Dynamic Contact Modeling of Hip Impacts: Characterization of Viscoelastic and Geometric Properties

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Hip impact model errors vary based on sex, soft tissue thickness and individual characteristics

INTRODUCTION

Fall-related lateral impacts to the hip have commonly been modeled as a simple single-degree-of-freedom (SDF) mass-spring (MS) model. However, these models predict impact characteristics less accurately for experimental participants outside a body mass index (BMI) range of 21-24 kg/m^2 [1], and provide limited insight into how individual geometric and material characteristics influence mechanical likelihood of injury.

SDF models limit prediction accuracy through two proposed avenues: 1) exclusion of viscoelasticity of biological tissues, and 2) simplified representation of load distribution [1]. Solutions for these limitations range from addition of a damper (Voigt, VG) or distributed contact (Hertzian, HZ), to a Volumetric (VO) model, which allows interaction between contacting bodies based on individual material and geometric properties [2] (Figure 1).

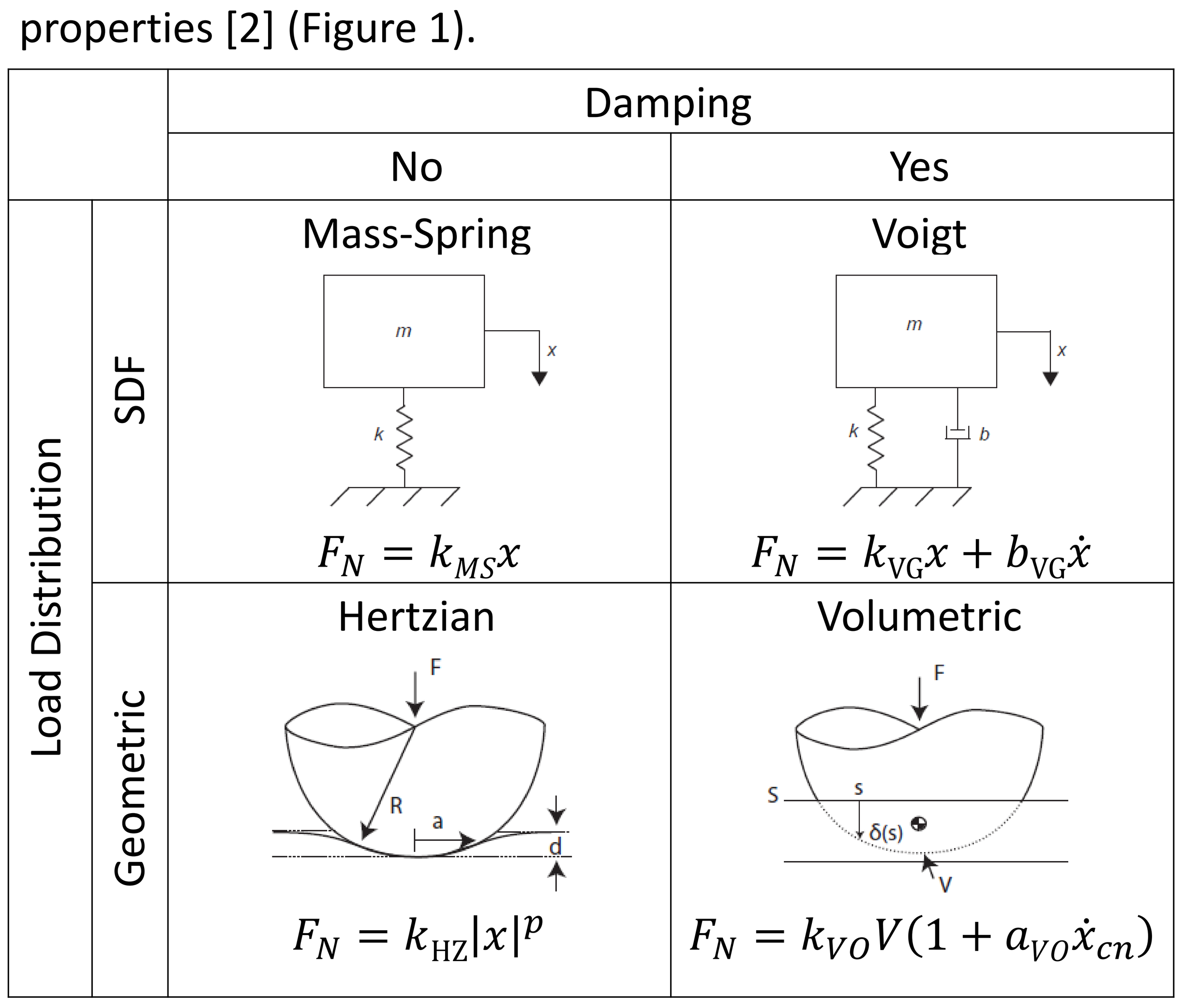

Figure 1: Model schematics and general normal force formulae for the models investigated.

