ORIGINAL RESEARCH

Application of the Modified RUST Score in Tibial Bone Transport and Factors Associated with Docking Site Complications

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Abstract

Aim: Reconstruction of segmental bone defects with bone transport is a well-established treatment. Mechanical complications at the docking site after frame removal are common. These complications include malunion, non-union, axial deviation and refracture. A simple tool to assess the healing of the docking site is currently lacking. The aim of this study is to evaluate the use of the modified RUST (mRUST) score in the setting of bone transport and to identify factors associated with an increased risk of docking site complications.

Methods: This retrospective study was conducted at a single tertiary centre in South Africa, included 24 patients with a tibial bone defect treated with bone transport and a circular frame between 2014 and 2023. Demographic data, clinical and bone transport characteristics were recorded. Mechanical complications, such as fracture, non-union, any angulation >5°, shortening >5 mm, or any other complication requiring reoperation, were recorded. The mRUST was adapted as a ratio for the purpose of this study to overcome the common occurrence of cortices being obscured by the frame. The mRUST ratio was applied before and after frame removal for each patient by three appraisers. Comparison between the groups with and without complications was performed regarding bone transport characteristics, docking site configuration and mRUST ratio. The correlation of the score between radiographs before and after frame removal was assessed. The inter-rater reliability of the mRUST was analysed using Fleiss Kappa statistics for each cortex individually and the intraclass correlation coefficient (ICC) for the mRUST ratio.

Results: In this study, 20 men and 4 women with a median age of 26 years were included. The overall rate of mechanical complications after frame removal was 21.7%. Complications were all related to the docking site, with two angulations, two fractures and one non-union. Demographics, bone transport characteristics and mRUST ratio before and after frame removal were similar between the two groups. Regarding the configuration of the docking site, an angle of 45° or more between the bone surfaces was associated with the occurrence of mechanical complications ($p < 0.001$). The correlation of the mean mRUST ratio before and after frame removal showed a moderate relationship, with a Spearman correlation coefficient of 0.50 (p-value 0.13). The inter-rater reliability of the mRUST was "fair" (kappa 0.21–0.40) for the scoring of individual cortices, except for one score which was "slight" (kappa 0.00–0.20). The ICC of the mRUST ratio was 0.662 on radiographs with the frame, and 0.759 after frame removal.

Conclusion: This study did not find the mRUST or mRUST ratio useful in assessing the healing of the docking site to decide on the best time to remove the frame. However, a notable finding was that the shape and orientation of the bone ends meeting at the docking site might well be relevant to decrease complication rates. If the angle between the bony surfaces is 45° or more, it may be associated with an increased risk of complications. It may be worthwhile considering reshaping these bone ends at the time of debridement or formal docking procedure to be more collinear, in order to reduce the potential for mechanical complications such as non-union, axial deviation or refracture at the docking site.

Keywords: Bone transport, Critical bone defect, Distraction osteogenesis, Docking site, Docking site complication, Frame removal, Ilizarov frame, Modified RUST score, Segmental bone loss.

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Introduction

Complex tibia fractures are common injuries and bone defects following open fractures or fracture-related infections are challenging to treat.[1] Distraction osteogenesis (bone transport) using a circular external fixator, as described by Ilizarov, is a well-established treatment option for the reconstruction of segmental bone defects.[1–3]

Mechanical complications following bone transport include refracture (4–21%), malunion (4–22%),[4–6] axial deviation (22–70%),[6] non-union (0–40%)[7–9] and callus subsidence.[10,11] These complications can be related to both the transport site and the docking site. A recent retrospective study on 103 patients noted a complication rate of 53% at the docking site.[8] Premature removal of the external fixator is one of the factors that has been associated with an increased rate of non-union at the docking site.[8]

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Although distraction osteogenesis is a well-known treatment, especially in low and middle-income countries,[12] the safe timing of frame removal to avoid such complications is still poorly defined.[13] Several methods have been described to assess the transport site (the regenerate bone), including a radiograph-based classification,[14] as well as pixel value ratio and DEXA.[15–18] On the other hand, there is currently no specific tool for assessing the union at the docking site. Given the high rates of complications reported at the docking site, particularly in terms of mechanical complications, guidelines for the safe and timely removal of the frame following bone transport using simple and inexpensive assessment, such as standard X-rays, would be of clinical value.

