Mass-based vs Structure-based --Comparison of Structure-based Scaling and Mass-Based Scaling Methods Applied to Long Bone Mid-Shaft Bending Tests

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Introduction

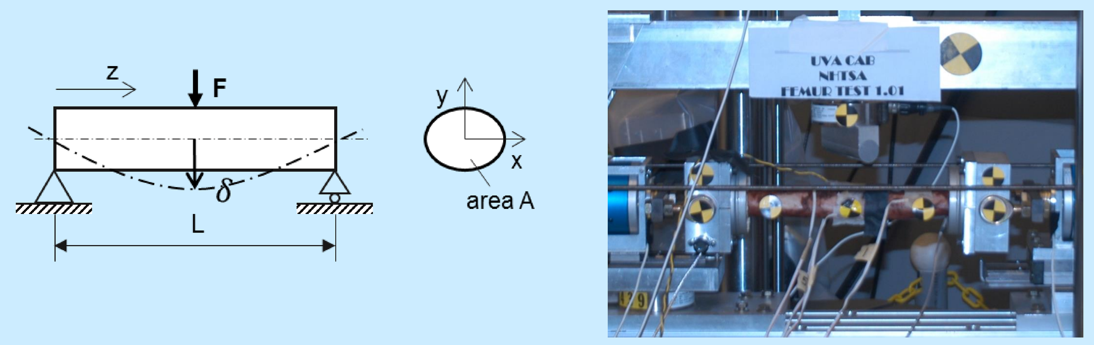
- Often, test subjects used in biomechanical studies have large variations in their physical characteristics such as size, shape, and loading conditions. Even if data can be collected for a specific type of subjects, data cannot be collected on some types of subjects. For example, data on impact responses and tolerance levels for children are very limited.
- Given these circumstances, biomechanics researchers must turn to scaling techniques either to normalize test data to a standard subject size or to extend the results from one sized subject to describe the response of other size subjects.
- Two different scaling methods are normally used. The first one is referred to as mass-based scaling, which is based on dimensional analysis (Langhaar,1951) and allows the unknown physical responses of a given system to be estimated from the known responses of a similar system by establishing fundamental scaling factors. (e.g. mass, and Young's Modulus). The second approach is structure-based scaling, which is based on idealized analytical models representing the structural characteristics of the human body regions and contact stiffness under multiple loading conditions.

Goal

Although scaling methods are widely used, these scaling methods were rarely validated and evaluated. The objective of this study was to compare and understand the benefits of both structure-based and mass-based scaling methods using PMHS (post mortem human subjects) bending test data from literatures.

Methods

- **Long-bone bending tests**



Schematic of 3-point mid-shaft bending test and test apparatus(Ivarsson,2009)

- **Scaling Methods**

Assumptions of two scaling methods

Mass-based Scaling	Structure-based Scaling
• Geometric similarity • Constant mass density	• Euler-Bernoulli Beam • Elliptical cross-section • Constant strain at outermost surface under bending • Linear constitutive material behavior

Scaling factors of two scaling methods

Entity	Mass-based scaling factor	Structure-based scaling factor
Mass	λ_m	λ_m
Young's Modulus	λ_E	λ_E
Characteristic Length	$\lambda_l = (\lambda_m)^{1/3}$	λ_x, λ_y*
Force	$\lambda_F = \lambda_l^2 \cdot \lambda_E$	$\lambda_F = \frac{\lambda_x \lambda_y^2 \lambda_E}{\lambda_L}$
Moment	$\lambda_M = \lambda_l^3 \cdot \lambda_E$	$\lambda_M = \lambda_x \lambda_y^2 \lambda_E$
Deflection	λ_l	$\lambda_\delta = \frac{\lambda_L^2}{\lambda_y}$
Span Length	λ_l	λ_L

