Development and Validation of a Distal Radius Finite Element Model to Simulate Dynamic Impact Loading

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Introduction

Despite considerable attention, the incidence of forward fall related distal radius fractures has remained relatively high and consistent over the last 20 years. Finite element modeling provides an attractive approach to studying these types of fractures. To date, only a few distal radius fracture models have been developed [1], and these have only been tested with static loads and no model validation has been presented.

Therefore, the purpose of this work was to develop and validate a finite element model of the distal radius that can be used to simulate dynamic impacts indicative of arresting the body after a forward fall.

Materials and Methods

Surface geometries of the cortical, cancellous and marrow regions were extracted from a 3D radius model (Mimics® medical imaging software, Materialise, Leuven, Belgium) that was created from CT images of a representative human radius. The surface geometry was exported in STL format and an 8-node solid hexahedral mesh was generated (TrueGrid® meshing software XYZ Scientific Inc., Livermore, CA, USA). The other components of the experimental impact device [2] were also meshed. These included a projectile that makes contact with an impact plate, which transferred the impact force through a surrogate lunate/scaphoid and onto the intra-articular surface of the radius [2].

Cortical and cancellous bone were modeled as elastic-plastic materials and the marrow and lunate/scaphoid as elastic materials. All other components were modeled as rigid. Bone material properties (*e.g.* moduli, density) were taken from the existing literature and, when possible, were radius-, age- and sex-specific (Table 1).

Three separate impact events were simulated using LS-DYNA® based on the experimental tests previously conducted on the specific specimen used to develop the model [3] (*i.e*., the appropriate impact velocities assigned to the model projectile): i) a pre-fracture event (defined experimentally as an impact where no radius damage occurred) where the model projectile had an initial axial velocity of 2.1 m/s; ii) a crack event (an impact event where, experimentally, external damage was noted but with no propagation beyond the intra-articular surface) with an initial axial velocity of 2.7 m/s; and iii) a fracture event (the specimen was fractured into at least two distinct pieces) by giving the projectile an initial axial velocity of 3.3 m/s. Element sets were created in the locations of the experimental strain gauges and model forces were recorded from the location of the load cell for validation purposes.

Bone mesh acceptability was quantified using three mesh quality metrics including the element Jacobians, aspect ratios and orthogonality. Values of 0.2, 1, and ±70° were considered acceptable, respectively.

Up to four validation measures were used to assess the accuracy of the model in predicting the relevant experimental outcomes (*i.e.*, forces (Fy (volar-dorsal), Fz (axial)), and the minimum and maximum principle strains). A validation metric (VM) (Eq. 1) [3] was used to quantify the relationship between model and experimental values over the full duration of the impulse.

$$VM = 1 - \frac{1}{N}\sum_{n=0}^{N} \tanh \left| \frac{y(t_n) - Y(t_n)}{Y(t_n)} \right| \qquad \text{(Eq. 1)}$$

The error of the model peak forces and strains with respect to the experimental values were also calculated. To assess the generalizability of the force results, the model force-time curves were compared to the ensemble averages (± 2 SD) of all the experimentally tested specimens (n=8). Finally, the location and severity of model and experimental bone fractures were compared. Model bone failure was assessed using the von-Mises stress criteria, such that elements whose von-Mises stress exceeded the critical level (cortical = 134 MPa; cancellous = 5 MPa) were considered to have failed.

Table 1: Summary of bone model material properties.

Part	# of Elements	Mass Density (kg/m3	Elastic Modulus GPa	Plastic Modulus GPa	Poisson's Ratio
Cortical	55800	1150	25.1	1.3	0.3
Cancellous	180000	970	1.8	0.09	0.3
Marrow	697500	1070	0.02	-	0.5

Results

The element Jacobians, aspect ratios and orthogonality measures ranged from 0.08 to 12, 1.1 to 26, and -70° to 80°, respectively.

The force VM ranged from 0.10 (Fx, pre-fracture) to 0.54 (Fz, crack), while those calculated for the strains varied between 0.35 (Max. Prin., Fracture) and 0.67 (Min. Prin., Crack) (Table 2).

Table: 2: Force and strain validation metrics.

Validation Metric	Pre-Fracture	Crack	Fracture
Fx	0.10	0.21	0.22
Fy	0.34	0.22	0.24
Fz	0.43	0.54	0.23
Max. Prin.	0.63	0.42	0.35
Min Prin.	0.67	0.41	0.39

The estimated peak forces along the y-axis were approximately 4.8 %, 3.5 % and 58.9 % greater than the experimental y-axis forces and the peak model forces along the z-axis were found to be 19.1 %, 28.5 % and 27.1 % greater than the peak forces determined from the experimental testing for pre-fracture, crack and fracture events, respectively. All forces across all impact events were shown to fall within ± 2 SD of the experimental ensemble averages. The predicted minimum and maximum principle strains were found to differ by a mean of 33 % across all impact events (3.0 % - 75 %). Finally, based on the von-Mises stress criteria, the model was found to accurately predict the location and severity of bone damage (Figure 1).

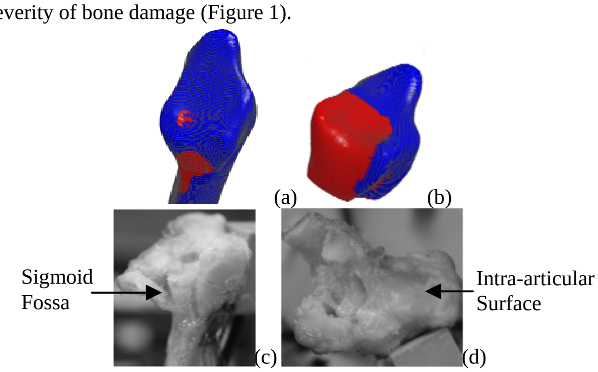

Figure 1: Comparison of model cortical (a) and cancellous (b) bone fracture to experimental (c-d) fracture patterns (red=failed element).

Discussion and Conclusion

The mesh verification metrics suggest that this was a quality mesh suitable for the purpose of these simulations, as less than 0.5 % of all elements did not meet the respective quality criteria.

The lowest VM and highest errors tended to occur during the crack and fracture impact events, and can be attributed to a change in the bone material properties experimentally (*i.e*,. decreased bone stiffness), as a result of the repeated impacts and the damage incurred during the crack event. However, in the current model, the changes in material properties were not simulated, thus the stiffness of the bone was maintained and the impact forces continued to increase. This model also appears to be generalizable to the larger sample, as all model forces fell within ± 2 SD of the experimental means over the entire impulse.

Overall, the model presented here is a valid representation of the distal radius. The impact forces, radius responses (strains) and resulting fracture patterns agreed well with the experimental findings.

References

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Acknowledgement

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