The RUST score – Radiographic Union Score for Tibial fractures – developed by Whelan et al.,[19] then modified by Litrenta et al.,[20] is a simple rating system based on standard X-rays. The modified RUST (mRUST) consists of scoring each cortex on the anteroposterior and lateral radiographs on a 4-point scale. The final score is the sum of the four cortices, with a value from 4 to 16. It has been demonstrated that the score is well correlated with bone healing and biomechanical properties in animal models.[21–23] A cut-off of 11 points is recognised as the minimum threshold for union, and 13 points as definite union.[20,21] The modified RUST has been shown to have good interobserver reliability[20,23] and has been used in various clinical settings,[24–27] including tibial shaft fractures with bone defects.[28] This latter study is, to our knowledge, the only one to include some patients with a circular external fixation frame. While the study did not look at bone transport specifically, it did highlight the potential problem of applying the mRUST score in this situation, due to the frame elements obscuring the view of one or more cortices.

To our knowledge, the mRUST score has never been applied to the docking site in the setting of bone transport with a circular frame. It could represent a simple tool to help determine the optimal time for safe frame removal with reduced risk of complications. We therefore aimed to assess the application and the interobserver reliability of the mRUST score in bone transport, in an adapted manner, to account for the potential obstruction by the frame. Secondarily, we aimed to identify factors associated with an increased risk of docking site complications.

Methods

This retrospective study was conducted at a single tertiary centre in South Africa. Ethical approval was obtained from the relevant ethics committee prior to conduction of this study (protocol reference number BREC/00006615/2024). Between 2014 and 2023, 29 patients underwent a tibial bone transport using a circular external fixation frame. Patients older than 13 years were included if complete radiological follow-up with the frame was available. For the analysis of complications, only patients with at least one additional follow-up visit after frame removal were retained. After reviewing the radiological records, five patients were excluded, three due to incomplete radiological records, and two due to not having completed their treatment at the time of the analysis. The remaining 24 patients were included in the study. Another patient was excluded from the complications analysis because no radiological follow-up was available after frame removal.

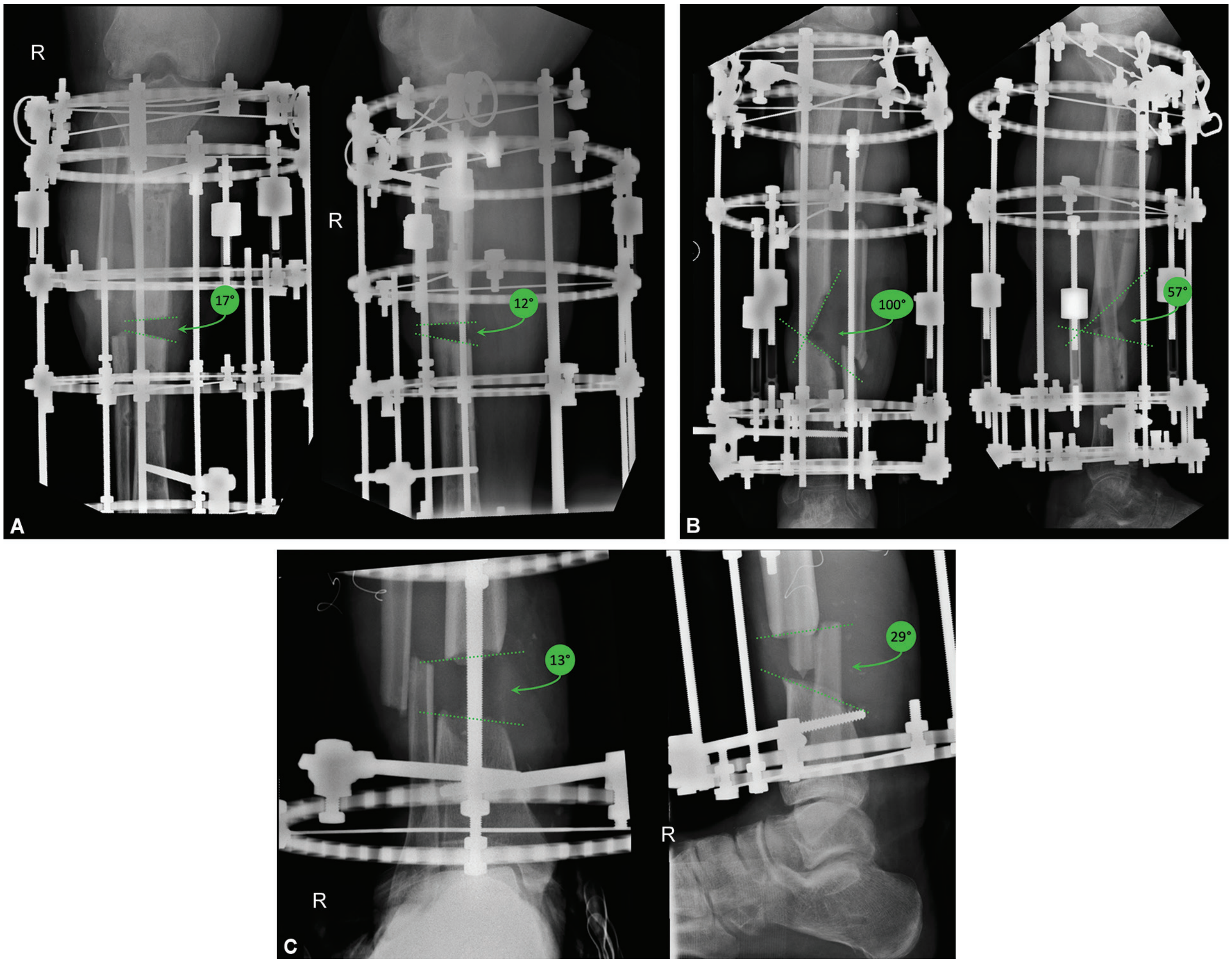
Demographic data (age, sex) and baseline bone transport characteristics were recorded as follows: we included the location and size of the bone defect at the time of frame application; the presence or absence of a cement spacer prior to transport frame application; the site of the distraction (proximal, distal or trifocal); the distraction regenerate size; the duration of bone transport; the total duration of the frame as well as the external fixator index (EFI) and the follow-up duration for each patient. The configuration of the docking site was described in terms of the relationship between the two bone ends and the angulation (collinearity) between their surfaces on anteroposterior and lateral views was recorded, with 0° corresponding to the two surfaces being parallel to each other (Fig. 1). This measurement was made on the postoperative radiographs providing the best views of both bone ends, taken within two months following the application of the transport frame. Complications occurring after frame removal, either at the docking site or at the transport site, were recorded, based on the radiological file, and defined as follows: fracture, non-union, any angulation >5°, shortening >5 mm, or any other complication requiring reoperation.

