Full-chain Biomechanical Analysis of Human Movement with Musculoskeletal Simulation and Wearable Sensors

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Summary

Recent studies have increasingly exploited wearable sensors to assess human movements. In this study, we integrated two types of wearable sensors with musculoskeletal simulation to enable a full-chain biomechanical analysis of human movement. Data were simultaneously collected from an integrated wearable sensor system including inertial measurement units (IMUs) and pressure insoles and a laboratory-based motion capture (Mocap) system. Five able-bodied participants performed walking, squat and sit-to-stand. Joint angles, joint torques, and muscle activations were estimated using the musculoskeletal simulation framework OpenSim. The results demonstrated that the wearable system could provide sufficiently accurate predictions on sagittal plane joint angles, ankle joint torque, and muscle activation trends. These findings highlighted the potential of wearable sensor-based motion analysis as a viable alternative to the conventional Mocap system.

Introduction

Measurement and biomechanical analysis of human movement are important in diverse fields, such as rehabilitation, sports science, ergonomics, and human-robot interaction. However, the accessibility of conventional motion analysis systems - typically based on the Mocap system and force plates - is limited by their high cost and spatial constraints. Recent studies have increasingly exploited the application of wearable sensors, such as IMUs and pressure insoles, to assess human movements. However, the integration of multiple sensor types for estimating internal biomechanical parameters, such as joint torques and muscle activations, remains underdeveloped and insufficiently validated [1]. In this study, we combined wearable sensors with musculoskeletal simulation to enable a full-chain biomechanical analysis of human movement.

Methods

Five able-bodied participants were instructed to perform three daily movements: walking, squat and sit-to-stand. Movement data were simultaneously measured with a wearable sensor system and a Mocap system. In the wearable system, 8 IMUs (x-IMU3) measured orientations of body segments and computed joint angles at 100 Hz [2], while a pair of pressure insoles (Moticon OpenGo) recorded vertical forces and center of pressure positions at 100Hz. Joint torques and muscle activations were estimated using OpenSim. The Mocap system (Vicon) recorded marker trajectories with 10 infrared cameras (100 Hz). Ground reaction forces were recorded with 4 force plates (AMTI Optima, 1000 Hz). Muscle activations of tibialis anterior, gastrocnemius medial and soleus were measured with electromyography sensors (Pico EMG) at 1000 Hz. OpenSim was also used for estimating joint angles and torques.

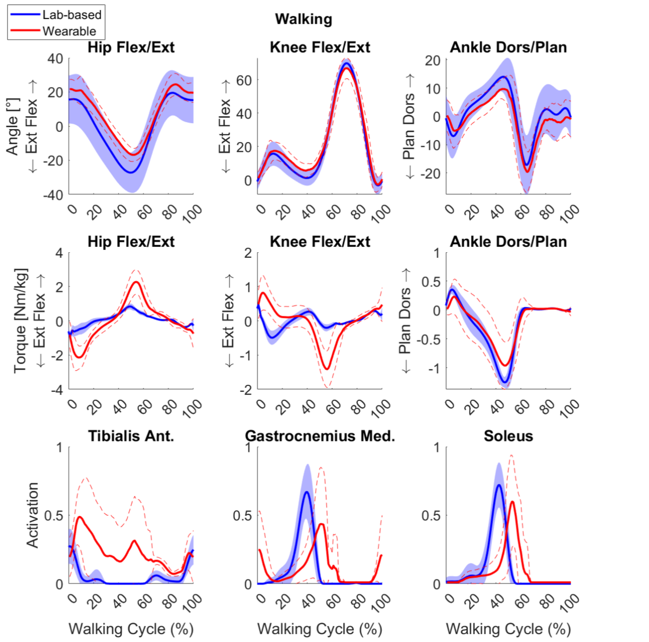

Figure 1: Lower limb joint angles (first row), torques (second row), and major ankle muscle activations (third row) during walking. The blue solid line and shade indicate the mean ±1 standard deviation of the laboratory-based Mocap system. The red solid line and dashed line indicate the mean ±1 standard deviation of the wearable system.

Results and Discussion

Overall, the wearable sensor system yielded results comparable to the laboratory-based system, particularly in joint angles (Figure 1). All three sagittal plane joint angles showed similar curve patterns between the two systems, with the best consistency in knee angle (RMSE=5.62°±2.63°). In terms of joint torques, the wearable system achieved the highest accuracy at the ankle joint while exhibiting lower accuracy at the hip and knee joints, primarily due to the absence of shear forces from pressure insoles. Despite a visible electromechanical delay of 10% gait cycle, muscle activation estimated with the wearable system showed a similar on-off trend as measured EMG data.

Conclusions

In conclusion, our findings demonstrated the feasibility of a fully wearable system for comprehensive biomechanical analysis of human movement beyond traditional lab settings. Future study should include additional participants and movement types.

Acknowledgments

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References

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