The objective of this study is to characterize the parameters for MS, VG and sphere-plane HZ and VO models of the pelvis during a simulated lateral hip impact. **Hypotheses:** (1) Model parameters will differ between males and females, as well as between low, moderate and high soft tissue thickness groups. (2) Model errors in prediction of peak force (**PF**) will be linked with body geometry and composition characteristics such as pelvis dimensions, body fat (%) and soft tissue thickness (**STT**).

METHODS

Participants: Twenty-six participants (12 male, 14 female, mean (SD) 26.0 (4.9) years) consented to participate. Group characteristics are presented in Table 1.

Table 1: Mean (SD) Participant Characteristics

Sex	Males			Females		
STT Group	L	M	H	L	M	H
STT (mm)	23.5 (5.5)	31.3 (2.7)	61.0 (14.0)	27.4 (2.5)	38.1 (2.4)	50.0 (4.7)
Body Fat (%)	19.5 (3.1)	16.5 (5.1)	33.1 (9.7)	22.3 (4.0)	34.9 (9.8)	39.6 (7.7)

Experimental Determination of Model Parameters:
Participants underwent lateral pelvis release trials (Figure 2) in quasi- static (QS) and dynamic (~0.6 and ~1 m/s) modes, which involved the lateral aspect of the hip impacting a force plate (AMTI, MA, USA), while motion of the pelvis was tracked using 3D motion capture (Optotrak Certus, NDI, Waterloo, ON, Canada). During the QS trials, the pelvis was incrementally lowered (<5mm/min) using a turnbuckle produce a negligible-velocity scenario. During the dynamic trials, an electromagnet is suddenly released from a height associated with the specified impact velocity. Trochanteric soft tissue depth was measured via ultrasound (SonoSite, Inc., WA, USA), while a soft measuring tape and skinfold calipers were used to characterize individual body geometry and composition.

METHODS

Figure 2: Pelvis release protocol. An electromagnet allows sudden release of the sling, while a turnbuckle allows fine adjustment and incremental lowering of the sling.

Parameter Identification: Parameters were identified for each model using individual body size and composition characteristics, and experimental data, as follows:

Table 2: Parameter Identification

	All Models	
Effective Mass	Mass (kg) of pelvis and peripheral body segments contacting the force plate at rest following each trial	
Pelvis Radius	GT to GT distance+ STT	
	Mass-Spring	Hertz
Stiffness	Fit to dynamic experimental force-deflection data between contact and peak force, using a least-squares method, satisfying:	
F_N	$= k_{MS}x$	$= k_{HZ}\|x\|^{(3/2)}$
	Voigt	Volumetric
Damped Stiffness	Fit to quasi-static experimental force-deflection data, using a least-squares method, satisfying:	
F_{QS}	$= k_{VG}x$	$= k_{VO}V$
Damping	Estimated by comparing experimental dynamic and QS forces, minimizing the cost function:	
c_{damp}	$= \sum_i (F^i_{dyn} - F^i_{QS} - b\dot{x})^2$	$= \sum_i (F^i_{dyn} - F^i_{QS}(1 + a\dot{x}))^2$

An example of the model fits for one trial are shown in Figure 3, below.

