■ TRAUMA

Posterior malleolar ankle fractures

PREDICTORS OF OUTCOME

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Aims

The primary aim of this study was to address the hypothesis that fracture morphology might be more important than posterior malleolar fragment size in rotational type posterior malleolar ankle fractures (PMAFs). The secondary aim was to identify clinically important predictors of outcome for each respective PMAF-type, to challenge the current dogma that surgical decision-making should be based on fragment size.

Methods

This observational prospective cohort study included 70 patients with operatively treated rotational type PMAFs, respectively: 23 Haraguchi Type I (large posterolateral-oblique), 22 Type II (two-part posterolateral and posteromedial), and 25 (avulsion-) Type III. There was no standardized protocol on how to address the PMAFs and CT-imaging was used to classify fracture morphology and quality of postoperative syndesmotic reduction. Quantitative 3D-CT (Q3DCT) was used to assess the quality of fracture reduction, respectively: the proportion of articular involvement; residual intra-articular: gap, step-off, and 3D-displacement; and residual gap and step-off at the fibular notch. These predictors were correlated with the Foot and Ankle Outcome Score (FAOS) at two-years follow-up.

Results

Bivariate analyses revealed that fracture morphology (p = 0.039) as well as fragment size (p = 0.007) were significantly associated with the FAOS. However, in multivariate analyses, fracture morphology (p = 0.001) (but not fragment size (p = 0.432)) and the residual intra-articular gap(s) (p = 0.009) were significantly associated. Haraguchi Type-II PMAFs had poorer FAOS scores compared with Types I and III. Multivariate analyses identified the following independent predictors: step-off in Type I; none of the Q3DCT-measurements in Type II, and quality of syndesmotic reduction in small-avulsion Type III PMAFs.

Conclusion

PMAFs are three separate entities based on fracture morphology, with different predictors of outcome for each PMAF type. The current debate on whether or not to fix PMAFs needs to be refined to determine which morphological subtype benefits from fixation. In PMAFs, fracture morphology should guide treatment instead of fragment size.

Cite this article: ***Bone Joint J*** **2020;102-B(9):1229–1241.**

Introduction

Ankle fractures are one of the most common fractures.[1-3] In 1998, Court-Brown et al[4] reported an incidence of 122 ankle fractures per 100,000 adults in UK. Interestingly, the incidence is rising,[5] but the length of hospitalization has decreased.[2] The current literature on the incidence of ankle fractures reports numbers varying from 70 to 180 per 100,000 person years.[2,4,6–8] Ankle fractures can be subdivided into isolated unimalleolar, bimalleolar, and trimalleolar ankle fractures: trimalleolar ankle fractures, with fracture involvement of the posterior malleolus, account for approximately 7% of all ankle fractures.[6] It is well-accepted that rotational type ankle fractures with a concomitant posterior malleolar fracture are associated with significantly inferior clinical outcome scores, compared to patients who sustain these injuries without a posterior malleolar fracture.[9]

In complex elbow fractures, it has been well-established that fracture morphology of the coronoid fragment is more important than fragment size. O'Driscoll et al[10] improved our understanding of complex elbow trauma over two decades ago. Coronoid fractures are characterized into three specific types based on fracture

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doi:10.1302/0301-620X.102B9. BJJ-2019-1660.R1 $2.00

Bone Joint J 2020;102-B(9):1229–1241.

morphology.[11] Fracture morphology predicts the overall pattern of the elbow injury and guides surgical decision-making.[12] In contrast, when caring for patients with rotational type ankle fractures and associated posterior malleolar ankle fracture (PMAF), surgeons are still struggling with the classical dogma that surgical decision-making should be guided by PMAF fragment size, rather than PMAF morphology or overall injury pattern.[13,14] Even the current POSTFIX prospective trial,[15] which aims to determine whether or not to fix 'medium-sized' PMAFs, randomizes patients based on fragment size as evaluated on lateral radiographs, which is known to offer an imprecise estimation of articular involvement[16] and does not characterize PMAF morphology.

Over a decade ago, Haraguchi et al[17] coined a classification system for PMAFs based on fracture morphology. To the best of our knowledge there are no prospective cohort studies using CT to evaluate the clinical relevance of Haraguchi's fracture morphology. However, current understanding of these potentially complex ankle injuries is advancing, partly because many authors have advocated pre- and/or postoperative (low-dose) CT that allows for better appreciation of both the overall injury pattern as well as recognition of the specific fracture morphology in PMAFs.[13,14,17-24] It is well-accepted that rotational type ankle fractures with a concomitant PMAF are associated with significantly inferior clinical outcome scores, compared to patients who sustain these injuries without a PMAF.[9,25,26] Unfortunately, debate continues about when and how to fix the posterior malleolar fragment in PMAFs, as reported by Solan et al[27] and White et al.[28] However, it is increasingly recognized that the 'classic' classification based on PMAF size may not be as important as PMAF morphology to guide treatment;[29] for example, PMAFs with medial extension (i.e. Haraguchi Type II) have significantly inferior outcome scores compared with the posterolateral Haraguchi Types I and III.[20]

