KANSAS JOURNAL *of* MEDICINE

Stacked 1/3 Tubular Plates for Fixation of Pediatric Forearm Fractures: A Biomechanical Study

Benjamin J. Cooper, M.D.[1,2], Alexander C. Wendling, M.D.[1,2],
Sharon R. Isaacs-Pullins, ME[1], Joel White, BSME, MSBME[3],
Steven M. Hollenbeck, M.D.[1,2]
[1]University of Kansas School of Medicine-Wichita, Wichita, KS
[2]Department of Orthopaedics
[3]Wichita State University, Wichita, KS
National Institute for Aviation Research

Received Nov. 16, 2021; Accepted for publication Nov. 29, 2021; Published online Feb. 9, 2022
https://doi.org/10.17161/kjm.vol15.16207

ABSTRACT

Introduction. Among operatively treated pediatric forearm fractures, many different fixation constructs are described. The goal of this study was to define the biomechanical properties of a double stacked 1/3 tubular plate construct used by the senior author for some fractures and to review available literature regarding the use of stacked plates.

Methods. Biomechanical testing was performed by 4-point bending of three different plate constructs: 1/3 tubular plate, stacked 1/3 tubular plates, and 2.7 mm LC-DCP plate. Five test specimens were evaluated for each of the three plate constructs. From stress-strain curves, flexural stiffness (N/mm), force to cause plastic deformation (N), and force to cause 10° bend (N) were calculated and compared using standard t-test statistics.

Results. Key outcome parameter means (± SD) for the three plate constructs (1/3 tubular plate, stacked 1/3 tubular plates, and 2.7 mm LC-DCP plate) were reported respectively as follows: flexural stiffness (55.4 ± 3.5 N/mm, 131.7 ± 3.5 N/mm, 113.3 ± 12.1 N/mm), force to cause plastic deformation (113.6 ± 11.0 N, 242.1 ± 13.0 N, 192.2 ± 17.9 N), and force to cause a 10° bend (140.0 ± 8.4 N, 299.4 ± 14.1 N, 265.5 ± 21.2 N). Mean values of all three measures were significantly larger for the stacked 1/3 tubular plates than for the other plate constructs.

Conclusions. The stacked 1/3 tubular plate construct was biomechanically superior to the other plate constructs tested. Stacked plating significantly improved stiffness of the fracture fixation construct supporting the use of this technique in selected trauma cases.

Kans J Med 2022;15:63-66

INTRODUCTION

Forearm fractures are among the most common fractures in pediatric patients. While many of these fractures can be managed nonoperatively, much controversy exists with regards to indications for operative treatment.[1,2] Indications for fixation can include open fractures, inability to achieve adequate reduction, loss of reduction, and limited remaining growth/remodeling. Once operative fixation is chosen, hardware selection for fracture fixation includes numerous different implants and often there is no clear indication to choose one type over another.[3,4] Even when selecting a plate and screw construct, many different geometries, materials, thicknesses, screw types, and other variables are available from numerous vendors. Surgeons must consider characteristics of the fracture being treated along with other patient and treatment factors when selecting the appropriate construct for fixation. Biomechanical research offers some insight into properties of plate and screw selection and provides clinicians objective information to guide clinical practice.

The inspiration for this study was the senior author's use of stacked 1/3 tubular plates in the treatment of pediatric forearm fractures. This work specifically aimed to perform a biomechanical analysis between fixation constructs using two different plates, as well as the stacked plate construct, to define the mechanical properties quantitatively. While the study design was chosen with this clinical application in mind, the results could be applied more generally. The mechanical properties and comparison between various commercially available plates are not well described by industry product guides or in the orthopaedic literature. Anecdotally, a thicker or larger plate, as well as stacking two plates, would increase the stiffness, but quantitative data were lacking.

The goal of this study was to characterize the mechanical properties of three different plate constructs and provide quantitative data which could be used by providers to guide clinical practice decisions. What evidence exists in current literature with regards to stacking plates for fracture fixation? How does quantitative biomechanical performance (flexural stiffness, force to cause plastic deformation, and force to cause 10° bend) by 4-point bending compare between the 1/3 tubular plate, stacked 1/3 tubular plate, and 2.7 mm LC-DCP plate? This study presents and discusses possible applications of the stacked plating construct, as well as limitations and potential for further work.

