

Reducing the Risk of Ring Breakage in Taylor Spatial Frames: The Effect of Frame Configuration on Strain at the Half-ring Junction

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ABSTRACT

Aim: We have encountered four cases with Taylor spatial frames (TSF) (Smith & Nephew, Memphis, TN, USA) with breakage at the half-ring junction of the distal ring. This study examines the strain produced on different locations of the distal ring during loading and the effects on the strain of altering the frame construct.

Materials and methods: We mounted two ring TSF constructs on tibia saw bone models. The proximal ring was the same in all constructs and consisted of a 2/3 180 mm ring attached with three wires. Construct 1 is reproducing the configuration of cases where failure was seen. The distal 155 mm ring is attached with three half pins. The half-ring junction is located in the midline. Construct 2 has a different half pin placement and an additional wire on the distal ring. Constructs 3 and 4 have the same half pin configuration to construct 1 but the distal ring is rotated 60° internally and externally, respectively. Strain gauges were attached to different locations and measurements recorded during loading. Statistical analysis was performed.

Results: Highest strain values were recorded at the half-ring junction of constructs 1 and 2 (>600 microstrains (µε) in tension). Rotating the ring 60° internally significantly reduces the strain at the half-ring junction (<300 µε) whilst external rotation by 60° further reduces the strain (<180 µε). Ring strain is higher in areas close to half pin attachments.

Conclusions: The highest strain is in the half-ring junction as the half rings are subjected to different loading modes. The thickness of the half-ring is halved and the second moment of area reduced further increasing breakage risk. Placing this junction close to the half pin-frame interface, as dictated by the anatomical safe zone further increases the strain. Rotating the distal ring 60° significantly reduces the strain at the half-ring junction.

Clinical significance: Ring breakage is a rare but significant complication. This is the first study to address this potential mode of TSF failure. Insights and technical tips from this study can help reduce this.

Keywords: Circular external fixator, Complication, Deformity correction, Taylor spatial frame.

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INTRODUCTION

The use of external fixator frames has evolved, both as a result of a better understanding of principles and techniques in their application and hardware development, to allow the treatment of a wide variety of orthopaedic pathologies.^{1,2} There is extensive literature exploring the biomechanics of these constructs.³⁻⁸ Common complications, such as pin site infection have been thoroughly investigated to develop techniques to prevent and address them.⁹⁻¹²

Ring fracture is a rare but significant complication in reconstructive surgery employing frames. There is a need for revision surgery and prolonging the course of treatment. In our unit, we perform large numbers of cases where frames are applied for a variety of pathologies and treatment modalities. We have encountered four cases where there has been breakage at the half-ring junction of Taylor spatial frames (Smith & Nephew, Memphis, TN, USA) (Fig. 1). The half-ring junction is an area of weakness as the thickness of the individual half rings is halved and hence the second moment of area is reduced eight-fold. There are various situations where the anatomy of the patient, the underlying pathology or implant availability and the frame configuration preclude the application of full rings.

This study aims to examine the strain produced at different locations on the ring during loading and the effect of altering the construct configuration, to determine ways to reduce the risk of

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breakage. To our knowledge, there has been no previous study examining this mode of failure, the strain patterns in different locations on the ring and the effect of altering frame configuration in the strain produced.

MATERIALS AND METHODS

We conducted an experimental observational study. We created four frame constructs similar to those employed in clinical practice using

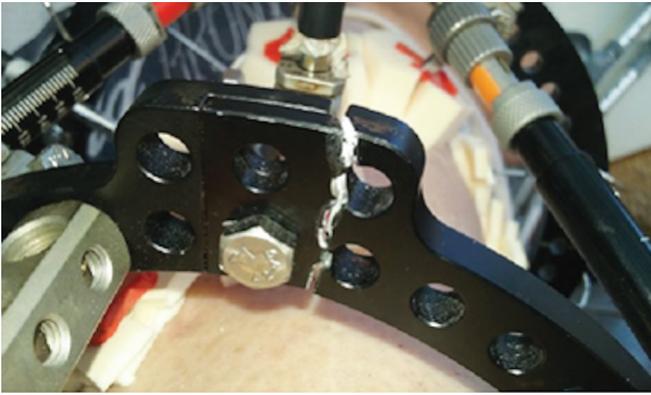


Fig. 1: Breakage of the distal ring at the half-ring junction encountered in our practice

