Comparison of the axial stiffness of carbon composite and aluminium alloy circular external skeletal fixator rings

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Summary
Objectives: The purpose of this study was to compare the axial stiffness of aluminium alloy and carbon composite single-ring constructs.
Methods: Single-ring constructs were made with rings of different material compositions (aluminium alloy and carbon composite), diameters (55 mm, 85 mm, and 115 mm), and thicknesses (6 mm for the single-ring, 12 mm for the double-ring) with all other components remaining constant. Stiffness of each construct was determined under loading in axial compression with a materials testing machine. The axial stiffness of each group was compared using a three-factor factorial analysis of variance investigating all main effects and interactions between ring diameter, ring thickness, and ring material composition; p <0.05 was considered significant.
Results: Carbon composite constructs were 16-55% as stiff as corresponding aluminium alloy constructs. Within each combination of ring material composition and ring diameter, stiffness did not significantly increase when the ring thickness was doubled. Within each combination of ring material composition and ring thickness, stiffness significantly decreased with increased ring diameter. Clinical significance: Aluminium alloy rings were found to be significantly stiffer than carbon composite rings. Although the carbon composite rings were considerably less stiff, clinical recommendations cannot be made from a single-ring in vitro analysis. Further studies are needed to evaluate the behaviour of these rings in vivo.

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Introduction
Circular external skeletal fixators have gained popularity over the past few decades in human and veterinary medicine (1-6). This method of external fixation can be used to stabilize fractures, correct skeletal deformities, transport bone, and stabilize arthrodeses (1-5, 7, 8). Another, more recent application is in the reduction and realignment of fracture fragments and restoration of normal limb length when performing minimally invasive plate osteosynthesis (9). There are various sizes and styles of components of these fixation systems which allow them to be modified to meet the specific requirements of different patients and clinical scenarios. Differences in the individual components of these constructs and the interactions between components can greatly affect the biomechanics of the construct and heavily influence clinical performance (5, 10-16). Traditionally, these systems used stainless steel or, more recently, aluminium alloy rings (11). The majority of the other components are made of stainless steel. One of the major limitations of these rings is that they are radiopaque and can obscure critical evaluation of postoperative and follow-up radiographs (12). Radiolucent carbon composite rings have long been available in human medicine and have recently become available for veterinary patients (12, 13, 16). Though these rings allow superior evaluation of radiographs, how they compare mechanically to rings made of other materials has not yet been evaluated.

The purpose of this study was to compare the axial stiffness of aluminium alloy and carbon composite single-ring constructs. We hypothesized that the stiffness of carbon composite ring constructs would not be significantly different from the stiffness of aluminium alloy ring constructs of similar diameter. Additionally, we hypothesized that construct stiffness would significantly increase when ring thickness was doubled.
Materials and methods

Rings
The carbon composite and aluminium alloy rings used in this study were identical in shape and size. Each ring contained large oval holes instead of traditional round holes to allow components to be more freely adjusted (Figure 1). The aluminium alloy rings (85 mm diameter aluminium rings) \(a\) are commercially available and have been in standard production for a number of years. The carbon composite rings were a small series production made for the purpose of testing and preliminary clinical use.

The carbon composite rings were made using a commercially available composite. The composite used 3K high strength braided carbon fabric with a fibre areal weight of 195 g/m\(^2\). The fibres were radially oriented with 36 degrees between layers for a total of 10 layers and a final thickness of 6 mm. The fibres were impregnated with 42\% by weight D120 resin. Final fibre content was 58\% by weight. The resin was activated in a mould using polypropylene sheets as a mould releasing film. They were autoclaved at 1 bar and waterjet cutting was used to create the bolt holes in the rings.

Construct preparation
Each single-ring construct consisted of a centrally-placed, 60 mm long, 19 mm diameter, 6 mm wall thickness, polyoxymethylene cylinder\(b\) to simulate a bone segment. Two 1.5 mm diameter Kirschner wires were passed through each segment in the centre of the cylinder, visually aligned at 90 degrees to one another. The wires were alternately tensioned to 60 N using a dynamometric wire tensioner\(c\) and secured to the ring with wire fixation bolts\(d\), washers\(e\), and nuts\(f\). The nuts were tightened to a torque of 10 Nm using a torque wrench\(g\). Four 80 mm stainless steel threaded rods\(h\) were affixed to the ring with two stainless-steel nuts to support the construct on the load cell. The rods were positioned such that they extended 3 cm beyond the end of the cylinder below the ring. An additional nut was placed at the end of each threaded rod. Component variables evaluated were: material composition of the ring (carbon composite and aluminium alloy), ring diameter (55 mm, 85 mm, and 115 mm), and ring thickness (6 mm and 12 mm). Twelve millimetre thickness rings were made by stacking two 6 mm thickness rings directly on top of one another. Six constructs were made for each configuration tested, for a total of 72 constructs.