METHODS

Sawbones® (part #3403-24, cylinder 10 mm OD x 2.5 mm wall thickness) were acquired and used for this fracture model (Pacific Research Company; Vashon, WA, USA). A transverse fracture was created with a saw and plate fixation was applied leaving a 1-mm fracture gap. Plate constructs included three different groups: 6-hole 1/3 tubular plate (Synthes® item # 241.36), double stacked 6-hole 1/3 tubular plates (item # 241.36), and 7-hole 2.7-mm LC-DCP (Synthes® item # 242.207); 2.7-mm cortical screws of appropriate length were used for fixation of all groups (Synthes®; West Chester, PA, USA). The 6-hole 1/3 tubular and 7-hole 2.7-mm LC-DCP plates were chosen due to similarity in overall construct length due to the symmetry of hole spacing in the 2.7-mm plate versus elongated span between central holes on the 1/3 tubular plate (Figure 1).

Figure 1. Plate constructs used in this study included: (A) 2.7-mm LC-DCP plate, (B) 1/3 tubular plate, and (C) stacked 1/3 tubular plates.

Testing was performed at the National Institute for Aviation Research mechanical testing lab (NIAR, Wichita State University, Wichita, KS) on an 810 Material Test System (MTS®, Eden Prairie, MN). The test system is shown in Figure 2. The 4-point bending setup was adapted to fit the specimens from testing specifications of the American Society for Testing and Materials (ASTM).[5] Support span was set at 81 mm; load span was set between 25.5 mm and 27 mm based upon screw location to ensure load was applied between screw heads and would not interact with screws during bending (Figure 3). While changing the load span would introduce variability in the results, a change within 1.5 mm over the 81-mm support span would be minimal and allow the benefit of not loading directly onto a screw head, which would lead to slippage during loading. Load rate was 0.015 mm/sec; load and deflection were sampled at 60 Hz. Specimens were tested through elastic and plastic deformation to a deflection of at least 5 mm. A representative plot from testing of a double stacked 1/3 tubular plate is shown in Figure 4.

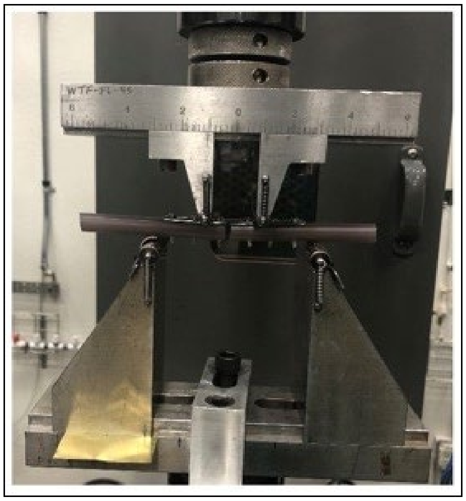

Figure 2. Test setup on MTS® machine.

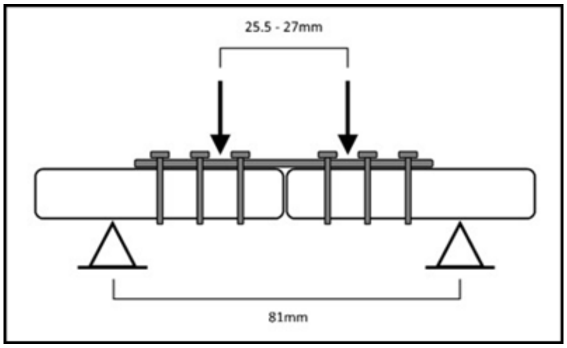

Figure 3. Test setup force diagram.

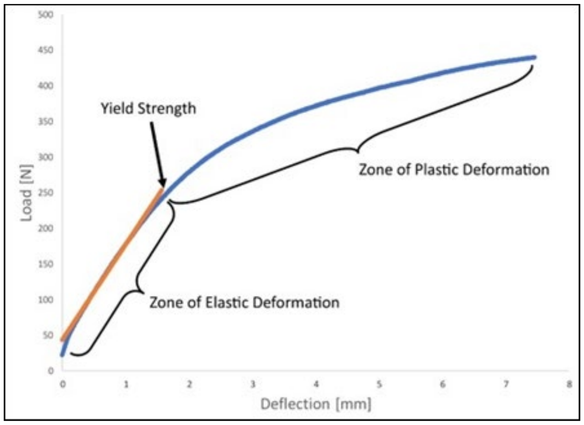

Figure 4. Representative plot from the testing of double stacked 1/3 tubular plate construct showing stress-strain data collected from testing and labeling zones of elastic and plastic deformation as well as yield strength.

