Orthogonal Digital Radiographs - A Novel Template for a Paediatric Femur Finite Element Model Development

D.S. Angadi[1], D.E.T. Shepherd[2], R.Vadivelu[1,3], and T.G. Barrett[1,3]

[1] School of Clinical and Experimental Medicine, University of Birmingham, Edgbaston, Birmingham, UK
[2] School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, UK
[3] Birmingham Childrens Hospital NHS Trust, Steelhouse Lane, Birmingham, UK

Abstract— **Surgical treatment options of paediatric femur fracture include flexible or rigid intramedullary nails and submuscular plate fixation. Current computational technology has enabled virtual testing of fracture fixation implants using finite element analysis (FEA) models. Unlike FEA models based on adult femur, limited literature is available for paediatric femur. The aim of the study was to develop and validate a FEA model based on simplified geometry of composite paediatric femur using digital radiographs as a template. The model consisted of two cylinders which intersected at 130 degrees. The first hollow cylinder represented the shaft whilst the second solid cylinder represented head, neck and trochanteric region. Material properties of a composite femur (compressive strength = 157 MPa, compressive modulus = 16.7 GPa, yield strength = 93 MPa, Poisson's ratio = 0.26) were used. Simulation testing was performed in SolidWorks to estimate axial, four-point bending and torsional stiffness (k_{FEA}). An experimental study was undertaken on 4 femur specimens (k_{Exp}). FEA model predicted axial stiffness ($k_{FEA\ Axial}$ = 704.83 N/mm). In comparison mean axial stiffness of the femur specimens measured $k_{Exp\ Axial}$ = 667.39 N/mm (+/- 73.49). Four-point bending stiffness of FEA model measured ($k_{FEA\ Bending}$ = 369.1 N/mm) whereas the mean four-point bending stiffness of femur specimens was $k_{Exp\ Bending}$ = 353.49 N/mm (+/- 16.05). Torsional stiffness in external and internal rotation of FEA model was noted at $k_{FEA\ Torsion\ ER}$ = 3.49 N m/deg and $k_{FEA\ Torsion\ IR}$ = 3.49 N m/deg respectively. Mean torsional stiffness of femur specimens measured $k_{Exp\ Torsion\ ER}$ = 3.58(+/- 0.05) N m/deg and $k_{Exp\ Torsion\ IR}$ = 3.48 (+/- 0.14) N m/deg. Orthogonal digital radiographs can be used as a template to develop a simplified finite element model of paediatric femur. FEA model based on simplified geometry may be used for evaluation of routine stiffness parameters of paediatric femur.**

Keywords— **Paediatric, femur, finite element analysis, digital, radiographs.**

I. INTRODUCTION

Paediatric femur fracture is a severe injury with a reported incidence of 20 - 33 per 100,000 a year [1]. Surgical treatment options described in the current literature include external fixation, open reduction and internal fixation with plate and screws including minimally invasive plate osteosynthesis (MIPO), flexible and rigid intramedullary nails [2]. Laboratory based biomechanical testing of implants is useful yet an expensive and time consuming process. Evolution of computational technology has enabled virtual testing of fracture fixation implants using finite element analysis (FEA) models of bones and implants.

Development of FEA bone models from computed tomography (CT) data is well documented. Some authors argue that although this approach can provide accurate geometry of the bone, it is associated with an enhanced radiation risk and is resource intensive (in terms of the additional segmentation and volume rendering software required) [3]. Biomechanical testing of paediatric fracture fixation implants has relied on the use of sawbones due to the lack of cadaveric specimens. Additionally the sawbones offer standard geometry with minimum inter-specimen variability. The standardised FEA model of sawbone (available as an open source download - http://www.biomedtown.org) is based on the geometry of an adult femur [4]. Furthermore studies have shown that this generic model may not be suitable to all research scenarios and adapting it for paediatric biomechanical research can be demanding both on time and computational resources [5]. In comparison to the adult femur FEA model, limited literature is available on the paediatric femur FEA model and only a few studies [6, 7] have addressed biomechanical testing of implants. A FEA model based on simplified geometry of paediatric femur can provide useful information to evaluate implant performance with relatively less computational resources. Hence the objectives of the current study were to i) develop a FEA model based on simplified geometry of the paediatric femur using digital radiographs of sawbone ii) validate the FEA model with the experimental data (axial, four-point bending and torsional stiffness) of the sawbones.