Mechanical testing
One of each size aluminium alloy ring was placed within each other; the largest (outermost) ring was secured to a 153 mm x 153 mm x 13 mm stainless steel block\(i\) with nuts and bolts (Figure 2). The stainless steel block was then secured to the load cell\(j\) of a servohydraulic materials testing machine. Each construct was placed into the materials testing machine with the bottom nut on each threaded rod seated securely into the ring affixed to the load cell and the central polyoxymethylene cylinder visually aligned with the actuator of the mechanical testing frame (Figure 2). The actuator was lowered until it engaged the polyoxymethylene cylinder of the construct and a preload of 20 ± 2 N was achieved. Each construct was conditioned by cyclically loading 20 times from 20 N to 200 N at a rate of 1 Hz in load control. Following conditioning, each specimen was axially loaded to an actuator displacement of 2 mm. The specimens were loaded in displacement control at a rate of 0.1 mm/sec. Load and actuator displacement were recorded at a rate of 10 Hz using dedicated computer software\(k\).

Measurement of stiffness
A load-displacement curve was made by plotting the load and displacement data for

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\(a\) Ad Maiora, Caviglio, Italy
\(b\) Delrin\(\textregistered\): McMaster-Carr, Aurora, OH, USA
\(c\) Perforated screw (16 mm M5 for single ring and 20 mm M5 for double ring): Ad Maiora, Caviglio, Italy
\(d\) 5.5 mm internal diameter rectangular washer and 15 mm external diameter 5.5 mm internal diameter round washer: Ad Maiora, Caviglio, Italy
\(e\) Stainless steel large flat M5 nut: Ad Maiora, Caviglio, Italy
\(f\) 80 mm M5 stainless steel threaded rod: Ad Maiora, Caviglio, Italy
\(g\) Torque wrench, adjustable click type, fixed-ratchet: Snap-on, Kenosha, WI, USA
\(h\) Multipurpose stainless steel (type 304) block: McMaster-Carr, Aurora, OH, USA
\(i\) Model 75-1507-04: Sensotech, Columbus, OH, USA
\(j\) Model 8511: Instron, Norwood, MA, USA
\(k\) Labview 7 Express: National Instruments Inc., Austin, TX, USA
each construct during testing in a scatter graph using commercially available software. The linear elastic region was identified visually and a best-fit linear trend line and corresponding $R^2$ value were determined using a sum of least squares with the same software. The slope of this line was the stiffness value and was reported in units of N/mm. The axial stiffness of each group was compared using a three-factor factorial analysis of variance investigating all main effects and interactions between ring diameter, ring thickness, and ring material composition; $p < 0.05$ was considered significant.

## Results

The mean weights of the 55, 85, and 115 mm diameter carbon composite rings were 13.7, 19.8, and 26.8 g, respectively. The mean weights of the 55, 85, and 115 mm diameter aluminium alloy rings were 26.5, 38.8, and 50.8 g, respectively. The 55, 85, and 115 mm diameter carbon composite rings were 51.7%, 51.0%, and 53.8% of the weight of the corresponding aluminium alloy rings, respectively.

The mean ± standard deviation axial stiffness values were determined for carbon composite and aluminium alloy single-ring constructs of different ring diameters and thicknesses. Within each combination of ring diameter and thickness, carbon composite rings were significantly less stiff than aluminium alloy rings ($p < 0.01$) (Figure 3). Within each combination of ring material composition and ring thickness, stiffness significantly decreased with increased ring diameter ($p < 0.01$). All but one of the 55 mm ring diameter construct groups were significantly stiffer than corresponding 85 mm ring diameter and 115 mm ring diameter construct groups. The only exception to this was that the mean stiffness of the 85 mm diameter, 12 mm thickness aluminium alloy alloy constructs was not significantly different than that of the 55 mm diameter, 12 mm thickness aluminium alloy constructs ($p < 0.01$). All 85 mm ring diameter constructs were significantly stiffer than the corresponding 115 mm ring diameter constructs.

Within each combination of ring material composition and ring diameter, the stiffness of 6 mm ring thickness constructs was not significantly different than that of the 12 mm ring thickness constructs. The only exception to this was the 55 mm aluminium alloy ring group, in which the mean stiffness of the 6 mm thickness ring constructs was significantly stiffer than the 12 mm thickness ring constructs ($p < 0.02$).

None of the constructs showed any visual signs of plastic deformation or component failure during testing. Additionally, none of the load-displacement curves had significant changes in slope that would represent yield point or component failure.

## Discussion

Our results indicated that aluminium alloy rings were significantly stiffer than carbon composite rings in all tests. Across all groups, the carbon composite constructs were 16-55% as stiff as the corresponding aluminium alloy constructs. These results suggest that it may not be appropriate to use carbon composite rings interchangeably with aluminium alloy rings of the same shape and size. Although the carbon composite rings were considerably less stiff, it is not possible to determine from this study whether or not they are appropriate for clinical use. Further studies are needed to determine how they can be used appropriately in clinical cases considering their significantly lower stiffness.