Analysis was performed on data to calculate the flexural stiffness (N/mm) based on the linear region of the stress/strain curve. Force to cause a plastic deformation was defined as a deviation of greater than 5% from the linear stress/strain relationship. Force to cause a 10° bend was identified along the stress/strain data based upon the geometry of the test setup, as shown in Figure 2, to provide a clinical corollary of construct strength. Data were compared with standard t-test statistics with a selected significance value of $p = 0.05$. T-tests were run for the following comparisons: 1/3 tubular vs. stacked 1/3 tubular, 1/3 tubular vs. 2.7-mm LC-DCP, stacked 1/3 tubular vs. 2.7-mm LC-DCP.

RESULTS

The three plate constructs (1/3 tubular plate, stacked 1/3 tubular plate, and 2.7-mm LC-DCP plate) were each tested with n = 5 and the following results are reported respectively with standard deviations (Table 1): flexural stiffness (55.4 ± 3.5 N/mm, 131.7 ± 3.5 N/mm, 113.3 ± 12.1 N/mm), force to cause plastic deformation (113.6 ± 11.0 N, 242.1 ± 13.0 N, 192.2 ± 17.9 N), and force to cause a 10° bend (140.0 ± 8.4 N, 299.4 ± 14.1 N, 265.5 ± 21.2 N).

Table 1. Results from biomechanical testing.

Construct	Flexural stiffness (N/mm)*	Force to cause plastic deformation (N)*	Force to cause 10° bend (N)*
1/3 tubular plate	55.4 ± 3.5	113.6 ± 11.0	140.0 ± 8.4
Stacked 1/3 tubular plate	131.7 ± 3.5	242.1 ± 13.0	299.4 ± 14.1
2.7 mm LC-DCP plate	113.3 ± 12.1	192.2 ± 17.9	265.5 ± 21.2

*Tabulated values are mean ± standard deviation.

Statistical significance by t-test was performed for each of the three reported results (flexural stiffness, force to cause plastic deformation, and force to cause a 10° bend). When comparing 1/3 tubular plate against stacked 1/3 tubular plate and 1/3 tubular plate against 2.7-mm LC-DCP plate, all were significant at $p < 0.001$. When comparing stacked 1/3 tubular plate versus 2.7-mm LC-DCP plate, flexural stiffness was significant at $p = 0.0114$, force to cause plastic deformation was significant at $p = 0.0010$, and force to cause 10° bend was significant at $p = 0.0177$. Failure analysis of test specimens after bending also was performed, which showed that 2.7-mm LC-DCP plates failed at a single point of bending at the center screw hole overlying the fracture, whereas 1/3 tubular plates (stacked and single) failed by bending at the 2 screw holes adjacent to the fracture (Figure 5).

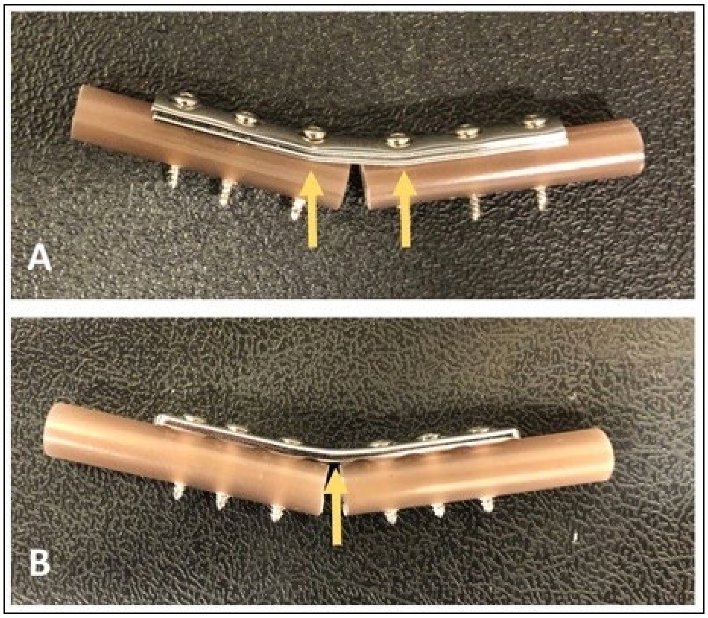

Figure 5. Failure analysis of (A) stacked 1/3 tubular plates and (B) 2.7-mm LC-DCP plate. Arrows show the site(s) of bending in each construct.

DISCUSSION

This study confirmed the hypothesis that stacked 1/3 tubular plates are biomechanically superior to a 2.7-mm LC-DCP plate. Further, it demonstrated that stacked plating provided a better than additive quantitative mechanical improvement in bending. This was true of the three metrics reported in this study of 4-point bending: flexural stiffness, force to cause plastic deformation, and force to cause a 10° bend.

