Hala El-Shaffey*, Stephan Klein, Franziska Hainer

Development of a Novel Pediatric Forearm Fracture Treatment: Simulation, Prototype and Evaluation

Abstract: A treatment gap exists for moderately displaced pediatric distal forearm fractures (DFF), which carry a potential risk of improper reduction when treated conservatively. Currently, no standard method for the correction of the initial reduction of pediatric DFF is available. A novel closed reduction method has been proposed to correct and maintain a successful reduction throughout the healing process. This study further develops this novel cast system and evaluates its mechanical behavior through the design, construction, and testing of a biomechanical CAD model and pediatric forearm phantom. Initial results support the novel system as an improved treatment for pediatric fractures. Both the CAD model and tissue phantom indicate the ability of the system to manipulate a 15° fracture, with 0-1° of residual angulation.

Keywords: pediatric forearm fractures, conservative fracture treatment, closed reduction, biomechanical CAD, artificial tissue model

DOI 10.1515/abc-YYYY-XXXX

1 Introduction

1.1 Background

The physiology and microstructure of pediatric bone result in unique biomechanical behavior and age-specific fracture patterns. Distal forearm fractures (DFF) are among the most common childhood injuries [1]. Current treatments are split between conservative casting, with closed reduction when necessary, and surgical treatment options. The primary aim of both options is proper fracture reduction, the process by which the fragments are restored to their correct anatomical position.

While conservative techniques are more common for pediatric DFF, they carry a higher risk of re-displacement and improper fracture reduction, particularly for fractures with a larger initial displacement [2]. In contrast, surgical treatments typically result in proper reduction but are primarily reserved for largely displaced fractures.

The currently available treatments leave a gap in the reduction of moderately displaced DFF, which are associated with a higher rate of improper reduction when treated conservatively with a closed reduction [2]. The fracture therapy further developed in this study, aims to fill this gap by introducing a novel fracture treatment and reduction method without the need for invasive surgery.

1.2 Current Reduction Methods

Fracture reduction can be achieved by various means. Most closed reduction methods accompany conservative treatments and involve manual manipulation of the fragments under anesthesia, while open reduction repositions the bone fragments via surgical exposure of the fracture site [1].

Cast wedging is a closed method for the correction of fracture angulation. In this case, the cast is cut at the center of rotational alignment of the fracture, creating a hinge in the cast at the fracture site, and a plaster wedge is inserted into the gap to counteract the angle externally.

Cast wedging along with other proposed closed manipulation methods are often limited by cast stiffness, radiograph measurements, lack of qualified personnel, and patient compliance. Currently, no standardized technique exists which allows doctors to easily manipulate pediatric DFF or correct the initial reduction.

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2 Novel Fracture Treatment

2.1 Mechanical Function

The novel treatment consists of a hinged cast system with adjustable external angulation to manipulate the fracture and maintain a successful reduction during the healing process. The mechanical behavior of the system is made possible through a cast attachment component which is positioned on the forearm between the padding and casting material (see **Figure 1**). Three hooks transfer an externally applied tension to the cast body, resulting in a hinge-like rotation at the truss joint (see **Figure 2**). The aim of the system is to transfer the external cast angulation into an internal angulation of the bone fragments, to counteract and correct the initial fracture angle, resulting in a successful fracture reduction.

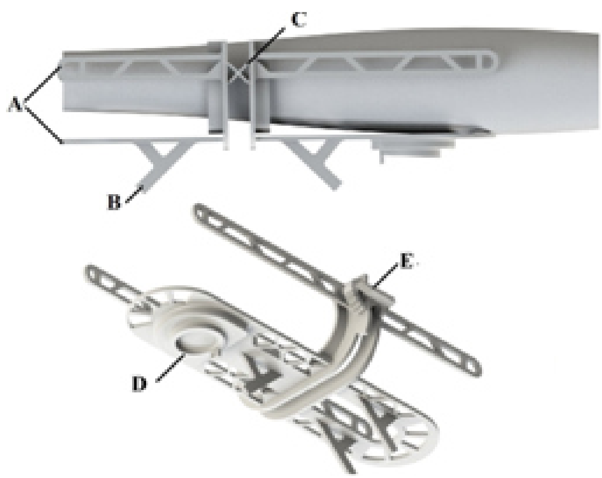

Figure 1: The cast attachment is positioned on the patient's arm after padding is in place: (A) main body, (B) guide hooks, (C) truss joint, (D) dial mount, (E) corrective angle indicator.

