Biomechanical comparison of strategies to adjust axial stiffness of a hybrid fixator

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Keywords
External skeletal fixation, hybrid fixation, biomechanical properties

Summary
Objectives: To evaluate strategies for increasing the axial stiffness of a hybrid external bone fixator.

Materials and methods: Type Ia hybrid fixators, consisting of a uniplanar linear component connected to a circular ring, were tested in displacement controlled loading in axial compression. The basic hybrid construct was modified to explore strategies considered to increase fixator stiffness including: decreasing ring diameter, increasing ring thickness, adding pins to the ring fixation, and adding struts between the ring and vertical post components of the device. Stiffness in the initial phase of loading was compared between the groups.

Results: The addition of a single diagonal bar between the ring and linear connecting rail did not significantly improve the stiffness of constructs. However, the addition of two half-pins to the ring, the addition of two struts between the ring and linear connecting rail, or decreasing the internal ring diameter from 115 to 85 mm progressively increased the stiffness of the frame. The most effective strategy consisted of increasing the thickness of the ring from 6 to 12 mm, thereby increasing the stiffness of the control frame by 335%.

Clinical significance: Modulating the ring thickness, adding two struts between the ring and linear connecting rail, and reducing the ring diameter appear to be the most effective, simple, and clinically versatile ways to increase axial stiffness, most likely due to their impact on reducing ring bending.

Introduction

Hybrid external skeletal fixation combines elements of linear and circular external skeletal fixation. Linear external skeletal fixation is relatively easy to use as well as cost effective and light, but it has some inherent structural limitations, including the amount of bone stock required for pin insertion in each segment and the limited possibility to address residual angular deformities in a consistent manner. Circular external skeletal fixation offers a greater versatility, minimizes soft tissue trauma through the use of tensioned wires, and can be implanted in short bone segments (1). The application of circular fixators is technically more challenging, especially around joints where placement of rings should minimize interference with the range-of-motion. Hybrid fixation is especially relevant to the treatment of peri-articular fractures, and it has gained popularity in the management of high-energy proximal fractures of the tibia in humans (2–4). Several case reports and retrospective clinical studies describe the use of hybrid fixation in small animals (5–7). Scientific value of these studies is affected by their retrospective design and small population size, but hybrid fixation seems to offer similar clinical benefits in animals with juxta-articular fractures as those reported in humans.

Although hybrid fixation has been gaining popularity in humans and animals, its biomechanical characteristics have not been as well investigated as those of circular external skeletal fixation and linear external skeletal fixation (8, 9). Linear fixators loaded in axial compression produce a load-displacement curve following a linear pattern, whereas the stiffness of circular fixators increases with loading, correlating with the tension applied on wires. Under similar conditions, the initial load-displacement curves generated by hybrid fixators follow a non-linear pattern similar to that of circular fixators (9). However, the behaviour of hybrid fixators has been reported to approach that of linear fixators at higher loads, as their stiffness no longer increases with tension (10, 11). Linear fixators are stiffer than circular fixators in axial loading and hybrid fixators are generally less stiff than equivalent circular fixators (9, 11, 12). In human orthopaedics, most studies have focused on comparing the stiffness of commercially available fixators, but very few have tried to determine the influence of individual components within a frame (8, 12, 13). In a study where tibial plateau levelling osteotomy was performed in five canine cadavers, hinged hybrid external fixation was found to result in

doi:10.3415/VCOT-11-04-0053
Received: April 8, 2011
Accepted: January 11, 2012
Pre-published online: March 26, 2012

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Vet Comp Orthop Traumatol 3/2012
a more accurate correction of the tibial plateau slope but it provided less axial stiffness of bone implant constructs than internal fixation (14). The authors are unaware of any study assessing the relative contribution of individual elements to the overall stiffness of hybrid fixators in small animals.

The goal of this study was to analyze the potential impact of various strategies designed to increase the stiffness of type Ia hybrid fixator. The authors hypothesized that the addition of struts and half-pins, as well as modifying the ring diameter and thickness, would increase the axial stiffness of a basic hybrid external fixation.

Material and methods

Bone model

Thirty millimetre-diameter cylinders of synthetic material simulating bone were selected to eliminate the variability inherent to biological specimens. To evaluate load-bearing capabilities of each construct, a separation of 10 mm was maintained between the proximal and distal cylinders. This design was selected to simulate the application of hybrid external fixation to clinical situations where bone defects and non-reducible fracture configurations prevent load sharing between the bone and the implant. This model allowed the axial stiffness of the fixation device to be established without dependence on the bone model.