The results also showed that doubling the ring thickness did not significantly increase the stiffness of the constructs. In this study, ring thickness was doubled by stacking two rings on top of one another. This would suggest that stacking rings is not an appropriate method of adding axial stiffness to a construct. Although increasing ring thickness would logically seem to increase stiffness, it is not clear why this does not significantly change the stiffness of the construct. Grivas and Magnissalis evaluated a twin-ring Ilizarov external fixator, which used stacked rings to increase the stiffness of the construct near a joint (17). Biomechanical testing showed that stacking the rings actually decreased the stiffness of the construct in axial compression and increased stiffness in shear loading, but no clear explanation was elucidated (17). Although not specifically evaluated in this study, one possible reason for this finding is that increasing ring thickness also increases the distance between the orthogonal Kirschner wires, which could decrease stiffness in axial loading.

Results also showed that construct stiffness significantly decreased with increased ring diameter. This result was expected and was due to the increased length of exposed wire. This finding has been demonstrated in previous studies and is the reason that using the smallest diameter ring possible is recommended when using circular external skeletal fixators (10, 14, 16). Since the

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1. Microsoft Office Excel 2010: Microsoft Corp., Redmond, WA, USA.
The ring diameter chosen for a fixator is determined by the size of the patient and effects overall construct stiffness, all results in this study, other than those for the effect of ring diameter, were reported within similar ring diameter sizes.

An important limitation of stainless steel or aluminium rings is their radiopacity (12). Using radiopaque rings in addition to all of the other radiopaque components of circular external skeletal fixators can significantly obstruct viewing of the bone on radiographs and can inhibit critical evaluation of those radiographs. This can make it difficult to accurately assess healing and make decisions on patient care. For this reason, the use of radiolucent fixator rings would greatly benefit clinicians in evaluation and management of clinical cases. An additional advantage of carbon composite rings is that they are significantly lighter than traditional rings. The carbon composite rings used in this study were nearly half the weight of aluminium alloy rings of the same size. This can make the fixators less cumbersome and more comfortable for patients.

Carbon composite using long carbon fibres was chosen for these rings because the structure of this composite is much more consistently isotropic as compared to randomly distributed short carbon fibres, which may be anisotropic depending on the random distribution of the fibres. Because of the consistent mechanical response, long carbon fibre composites have been the industry standard for many different applications. Additionally, a preliminary study performed by one of the authors (G. L. Rovesti, unpublished data) showed long fibre and random short carbon composites to behave very similarly. In this study, long fibre carbon composite rings, similar to those used in the current study, were compared to those made of random short fibre epoxy resin composite in progressive wire tension testing. Both rings demonstrated very similar planar deformation during testing and elastic behaviour when released.

One limitation of this study is that it tested single-ring constructs. Whereas this allows the comparison of two fixator rings, it does not give information on how those rings would behave as part of a complete external skeletal fixator construct. In order to show this, constructs consisting of two or more rings would need to be evaluated. Similarly, this study did not evaluate fracture gap stiffness. This information would be most important in making conclusions about clinical use. Another limitation is that central cylinders of the same diameter were used for each construct, regardless of the ring diameter. Since the diameter of the ring used in a clinical scenario is based on the diameter of the limb, some of these ring sizes may not be appropriate for a limb with bone the same diameter as the central cylinder of our constructs. Ring diameter selection in clinical cases is based on bone diameter and soft tissue coverage of the bone. Additionally, this study only evaluated stiffness in axial compression. Axial compression testing was chosen because this is the major force in weight-bearing and would be the most significant mode of loading the constructs clinically. However, a more thorough evaluation including bending and torsional loading forces may have led to different conclusions.
Aluminium rings have been used in ring fixators for many years in veterinary medicine with great success (1-4). For this reason, they were used as the standard to which carbon composite rings were compared for the purposes of this study. It was assumed that aluminium alloy rings provide a mechanical environment that is appropriate for clinical use (11). Considering that the carbon composite ring constructs were significantly less stiff than the aluminium alloy ring constructs, it cannot be confirmed that they are appropriate for clinical use, though we also do not have enough information to conclude that they are unfit for clinical use. These rings may still be stiff enough to inhibit destructive forces and provide an appropriate healing environment at the fracture gap in vivo. Additionally, these rings could be useful in scenarios where a less rigid fixator is preferred. To better evaluate how these rings would behave in vivo, either a biomechanical evaluation of a multiple-ring construct focusing on fracture gap stiffness or a clinical trial would be necessary.

On the basis of the results of this study, it cannot be stated that these carbon composite fixator rings are appropriate for clinical use. Though the carbon composite rings were considerably less stiff, clinical recommendations cannot be made from a single-ring, in vitro analysis. Further studies are needed to evaluate how these rings would behave as part of a three- or four-ring external skeletal fixator or in vivo. It is possible that, though less stiff, these rings are still sufficiently stiff for use in select clinical cases.

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Conflict of interest

One of the authors (GL Rovesti) owns shares of the Ad Maiora Company. There are no conflicts of interest to declare for the other authors.

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