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DEVELOPMENT OF A PEDIATRIC FOREARM FINITE ELEMENT MODEL FOR CHARACTERIZING MECHANICAL RESPONSES OF BACKWARD FALL

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Introduction

Distal radius and carpal fractures in children and adolescent account for approximately 25% of all pediatric fractures [1]. For the age distribution, 5 to 14 years olds group comprised largest proportion (26%) of all hand and forearm fractures than other age groups. Radius and/or ulna fractures took up the largest proportion of fractures (32.9%) in age group 5 to 14 years old. A population-based study revealed that the incidence rate of forearm fractures in boys and girls aged 5 to14 years increased dramatically. In particular, the age group 10 to 14 has the highest increase in the period from 1997 to 2009 [1].
The pediatric musculoskeletal system is distinctly different from that of adult. Although these differences decrease with age, they present unique injury patterns and challenges in the diagnosis and treatment of pediatric orthopedic problems. Pediatric bone is highly cellular and porous, and it contains a great number of collagen and cartilage compared with adult bone. The abundance of collagen leads to a reduction of tensile strength and prevents the propagation of fractures, whereas the large amount of cartilage enhance resilience [2]. The wrist bones consist of eight irregular shape bones: scaphoid, lunate, pisiform, triquetrum, trapezium, trapezoid, capitate and hamte. The pisiform does not appear on radiographs until 9 or 10 years of age. Pediatric forearm fractures has been described in several studies [2, 3], but the proportion of fractures in these studies are controversial. For example, Katrina et al. indicated that scaphoid fractures are most common in the age 15 to 30 years and are rare under the age of 10 [3], whereas Carson et al. pointed out that as in adults, the scaphoid fracture is the most commonly fracture in children [2].
The primary methods of studying human injury mechanisms are biomechanical experiments and computational simulations. Due to ethical concerns, pediatric cadavers are rarely used for biomechanical experiments. Using animal is challenging, because of different growth stages. Also, the anatomical structures and tissue properties of child are significantly different from those of animal. It is difficult to correlate injury mechanisms in children and in animal. Finite element (FE) method is an effective way to investigate injury mechanism which can provide child-specific biomechanical response at tissue level.
It is difficult to study biomechanics of forearm because of its complex anatomy, closely situated, interrelated structures and highly dynamic movement patterns. Currently, no pediatric forearm FE model has been reported in literature specifically related to impact biomechanics, even adult forearm FE model data are very limited. Carrigan et al. (2003) developed an adult carpal model from CT scan without metacarpals and phalanges, which provided detailed stiffness value of ligaments [4]. Gislason et al. (2010) developed an adult wrist model from MRI scans without phalanges, which provided a useful guidance for others attempting to develop similar models [5]. Javanmardian et al. (2010) developed an adult wrist model from CT scans without ligaments and phalanges to evaluate contact stress [6].
In this study, a three-dimensional ten-year-old child forearm FE model, which includes the ulna, radius, carpal bones, metacarpals, phalanges, cartilages, and ligaments, was developed to characterize mechanical responses of backward fall.

Material and Methods

The geometry was scaled from adult FE model, based on the radiologic image [9]. The scale factors for 10-year-old child were $\lambda x = 0.647$; $\lambda y = 0.647$; $\lambda z = 0.787$ [7], along the anteroposterior, left-right, and inferosuperior direction, respectively. The hexahedral FE meshes were created using a multi-block approach in ANSYS ICEM

CFD/HEXA12.0 (ANSYS, Canonsburg, PA, USA). This method allows easy adjustment the mesh size through controlling the block parameters. The mesh size was 1-3 mm in order to capture detailed anatomical structures within current computational capabilities. The solid elements were used to model cancellous bones and the shell elements were used to model cortical bones. The ligaments were created in Hypermesh 10.0(Altair Co. Troy, MI) using beam elements. In total, 10,510 hexahedral, 7,430 shell elements and 173 bar elements (Figure 1). The Jacobian of the hexahedral mesh was larger than 0.4 to ensure accurate results. Cortical and cancellous bones usually reveal elastic-plastic behavior. Ligaments only take tension. In the model, a piecewise-linear-plasticity material (MAT 24) was used to simulate the cortical and cancellous bones of the forearm. An elastic tension only bar element (MAT 74) was used to simulate ligaments. Currently, there is no report about pediatric forearm material properties. In adult, the Young's modulus was reported to range from 10 to 18 GPa for cortical bones, 100 MPa for cancellous bones, and 10 MPa for cartilages. According Mertz et al. (2001), the scale factor of the elastic modulus for 10-year-old child is 0.854. Hence, for the baseline 10-year-old child forearm model, the initial Young's modulus of cortical bones, cancellous bones and cartilages were defined as 8.54 GPa, 85.4 MPa and 8.54 MPa, correspondingly. The maximum principle strain assumed for failure of the cortical bone was 0.02.