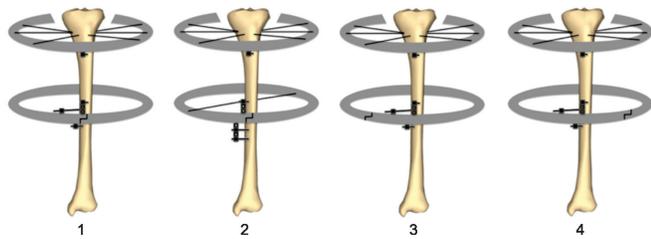


Fig. 2: Different constructs created for our experiment; (1) three half pins near the half-ring junction, all attached to one half-ring—as seen in the constructs where breakage was observed, (2) three half pins near the junction and one additional olive wire, (3) same half pin configuration as construct A with the half-ring junction rotated 60° internally, (4) same half pin configuration as construct A with the half-ring junction rotated 60° externally

the Taylor spatial frame (TSF). All were two ring constructs using a 180 mm 2/3 proximal ring and a 180 mm distal ring (two half rings) connected by six medium Fast Struts. They were mounted on 4th generation composite, 17 PCF Solid Foam Core, Large Tibia Sawbones (Sawbones Europe AB). One 6 mm half pin and three tensioned 2 mm olive wires were used for the proximal 2/3 ring and mounted using TSF instrumentation. Using a saw, the bone was excised to create a 2 cm gap preventing any contact between the proximal and distal parts for the load to be distributed across the frame.

For the distal rings, four different constructs were created for this experimental study. Construct 1 has three half pins attached in a configuration similar to the constructs that failed in our practice. Construct 2 has a different configuration with three half pins and a wire. Construct 3 has the same half pin configuration as construct 1 but with the distal ring internally rotated 60° whilst construct 4 has the junction 60° externally rotated (Fig. 2).

Uniaxial strain gauges (SG) (GFLA-3-50, Tokyo Sokki Kenkyujo, Tokyo, Japan) were attached to three locations on the distal rings (Fig. 3); location 1 is 60° medial to the mid coronal plane, location 2 is in the mid coronal plane and location 3 is at 60° lateral to the mid coronal plane. One strain gauge was attached to the top and one to the bottom of the ring to measure tension and compression strain, respectively. Whenever the half-ring junction was in one of the locations, one strain gauge was attached on each side of the junction and a third strain gauge was attached directly over the joint to measure tension strain.

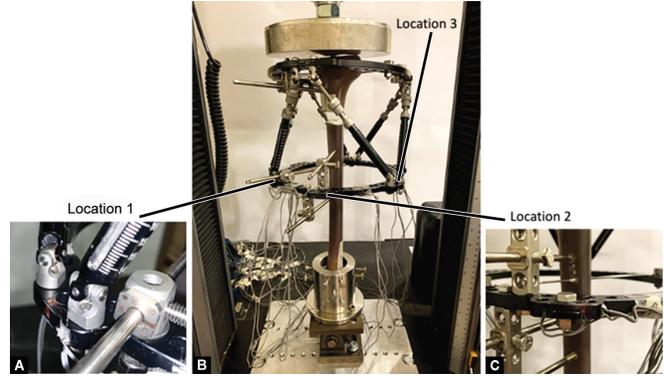


Fig. 3: The three different locations at which strain gauges were placed. Location 1 is 60° medial to the mid coronal plane, location 2 is in the mid coronal plane and location 3 is at 60° lateral to the mid coronal plane. This picture shows construct 2 whereby the half-ring junction is found in location 2. The position of the strain gauges in locations 1 and 3 are the same, whereas an additional strain gauge is placed on top of the joint at the half-ring junction (location 2)

The sites of strain gauges were degreased with ethanol and roughened with 400 grit sandpaper and then cleaned with ethanol again. Strain measurements were collected after loading to 200N using a universal testing machine (Instron 5969, Instron, Northwood, MA, USA). We repeated the loading process six times for each construct to improve the accuracy and reliability of our data. 200N loads were applied as they are well within the range of elastic deformation of the rings so that all repeat measurements could be performed and considered independent.

Statistical analysis of our data was performed using SPSSv21.0 (IBM, NY, USA). Kolmogorov–Smirnov was used to explore the normality assumption for each group. Kruskal–Wallis test and post hoc analyses were subsequently performed.

RESULTS

Construct 1

In location 1, strain gauge (SG) 1 (top of the ring) recorded tension meaning that the ring is bending. The strain is 148.64 $\mu\epsilon$. SG2 (bottom of the ring) recorded a strain value of 12.89 $\mu\epsilon$ in compression.

Location 2 is the half-ring junction. SG1 (left of the joint) recorded a compressive strain of 125.60 $\mu\epsilon$. SG3 (right of the joint) and again recorded compressive strain with a value of 11.08 $\mu\epsilon$. SG2 measures strain at the top part of the half-ring junction. It recorded 651.18 $\mu\epsilon$ in keeping with the area being the most susceptible to failure.