*y is the diameter of mid-shaft cross section in the loading direction

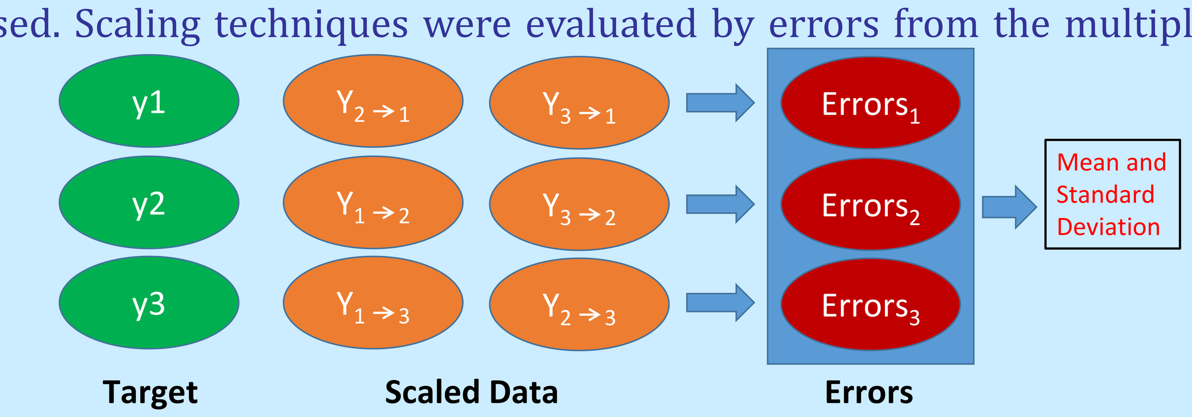
- **Data Sources**

Body Part	Sources	Sample Size	Loading Condition
Humerus	*Kirkish et al. (1996)*	20 (male),1(female)	Loading rate:0.635/218 (mm/s) Variable span length
	Duma et al. (1999)	10 (female)	Loading rate: 3.63 (m/s) Constant span length
	Kemper et al. (2005)	6 (male),2(female)	Loading rate: 0.01/3 (m/s) Constant span length
Femur	*Funk et al. (2004)*	15 (male)	Loading rate: 1.2 (m/s) Variable span length
	Ivarsson et al. (2009)	5 (male), 5(female)	Loading rate: 1.5 (m/s) Variable span length

- All reported fracture moment, Kemper, Funk and Ivarsson reported force-deflection responses. Only Kirkish tested specimens in either lateral-medial(L-M) or anterior-posterior(A-P) direction, other tested in A-P directions.
- All specimens included following information: body mass, height, age, cross-section properties. Kirkish reported rate of mineralization(ash weight/dry weight in %), others reported Bone Mineral Density(BMD) and estimated young's modulus.

- **Evaluation Procedure**

- All the data were divided into multiple data sets, according to loading direction, body parts and Mineral information.
- In each data set, a procedure involved with multiple scaling trails was proposed. Scaling techniques were evaluated by errors from the multiple trials.