Bone Transport Procedure

All bone transport procedures were performed by three experienced consultant surgeons in limb reconstruction surgery in a limb reconstruction unit, applying a standardised management strategy. The index surgery consisted of cement spacer and monolateral external fixator removal, followed by the application of a circular transport fixator with a combination of fine-wires and half-pins. A metaphyseal tibial osteotomy was then performed according to De Bastiani technique,[29] either proximal or distal as appropriate, or at both sites in the case of trifocal transport. Bone transport was started 7 days after the procedure, at a rate of 1 mm or 0.5 mm per day in 0.25 increments for proximal-to-distal and distal-to-proximal transport, respectively. Once the transport bone segment reached the end of the bone gap, that is, the docking site, the second procedure was performed. Autogenous bone graft was inserted at the docking site together with fracture end refreshening and compression of bone ends (formal docking procedure). Weight-bearing as tolerated was allowed during the whole duration with the frame. The patients were followed up on an out-patient basis with clinical and radiographic examinations every 4–6 weeks. Once the docking site and regenerate bone site was deemed to have sufficient mineralisation or "united" by the senior surgeons, the frame was "destabilised" by modifying the frame to allow full weight-bearing of the bone through both the regenerate site and docking site and the frame was left *in-situ*. The patient was allowed to continue full weight-bearing for a further 2 weeks, whereafter the frame was removed if the patient had not experienced pain, subsidence or any angulation at the regenerate or docking site upon clinical and radiographic examination. After frame removal, additional radiographs were obtained and assessed.

Adaptation and Application of the mRUST Score

For each patient, the mRUST score was calculated for the docking site twice, before and after frame removal, on anteroposterior and lateral X-rays taken on the same day. Two consultants and one senior orthopaedic surgeons, experienced in bone transport, participated in the scoring process. The appraisers were blinded to the name of the patient and radiological history. They were asked to score each cortex on sets of anteroposterior and lateral radiographs, in two random sequences, for pre- and post-frame removal. According to the mRUST score,[20] each cortex (four in total) was graded as: 1 = no callus, 2 = callus present, 3 = bridging callus



Figs 1A to C: Examples of measurements of the angle between the surfaces of bone ends that will meet to form the docking site, on anteroposterior and lateral views. For each case, the absolute value in degrees was used to compare the median between the groups with and without complication, on the anteroposterior and lateral views, respectively. For cut-off analysis, an angle of ≥45° on at least one of the two views was considered to be above the cut-off. (A) and (C) are examples of cases below the cut-off and without complications, whereas (B) is an example of a case above the cut-off of 45°. The case shown in (B) was complicated by a fracture at the docking site 2 years after frame removal

and 4 = remodelled, fracture not visible. Each cortex was scored individually and combined to give a final score.