II. MATERIALS AND METHODS

A. Experimental model - The small fourth generation composite femur Sawbone® (model 3414, Pacific Research Laboratories Inc, Vashon, USA) was used an experimental

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model. These validated composite femurs have been used extensively in paediatric biomechanical testing [8].

B. Biomechanical testing - Stiffness parameters (axial, four-point bending and torsion) of four composite femur specimens were established using custom designed jigs, polymethylmethacrylate (PMMA) split molds and Instron TT-D materials testing machine (Instron, High Wycombe, UK).

A compressive load of up to 600 N was applied at a displacement rate of 0.17 mm/s during axial loading test. Four-point bending test in the anteroposterior direction was performed with a force of 400 N applied through a top unit with two rollers separated by a distance of 70mm. The base had the first roller set perpendicular and second roller at an oblique angle to the long axis to provide a stable support for the composite femur near the lesser trochanter. Displacement rate was set at 0.17 mm/s. The resultant displacement was noted. During torsion tests proximal and distal aspects of each femur was encased in PMMA split molds and placed inside proximal and distal aluminium cylindrical units respectively. This arrangement aligned the mechanical axis of the composite femur to the mid-axis of the cylindrical units. Torque was applied in 0.2 N m increments up to 4 N m using calibrated weights suspended on an aluminium bar attached to the proximal cylindrical unit. The resultant rotation was measured using a digital inclinometer mounted on the aluminium bar.

Each of the above tests was repeated six times on each specimen. The data was entered into Microsoft Excel to determine the slope of load-displacement (or torque-rotation) curve. The slope represented the stiffness in N/mm for axial compression and bending tests and torsional stiffness in N m/degree for the torsion tests.

C. Finite Element Model - Orthogonal views (anteroposterior / lateral) of the digital radiographs of a paediatric femur (sawbone) were initially processed using Adobe Photoshop (Adobe, San Jose, California) and imported into SolidWorks^{TM} software (Dassault Systèmes, France). Digital radiograph dimensions were adjusted in SolidWorks^{TM} to match the geometric parameters of composite femur. Orthogonal views of the digital radiographs were used as a template for the finite element model. Using the spline and sweep functions a FEA model based on simplified geometry of the paediatric femur was developed. The model consisted of two cylinders which intersected at 130 degrees. The first hollow curved cylinder (length 350 mm, outer diameter 20 mm, inner diameter 9.5 mm, radius of curvature 1031.72 mm) represented the shaft whilst the second solid cylinder (length 96.92 mm, diameter 25 mm) represented the head, neck and trochanteric region. Fig. 1 and 2.

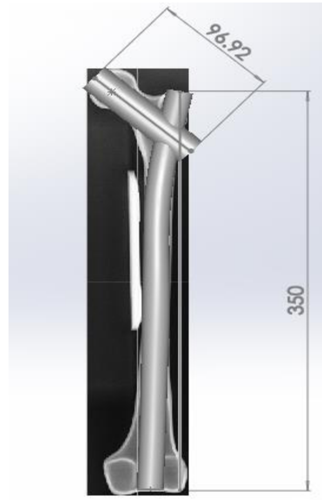

Fig. 1 Anteroposterior view

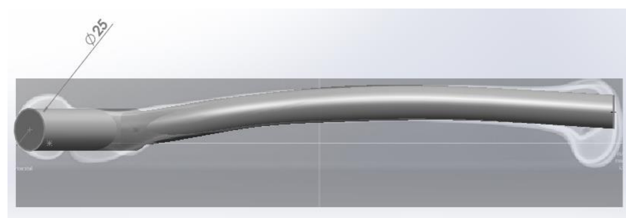

Fig. 2 Lateral view

Material properties of the composite femur (compressive strength = 157 MPa, compressive modulus = 16.7 GPa, yield strength = 93 MPa, Poisson's ratio = 0.26) were assigned to the model. The material properties of the FEA model were assumed to be isotropic and linearly elastic.

