Evaluating the Role of Ground Reaction Forces in Biomechanical Simulations of Back-Support Exoskeletons

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Summary

This study evaluated the role of ground reaction forces and moments (GRF&M) in biomechanical simulations of back-support exoskeletons using OpenSim. Eight participants performed squatting while wearing the BackX exoskeleton, with kinematics recorded via motion capture and GRF&M measured using force plates. Simulations were conducted both with and without GRF&M. Omitting GRF&M caused no significant change in reaction forces at L5-S1 but significantly affected hip flexion moment. The spine's kinetics, resolved top-down for the upper body, allow for consistent estimation of joint forces using only kinematics and external forces applied on this segment. While this was theoretically expected, the empirical verification in the presence of exoskeleton support validates modeling assumptions for applied exoskeleton research. This study demonstrated that back-support exoskeletons could be modeled for spine loading without GRF&M, enabling future research in field settings where such measurements are challenging.

Introduction

Modeling exoskeleton support in biomechanical simulations offers insights into their impact on deep muscle activation and joint reaction forces, which are difficult to measure directly. These simulations rely on inputs like movement kinematics and external forces. While capturing workers' motion wearing exoskeletons in the field is feasible, measuring ground reaction forces and moments (GRF&M) poses a greater challenge. Evaluating the role of GRF&M in simulations provides insights into the accuracy of exoskeleton support modeling with limited inputs in future studies. Therefore, this study evaluated the impact of including versus omitting GRF&M on the simulation outcomes in the upper and lower body, while considering back-support exoskeleton assistance.

Methods

Eight participants (sex-balanced; BMI:26±4 kg/m^2) were recruited. Each was fitted with the BackX exoskeleton (SuitX), which supports the back through chest and thigh pads. Participants performed squats at self-selected speeds. Kinematic data were captured with a 9-camera motion capture system (Vicon) using 41 reflective markers on participants and 22 on the exoskeleton. GRF&M were recorded with two force plates (AMTI). Exoskeleton support was modeled as force vectors at chest and thigh pads, with magnitudes based on the torque values acquired from [1]. Simulations were conducted in OpenSim using the new FATLS musculoskeletal model [2]. The model was scaled to each participant, with the exoskeleton's weight (~3.2 kg) added to the pelvis after scaling. Joint angles were calculated via inverse kinematics, and muscle activations were estimated using static optimization. Joint reaction force analysis was run, and the outcomes were normalized to body weight. Simulations were run twice: with and without GRF&M as external forces, while exoskeleton support was always modeled as external forces.

Results and Discussion

(Figure 1) shows the L5-S1 joint reaction force and the hip flexion moment from the model's ideal actuator. Statistical parameter mapping (SPM), using a paired t-test ($\alpha = 0.05$), reveals significant differences in hip flexion moment but no significant differences in most of the squat cycle for L5-S1 joint reaction force. This can be attributed to the modeling structure in OpenSim and the musculoskeletal model. The pelvis serves as the base segment referenced to the ground, with spine kinetics resolved top-down from the arms to the pelvis, while lower limb kinetics follow a bottom-up approach. Therefore, as long as the exoskeleton's support applied to the trunk is accurately modeled, omitting GRF&M does not affect the analysis of forces in the spine. However, it does influence simulation outcomes for the lower limbs.

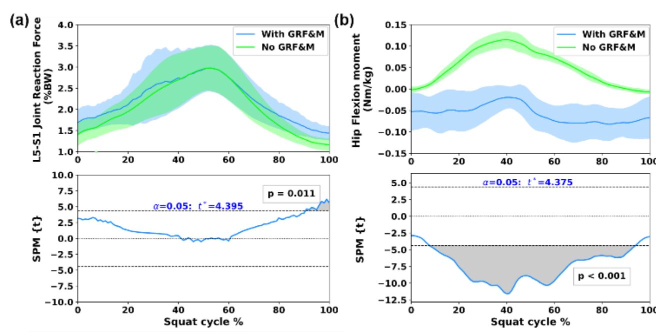

Figure 1: (a) L5-S1 joint reaction forces and (b) hip actuator moments under two GRF&M conditions, with SPM analysis in the second row.

Conclusions

This study showed that a back-support exoskeleton can be modeled in OpenSim without GRF&M using a model with pelvis as the base segment to estimate spine forces, with results similar to those obtained when GRF&M is included. Therefore, future studies on the impact of back-support exoskeletons, such as BackX, on spine loading can rely only on upper body external forces and movement kinematics.

References

[1] Madinei et al. (2022). *J Biomech*, **145**: 111363.
[2] Akhavanfar et al. (2024). *Ann Biomed Eng*, **52**: 259-269.