To overcome the common occurrence of the bone cortices being obscured by the frame, we made the following adaptations to the mRUST score. On the pre-frame removal radiographs, if one or more of the cortices were not visible, the scorers were instructed to score this cortex as "X". Instead of using the sum of the four cortices (as the mRUST was originally described), we used the mRUST as a ratio to allow assessment of the score even when some of the cortices were hidden by the frame and to allow comparison between the two sets (before and after frame removal). This ratio was calculated by dividing the sum of the scored cortices by the highest possible score, that is divided by 16 if the four cortices were visible, by 12 if only three cortices were visible, by 8 for two cortices and by 4 for a single visible cortex (Fig. 2). The maximum mRUST ratio is therefore 1. The mRUST ratio applied to the sets of radiographs after frame removal would always be obtained by dividing the sum by 16, as the four cortices are visible in this situation. Since an mRUST score of 11 is recognised as the minimum threshold for union,[20,21] this corresponds to an mRUST ratio of 0.69 (11/16). Similarly, an mRUST ratio of 0.81 (13/16) represents the cut-off for definite union.

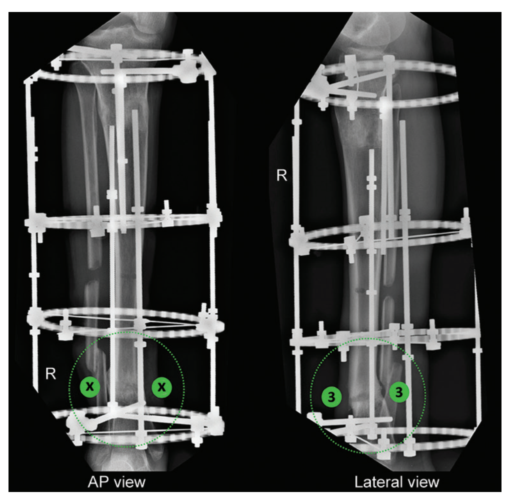


Fig. 2: Example of the application of the mRUST ratio at the docking site. mRUST scores: 1 = no callus, 2 = callus present, 3 = bridging callus, 4 = remodelled, fracture not visible. mRUST ratio = (sum of the grades of each visible cortex)/(number of visible cortices × 4). In this example, mRUST ratio = (3 + 3)/(2 × 4) = 0.75

The score of each individual cortex and the mRUST ratio of the three appraisers were recorded for each set of radiographs, as well as the number of cortices seen by each appraiser for each set of pre-frame removal radiographs.

Statistical Analysis

Data were processed and analysed using Stata 15.0 (StataCorp. College Station, Texas), Jamovi statistical software (version 2.2.1) and IBM SPSS Statistics (version 29.0.2.0). The Shapiro–Wilk test was used to analyse the distribution of the data. Baseline data and complication rates were presented as descriptive statistics. Continuous variables were reported as mean (standard deviation [SD], range) or median (interquartile range [IQR], range), and categorical variables as number and percentages.

The Mann–Whitney *U* test and Fisher's exact test were used to compare baseline characteristics between the groups with and without complications for continuous and nominal variables, respectively. To analyse the relationship between the mRUST ratio and the occurrence of complications, the mean mRUST ratio of the three reviewers was used and compared between the two groups by linear regression. The number of cortices seen on the pre-removal radiograph sets was also compared by linear regression. Spearman's rank correlation was used to determine the correlation between the pre-and post-removal mRUST ratios, using the interpretation of the coefficient reported by Schober et al.[30] All tests were two-sided, and the level of significance was set at $p < 0.05$.

Inter-rater reliability was assessed for the mRUST ratio and the individual score given to each cortex, before and after frame removal, and for the number of cortices seen on the radiographs before frame removal. The Fleiss Kappa coefficient and Krippendorff's Alpha (KA), which are appropriate for assessing the inter-rater reliability of ordinal data, were used.[31,32] The interclass correlation coefficient (ICC), which is appropriate for continuous data, was also calculated, in a two-way random model with absolute agreement, to allow comparison with previous studies on the reliability of the RUST score.[19,20,23,33] For both coefficients, a value of 1 indicates perfect agreement. The strength of agreement proposed by Landis et al.[34] was used to interpret the kappa statistics. To our knowledge, no interpretation of the ICC has been described, except that 0 indicates no agreement and 1 indicates perfect agreement.