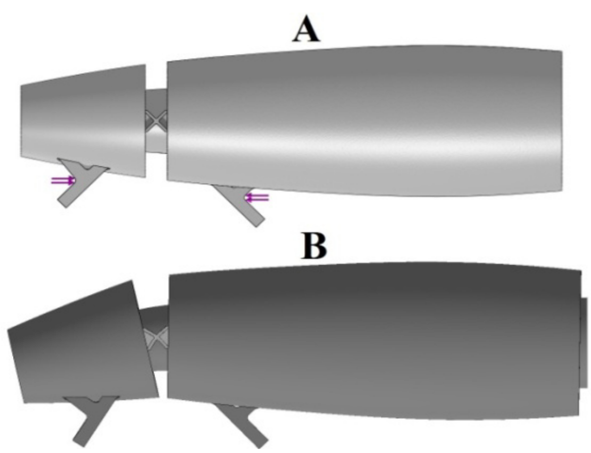

Figure 2: Mechanical behavior of total cast system (A) before and (B) after the external load is applied. An external closure mechanism applies a horizontal force (purple vectors) at each hook, creating a hinge-like reaction at the truss joint.

2.2 Specific Study Aims

Previous research has focused on concept development and general system behavior. There remains a need for determining how the externally applied load is transferred to the forearm tissues and bones. An accurate biomechanical model of the pediatric forearm is needed to examine the unique pediatric tissue properties within the system.

This study examines the cast system in a biomechanical CAD simulation of the pediatric forearm, followed by functional testing of the system with an artificial tissue phantom. The primary study aims include:

1. Derivation of the relationship between external cast angle and resultant internal fracture angle
2. Implementation of design changes based on study findings

3 Biomechanical Simulation

3.1 Materials and Methods

Age-specific, anthropometric, empirical data was used to construct a CAD model of the pediatric forearm and novel cast system. All dimensions and material properties were selected to reflect the anatomy of a 9 to 10-year old child, to reflect the age group with the highest incidence of this injury [1]. The system components were simplified and constructed to form the following distinct layers: casting material, cast attachment component, padding, skin, soft tissue and bone (see **Figure 3**). The mechanical behavior of the fracture site was modeled as a hinge-joint and the padding layer was replaced by a no-penetration connection with friction between the skin and cast layers. A literature review was performed to define each component's modulus of elasticity, Poisson's ratio, and density [3].

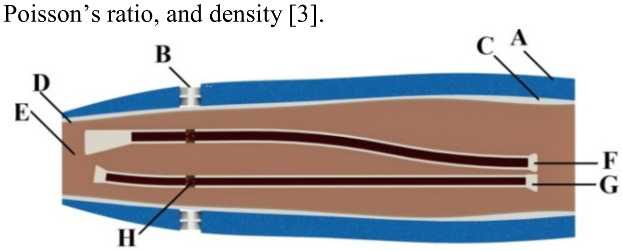

Figure 3: Cross-section of CAD forearm model and cast system: (A) casting material, (B) imbedded cast attachment, (C) padding, (D) skin, (E) soft tissue, (F) radius, (G) ulna, (H) fracture site (modeled as hinge joint).

The tissues and bones were defined as fixed at the proximal end due to their connection to the tissues of the upper arm and humerus, respectively. A horizontal load was applied to each of the hooks as seen in **Figure 2.A**, with the two distal hooks each bearing a load half the magnitude of the proximal hook. The system was discretized with a solid mesh of tetrahedral elements with convergence being reached at a final element size of 1.0-5.0 mm.

