCK). A constant velocity Kalman filter was implemented to reduce frame-to-frame jitter. The final system streamed smoothed 3D keypoints to a Unity-based interface for real-time visualization and biomechanical feedback, as illustrated in Figure 1.

Results and Discussion

Among the evaluated models, YOLOv8m-pose demonstrated the optimal trade-off between speed and accuracy, achieving a mean error of 49.94 mm and an inference time of 32.10 ms per frame. The complete system utilized three low-cost webcams to deliver real-time 3D motion capture and feedback.* Biomechanical analysis included real-time tracking of joint angles, segment alignments, and movement dynamics. Scoring metrics and repetition-counting algorithms were designed in consultation with a biomechanics expert to provide meaningful performance feedback. The system generalized effectively to live users, demonstrating robustness and usability outside of controlled environments.

*https://www.youtube.com/shorts/i7rh2zCldGk

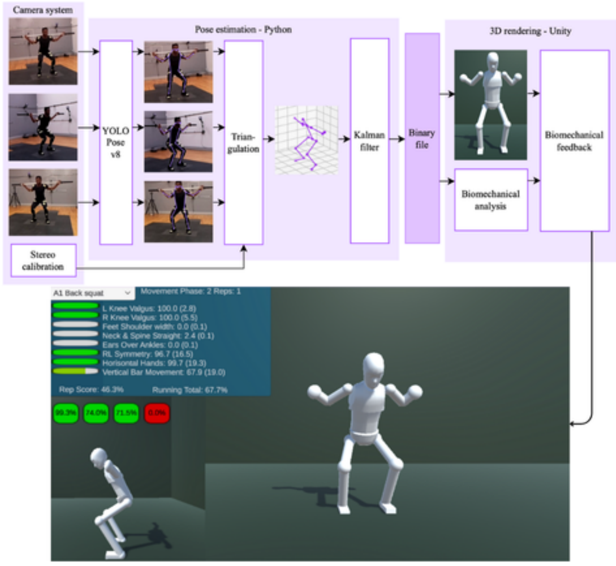

Figure 1: Full pipeline of the real-time biomechanics feedback system featuring subject 3 from the SU-EMD dataset.

Conclusions

This research presents a novel, real-time markerless 3D motion capture system that provides biomechanical feedback using low-cost hardware and open-source software. By reducing the reliance on expensive, lab-based equipment, the system offers a practical solution for performance monitoring and injury prevention in athletic, clinical, and home environments. While initial results are promising, limitations such as sensitivity to video quality and the need for broader validation remain. Future work will focus on refining pose estimation through machine learning and expanding the dataset to encompass a wider range of movements and populations. This research establishes a foundation for more accessible and scalable biomechanical assessment technologies.

References

[1] Pedro Forte and José E Teixeira. Exercise biomechanics for health: evaluating lifelong activities for well-being. In *Healthcare*, volume 11, page 900. MDPI, 2023.

[2] Stacy A Schurr, Ashley N Marshall, Jacob E Resch, and Susan A Saliba. Two-dimensional video analysis is comparable to 3d motion capture in lower extremity movement assessment. *International journal of sports physical therapy*, 12(2):163, 2017.

[3] Michael Deyzel and Rensu P Theart. One-shot skeleton-based action recognition on strength and conditioning exercises. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 5169–5178, 2023.