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# Finite Element Assessment of Pediatric Femoral Response to Loading During Ambulation: Normal vs. Osteogenesis Imperfecta (OI) Bone

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# FINITE ELEMENT ASSESSMENT OF PEDIATRIC FEMORAL RESPONSE TO LOADING DURING AMBULATION: NORMAL VS. OSTEOGENESIS IMPERFECTA (OI) BONE

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## INTRODUCTION

Osteogenesis imperfecta (OI) is a heritable disorder characterized by skeletal deformity and bone fragility. While the mechanisms are not fully understood, the fragility is believed to stem from a combination of bone mass deficiency and compromised bone material properties [1, 2]. Poor bone quality poses unique orthopaedic and rehabilitation challenges for treating persons with OI. Risk of fracture becomes a major consideration not only for prescribing physical therapy but also for activity restrictions and modifying activities of daily living (ADLs). Unassisted ambulation may result in a high enough load to cause a fracture in persons with moderate to severe OI. Due to these challenges, fracture risk quantification can be an invaluable tool in OI management and fracture rehabilitation. Finite element (FE) models have recently been applied to quantitatively assess *in vivo* loads experienced by long bones in persons with OI [3, 4]. Material properties reflective of the mechanical response of OI bones to loading are imperative to accurate fracture risk assessment [5]. A recent study confirmed that cortical bone material strength of OI bone is substantially lower than normal pediatric bone, indicating that reduced mechanical tissue quality is a contributing factor to fracture risk in this population [6].

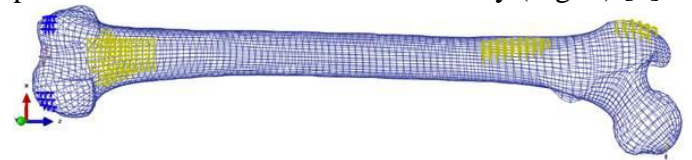
The present study examined the response of an FE model of pediatric femurs with normal, mild-moderate OI and severe OI material properties under ambulatory loads (i.e., joint forces and moments and intrinsic muscle activation forces).

## METHODS

Three-point bending tests were performed on bone specimens obtained from the femoral diaphysis of

three donors: 1) an 11-year-old male (cadaveric) with no known bone disorder, 2) a 10-year-old male with OI type I (mild-moderate), and 3) an 11-year-old male with OI type III (severe). The OI specimens were acquired and tested under informed consent/assent and following a protocol approved by our Institutional Review Board (IRB). Longitudinal and transverse Young's modulus ( $E$ ) and yield strength ( $\sigma_y$ ) were determined for each specimen.

A previously developed hexahedral FE model of a pediatric femur was used for this study (Fig. 1) [7].



**Figure 1:** Finite element (FE) model of the femur with boundary conditions (condyles) and representative loading during mid-stance.

Three models were created, corresponding to the material properties of each cortical bone specimen (Table 1). Young's modulus for cancellous bone was conservatively modeled as being 60% of cortical bone [8]. Shear modulus was estimated assuming transversely isotropic material behavior. Each model was loaded based on forces experienced during the mid-stance phase of gait. Gait data was previously collected under IRB approval from a 12-year-old with OI type I [3]. All three femurs were modeled with normal geometry (no bowing). The geometry and loading were kept constant among the three models in order to solely focus on the effects of the bone material properties (Fig. 1). Maximum longitudinal stresses and strains were analyzed. Results were compared between models as well as against yield strength from the mechanical analyses.

## RESULTS AND DISCUSSION

The model's material properties and the resulting maximum stresses and strains are presented in Table 1. While the analysis did not show major differences in the maximum longitudinal stress values between bone types, these values are much closer to a level of stress causing yield for the OI bones than for a normal pediatric femur. This can be clearly seen by looking at the maximum longitudinal stress as a percentage of  $\sigma_y$ , which provides a metric for proximity to fracture level. Maximum transverse stresses only reached a maximum of 13.5 % of transverse yield strength for OI type III bone, with lower values in the other two models. However, the severe OI (type III) reaches about 80% of its longitudinal yield strength. It must also be kept in mind that persons with OI often have deformed long bones. Increases in lateral bowing of the femur have been shown to cause a linear increase in maximum stress results [5, 7].

## CONCLUSIONS

This study demonstrates the need to not only understand the difference in mechanical properties, such as Young's modulus, seen in OI bone, but also their failure loads and mechanisms. Finite element modeling and analysis has the capabilities to estimate safe loading levels from activities such as

walking, running and jumping in which children with OI may want to participate. The current work, combined with previous analyses, shows the multifactorial requirements for subject-specific FE analysis of material properties, loading and geometry to provide the most accurate assessment of femoral loading during ADLs [5, 7, 8].

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**Table 1:** Material properties for the finite element model of the femur; Young's modulus (E), shear modulus (G), and Poisson's ratio ( $\nu$ ). The three right columns show the maximum longitudinal stresses and strains for each femur as well as the maximum longitudinal stress as a percentage of yield strength ( $\sigma_y$ ) to represent a fracture (FX) risk value.

		Longitudinal Properties				Transverse Properties				Results		
		E (GPa)	G (GPa)	$\nu$	$\sigma_y$ (MPa)	E (GPa)	G (GPa)	$\nu$	$\sigma_y$ (MPa)	Max Stress (MPa)	Max Strain (%)	FX Risk (Max Stress as % of $\sigma_y$ )
Normal	Cortical	15.0	5.8	0.3	157	8.2	3.1	0.3	75	55.0	0.36	35.0
	Cancellous	9.0	3.8	0.2		4.9	2.1	0.2				
OI Type I	Cortical	7.4	2.8	0.3	85	4.6	1.8	0.3	47	56.0	0.74	65.9
	Cancellous	4.4	1.9	0.2		2.8	1.2	0.2				
OI Type III	Cortical	5.7	2.2	0.3	72	3.7	1.4	0.3	37	56.7	0.98	78.8
	Cancellous	3.4	1.4	0.2		2.2	0.9	0.2				