A linear static finite element simulation study was performed for applied proximal loads of 25-100N. Angular displacements of the distal radius and distal outer cast were calculated, respectively and a linear regression was used to derive the relationship between internal and external angulation. Maximum von Mises stress within the cast attachment was compared to the ultimate strength of ABS plastic (30.0 MPa) to evaluate potential material failure [4].

3.2 Results

The simulation results indicate the ability of the system to manipulate the fracture internally with a linear relationship between the external and internal angular displacements (see **Figure 4** and eq 1).The derived relationship shown by equation 1 can be further simplified, as the fracture angle is clinically measured to the nearest degree. This simplification results in a piecewise linear approximation of the manipulated fracture angle ($\boldsymbol{\theta_M}$) and the external cast angle ($\boldsymbol{\theta_E}$), where $\boldsymbol{\theta_{Fi}}$ denotes the initial fracture angle (see eq 2).

$$\boldsymbol{\theta_M \approx \theta_{F_i} - 0.88\theta_E} \quad (1)$$

$$\boldsymbol{\theta_M \approx \theta_{F_i}} - \begin{cases} \boldsymbol{\theta_E - 1}, \text{ if } \quad \boldsymbol{\theta_E} < 13 \\ \boldsymbol{\theta_E - 2}, \text{ if } \boldsymbol{13 \le \theta_E \le 20} \\ \boldsymbol{\theta_E - 3}, \text{ if } \quad \boldsymbol{\theta_E} > 20 \end{cases} \quad (\mathbf{2})$$

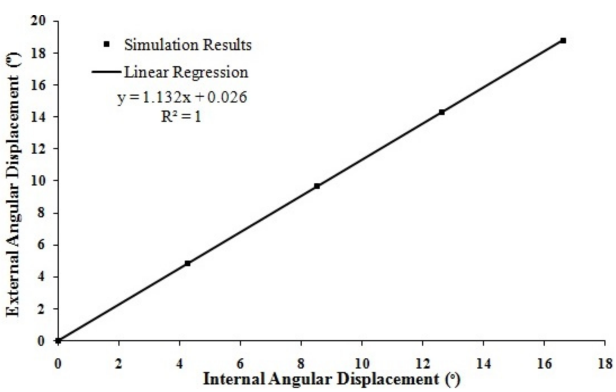

Figure 4: External versus internal angular displacement. Markers indicate calculated simulation values with a corresponding linear regression and an R^2 value of 1.

The simulation also suggests that the maximum von Mises stress is concentrated in the truss joint of the cast attachment with stress values exceeding the reported ultimate strength of the material for a desired internal displacement of 15°, suggesting a potential material failure condition. This finding is further addressed in the following redesign section.

4 System Redesign and Prototype

4.1 Redesign

The CAD model and simulation revealed several necessary design changes which were implemented to improve the integration of the cast attachment and prevent material failure (see **Figure 5**). The geometry was redefined to closely reflect the pediatric forearm anatomy, resulting in a more compact and contoured design. In addition, the truss joint geometry was updated to reduce stress concentration by reducing sharp corners and increasing the area for force distribution. The new design supports the mechanical function of the system by reducing movement between the cast system components.

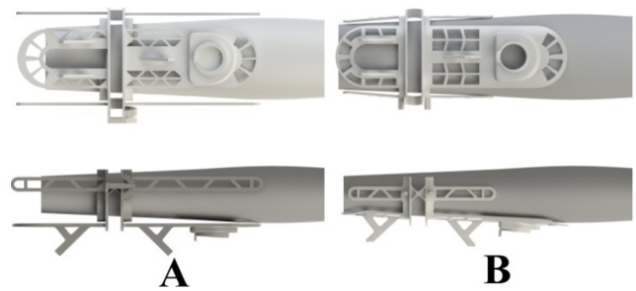

Figure 5: (A) original and (B) redesigned cast attachment. New design accommodates pediatric forearm dimensions, reducing gaps between padding and cast attachment components.