Table 1: Demographics and transport characteristics

Characteristic	*n = 24*
Age	25.5 ± 14 (16–47)
Gender ratio (male:female)	20:4
Fracture side (right:left)	12:12
Cement spacer before transport frame	23 (96%)
Tibia bone defect site	
Proximal third	1 (4.2%)
Middle third	15 (62.5%)
Distal third	8 (33.3%)
Site of distraction	
Proximal	22 (91.7%)
Distal	1 (4.2%)
Trifocal	1 (4.2%)
Bone defect size, mm	43.5 ± 27 (15–114)
Distraction regenerate size, mm	44.0 ± 32 (20–113)
Duration of transport, days	80.5 ± 61 (42–222)
Duration with frame, days	311.5 ± 162 (209–537)
External Fixator Index, days/cm	67 ± 55 (24–305)
Follow-up after frame removal, days	112 ± 205 (0–989)

Values are presented as median ± IQR (range) or *n* (%) unless indicated otherwise

Table 2: Complication rates

Complication	*n = 23**
Overall complications	5 (21.7%)
Transport site complications	0
Docking site complications	5 (21.7%)
Angulation at docking site	2 (8.7%)
Fracture at docking site	2 (8.7%)
Non-union at docking site	1 (4.4%)
Shortening	0
Reoperation (1× angulation, 1× fracture, 1× non-union)	3 (13%)

Values are presented as *n* (%). *One patient excluded as no follow-up available

Results

The study population consisted of 20 males and 4 females, with a median age of 26 years. The most common defect location was the middle third of the tibia and the most common type of distraction was bifocal transport, from proximal-distal. The median EFI was 67 days/cm and the median follow-up after frame removal was 112 days. Demographic and detailed transport characteristics are shown in Table 1.

The overall rate of mechanical complications was 21.7%, occurring in five patients (Table 2). All complications were related to the docking site and three patients required reoperation. These three patients all underwent intramedullary tibia nailing. The first patient had a 16° valgus angulation occurring 3 weeks after frame removal (Fig. 3). The second patient sustained a docking site fracture two years after the removal of the frame, and the third had a persistent non-union at the docking site. The two remaining patients with complications were treated non-operatively. The first had a gradual valgus deformity which never progressed beyond 7°, and the other, lost to follow-up for 1-year post removal, presented with hypertrophic callus at the docking site and signs of previous fracture, and was again lost of follow-up before management of this hypertrophic non-union.

The 5 patients who developed complications were compared to the 18 patients without complications (Table 3). No statistical difference was found in demographics and bone transport characteristics, except for the length of time of the follow-up. The mean mRUST ratio was not statistically different between the two groups, on radiographs before and after frame removal. For both groups, the mean mRUST ratio was above the minimum threshold for union, namely 0.69. The mean number of cortices seen on X-rays with the frame was 2.96 and 3.40, for the group without complications and with complications, respectively. Therefore, the radiological assessment of the docking site was not made more difficult by the potential obstruction of the cortices by the frame in the patients who had complications.

For the entire study population, the mean number of visible cortices was 3.0. The mean mRUST ratio was 0.70 with the frame and 0.77 without the frame. The correlation of the mean mRUST ratio before and after frame removal showed a moderate relationship, with a Spearman correlation coefficient of 0.50 (*p*-value 0.13).

Figs 3A to E: 41-year-old male, with a left tibia bone defect of irregular shape, initially managed with monolateral external fixator and cement spacer (A). Bone transport was performed over a length of 34 mm. The EFI was 81 days/cm. Angles of the surfaces at the docking site are shown in (B). The circular frame was removed 273 days after its application (C). A 16° valgus angulation was noted 3 weeks after frame removal (D) and was treated with tibia nailing (E)

Table 3: Comparison of groups with and without complications following removal of the frame

Variable	*No complication (n = 18)*	*Complication (n = 5)*	*p-value*
Demographics and transport characteristics			
Age	24.5 ± 13 (16–47)	29 ± 20 (20–45)	0.491[a]
Gender (male:female)	14:4	5:0	0.539[b]
Tibia bone defect site			
Proximal third	1 (5.6)	0	1.00[b]
Middle third	10 (55.6)	4 (80)	0.611[b]
Distal third	7 (38.9)	1 (20)	0.621[b]
Site of distraction			
Proximal	16 (88.9)	5 (100)	1.00[b]
Distal	1 (5.6)	0	1.00[b]
Trifocal	1 (5.6)	0	1.00[b]
Bone defect size, mm	43.5 ± 25 (15–114)	32.6 ± 45 (26–82)	0.971[a]
Distraction regenerate size, mm	44.0 ± 20 (22–113)	33.6 ± 53 (20–80)	0.745[a]
Duration of transport, days	76 ± 49 (42–222)	98 ± 50 (49–119)	0.446[a]
Duration with frame, days	297 ± 72 (209–537)	364 ± 164 (273–503)	0.111[a]

(Contd...)

