Modeling Pelvis Contact During Lateral Falls: Multi-Criteria Evaluation of Model Performance and Error Source Identification

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Introduction: Hip fractures are a substantive public health issue. Within the multibody dynamics literature, the lateral pelvic impacts that cause hip fractures have commonly been modeled as simple mass-spring or mass-spring-damper systems. However, the biofidelity of these models is questionable as the femur/pelvis system is comprised of complex interactions between biological soft and skeletal tissues. This study investigated how increasing the complexity of contact models (from geometric and damping perspectives) influenced the accuracy of impact dynamics predictions during sideways falls, and the biomechanical sources of errors for each model.

Methods: Forty-six participants (<35 years) underwent simulated sideways falls which involved their pelvis impacting a force plate with a low (but clinically relevant) velocity of 1 m/s. Simulations implementing five contact models (mass-spring(MS), Voigt(VG), Hertzian(HZ), Hunt-Crossley(HC), volumetric(VO)) estimated normal force during impact (Figure 1). Subject-specific input parameters (mass, stiffness, and damping) were incorporated using previously-derived regression equations. Model predictions of peak force magnitude(Err_{max}) and loading duration(Err_{TTP}), and performance over the impact period (Figure 2: RMSE(Err_{RMSE}), impulse(Err_{imp}), and prediction within an experimental corridor(Err_{corr})) were evaluated against subject-specific experimental data. Errors were correlated with individual (e.g. percent body fat) and impact characteristics to guide future model characterization.

Results: Peak force estimates were substantively over-predictive for MS and VO, substantively under-predictive for VG, and moderate for HZ and HC (Figure 3a). Time- to- peak force predictions were best for models with damping components

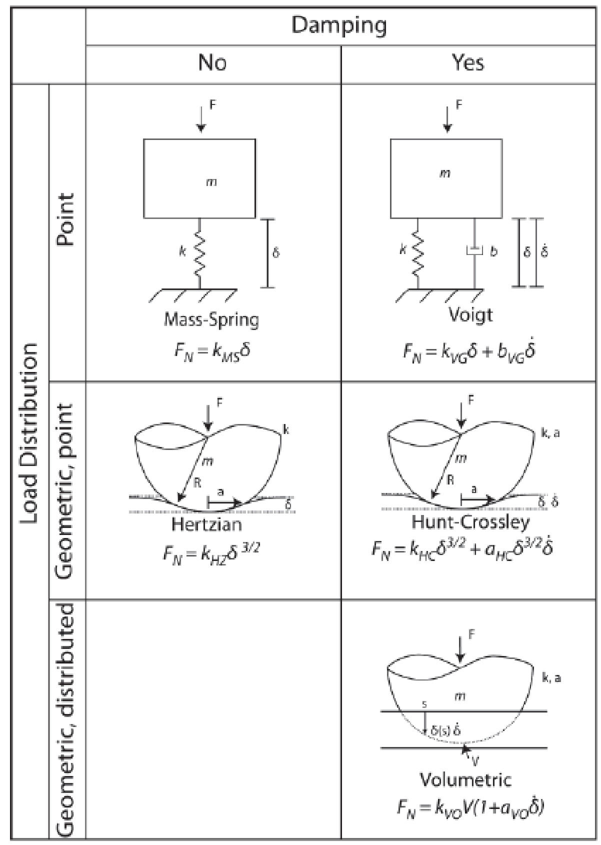

Figure 1: Model schematics and normal force formulae for the MS, VG, HZ, HC and VO systems, indicating geometric and damping complexity.

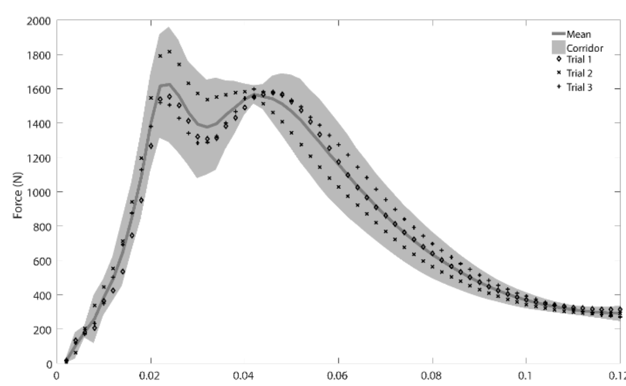

Figure 2: Experimentally-determined loading response corridors. Trial data (markers) were used to develop a time-varying mean (grey line) and two-standard-deviation corridor (grey band) for comparison.

