Segment Mass Property Errors Have Less Impact on Estimated Joint Loading in Human Gait Than Ground Reaction Force Errors

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Introduction

Estimating joint loading during human movement is a cornerstone of biomechanics research. Traditionally, joint loads are estimated using musculoskeletal models to solve the inverse dynamics problem. Relying on Newton's second law of motion, we sum the external forces acting on a body segment and set that equal to the body segment dynamics[1]. This approach is powerful because it allows researchers to estimate the reaction loads at each joint that are impossible to physically measure without invasive surgeries[2]. However, this approach relies on assumptions and physical measurements that are difficult to quantify and prone to measurement error.

Therefore, the purpose of this study was to evaluate how the accuracy of joint load estimates are impacted by errors in both segment mass properties. To further explore the impact of experimental measurements, we tested the sensitivity to shear ground reaction force errors. We hypothesized that changing the mass properties and shear ground reaction forces would differentially impact estimated joint loading, with the smallest effects on the ankle and the greatest effects on the hip.

Methods

We recruited 8 healthy adults (6 males, 2 females; 30 ± 4 years; BMI, 24.1 ± 3.2 kg / m^2) who provided written informed consent. We collected traditional motion capture data during flat ground walking at self-selected speeds and performed inverse dynamics to establish a gold-standard range for sagittal joint load estimates. We then systematically introduced error by manipulating the mass properties of the musculoskeletal model and the magnitude of the externally applied loads. To this end, we scaled both by 0 to 200% in 5% increments, resulting in 1,600 simulations per subject. From this, we compared the peak joint load estimates from each error condition with the gold-standard across the joints in the lower extremities.

Results and Discussion

We found that shear ground reaction force errors had large impacts on joint load estimates while segment mass errors had less of an impact. These joint load estimate errors increased in the more proximal joints. The hip saw changes in mass resulting in around 35% error, changes in shear resulting in 82% error, and a worst-case scenario of 116% error. The knee saw changes in mass resulting in errors of 8%, changes in shear resulting in 140% error, and a worst-case scenario of 147% error. The ankle was least affected, with changes in mass resulting in errors of less than 2%, changes in shear resulting in 17%, and a worst-case scenario of 18%.

These results confirm our hypothesis that the ankle would be least sensitive to changes in mass and shear. This makes sense, as the segments distal to the ankle joint have relatively little inertial force potential compared to the loads experienced by the joint. It was surprising to see that the knee was very sensitive to changes in shear. This is likely due to the ratio of peak joint load to shear force, which in this case is roughly half that of the ankle. Errors in the hip were largely expected as it has the largest distal segment in the lower limbs. In addition to walking, we analyzed other activities of daily living and found that vertical movements like bouncing and heel raises had much smaller errors caused by ground reaction force differences.

Significance

Our results show that while some research areas such as forward simulation in rehabilitation and tendon transfer simulation might require very high-fidelity measurement techniques, there are many scenarios where faster, more convenient measurement solutions would result in very accurate data. Specifically, the ankle appears to be a largely unaffected by inertial factors and even some errors in shear measurements. These results are encouraging for researchers interested in making measurements outside of the biomechanics lab, both in the clinic and in the field.

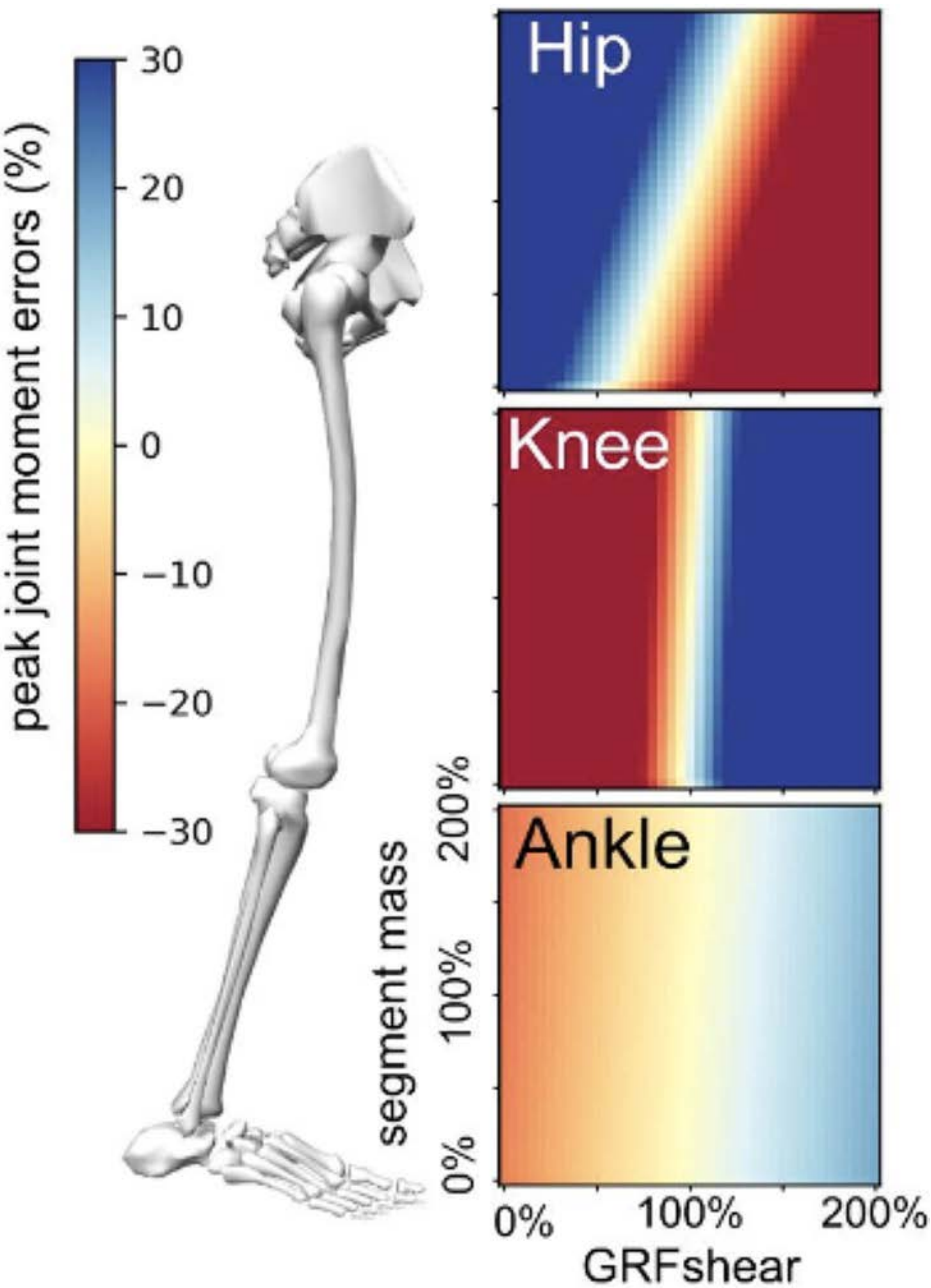

Figure 1. We visualized the precent errors in peak hip, knee, and ankle moments between each error condition and the gold standard measurement through diverging heat maps. Here, blue represents over approximations, red represents under approximations, and light yellow represents accurate approximations of joint moments.

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References

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2. Bergman, *et al.* *J Biomech.* 2001; 34: 859-71