Calibrationless Monocular Vision for Estimating Ground Reaction Forces and Knee Adduction Moment During Gait

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Summary

A calibrationless monocular vision combined with musculoskeletal modelling was used to estimate ground reaction forces (GRFs) and knee adduction moment (KAM) from a monocular video. The estimated GRFs showed strong correlation with measured values, while the first KAM peak demonstrated no significant difference and moderate correlation.

Introduction

The KAM is an important indicator of knee osteoarthritis (OA). Traditional motion labs use mocap systems and force plates to measure marker data and GRFs, enabling musculoskeletal modeling for KAM estimation. However, these methods are costly, time-consuming, and require specialists [1], limiting accessibility for many clinicians and hospitals. Researchers have addressed traditional mocap challenges with computational approaches. Estimating GRF during double-limb support presents difficulties due to the redundant dynamics system. Minimizing the sum of squared contact forces is suboptimal for gait analysis, as it may underestimate contact forces while still satisfying multibody dynamics [2]. In this study, weighted joint torque minimization in the sagittal and frontal planes was incorporated in optimization to correct medio-lateral and antero-posterior GRFs underestimation. A two-stage musculoskeletal simulation was implemented: to determine (1) GRFs and (2) KAM. Hence, this study aims to evaluate the efficacy of a calibration-free monocular vision system for estimating GRFs and KAM during gait.

Methods

Gait data from the OpenCap dataset [1], including mocap and smartphone videos of 10 healthy adults, was used. Video from 'camera 1' (45° offset from the frontal plane) served as input for 3D pose estimation and musculoskeletal modeling. ***3D pose estimation:*** HuMoR [3] was used to extract 3D poses from monocular video for its accurate motion reconstruction and foot-ground contact preservation. A keypoint detector identified 2D joint positions, while HuMoR optimized alignment between reprojected SMPL joints and estimated 2D joints. ***Musculoskeletal modelling:*** CusToM [4] was used for musculoskeletal simulation in two stages: estimating GRFs and using these GRFs to calculate KAM. In stage one, a 42-DOF full-body model was used, with hip, knee, and ankle joints modeled as 3, 1, and 2 DOF, respectively. Subject-specific models were refined by optimizing segment lengths and marker positioning. Each foot had 12 contact points activated upon ground interaction, determined by vertical displacement (<0.05m) and velocity (<0.8m/s). Optimization minimized combined joint torques in the sagittal and frontal planes to avoid GRF underestimation. In stage two, a 48-DOF full-body model calculated KAM, with hip, knee, and ankle joints modeled as 3 DOF each. Inverse kinematics and dynamics were performed using estimated GRFs. ***Statistical analysis:*** Statistical analysis included GRFs and KAM during the left leg stance phase. RMSE and Pearson correlation coefficients were calculated for GRFs and KAM from monocular video. First KAM peaks were analyzed using paired t-tests and Pearson correlation.

Results and Discussion

Monocular video-estimated GRFs strongly correlated with measured GRFs (Pearson: 0.74–0.94; RMSE: 1.06–7.99 %BW). Monocular video-estimated KAM had a moderate Pearson correlation (0.57) and an RMSE of 0.69 %BW*BH (Figure 1). The first KAM peak from monocular video showed no significant difference ($p = 0.801$, $R = 0.45$). KAM underestimation in double support stance phase may stem from challenges in pinpointing the force vector's location, causing error propagation throughout the algorithm. While in the late stance phase, KAM underestimation may due to medio-lateral GRF overestimation during terminal double-limb support. The model may not fully capture toe bending, affecting contact dynamics accuracy.

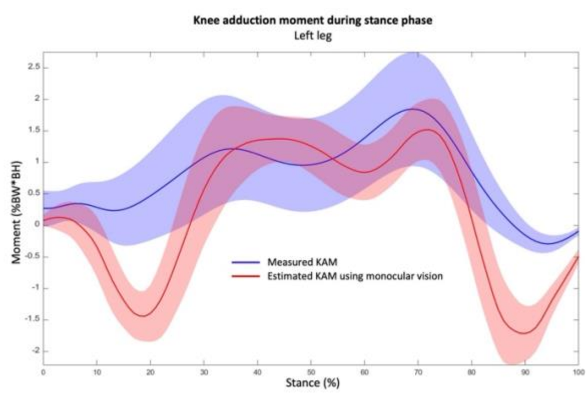

Figure 1: The knee adduction moment profile computed from monocular vision GRFs and measured GRFs.

Conclusions

The proposed monocular vision pipeline estimates GRFs with strong correlation to measured values. The moderate KAM correlation from a mobile system with minimal setup shows promise for clinical gait assessment outside the lab.

References

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