The model was loaded according to Richard et al. (1998). An effective mass of 10.8 kg, approximately 1/3 of the body mass of an average ten-year-old child was added to proximal ends of the radius and ulna and the impact velocity was assumed 2.8 m/s to simulate a fall from 0.4 m. Based on literature surveys, three relevant angels were analyzed: the angel between forearm and platform, angle of dorsiflexion, and angle of internal rotation (pronation) [8]. The ranges of these angels were set as 75±15, 40±8 and 10±2 degrees, correspondingly. A three-factor, three-level full factorial analysis was designed, for a total of 27 cases, in order to systematically evaluate the effect of these angles on the risk of distal radius and carpal fractures. All simulations were performed and analyzed using LS-DYNA 971 (LSTC, Livermore, CA) MPP version.

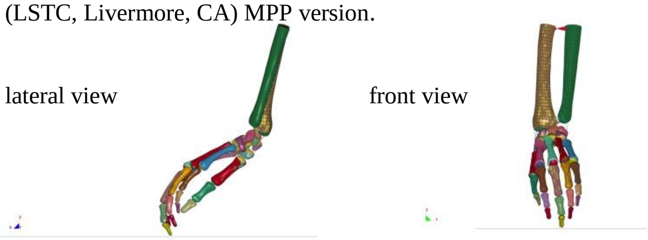

Figure 1: The 10-year-old forearm FE model

Results

All 27 simulated cases resulted into fractures, with distal radius/ulna fractures observed in 77%, radius shaft in 59%, and ulna shaft factures in 48% of the cases, which was consistent with the literature report that radius/ulna fracture was the most observed fracture among all pediatric fractures. The peak forces were ranged from 1,400 and 3,300 N. Full factorial analysis revealed that the angel between forearm and platform had important effect to predict distal radius/ulna, radius shaft and ulna shaft fractures when comparing with other two angels (Figure 2). When the angel between forearm and platform increased to 90 degrees, the chance to cause distal radius/ulna fracture reached to the highest value, whereas the chance to have radius shaft and ulna shaft was lowest (Figure 2). When the angel of internal rotation was 12 degrees, the chance of distal radius/ulna fracture was highest and the probability to cause radius shaft and ulna shaft fracture was lowest. When the angle of dorsiflexion was 40 degrees, the chance to have radius shaft fracture was highest (figure 2).

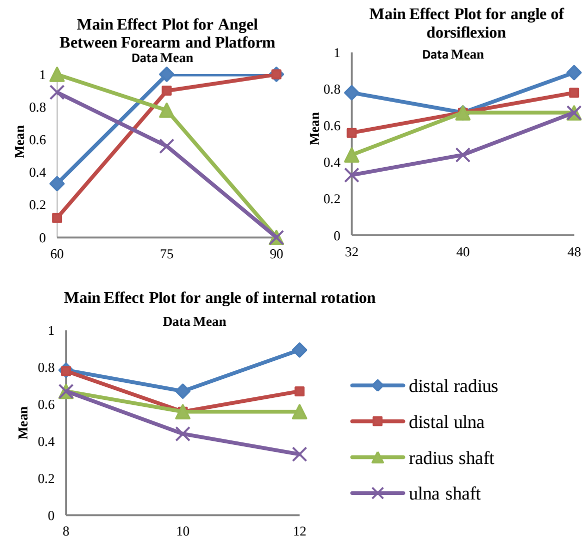

Figure 2: Main effect of fracture. Vertical axis: 0-no fracture, 1-fracture.

Discussion

This study established a stable numerical model that can be used to predict forearm injuries and design safety countermeasures. To the best of the authors' knowledge, no experimental data on 10-year-old pediatric subjects has been reported, thus comparisons between experiments and simulations were not feasible. In the future, more research is needed to determine the effect of muscles on impact force attenuation as well as other impact scenarios such as higher speeds at different angles.

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