Hybrid external fixation

All constructs shared the same basic design of a type Ia hybrid fixator, with a ring in the distal segment and a unilateral linear fixator in the proximal segment (Fig. 1) (15). All constructs included a 150 mm long linear rail which was attached to the ring to transfer loads between the bone segments. The rails were composed of 6 mm thick and 15 mm wide aluminium alloy, and contained 8 mm wide slots to allow fixation of threaded pins. The rings were made of 6 mm thick aluminium alloy, and contained 8 mm wide slots to allow fixation of wires and threaded pins. The rings were attached to a shorter (40 mm) section of the synthetic cylinder with two 1.57 mm diameter Kirschner wires. The wires were placed perpendicular to each other and to the long axis of the bone, and were fixed to the ring at both ends. The wires were secured to the ring by passing each end through a hole in a specialized bolt, which could then be tightened to fix the wire to the ring. After one end of each wire had been secured to the ring, the two wires were alternatively tensioned to approximately 500 N (50 kg-force) before they were tightened in position. A rail was then attached to the ring by means of a threaded segment engaged through the slot in the ring, and locked with a nut on the opposite side of the ring. Three positive profile threaded pins (3.67 mm diameter) were placed at standardized positions in the proximal long segment of each construct and clamped to the rail with custom-designed bolts. Seven hybrid configurations (Fig. 1) were investigated in this study:

- **Group 1 – Control group**: Type Ia hybrid fixator consisting of a ring of 115 mm internal diameter, two orthogonal Kirschner wires connected to the ring, and three half pins in the proximal segment, attached to a rail (Fig. 1A).
- **Group 2 – Small ring**: Identical to group 1, but with a ring of 85 mm internal diameter.
- **Group 3 – Thick large ring**: Identical to group 1, but with a 12 mm thick ring, formed by bonding two 115 mm rings together with cyanoacrylate adhesive under approximately 1 kN of load to ensure formation of a thin bond layer (Fig. 1B).
- **Group 4 – Thick small ring**: Identical to group 2, but with a 12 mm thick ring, formed by bonding two 85 mm rings together as for Group 3.
- **Group 5 – Large rings with half-pins**: Identical to the group 1, with the addition of two half-pins connected to the 115 mm diameter ring with the same type of bolts used for securing half-pins to the rail (Fig. 1C).
- **Group 6 – Large ring with half-pins and two malleable struts**: Identical to group 5, with the addition of two 3 mm diameter malleable stainless steel bars connecting the rail to the ring (Fig. 1D). The malleable bars could be contoured so they locked into custom-designed, stainless steel hooks. One hook was fixed at each end of the bar. The proximal and distal hooks were passed through 3 mm holes coplanar to the linear rail and circular ring, respectively. The hooks were immobilized with nuts on the opposite side of the rail and ring, thereby fixing the bar in position.
- **Group 7 – Large ring with half-pins and a rigid strut**: These frames are identical to group 5, with the addition of one 3 mm diameter, aluminium alloy bar, connecting the rail to the ring (Fig. 1E). This bar was rigid and could not be contoured. The bar was aligned relative to the circular ring and linear rail by adjusting the orientation of each clamp. These cylindrical clamps had a 4 mm diameter hole to allow passage of the bar which was then locked with an interferential screw.

Biomechanical testing

Once assembled, each configuration of the fixator apparatus was tested using a 10 kN servo-hydraulic axial testing machine. A compressive pre-load of 10–15 N was applied for aligning and securing the construct to the load frame. The construct was attached to the testing machine with ball and cup connections designed to allow rotation, thereby simplifying loading analysis in comparison to rigid attachment. In each trial, the construct was loaded and unloaded in a compression cycle using displacement control, recording the force response using a 1.0 kN load cell. Displacement, rather than load-controlled testing...
was selected for safety reasons. Each load-
ing-unloading cycle was conducted over a
total of 12 seconds at displacement rates
ranging from 0.5 to 2.5 mm/sec. Stiffer
constructs were displaced between 3 and 5
mm while weaker constructs were dis-
placed 6 to 7.5 mm. Displacements were re-
duced for stiffer constructs to avoid dam-
age to the artificial bones. Additionally, the
trials were monitored with images, taken by
a high performance mega pixel camera at
33 msec intervals throughout each trial, re-
sulting in a total of 181 images per trial. The
sampling rate for the pictures was set with
custom programming.

