Machine Learning-Based Estimation of Knee Loading Conditions from Motion Capture Data

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Summary

This study explores machine learning-based estimation of knee contact forces (KCFs) using motion capture data from six patients in the CAMS-Knee dataset. A bi-directional Long Short-Term Memory (bi-LSTM) neural network was trained on joint angles, ground reaction forces (GRFs), and electromyography (EMG) data to predict in vivo KCFs. The model demonstrated accurate KCF predictions, with Root Mean Squared Errors (RMSEs) ranging from 0.37 to 0.92 BW, achieving Pearson Correlation Coefficients (PCCs) of up to 0.90. The results highlight the feasibility of deep learning for estimating KCFs, providing a cost-effective, clinically accessible alternative to musculoskeletal modelling for improving Total Knee Arthroplasty (TKA) outcomes.

Introduction

With the increasing prevalence of TKA in younger individuals, the long-term success of implants has become a critical concern. Aseptic loosening and instability, often linked to abnormal joint loading, are among the leading causes of TKA failure [1]. Accurate estimation of KCF is therefore essential for improving surgical outcomes. To enhance the accuracy and clinical applicability of KCF estimation, this study explores the feasibility of leveraging advanced machine learning techniques to predict KCFs based on *in vivo* biomechanical datasets from the CAMS-Knee project [2].

Methods

Data from six TKA subjects with instrumented knee implants performing multiple trials of various functional activities were obtained from the CAMS-Knee dataset [2]. Inputs to train the neural network comprised lower limb joint angles from skin-marker-based motion capture, GRFs, and EMG recordings from eight muscle groups (Figure 1). Inputs to the network also included *in vivo* KCF data and tibiofemoral kinematics derived from video fluoroscopy.

The neural network was composed of bi-LSTMs [3] which were trained, validated, and tested using pre-processed data. The model featured 4 bi-LSTM layers each with 512 hidden units, followed by 4 dense layers each with 256 neurons.

To minimize overfitting due to the limited dataset size, a Leave-One-Subject-Out cross-validation approach was used. Here, the model's predictive performance was evaluated using various metrics, including RMSE and PCC, to assess the agreement between predicted and *in vivo* measured KCFs.

Results and Discussion

Overall, the network provided accurate KCF estimates across various tasks and subjects. The medial KCF prediction had an RMSE ranging from 0.17 to 0.66 BW, corresponding to an average error of 24% relative to the peak value, with PCC values between 0.64 and 0.92. Similarly, lateral KCF predictions showed RMSEs from 0.13 to 0.35 BW, indicating an average error of approximately 19%.

The model achieved consistent accuracy for level walking, downhill walking, and stair descent, maintaining RMSE values around 0.50 BW and average PCCs near 0.90. However, accuracy declined for squatting and sit-stand-sit transitions, where RMSEs reached up to 0.75 BW and the average PCC dropped to around 0.80. The model yielded the most precise predictions for subject K2L (RMSE 0.37 BW, PCC 0.90) and the least accurate KCF estimates for subject K5R (RMSE 0.92 BW, PCC 0.71).

Conclusions

The deep learning approach developed in this study provides reasonably accurate estimates while efficiently predicting KCFs across multiple functional activities. This method offers a cost-effective, time-efficient alternative to complex musculoskeletal modeling, making it particularly suitable for clinical applications where modeling expertise is limited.

References

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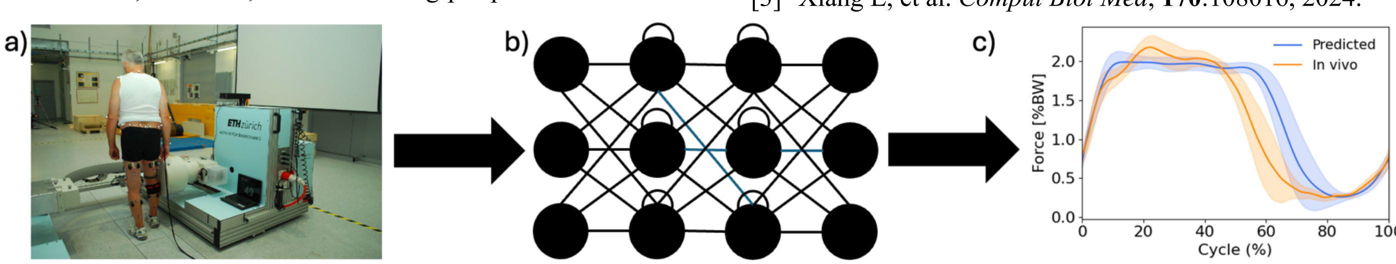

Figure 1: (a) The CAMS-Knee dataset provides comprehensive data on in vivo knee loading and kinematics. (b) A schematic representation of the bi-LSTM network used to analyze relationships between biomechanical parameters. (c) An exemplary output comparing predicted and in vivo measured knee contact force, for a walking trial of subject K3R.