Schematic diagram for the evaluation of scaling techniques using PMHS test data

Discussion

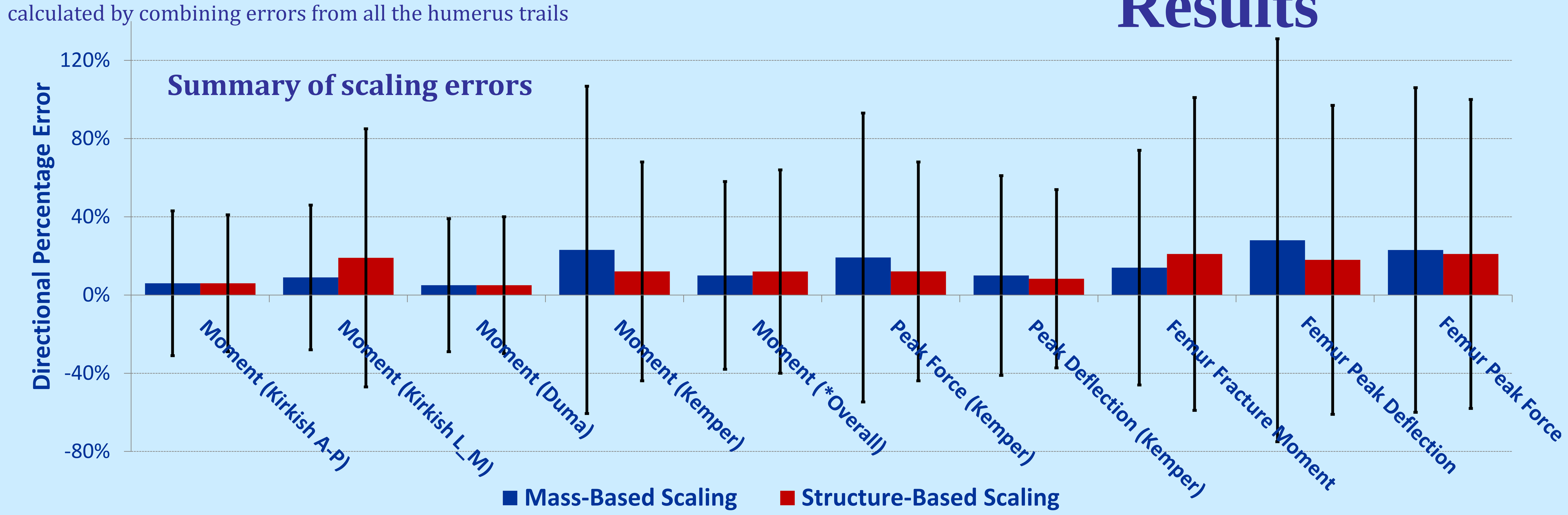
- The scaling errors depend on the samples. Ideally when more data were included, the experimental errors would be negligible, the errors would be used to evaluate the scaling techniques.
- The structure-based scaling method has several limitations that most likely affected the accuracy of the results. A limitation of the structure-based scaling method is the idealized model itself, including but not limited to the assumptions of a constant cross-section along the length of the shaft and elliptical cross-section.
- Correlation analyses showed that the idealized model may not necessarily applicable to all long bones. Idealized models are not always applicable, which is another limitation of structure-based scaling.
- Mass-based scaling depends on dimensional analysis, which would scale loading conditions (e.g. span length in this case) according to the mass of the specimens. So mass-based scaling can only be applicable to special loading conditions or situations when loading conditions were not relevant.

Conclusions

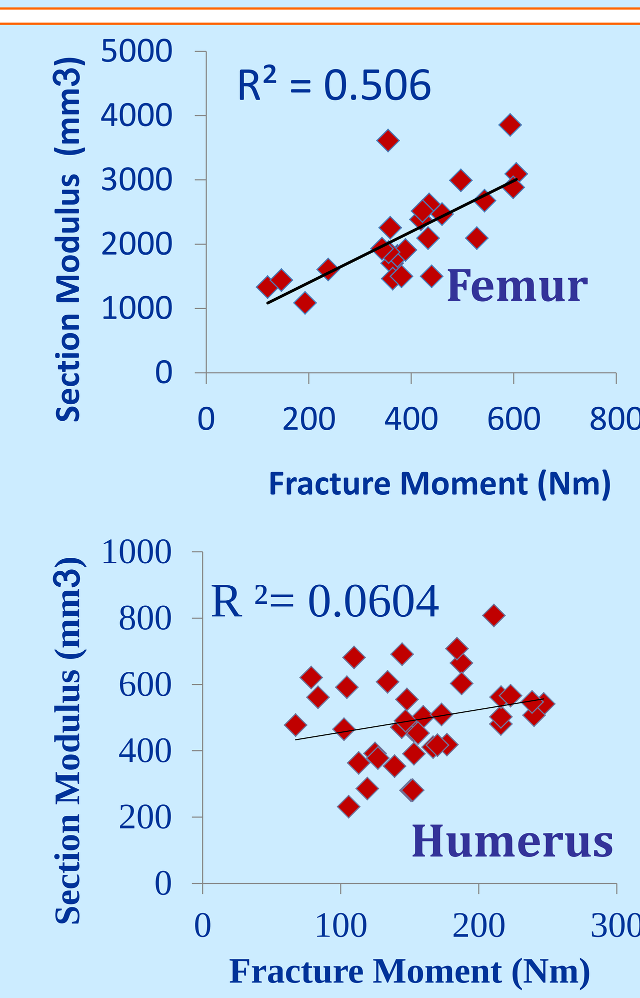
1. The structure-based scaling method didn't generate more accurate long bone fracture moment than mass-based scaling method. Both methods resulted in large standard deviation because of the large variability associated with biological specimens
2. Structure-based predict more accurate results when loading conditions are relevant.