Five constructs were tested for groups 1,
5, 6, and 7, whereas three constructs were
tested for groups 2, 3, and 4.

Data analysis
For the purpose of this study, an initial stiff-
ness (N/mm) was defined as the slope of
the load-displacement plot for the first 80
N of loading in each trial. The 15–80 N
loading range was chosen because the load-
displacement plot could be accurately ref-
lected by a linear regression in that region.
The median stiffness was calculated for
each configuration and compared for sta-
tistical differences between groups using
Kruskal-Wallis one-way analysis by ranks.
Significance level was set at $p < 0.05$
throughout the study.

Results

Figure 2 represents the typical load-
displacement responses from both ring di-
ameters of the control configuration
(groups 1 and 2). These curves were not lin-
ear. The initial loading phase generated
the highest stiffness and, due to varying
strengths, this initial region was the only re-
gion of the curve that could be compared
between all constructs. The stiffness of each
construct is provided in Table 1 and Figure 3.
In comparison to the control con-
struct (group 1), the stiffness of the con-
structs was significantly increased by de-
creasing the ring diameter (group 2),
doubling ring thickness (group 3 and 4),
adding two half-pins to the ring (group 5),
or adding two malleable struts (group 6).
However, in comparison to the control

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Footnotes:

1. High performance, mega pixel camera, model PL-B741: PixeLINK, Ottawa, ON, Canada
2. LabVIEW: National Instruments, Austin, TX, USA
construct (group 1), there was not a significant increase in stiffness with the addition of a rigid diagonal strut (group 7). Figure 2 illustrates the positive impact of decreasing ring diameter on construct stiffness in comparison to group 1. Ring fixation appeared to be the weakest component of our control group. Figure 4 is an overlay of the single 115 mm ring at 0 and 3 mm displacement. Ring bending can subjectively be appreciated based on the difference between the magnitude of the displacement on the side of the connecting bar compared to that of the opposite side of the ring.

Discussion

Our study investigated strategies to increase the stiffness of type Ia hybrid fixators composed of 85 and 115 mm diameter rings. The main results of our study were as follows: 1) The addition of a single diagonal bar between the ring and linear connecting rail did not significantly change the stiffness of our control constructs; 2) The addition of two half-pins to the ring increased significantly the stiffness of the construct; 3) The addition of two struts between the ring and the linear connecting rail, and decreasing the internal ring diameter from 115 to 85 mm produced a similar effect, a near doubling of the stiffness of the control frame, which is consistent with previous biomechanical studies of hybrid fixators (9); 4) The most effective strategy consisted of increasing the thickness of the ring from 6 to 12 mm.

Lewis et al. determined the axial stiffness of a circular fixator with similar ring sizes as those in our study (16). The stiffness of their apparatus ranged from 80 to 100 N/mm for a circular fixator with rings of 118 mm in diameter. These values are higher than those reported here, but are within a reasonably similar range considering the difference in the type of external fixation. Indeed, the stiffness of hybrid fixators has previously been reported as lower than that of equivalent circular fixators (9, 11, 12). This difference may be attributed to the mechanical behaviour of the linear component and the connection between the circular and linear elements of the frame. This connection acts as a stress riser because it is expected to counteract all the forces acting on the fracture. A type Ia configuration was selected as a control frame in our study because of its technical simplicity. Controlled axial loading between bones has been shown to enhance bone healing, but excessive micro-motion will lead to bone resorption and delay healing (17, 18). Based on a kinetic evaluation of healthy dogs at the walk, a 35 kg dog applies about 70 N to each hindlimb (20% of the body weight) and 100 N (30% of the body weight) to each forelimb (19). Those numbers increased to 180–240 N on each hindlimb (70% of the body weight) and 326 N on each forelimb (95% of the body weight) during the trot (20, 21). Although lameness after fracture repair would affect load bearing on the limb, these values raise concerns regarding the application of the basic construct (group 1) in larger dogs. These dogs would normally be capable of producing hundreds of Newtons per step, thereby inducing a displacement exceeding 5 mm (Fig. 2) at the fracture site. This magnitude of displacement justifies investigations of strategies to increase the stiffness of our control frame.