At location 3, SG1 (top) recorded a strain of 67.94 $\mu\epsilon$ in tension and SG2 (bottom) a strain of 6.49 $\mu\epsilon$ in tension.

Construct 2

In location 1, SG1 recorded tension of 46.83 $\mu\epsilon$ and SG2 3.81 $\mu\epsilon$. These strains are in the same magnitude as location 3 (60 degrees lateral to the junction).

Location 2 is where the half-ring joint is located. SG1 (left) recorded a compressive strain of 166.57 $\mu\epsilon$. SG3 (right) recorded a compressive strain of 47.46 $\mu\epsilon$. SG2 (top of the joint) recorded a strain of 689.68 $\mu\epsilon$ in tension. These values again demonstrate that the highest strains are experienced at the half-ring junction.

Construct 3

In location 1 where the half-ring junction is in this construct, SG1 (left) recorded a compressive strain of 151.14 µε. SG2 (top) recorded 305.88 µε in tension. The rotation of the half-ring joint by 60° to this location has reduced strain by >50%. SG3 (right) recorded 31.56 µε in compression.

In location 2, SG1 recorded tensile strain of 283.90 µε and SG2 compressive strain of 47.17 µε. In location 3, SG1 recorded tensile strain of 214.17 µε and SG2 compressive strain of 15.82 µε.

Construct 4

For the final part of our experiment, we rotated the half-ring junction 60° lateral to the midline. This further reduced the strain recorded at the top of the junction (SG2) to 158.34 µε. This is the lowest strain value recorded for the half-ring junction in our study.

As we have repeated the loading process six times for each construct, we have obtained six maximum strain values for each construct for the top of the half-ring junction location which has been our area of interest (Fig. 4, Table 1).

Kolmogorov–Smirnov test suggested normality was met in each group ($p > 0.05$); however, this test lacks the power to detect violation from normality in small samples. According to skewness indicators, normality of the dependent variable strain was met in constructs 1–3, whilst construct 4 showed a slightly right-skewed distribution. This was not due to the presence of outliers.

Therefore, the non-parametric test Kruskal–Wallis was used to test for group differences. This showed significant differences between constructs (construct 1: M (SD) = 691,99 (3,51); construct 2: M (SD) = 604,76 (7,35); construct 3: M (SD) = 311,00 (11,93); construct 4:

M (SD) = 155,95 (1,11). (H (3) = 21.60; $p = .000$). Post-hoc analyses (stepwise step-down method for homogeneous subsets) indicated that significant differences occur between each of the four constructs.

DISCUSSION

Reflecting on the four cases encountered in our practice where there has been a failure of the construct by breakage of the ring at the half-ring junction we sought to determine the mode of failure. Based on the patterns observed we have attributed this to net tension failure.

Analysis of our experimental results raises various points for consideration. In the first construct, the highest strain is recorded at the top of the half-ring junction (651.18 µε). This, coupled with the inherent weakness of the ring in this area is in keeping with it being the most susceptible to failure. Comparing the values obtained in location 1 (148.64 µε) and location 3 (67.94 µε) we see that ring strain is less in these parts of the half rings and that the further away they are from half pin attachments the less is the strain.

On the second construct, we have altered the half pin interface position to allow for a wire to be placed determining whether there is an effect on reducing tension at the junction by allowing for a more balanced distribution of loads across both half rings. This has not been observed. The closer proximity of the half pins to the junction (to allow for wire placement) has led to higher strain production at the top of the junction (689.68 µε). Small changes in strain are seen in locations 1 and 3 when compared to construct 1 as a result of the proximity to the wire attachment.

The most significant changes in the strain at the junction are seen on rotating the distal ring. In construct 3 the strain observed is more than halved (305.88 µε) by 60° of internal rotation. In construct 4 the most significant reduction is observed, the strain is further reduced (155.56 µε) by externally rotating the ring, and therefore, placing the junction the furthest from half pin attachments.

The half-ring junction is a potential area of weakness for two reasons. The thickness of the individual rings at this junction in TSF is halved, and therefore, the second-moment area of the structure is significantly reduced as it is inversely proportional to the third power of the width. This is not the case in Ilizarov frames (Fig. 5).