Table 3: *(Contd...)*

Variable	*No complication (n = 18)*	*Complication (n = 5)*	*p-value*
External Fixator Index, days/cm	61.4 ± 62 (24.3–142.7)	81.2 ± 155 (45.5–304.8)	0.638[a]
Follow-up after frame removal, days	70 ± 97 (21–497)	483 ± 575 (133–989)	0.002[a]
Assessment of mRUST			
mRUST ratio with frame*	0.70 ± 0.098	0.72 ± 0.116	0.700 (95% CI: –1.559 to 2.279)[c]
mRUST ratio without frame*	0.78 ± 0.107	0.71 ± 0.104	0.196 (95% CI: –0.173 to 0.038)[c]
Number of cortices seen for all reviewers*	2.96 ± 0.57	3.40 ± 0.43	0.129 (95% CI: –0.077 to 0.563)[c]
Assessment of bone ends angulation at docking site			
Angle of bone ends at docking site on AP view, degree	19.0 ± 22 (0–106)	45 ± 37.5 (32–100)	0.007[a]
Angle of bone ends at docking site on lateral view, degree	14.0 ± 14 (0–38)	45 ± 35.5 (12–57)	0.024[a]
Angle ≥45° on one view	2 (11)	5 (100)	<0.001[b]

Not normally distributed continuous variables are presented as median ± IQR [range] and normally distributed variables* as mean ± SD. Categorical variables are presented as *n* (%) unless indicated otherwise. [a]Mann–Whitney *U* test; [b]Fisher's Exact test; [c]Linear regression

Table 4: Inter-rater reliability of the mRUST score and mRUST ratio before and after removal of the external fixator

Variable	*Fleiss kappa*	*KA*	*ICC*	*95% CI*
Before removal of the frame				
Number of cortices seen	0.033	0.047	0.552	0.149–0.786
mRUST ratio	*	*	0.662	0.339–0.842
Anterior cortex mRUST score	0.245	0.256	0.660	0.344–0.840
Posterior cortex mRUST score	0.205	0.216	0.638	0.288–0.831
Lateral cortex mRUST score	0.307	0.316	0.593	0.229–0.806
Medial cortex mRUST score	0.205	0.216	0.476	0.047–0.744
After removal of the frame				
mRUST ratio	*	*	0.759	0.531–0.887
Anterior cortex mRUST score	0.129	0.141	0.729	0.476–0.873
Posterior cortex mRUST score	0.377	0.385	0.859	0.721–0.934
Lateral cortex mRUST score	0.270	0.280	0.729	0.469–0.873
Medial cortex mRUST score	0.311	0.320	0.739	0.495–0.877

*not used as variable is continuous

The results of the inter-rater reliability analysis of the mRUST ratio, and the scoring for each cortex individually, are shown in Table 4. The agreement between the three appraisers is "slight" for the number of cortices that could be scored, with a Fleiss Kappa of 0.033. Overall, the agreement is "fair" (Kappa 0.21–0.40) for the scoring of individual cortices, apart from one score, which is "slight" (Kappa 0.00–0.20). In contrast, the inter-rater reliability of the mRUST ratio shows higher agreement than the individual cortex scores, with an ICC of 0.662 with the frame and 0.759 without the frame.

Post-hoc analysis revealed that the only factor associated with an increased risk of complications at the docking site was the configuration of the docking site, represented by the angulation of the bone ends (Table 3). After analysing different cut-offs (≥ 30°, 45° or 60° on at least one of the anteroposterior or lateral views), we found that 45° represented the best cut-off angle related to the presence or absence of complication, ($p < 0.001$ with a *post-hoc* power of 97.9%).

Discussion

Distraction osteogenesis is a well-recognised treatment method to address lower limb bone defects, and is often the only option for limb salvage, despite a potentially high rate of complications. In our study, we found a rate of 21.7% of mechanical complications and all were related to the docking site.

