Democratizing Biomechanical Analysis: High-Fidelity Golf Swing Analysis Using OpenCap for Motion Capture and Statistical Pattern Recognition

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Introduction

Biomechanical analysis of human movement, particularly in sports like golf, traditionally relies on expensive, laboratory-grade optoelectric motion capture systems. While these systems offer high accuracy, their cost, complexity, and limited accessibility create a barrier for broader research, educational, and athletic use. For instance, state-of-the-art facilities like the Sprivail Golf & Sports Medicine program employ multi-camera marker-based systems in controlled environments to assess swing mechanics and prescribe improvements [1]. With the advent of markerless, camera-based motion capture tools, a new opportunity has emerged to democratize biomechanics research.

This project leverages **OpenCap**, an open-source, smartphone-based motion capture platform, to perform high-resolution kinematic analysis of the golf swing (specifically the seven-iron swing). OpenCap has been previously validated against marker-based systems, showing joint angle errors below 5°, sufficient for detecting gross motor patterns in dynamic movements like the golf swing [2]. The central question addressed is whether OpenCap can provide biomechanical data of sufficient quality to distinguish collegiate-level expert (professional) from novice (amateur) performance patterns, specifically without the aid of commercial biomechanical modeling software or proprietary hardware.

The goal of this study was to determine if OpenCap alone could be used to (1) extract joint kinematic data across key swing phases, (2) evaluate intersubject variability, and (3) perform dimensionality reduction and group clustering using Principal Component Analysis (PCA). We hypothesize that OpenCap data, when rigorously segmented and analyzed, can expose joint coordination patterns that are both statistically significant and skill-level dependent, supporting its viability as a standalone tool for advanced human motion research.

Materials and Methods

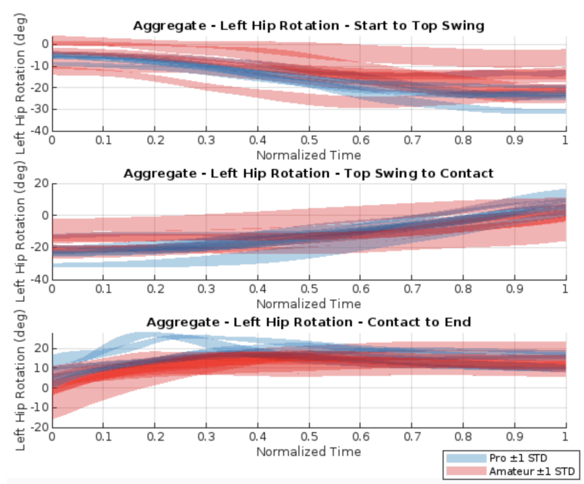
Motion capture data were collected using **OpenCap**, a free, open-source platform that generates 3D kinematic estimates using synchronized video from multiple smartphone cameras. Two iPhones mounted on standard tripods were positioned at ~45° angles relative to the front of the subject to capture high-fidelity swing motion from multiple perspectives. No external markers, sensors, or proprietary software were used.

Six subjects participated in the study, including a mix of experienced collegiate-level (professional) and novice (amateur) golfers. Each subject completed **20 full swings** using a standard **seven-iron** golf club, hitting golf balls in an appropriate and well-lit environment to simulate on-course conditions. The OpenCap system automatically generated a `.mot` file for each trial, containing joint angle trajectories over time for 3D skeletal segments.

Each swing was temporally segmented into three discrete phases: (1) address to top of swing, (2) top to ball contact, and (3) contact to follow-through. These timestamps were manually recorded for every trial. Joint kinematics were interpolated from each phase to a normalized time base of 100 points. Joint angle data were then processed in MATLAB for statistical comparison, pattern recognition, and dimensionality reduction via Principal Component Analysis (PCA). Group-level comparisons were also tested using a Monte Carlo simulation.

Results, Conclusions, and Discussion

Analysis focused on six joint variables across three golf swing phases, emphasizing left hip rotation as a key biomechanical differentiator for determining consistency. Mean joint angle trajectories and standard deviations were computed from their 20 swing trials for each subject. Group-level plots showed consistently tighter variability bands in professionals compared to amateurs, particularly during the transition from backswing to contact.



In 2D and 3D Principal Component Analysis (PCA) space, subjects tended to cluster based on skill level, with professional golfers exhibiting grouped PCA scores with positive PC2 Loadings. All professional subjects demonstrated positive weights on PC2, while all amateur subjects showed negative weights. This suggests PC2 may capture an essential coordination pattern or temporal characteristic that distinctly separates expert from novice swing mechanics.