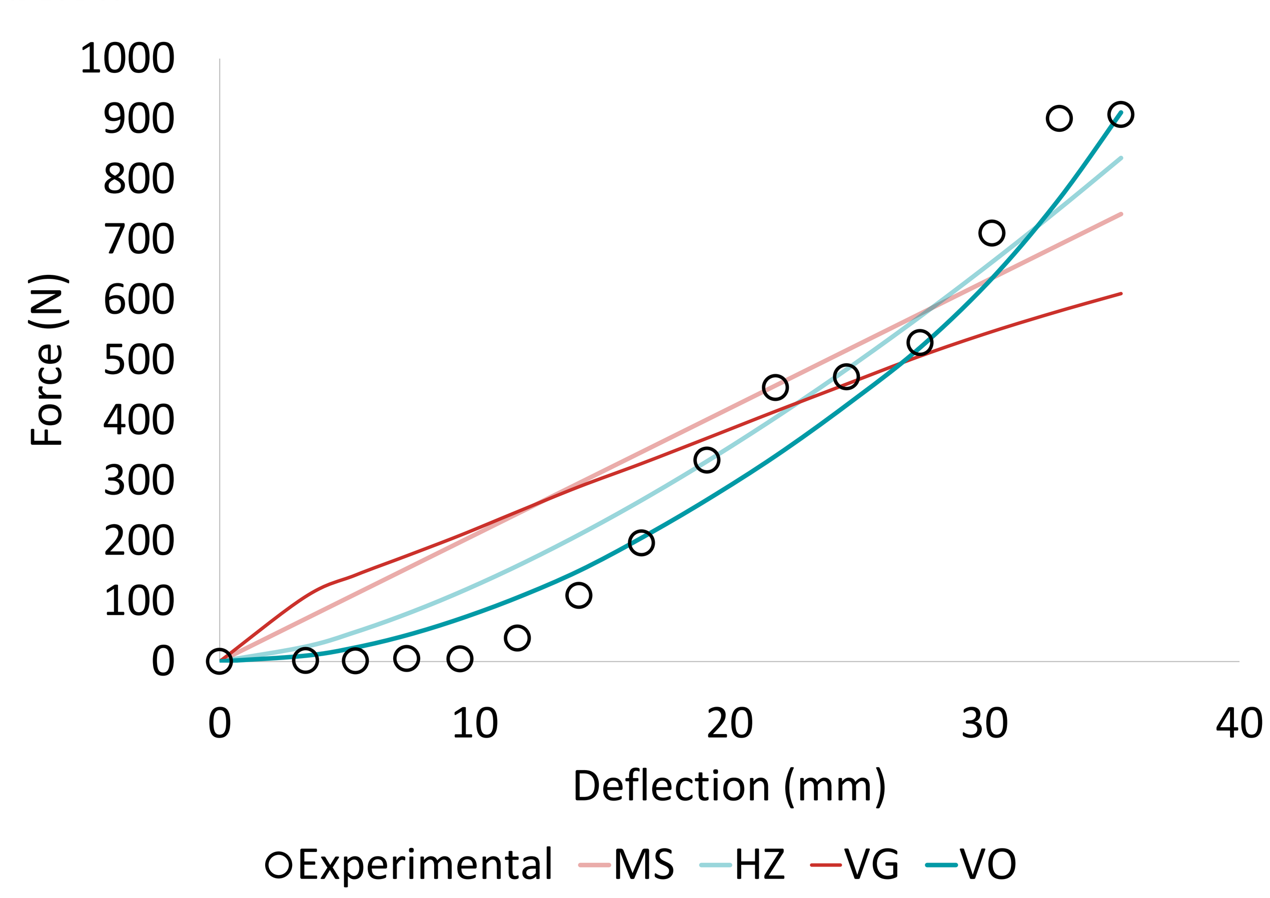

Figure 3: Comparison of experimental dynamic trial data with model fit between initial contact and peak force for a low-STT female.

Model Implementation: Models were simulated within MapleSim (Version 6.4, Waterloo, ON, Canada), using *g*=9.81 m/s^2, initial vertical displacement of 0.05m.

RESULTS

(1) Model parameters did not differ (all p>0.05) between sexes and STT groups (Table 3). Highlighted (*) parameters are similar to those previously reported [3]

Table 3: Mean (SD) Experimentally Determined Parameters

MS	k (N/m)	4.47 x 10^4 (1.55 x 10^4)*
VG	k (N/m)	1.40 x 10^4 (17.21 x 10^3)
	b (Ns/m)	4.43 x 10^2 (2.3 x 10^2)*
HZ	k (N/m$^{(3/2)}$)	3.21 x 10^5 (1.53 x 10^5)
VO	k (N/m^3)	1.77 x 10^6 (3.06 x 10^6)
	a (Ns/m^3)	6.18 (6.68)

RESULTS

Accuracy of peak force prediction (**MaxE**) differed between models (F=9.287, p=0.001), with a significant model-sex-STT interaction. High-STT males had significantly higher errors than all other interaction groups except mod-STT males (Figure 4). MS had lower error than all other models.