To date, there is no real consensus on the best approach to avoid docking site complications, as highlighted by Giotakis et al.[35] Several management options have been advocated: the accordion technique, percutaneous osteotomy of bone ends, removal of soft tissue interposition and bone grafting.[35] Performing a routine docking revision procedure is not ubiquitous. However, according to Tetsworth et al.,[36] most authors currently recommend this procedure. A recent systematic review[37] including 23 studies and 1,153 patients showed a significant difference in docking site union with a union rate of 90% if a planned docking procedure was performed, versus 66% in the group without. In the seven included studies reporting planned docking procedure, this procedure consisted of refreshing of bone ends and/or autologous bone grafting. However, the heterogeneity of the studies remains a limitation in drawing conclusions about the optimal approach.[37] Bone transport through an induced membrane may possibly improve the chance of docking site union, as shown in the randomised controlled trial (RCT) by Thakeb et al.,[9] including 30 patients, who found that docking site non-union was significantly lower in the induced membrane transport group (0%), negating the need for a docking procedure, compared to 40% in the other group.

Our study showed a lower rate of mechanical complications at the docking site compared to Feng et al.,[8] who reported 21.4% delayed union, 18.4% axial deviation and 9.7% soft tissue incarceration rates. Interestingly, a formal docking site grafting was not performed as a routine procedure in this study. Distal third tibia bone defects as well as the overall defect size were highlighted as independent risk factors for delayed union. These factors were not associated with complications in our study. Spiegl et al.[38] in their series of 24 patients, with a formal docking procedure performed routinely, described one non-union and four axial deviations, without specifying whether these deviations occurred at the docking site or at the transport site. Liu et al.[39] in their large retrospective study including tibia and femur bone transport, reported 19% axial deviation, 19% delayed union and 8% refractures of docking sites amongst their major complications. A narrative review by Aktuglu et al.[4] analysed a total of 27 studies and only 3 of these reported to be doing routine docking procedures. However, overall 40.1% of patients required docking site grafting after completion of the transport due to delayed- or non-union.

In our study, all patients underwent a formal docking procedure and a transport through an induced membrane. Mechanical complications at the docking site were recorded in more than 1 in 5 (21.7%) patients. This complication rate is comparable to rates reported in the literature. However, the comparison is limited due to the heterogeneity of docking site management in other studies. In our experience, the docking site is much more often a source of complications than the regenerate site.

As there are no clear recommendations in the literature regarding the optimal time to remove the frame, we evaluated the application of the mRUST to the docking site to assess whether this score could be relevant in deciding whether it is safe to remove the frame to avoid mechanical complications. We found no difference between the two groups with or without complications in terms of the mRUST score. The threshold for union was achieved before the removal of the frame in both groups. Therefore, the mRUST does not appear to be clinically useful in predicting the occurrence of mechanical complications after frame removal. This result could be explained by the fact that the docking site does not have the same biological behaviour as a fracture. It has been shown that while the docking site does not differ histologically from the normal process of indirect or secondary consolidation of a fracture, with endochondral ossification, this process occurs in a slower manner.[40] In addition, the initial gap is gradually filled by fibrocartilaginous tissue, creating a situation similar to non-union, and in some cases, soft tissue can be interposed at the docking site during the transport process.[35]

It should be noted that an easy way to assess the healing of the docking site would be to perform a CT scan, but this modality is not widely available in low- or middle-income countries due to resource constraints. In our setting, the waiting time for a non-urgent CT scan is more than 6 months and could therefore not be routinely used.

The inter-rater reliability of the mRUST, applied to individual cortices at the docking site, was only “fair” or even “slight”, considering the Fleiss Kappa and KA coefficients, which are appropriate for the assessment of ordinal data. Despite our ICC values being comparable or even higher than previous studies, evaluating the inter-rater reliability of the RUST or mRUST score,[20,21,23,26,33] we believe that the values of Fleiss Kappa and KA coefficients should be considered instead of the ICC. In fact, assessing the inter-rater reliability of ordinal data in the same way as continuous data may lead to overestimation of the reliability. This is because the analysis will show better agreement when using the ICC since the number of scoring possibilities is supposedly unlimited. However, in the case of the mRUST score, only four different scores are used. This difference in results between ICC and KA coefficient is also shown in the study by Mitchell et al.[28] on the reliability of the mRUST score in tibial fractures with bone defects. To the best of our knowledge, this is the only study that has used the KA coefficient for this purpose. In their study, the differences between the two methods of analysis are smaller than in our results. This could be explained by the larger sample size compared to our study.