Furthermore, one of the two half rings often has all the half pin attachments to the bone and this creates different loading modes between the two halves as demonstrated in our study. This is because the insertion of half pins in the distal ring is dictated by the anatomy and safe zones that are established.¹³ Given the triangular anatomy of the bone at this level, all attachments are commonly placed near the half-ring junction (when it is placed in the midline) and on only one of the two half rings as has been the case in our constructs. Despite full rings being available their use is often not possible due to various intra-operative technical aspects such as patient anatomy, sequence of the frame assembly and ring fixation.

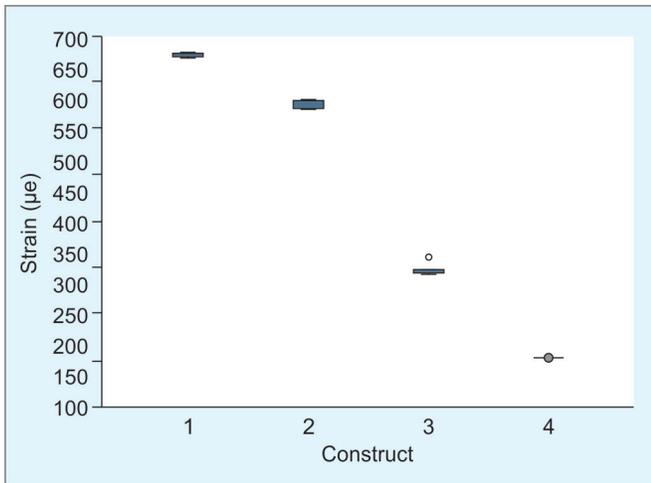


Fig. 4: Box plot of strain measurements of the four constructs

Table 1: Strain recordings at the top of the joint of the half-ring junction in each of our four constructs

TSF constructs	Maximum strain measurements (µε) @ top of the half-ring junction						Average
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	
Construct 1	689.48	695.91	691.64	688.61	689.54	696.72	691.98
Construct 2	613.15	613.69	596.60	605.29	598.12	601.70	604.76
Construct 3	303.48	301.45	308.10	305.56	313.58	333.81	311.00
Construct 4	155.56	155.92	157.84	155.74	154.41	156.22	155.95



Fig. 5: Differences between the Taylor spatial frame (top) and Ilizarov frame (bottom) at the half-ring junction

One limitation of this study is the small number of loading repetitions per each construct and this should be taken into consideration when interpreting our results.

In frame constructs in which wires are used, the strain will change with cyclic loading from the slippage of the wires in their fixation points and loss of tension. This is important in that the strain behaviour of the construct may change accordingly.

Furthermore, a simple loading condition (standing position) was considered in the current analysis. Further testing in cyclic and dynamic (walking) loading conditions may provide additional information. Further analysis of strain at different locations and load mapping may provide us with more information and allow us further understanding the complex distribution of forces in these constructs.

There is variation in results obtained within constructs on repetitive loading. A control analysis was performed (repeated measures ANOVA) which has demonstrated that this is of no significance. It may be accounted for by the relatively minor changes in the position of the construct within the loading apparatus as it is secured by tightening bolts or wire slippage as previously mentioned. Loading to 200N is well within the range of elastic deformation of the rings and should therefore not affect subsequent results.

In all of our cases, the frames were applied for prolonged treatment periods and all of our patients had high BMIs. A linear relationship between load and strain is demonstrated in all of our measurements. Therefore, the constructs were subjected to high loads and the high strain was produced over a prolonged period leading to fatigue failure. Therefore, the observations from our study would be more relevant when dealing with such cases.

Finally, frames are applied for a great range of pathologies and deformity corrections, and therefore, the frame alignment will have a significant effect on load distribution and strain production. When employing chronic mode for correction one would anticipate the frame to be aligned during the consolidation phase. Given

that fatigue failure of the construct will most likely occur during this period our experimental constructs were overall aligned to reflect that.

CONCLUSION

Our results demonstrate that upon loading, a high strain is produced at the half-ring junction of the distal ring as a result of the different loading patterns in the two half rings. The strain is significantly higher in locations close to half pin attachments.

Although rare, ring breakage has been observed and it is more likely to occur at the half-ring junction in TSF due to the thickness of the individual rings being halved.

Rotating the distal ring allows us to place the junction at a distance to the frame bone interfaces and this leads to a significant reduction in strain in this area which is the most susceptible to failure. Externally rotating the distal ring by 60° leads to the most significant reduction of approximately 75%.

CLINICAL SIGNIFICANCE

This simple technical tip should be taken into consideration in relevant cases to try and minimise the risk of failure. To our knowledge this is the first study to address this potential mode of failure of TSF.

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We have not sought any approval for conducting this study involving only experimental models and testing in laboratory conditions. Written consent has been obtained for the use of clinical photographs (Fig. 1).

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