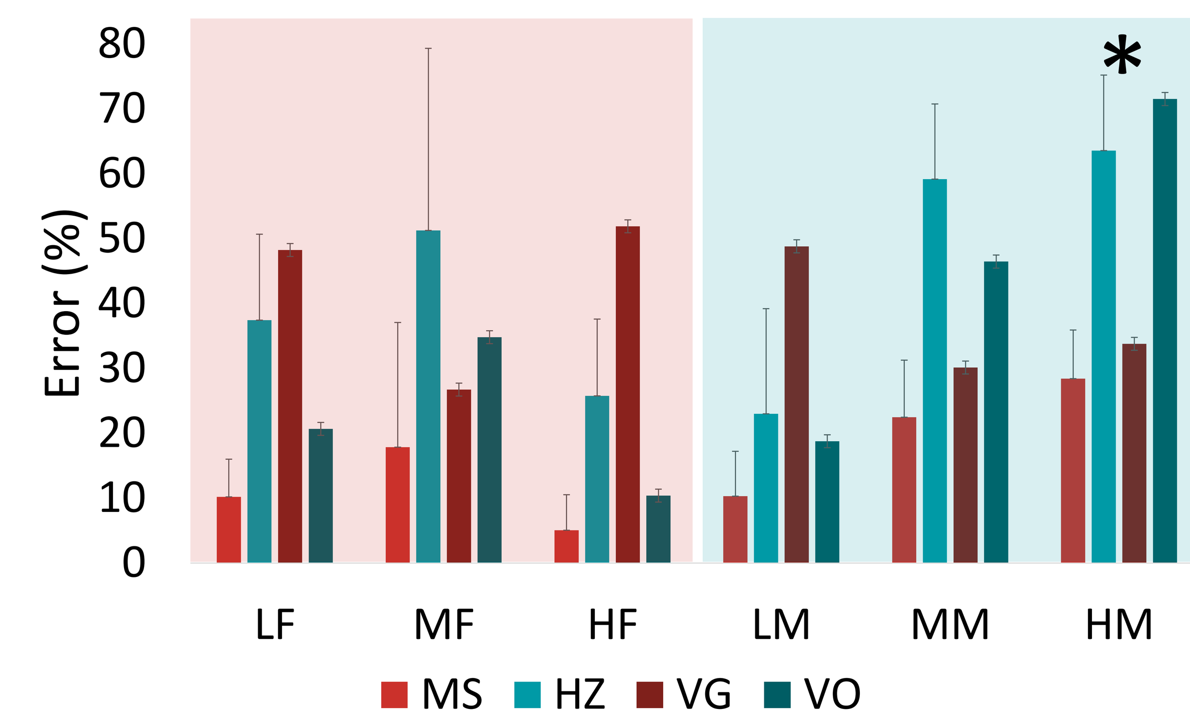

Figure 4: Absolute percent error in peak force prediction by model type and STT-sex interaction group. Females (red) and males (teal) are divided into low (L), moderate (M) and high (H) STT groups. * different from all groups except MM, p<0.01.

(2) Errors in peak force prediction were positively correlated (p<0.05) with waist-hip ratio (**WHR**) for MS, HZ and VO.

Height, weight, hip circumference, pelvis dimensions, and skinfolds of the abdomen and suprailiac region were not related to any model parameters or model errors.

Discussion and Conclusions

- While parameters did not differ between participants, specific model performance varied between sex-STT interaction groups. Different model or parameter selection strategies may be required to improve model accuracy for each group.
- While high-STT males typically have lower mechanical risk of hip fracture, poor model performance for this group improves understanding of impacts to the hip and how to model them. Specifically,
  - Positive correlations between WHR and MaxE for MS, HZ and VO suggest that contact of the abdomen in high-WHR participants may violate the assumptions of these models.
  - Model performance could be improved via analysis of how the loads are distributed in the contact plane between the pelvis and floor.
  - Alternative geometry, such as cylinder-on-plane may more accurately represent the contact mechanics of a faller than sphere-on-plane.
- Individual body geometry characteristics such as height and pelvis dimensions were not related to any parameter or error. In contrast, body composition characteristics such as body fat, and thigh-specific tissue thickness, were related to both parameters and model errors.
- More work is required to determine the optimal parameter selection balance between model performance and implementation in individual-specific fracture models.

REFERENCES

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