D. Mesh Selection and Convergence - The type of mesh (standard / curvature) and adaptation was selected based on the following criteria: i) Ability of the generated mesh elements to appropriately represent the geometry and shape of the model components. ii) Total solver/computational time of each type of mesh for a given simulated load. iii) Flexibility of the mesh to allow subsequent modification during iterative testing of the model.

Curvature type mesh was selected as it met the above criteria and had the least computational time. A convergence analysis was undertaken to detect the influence of element size on displacement results. The element size was sequentially decreased from the default size for a simulated load till the displacement results had plateaued. Satisfactory convergence was noted for an element size of 2 mm. The final FEA model of paediatric femur consisted of 135,788 elements in total.

E. Boundary conditions - For axial loading test the lower end of the shaft cylinder was fixed using the 'fixed geometry' option. The top end of the shaft cylinder was fixed using 'advanced fixture' option which permitted axial collapse of the shaft with incremental load but restricted mediolateral translation. Simulated axial load was applied at 60 N increments up to a maximum of 600 N. The predicted displacement value from the solver was noted for each axial loading condition and axial stiffness was estimated as described earlier.

The 'split line' command was used to create a set of four areas corresponding to the rollers (2 at the base for support and 2 at the top for application of bending load). The roller areas at the base were set at distance of 260 mm whereas the top roller areas were 70 mm apart. Simulated load was applied to top roller areas at 40 N increments up to 400 N. Displacement value from the solver was noted for each bending load condition and four-point bending stiffness was estimated.

For the torsion test the 'fixed geometry' option was applied to the distal area. The 'advanced fixture' option was used for proximal end face which allowed rotational movement but restricted excessive displacement in the anteroposterior and mediolateral directions. The long axis of the paediatric femur was marked. The femoral offset (distance from the center of rotation of the femoral head to a line bisecting the long axis of the femur) was estimated at 37 mm. Fig. 3

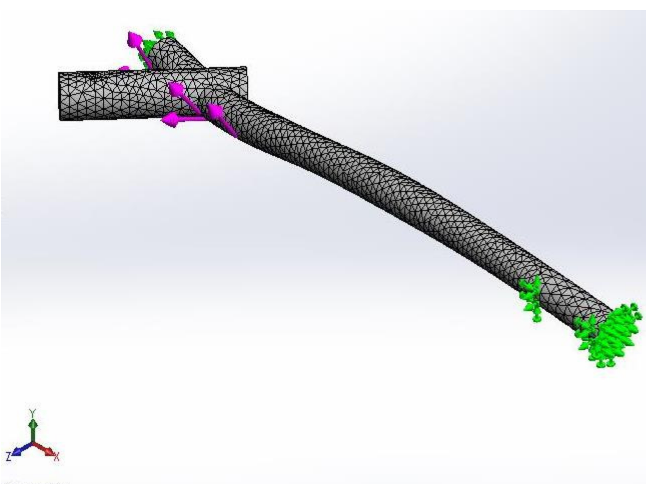

Fig. 3 Simulated torque (external rotation) test.

Simulated torque was applied at the proximal aspect of femoral shaft at 0.2 N m increments up to 4 N m. Positive torque produced internal rotation whereas negative torque resulted in external rotation. Displacement of the point (arc length) corresponding to the center of rotation of the femoral head was noted for each torsional loading condition. Angular displacement (in degrees) of the above point was calculated using arc of a circle principle wherein $\emptyset = (\text{Arc length} \times 180) / (\pi \times 37)$. Torsional stiffness (N m/deg) was obtained by plotting the torque against the angular displacement.