Influence of ring diameter

Lewis et al. reported the negative correlation between ring diameter and stiffness of the frame, which our results confirm (16). In fact, ring diameter was the most critical variable identified in a biomechanical study of multiple-ring circular fixation (17). Ring diameter plays a critical role in the biomechanical properties of hybrid fixators because most of the displacement in the apparatus seems to occur in the form of ring bending. Decreasing the diameter of a ring increases its resistance to bending, thereby impacting the biomechanical properties of the entire construct. In addition, reducing ring diameter decreases the distance between the bone specimen and the connecting bar in the linear portion of the apparatus. Decreasing the working length of pins will further contribute to axial stiffness (22). However, decreasing ring size to increase the stiffness of the fixation is a strategy that can bear anatomical restraints. A distance of at least one centimetre must be maintained between the skin and the inner ring to accommodate postoperative swelling of soft tissues (1). Larger animals will generally require larger rings where increased stiffness would assist in load sharing, warranting considerations of alternative strategies.

Table 1 Median and range of initial stiffness values for each frame configuration.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Median (N/mm)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>25.98</td>
<td>22.72 - 41.04</td>
</tr>
<tr>
<td>Group 2</td>
<td>48.70</td>
<td>47.68 - 51.24</td>
</tr>
<tr>
<td>Group 3</td>
<td>94.04</td>
<td>85.05 - 104.58</td>
</tr>
<tr>
<td>Group 4</td>
<td>65.17</td>
<td>64.68 - 66.92</td>
</tr>
<tr>
<td>Group 5</td>
<td>38.50</td>
<td>35.55 - 41.59</td>
</tr>
<tr>
<td>Group 6</td>
<td>45.56</td>
<td>73.76 - 46.30</td>
</tr>
<tr>
<td>Group 7</td>
<td>35.69</td>
<td>32.02 - 41.01</td>
</tr>
</tbody>
</table>
Addition of linear components

Strategies to increase the stiffness of unilateral external fixators have been well established and contribute to the versatility of these implants. The composition and diameter of the connecting bar, the working distance of pins, pin separation across the fracture segments, number and diameter of pins, and placement of pins in different planes can all be adjusted to modulate the stiffness of a linear external fixator (8, 23). Factors found to increase the stability of circular fixators include a smaller ring diameter, increasing the diameter and tension of wires, use of olive wires, placing wires perpendicular to each other on the same ring, and the addition of a drop wire away from the ring (8, 24, 25). Fewer studies have focused on strategies to improve frame stiffness of hybrid fixators, thus prompting our study. Several in vitro experiments reported that multiple levels of fixation in the juxta-articular bone segment, consisting of rings, drop wires, or pins increase the stiffness of hybrid fixators (2, 8, 12). The addition of half pins to the ring immobilizing the short segment of our constructs did significantly improve the stiffness of our type Ia frames by 48%, based on a comparison between the medians of group 1 and group 5. However, this modification was the least effective means of increasing stiffness of the construct.