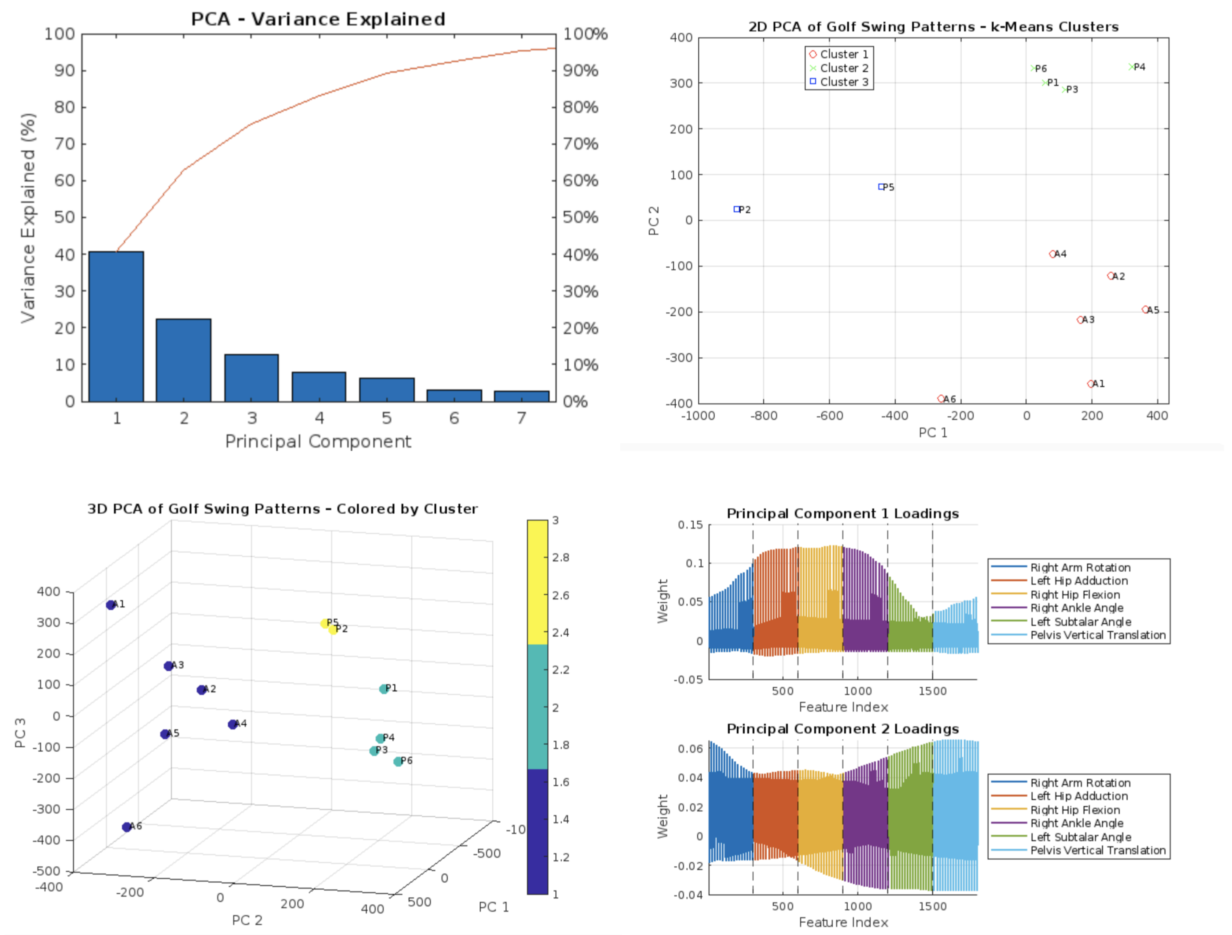


Figure: Principal Component Analysis of Golf Swing Biomechanics.

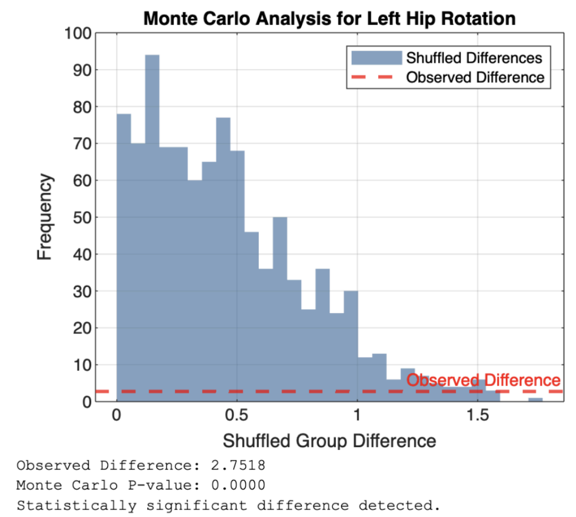
Top left: Variance explained by each principal component, showing the first three PCs capture over 85% of total variation.

Top right: 2D PCA scatterplot with k-means clustering (k = 3), showing subject separation by swing pattern.

Bottom left: 3D PCA plot visualizing subjects in PC1–PC3 space, with cluster assignment and anonymized labels (P = professional, A = amateur).

Bottom right: Loadings for PC1 (top) and PC2 (bottom), color-coded by joint variable, indicating which joint-segment combinations contribute most to variance in swing mechanics.

To assess the statistical reliability of observed differences, a Monte Carlo permutation test (1,000 iterations) was conducted on the trial-to-trial variability between groups. The observed difference in standard deviation between professional and amateur golfers for left hip rotation was statistically significant ($p < 0.01$), supporting the hypothesis that OpenCap-derived data can capture meaningful biomechanical differences. Monte Carlo permutation testing avoids assumptions of Gaussian distributions and reinforces the statistical rigor of group comparisons.



These findings demonstrate that **OpenCap, in the absence of expensive motion capture systems or musculoskeletal modeling software, enables high-resolution biomechanical analysis**. The combination of OpenCap with accessible tools like MATLAB opens up the possibility for biomechanics research, athletic training, and educational instruction outside of specialized laboratories. Meanwhile, newer smartphone-based solutions like Sportsbox.ai offer greater accessibility, but their reliance on a single camera angle often necessitates assumptions about joint motion and occluded limb positions [3]. While these results are promising, the study's limited sample size, focus on a single club type, and reliance on manual swing segmentation introduce constraints that should be addressed in future work. Expanding to a broader population, automating temporal segmentation, and incorporating kinetic data (e.g., ground reaction forces) could further validate and extend OpenCap's utility across sports and clinical applications. This project highlights OpenCap's potential as a disruptive and democratizing technology in human movement science.

References

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We thank the USC Golf Team for participating and supporting data collection. All subject data were anonymized and analyzed in accordance with approved IRB protocols.