Results

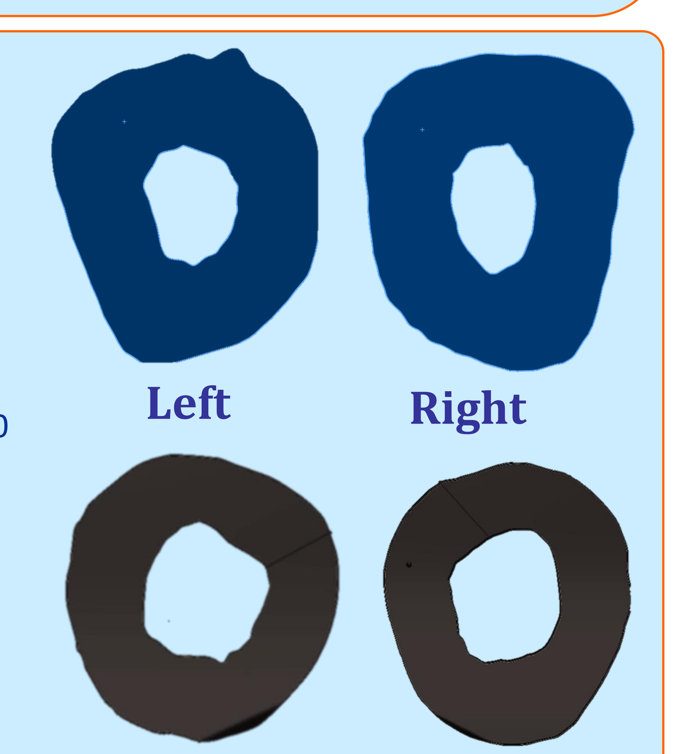
Directional % error= (scaled- true)/true·100. * The Overall error of humerus moment is calculated by combining errors from all the humerus trails



- In predicting fracture moment, the mass-based scaling showed 10% (humerus) and 14% (femur) errors in average while the structure-based scaling showed 12% (humerus) and 21% (femur) errors in average. In predicting peak deflection, the structure-based scaling performed better in predicting peak deflection (18% error in average) than those of the mass-scaling technique (28% error in average). It should be note that the standard deviation of the errors ranged from 30% to 103% of the average values.



Correlation analysis between Moment and section modulus



Mid-shaft cross section shapes of two pairs humeri. (CT record of Duma et al., 1999.) Note the biological variability.

Future Work

Future efforts will be necessary to fully compare these scaling methods in a wider range of sample size, in multiple component-level tests. More idealized models for structure-based scaling will be developed and evaluated.

References

1. Duma, S. M. et al.(1999). Dynamic injury tolerances for long bones of the female upper extremity. Journal of Anatomy, 194 Pt 3, 463–471.
2. Funk, J. R. et al.(2006). Dynamic bending tolerance and elastic-plastic material properties of the human femur. In Proc. 48th Annual Conference of the Association for the Advancement of Automotive Medicine (pp. 216–233).
3. Ivarsson, B. J et al.. (2009). The tolerance of the femoral shaft in combined axial compression and bending loading. Stapp Car Crash Journal, 53(November), 251–290.
4. Kirkish SL et al. (1996) Proposed provisional reference values for the humerus for evaluation of injury potential. SAE Technical Paper. (962416).
5. Langhaar, H. L. (1951). Dimensional analysis and theory of models. Wiley. New York.

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