The second strategy considered to improve the stiffness of hybrid fixators focuses on the addition of linear components between the circular and the linear portions of the frames (11, 12, 15, 26–30). These additions may consist of struts or ‘box’ hybrid configurations (two connecting bars on each side of the bone). The rationale for this approach relies on the origin of the deformation occurring during axial loading. Our results confirm that ring bending is the main mechanism contributing to this deformation, with the connection between the circular and linear components of the fixator acting as a fulcrum. The clinical application of a box configuration is limited to the distal limbs due to anatomical restraints. The application of struts enhances versatility but did not consistently improve the biomechanical properties of hybrid fixators used in humans (9). In our study, the addition of two malleable struts connected to the ring and connecting bar through custom designed hooks (group 6) increased the stiffness of the control group. This construction was more effective than adding a single rigid bar to the ring and connecting the bar through clamps (group 7). The difference in properties between the two frames may be due to the increased resistance to bending of the ring when supported by two struts placed in different planes. These results may also be explained by the methods used to link the struts to the ring and linear rails. All struts used in this study measured 3 mm in diameter, but differed in composition. The aluminium alloy bar is rigid and brittle, requiring adjustment of the clamps’ position to match the axis of the bar. Stainless steel bars are more malleable and can be contoured to accommodate the angle of the locking hooks on the rail and on the ring. This construct may be more effective at preventing the fulcrum at the connection between the linear rail and the circular ring of the fixator. Based on the results of this study, a strut composed of two malleable bars provides superior mechanical support in comparison to a single diagonal bar. These findings are also compatible with the mechanical theory of strut and tie models, mimicking the concept of internal stresses.
generated during eccentric loading of a long bone (31). In this model, bars are placed away from the neutral axis of the bone, one of them being subjected to compression while the contralateral bar is exposed to tension forces. This concept would not apply to frames formed with a single diagonal strut. This single bar could however be oriented in several directions, and further testing would be required to investigate the impact of this variable on the stiffness of the frame. The diameter of the struts in our study (3 mm) was dictated by the locking mechanism of bars with hooks passing through holes coaxial to the rail and ring. The rails and rings measure 6 mm in thickness, thereby limiting the diameter of the holes and hooks to 3.5 and 3.0 mm, respectively. These features allow the addition of light struts and eliminate the need for dedicated clamps, improving cost effectiveness. The diameter of the rigid bar was kept consistent with that of malleable bars. These bars required the use of heavier clamps to be locked, and did not compare favourably with malleable bars in this study. Struts measuring up to 9.5 mm in diameter are commercially available and these may be an alternative to improve the effects of struts on the stiffness of the frame.

Influence of ring thickness

Increasing ring thickness provides a simple, yet effective, alternative to increase the stiffness of the frame, by improving the resistance of the ring to bending. Indeed, the cross-sectional width of a material carries a linear impact on its resistance to bending. However, increasing the cross-sectional height of the same material will be more effective as it will increase its resistance to bending by an exponential factor of 3 or (height)³. This principle explains why increasing ring thickness seemed to be the most effective of the strategies tested here, increasing the stiffness of our control group (comparing group 1 and 3) by 335%. Our study was not designed to encourage clinicians to glue rings together prior to applications in small animals. Instead, these findings serve as a proof of concept to guide future improvement in the manufacturing process of these implants. In that regards, the lower stiffness of the 85 mm diameter double-ring configuration (group 4) compared to the 115 mm double ring configuration (group 3) may seem counter-intuitive. We suspect that the 85 mm double-ring reached a level of stiffness such that it was no longer the most flexible component in the apparatus. Although further investigations would be indicated to support our hypothesis, we believe that bending of the surgical pins, wires, and the linear element generated the majority of the deformation.

The study has inherent limitations. No direct conclusions for specific clinical suggestions can be drawn from a biomechanical test. Moreover, the test evaluated response to axial compression, but not to bending and torsional forces, which are involved in loading the fracture area as well. Finally, group size was limited by availability of implants and budgetary constraints, but remained consistent with previous biomechanical studies where the use of synthetic material limits variability (14, 27).

Conclusions

The control frame evaluated in this study, consisting of a 115 mm diameter ring and type la hybrid fixator, may not be rigid enough to treat comminuted fractures in large breed dogs. Adding two half-pins to the ring increased the stiffness of the construct by 48%. Decreasing the base construction ring diameter from 115 mm to 85 mm increased the initial stiffness of the construct by 175%. Selecting the smallest ring diameter is an effective strategy to increase the stiffness of the frame but remains limited by the local anatomical constraints. The addition of two struts between the ring and the linear connecting rail had a similar effect, increasing the construct stiffness by 75%. The addition of diagonal struts may increase the stiffness of the frame but adds complexity and can be limited by specific anatomical and frame construct constraints. Most of the placement noted during our testing seemed to originate from ring bending. Doubling the ring thickness caused the stiffness of our control frames to increase by 335%. Thicker rings provide a simple, effective way to increase stiffness and are not compromised by size or anatomy of the patient. Moving forward, further tests are required to characterize the specific role of linear components and the medio-lateral and torsional stability provided by constructs with thicker rings.

Acknowledgements

Testing was conducted at the AMTEL testing facility at the University of Illinois at Urbana-Champaign. The authors thank Dr. David Wilson, Colorado State University, for his assistance during the loading tests, John Greenwood, Western University of Health Sciences, for his editing assistance, and Dr. Francesco Dondi, University of Bologna, Italy, for his assistance in statistical evaluation.

Conflict of interest

Dr. Gian Luca Rovesti owns stock options of the Ad Maiora company.

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