Review of previously published works regarding stacked plating yielded only a few studies. Mudgal and Ring[6] published a technique report about using stacked plating in adult distal radius fractures that had metadiaphyseal extension. They suggested using a combination of a T-plate plus a dynamic compression plate to allow longer extension of the construct to span from the metadiaphyseal fracture to the distal radius continuously. In their work, they presented the technique, as well as two case reports of its use with good outcomes; however, no biomechanical analysis was done. A recently published case report[7] used a similar technique of stacking plates as a method of extending fixation across a metadiaphyseal segmental fracture in a pediatric patient with a good result. Uniquely, their construct combined titanium and stainless-steel plates. While the investigators reported successful fracture union without complication, they offered no biomechanical or construct analysis.

Another study completed in the field of veterinary surgery compared stacked plating for front leg fractures in canines.[8] Biomechanical analysis was performed with axial load cyclic testing to compare single plate versus stacked plates. In their stacked plate constructs they tested 8-hole plate constructs stacked with another plate of either eight holes, four holes, or two holes. This study found that single plate constructs failed and most of the stacked plate constructs did not. However, due to the design of their mechanical testing, they were not able to provide any quantitative data as to the added strength of implementing stacked plating.

When designing our testing model, 4-point bending was chosen as it was judged to be more relevant to the authors' clinical question regarding its use in pediatric forearm fractures. The complexity of the two bones in the forearm and typical fracture mechanism make bending more applicable over torsion. To analyze the difference in the constructs fully, as well as to apply these results to other fractures (such as distal fibula), further work is necessary to test the plates in torsion. Fatigue testing also deserves consideration in future work. However, in fracture fixation of pediatric fractures, perhaps cyclic testing is less clinically relevant since fractures typically achieve bony union quickly and often are treated with supplemental immobilization.

While limited work has been published on stacked plating, numerous studies of other plate and screw constructs populate the literature. Since the advent and popularization of locking plates and screws, their biomechanics and performance have been presented and analyzed.[9] Several studies have looked at how screw configuration, plate positioning, and bone quality impact biomechanical properties.[10-12] Other studies have evaluated biomechanical properties of various plate and screw constructs in the setting of ankle fractures.[13-15] While these works have drawn an array of conclusions with regards to their specific hypotheses, much can be learned and leveraged with regards to study design and methods. The testing design and parameters of the presented study were chosen with an aim to provide quantitative biomechanical data which would help to analyze the hypothesis objectively. Importantly, plastic deformation was achieved in all constructs which, unlike the only previously published biomechanical study on stacked plating,[8] enabled the ability to compare the quantitative stiffness and performance between groups.

The results of this study supported the use of stacked 1/3 tubular plates as a biomechanically superior construct compared to 2.7 mm LC-DCP plating. This is a technique that the senior author has utilized to manage a wide variety of operatively-treated pediatric forearm fractures, including radial shaft fractures in the setting of both bone forearm fractures and ulna fractures in the setting of Monteggia fracture patterns (Figure 6). Benefits for use of stacked 1/3 tubular plates included: (1) tubular plate shape improves bone-plate fit in many patients, (2) availability of implants in a community hospital or surgery center, (3) tubular plates more easily contoured independently with improved strength by stacking, and (4) reduced cost.

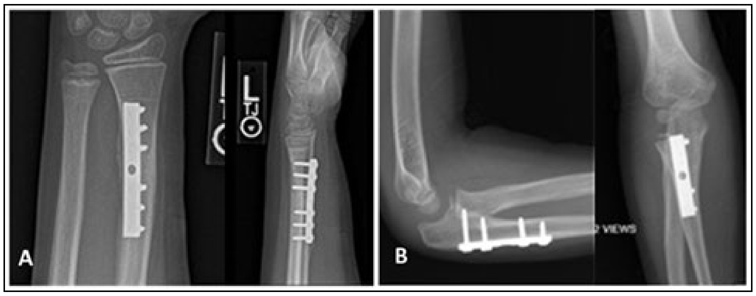

Figure 6. Radiographs showing stacked 1/3 tubular plate constructs used in pediatric patients to treat: (A) distal 1/3 both bone forearm fracture with fixation of the radius and (B) Monteggia fracture with fixation of the ulna.

While the purpose of this work was not to define or explore the use of stacked plating fully, it helped to define the mechanical properties of the stacked plate construct, which could be used to guide clinical decision making, and supported the use of stacked plating in many fractures. The described and tested construct of stacked 1/3 tubular plates offers clinicians another option in fracture fixation.

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Keywords: biomechanics, fracture fixation, bone plates, materials testing, equipment design