For the mRUST ratio, we used the ICC because the ratio is a continuous variable. However, as the ratio is the result of four ordinal measurements, this result should be treated with caution. Nevertheless, the finding of relatively high ICC values for the mRUST ratio (0.66 with the frame and 0.76 without the frame) can be explained by the fact that the discrepancy in scoring for individual cortices is reduced when the scores of the four cortices are considered together, (i.e., one reviewer scored two for the anterior cortex, three for the posterior cortex and another reviewer scored the opposite). Mitchell et al.[28] hypothesised that the level of reliability may be influenced by the severity of the original injury in patients treated with external fixation and the presence of a previous bone graft. This, in turn, may lead to an abnormal appearance during the healing process, thus explaining the lower level of agreement. We agree with this hypothesis and believe that the low level of reliability found in our study may be related to the inherently different nature of a docking site, that is, the abnormal bone ends with a biomechanical environment that is different from a normal fracture, and the presence of bone graft.

In light of our results, and the reasons given above, we do not consider the mRUST to be a reliable tool for assessing union at the docking site. However, its application to a larger study population is required to confirm this finding. Our findings suggest that the application of the mRUST score, as a ratio, could allow the score to be used despite cortices hidden by the frame, as the mean number of cortices seen with the frame was 3, and the correlation of the score with and without the frame was moderate. Therefore, the mRUST ratio could be considered to evaluate the healing of fractures treated with a circular frame and could overcome the difficulty in scoring reported by Mitchell et al.[28] when one or more cortices are hidden by the frame. A study evaluating the mRUST ratio in tibial fractures treated with a circular frame should be performed to confirm this assumption.

Therefore, the question of when it is safe to remove the frame remains unresolved. Some authors consider a solid docking site when corticalisation or bridging callus is achieved in three of four cortices,[38,39,41] while others only mention that the frame is removed when the docking site has healed without further details.[42–44] A “destabilisation” of the frame before removal is often described,[7,9,39,41,42,44,45] as well as a cast for 4 to 6 weeks after frame removal.[7,9,39,41] Our standard practice is to destabilise the frame for 2 weeks before removal, to ensure the absence of pain and/or radiographic displacements. Once the frame has been removed, the patient is allowed to full weight-bear without a cast or splint. As previously mentioned, our rate of mechanical complications is not higher than that reported in the literature.

An important point found in the *post-hoc* analysis of this study is the relevance of the physical configuration of the docking site in terms of the amount of bone contact and the orientation of the surfaces of the bone ends meeting at the docking site. There is a statistically significant difference in the angulation of the bone ends between the groups with and without complications, with a cut-off of 45°. This may have important clinical implications when considering the extent of the bone debridement. Although it may seem logical that a larger contact area offers a better chance of healing, the concern to preserve as much bone stock as possible when dealing with a bone defect can result in irregular bone ends or an oblique cut after debridement. Recommendations regarding the shape of bone ends in the context of bone transport are scarce in the literature. Liodakis et al.[37] mentioned that bone contact is influenced by the geometry of the bone cuts at initial debridement and by the accuracy of the alignment, while Giotakis et al.[35] reported that some surgeons have advocated a plunger and mortise shape to increase the contact and to eliminate the interposed fibrous tissue. In the present study, we found a high correlation between the occurrence of mechanical complications at the docking site and a divergence in the angle between the bony surfaces of 45° or more. It remains unclear if obtaining two parallel bone ends is more important than, for example, perfectly perpendicular cuts relative to the bone axis. Considering our results, we recommend that further research has to be done to determine the optimal shape of the bone ends to be docked.

The limitations of our study are the relatively small number of cases, the inherent limitations of a study based on radiological records and the relatively short follow-up. The latter is explained by the fact that access to health care can be a challenge in our setting. As a result, follow-up is terminated as soon as clinical and radiological results are deemed satisfactory. Despite these limitations, the main point highlighted by this study, that is, the importance of the shape and orientation of the bone ends at the docking site, can be considered as a valuable finding due to the high *post-hoc* power.

Conclusion

This study did not find the mRUST or mRUST ratio useful in assessing the healing of the docking site to help decide on the best time to remove the frame. However, a notable finding was that the shape and orientation of the bone ends meeting at the docking site might well be relevant to decrease complication rates. If the angle between the bony surfaces is 45° or more, it may be associated with an increased risk of complications as seen in our cohort. It may be worthwhile considering reshaping these bone ends at the time of debridement or formal docking procedure to be more collinear, in order to reduce the potential for mechanical complications such as non-union, axial deviation or refracture at the docking site.

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