(i.e. VG and HC, VO) but significantly over-predictive for MS and HZ (Figure 3b). Err_{corr} performance differed between males (Figure 3c) and females (Figure 3d), but was best for HC. Timing improvements introduced by damping components in Err_{TTP} resulted in better performance in Err_{imp} (Figure 3e). Err_{RMSE} was substantially improved for HC compared to all other models (Figure 3f). Errors for all models were significantly correlated with percent body fat (positive correlations: VG Err_{TTP}, VO Err_{imp}; negative correlations: MS Err_{max}, HZ Err_{max}, Err_{TTP}, VG Err_{corr}, VO Err_{max} Err_{corr}, HC Err_{TTP}, Err_{corr}, all $p<0.05$). Errors for models assuming a circular contact profile (HZ, HC,VO) were unaffected by the eccentricity or circularity of the experimentally-determined pelvis-floor contact profile.

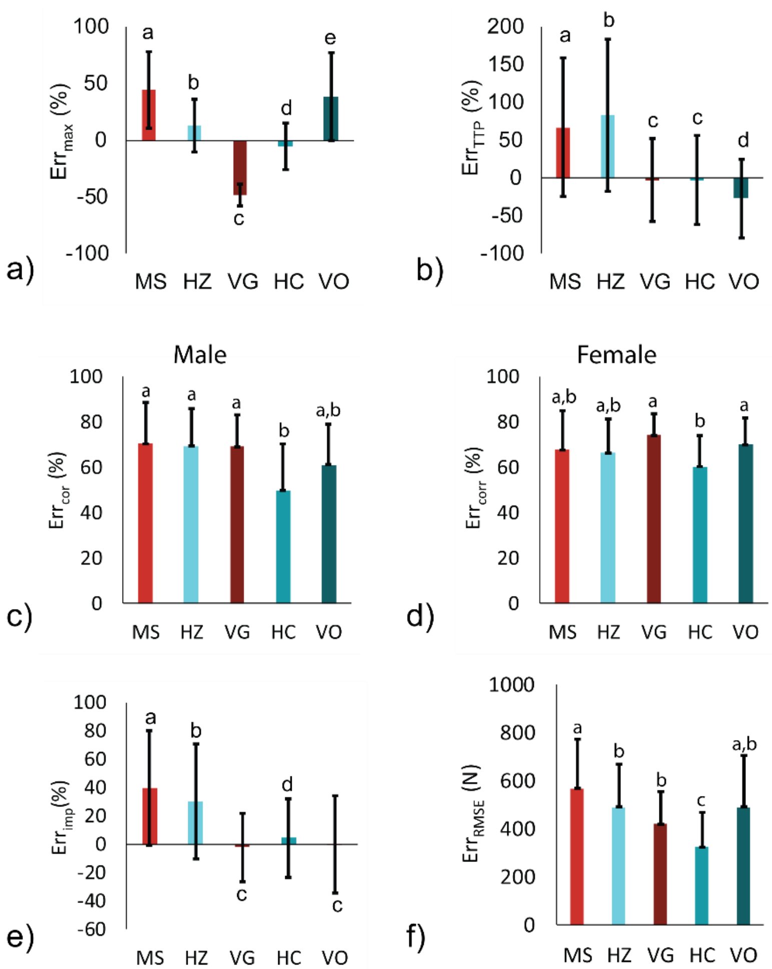

Figure 3: Model performance varied, with HC consistently performing within the most accurate group across criteria. Homogeneous subsets, based on pairwise comparisons, are indicated with letters (a, b . . .).

Discussion: We compared the accuracy of several contact models at predicting the loading response of the pelvis system during lateral impacts. Geometric components had stronger effects on peak force predictions, while damping components had stronger effects on timing characteristics, which carried through to performance in Err_{imp}, Err_{corr} and Err_{RMSE}. The Hunt-Crossley model performed the best across criteria, and is relatively simple/efficient to implement. Accordingly, it has potential to assist in developing more effective hip fracture prediction models, and could be used to load tissue specific (e.g. finite element) computational models. Model errors were primarily linked to percent body fat; this link may be used to tune model parameters in future iterations. No errors for HZ, HC or VO were linked the shape of the pelvis-floor contact profile, indicating that the fall simulation protocol produced a sufficiently round contact profile to satisfy the assumption of a circular contact profile for the geometric models.