4.2 Forearm Phantom and Prototype

A biomechanical pediatric forearm phantom was designed for the functional testing of the cast system [3]. Several concepts were evaluated based on their ability to simulate the desired material properties (modulus, Poisson's Ratio, and density) and forearm structure, complexity, and cost. The final design consisted of a cast silicone-based phantom with embedded 3D-printed bone models to simulate a both-bone complete DFF with a 15° initial fracture angle. Steel screws were placed in the bone ends to aid in radiographic visualization.

The redesigned cast attachment was 3D-printed via selective-laser-sintering from polyamide 12. The forearm phantom was covered with a cotton cast sleeve for the padding layer and the cast attachment was positioned over it, such that the truss joint aligned with the fracture axis of rotation of the phantom. Scotchcast^{TM}Plus synthetic casting material was wrapped around the cast attachment and phantom, leaving only the hooks and dial mount exposed. A Boa closure system (www.theboasystem.com) was attached externally to apply the load to the hooks (see **Figure 6**).

Figure 6: Final assembled prototype of redesigned cast system.

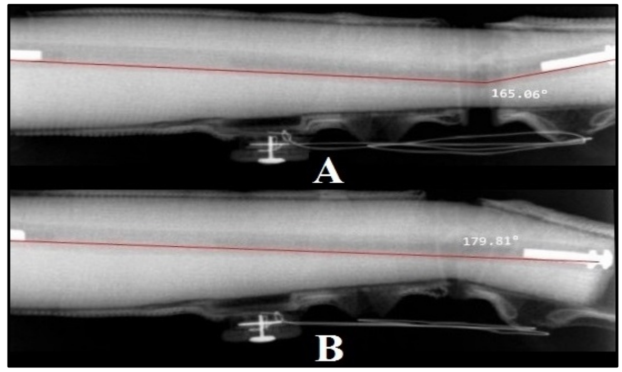

Figure 7: Lateral view of the cast system (A) before and (B) after manipulation shows an approximately 15°initial fracture angle that is reduced to approximately 0° of residual angulation.

5 Evaluation

5.1 Materials and Methods

The testing and radiographic imaging during the functional evaluation was performed in an operating room of the Department of Pediatric Surgery, UKSH, Luebeck Campus, under the supervision of a pediatric surgeon. An initial lateral radiograph was taken before any external load was applied to serve as a baseline measurement. The closure dial was rotated clockwise to produce a tension in the cables until an external angle of 17° was reached, theoretically indicating a 15° internal angular displacement, according to equation 2.Afinal lateral radiograph of the system was taken after the applied external angulation. MicroDicom medical image processing software was used to evaluate all radiographs.

5.2 Results

The angles measured within the MicroDicom software were reported as the obtuse angle measured clockwise from the distal to proximal screw (see **Figure 7**).Therefore, the internal angular displacement was calculated as the supplement of this value (see **Table 1**). Material failure was not observed in any part of the redesigned truss joint.

Table 1: Summary of lateral radiographs describes the measured angle, calculated fracture angle, external cast angle and the difference between the external and internal displacements before and after manipulation.

	Measured Internal	Calculated Internal	Cast Angle	Difference of Displacement
Initial	165.06°	14.94°	0°	-
Manipulated	179.81°	0.19°	16.57°	1.82°

6 Conclusion and Future Work

The cumulative results of this study support the positive capabilities of the novel fracture reduction therapy in the conservative treatment of pediatric DFF. Both the CAD model and the functional testing illustrate the ability of the system to reduce a 15° initial fracture to 0-1° of residual angulation. Further development will focus on material selection for commercial manufacturing and possible effects on the mechanical function. Future models should consider various muscle states to evaluate total treatment scope.

Acknowledgment: The authors would like to thank Dr. Ludger Tüshaus and Prof. Lutz Wünsch of the Department of Pediatric Surgery for their support during the testing phase.

Author's Statement
The authors state no funding involved or conflict of interest.

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