III. RESULTS

FEA model predicted a maximum axial displacement of 0.851mm at 600 N ($k_{FEA\ Axial}$ = 704.83 N/mm). In comparison mean axial stiffness of the femur specimens measured $k_{Exp\ Axial}$ = 667.39 N/mm (+/- 73.49), Table 1.

Table 1 Results of experiment and simulation tests

Stiffness Parameter	Experiment model	FEA model
Axial (N/mm)	667.39 +/- 73.49	704.83
Four-point bending (N/mm)	353.49 +/- 16.05	369.1
Torsion (Internal rotation) (N m/deg)	3.48 +/- 0.14	3.49
Torsion (External rotation) (N m/deg)	3.48 +/- 0.14	3.49

IV. DISCUSSION

An attempt was made in this study to develop a FEA model based on simplified geometry of the paediatric femur using orthogonal digital radiographs as a template. Digital radiographs enable development of FEA model that is simple yet representative of the overall dimensions and features viz. radius of curvature of the paediatric femur. This is an important requisite of femur FEA model used to assess the biomechanical parameters of intramedullary implants [9]. It has been demonstrated that omission of cancellous bone in femur FEA model does not significantly alter the overall stiffness results [10]. Therefore cancellous bone tissue was not modelled separately in the current paediatric FEA model to optimise computational time.

Results from simulation tests using the FEA model to estimate axial, four-point bending and torsional stiffness were similar to the experimental sawbone model. The above validated FEA model of paediatric femur can be used for evaluation of fracture fixation implants. Simulation data obtained using the paediatric femur FEA model can be useful in estimation of the range of loads that can be safely applied to a fracture fixation construct. This information can be helpful in planning and establishing parameters for an experimental setup [11].

Previous studies in this field [3, 12] have used specialised algorithms to develop 3 dimensional bone models from radiographs. However the lack of widespread availability of such algorithms limits their applicability. Enhanced processing capability of computers has enabled development of bone FEA models with good visual similarity through accurate geometric representation. However this approach does not necessarily guarantee the numerical accuracy of the results predicted by such models [13]. In their study Perez and colleagues [8] used the bone model available for download from the aforementioned source. The model measured 420 mm in length with a canal diameter of 9 mm which is probably representative of an adolescent femur. It has been noted that a change in the synthetic femur geometry from a large to small dimension can result in axial and torsional rigidity differences of 1.5 and 2.2 times respectively despite having the same Young's modulus for the cortical bone [14]. It will be of interest to note the predictions from their model if the overall dimensions were scaled down to be representative of a child's small femur. Krauze [9] performed biomechanical analysis comparing flexible intramedullary nails of two different materials. The femur FEA model in this study is reported to be based on a 5-7 year old child. However the details regarding development of the femur FEA model and its dimensions are not provided in the paper.

Paediatric femur has a complex shape and microarchitecture both of which contribute towards load transmission during weight bearing and activity. The simulation model in the current study was an attempt to simplify the femur anatomy using basic geometric entity like cylinder. Hence the results from this model can be used only as a general guide to predict the behaviour of the paediatric femur under different loading conditions. Accurate assessment using simulation models comes at the cost of significant computational resources. However this was not the main objective of the current study. In general simulation studies are based on a set of assumptions which are the inherent limitations and the current study is no exception to this rule.

V. CONCLUSIONS

Orthogonal digital radiographs can be used as a template to develop a simplified finite element model of a paediatric femur. FEA model based on simplified geometry may be used for evaluation of routine stiffness parameters of a paediatric femur.

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Address of the corresponding author:

Author: Darshan. S. Angadi
Institute: University of Birmingham
Location: Edgbaston
City: Birmingham
Country: UK
Email: DSA704@bham.ac.uk