These findings may contribute to a shift away from the classical dogma of fixing PMAFs that involve more than 25% to 33% of the articular surface of the tibial plafond.[29] Indeed, the recent review from Verhage et al[30] concluded that there was no clear association between outcome and posterior malleolar fragment size. Moreover, Bartoníček et al[29] concluded that PMAFs involving the fibular notch and the presence of osteochondral impaction of the tibial plafond seem to be of greater clinical relevance than PMAF size alone. A growing body of evidence include other predictors of outcome: the overall pattern of injury,[19] PMAF morphology,[17,20] postoperative residual articular congruity at the level of the tibial plafond,[31-34] and the quality of syndesmotic reduction.[29]

However, we are unaware of any prospective outcome data which examine the relationship with quantified postoperative CTs to identify potential predictors of outcome in PMAFs. Therefore, the primary aim of this study was to address the hypothesis that fracture morphology might be more important than PMAF size in rotational type PMAFs. The secondary aim was to identify clinically important predictors of outcome for each respective PMAF type, to challenge the current dogma that surgical decision-making should be based on fragment size.

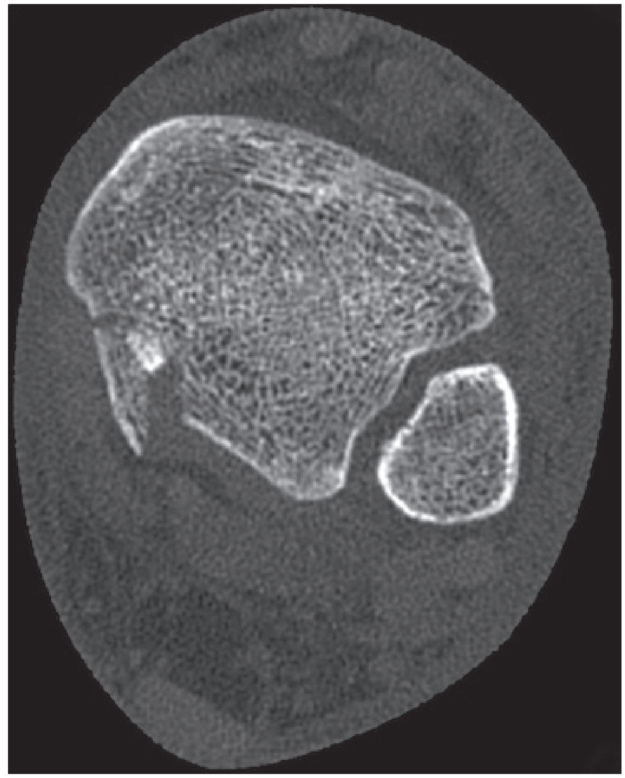


Fig. 1

An example of an axial CT reconstruction of an atypical ankle fracture with isolated impaction of the posteromedial tibial plafond in a 46-year-old male that sustained an ankle trauma.

Methods

In accordance with the Declaration of Helsinki,[35] our Institutional Review Board (IRB) approved a retrospective review of prospectively collected anonymous CT images of adult patients with ankle fractures from the randomized clinical EF3X-trial,[36] (Dutch Trial Register NTR 1902). The purpose of the EF3X-trial was to evaluate the added value of intraoperative use of 3D-fluoroscopy compared with 2D-fluoroscopy alone, in operatively treated ankle fractures with the quality of fracture reduction as the primary study outcome.[36]

All patients with a fractured ankle joint received fluoroscopy during surgery and radiographs and a CT exam (120 kV, 150 mAs) postoperatively. The radiation dose was approximately 50 μSv and 0.2 mSv, respectively. The total dosage for all radiological examinations performed as part of the EF3X-trial was less than 0.25 mSv. This is qualified as a 'minor' risk according to category IIa (0,1 to 1 mSv) of the ICRP (report ICRP62).[36] For the purpose of the EF3X-trial, postoperative CTs served as reference standard and secondary use of data are reported in this study.

Patients. The EF3X-trial[36] included 176 patients with an operatively treated ankle fracture. However, only 81 patients had PMAF and 11 of these patients had an atypical ankle fracture with impaction of only the posteromedial tibial plafond (Figure 1). The remaining 70 patients with a rotational type PMAF (AO/OTA Fracture Classifications; 44-A, 44-B, 44 C[37]) who were surgically treated with open reduction and internal fixation (ORIF) in our Level-I trauma centre were included in this study. These patients had a mean age at surgery of 47 years (SD 14.6 years), 30 patients were male (43%), and 16 (23%) were smokers. In 40 patients (57%) the right ankle was injured. The trauma mechanism ranged from: fall/slipped while walking (n = 39), fall from a bicycle (n = 10), an accident during sports (n = 7), a fall from height (n = 3), and was unknown in the remaining 11 patients.

All patients underwent postoperative CT scanning of the injured leg within one week after surgery. The postoperative CT scans had an axial slice thickness of < 1 mm (Somatom Definition AS+; Siemens, Erlangen, Germany) and were saved as anonymous Digital Imaging and Communications in Medicine (DICOM) files.

Primary study outcome: Foot and Ankle Outcome Score. In order to elucidate the potential predictors of outcome in rotational type PMAF, the potential predictors were correlated to the Foot and Ankle Outcome Scores (FAOS)[38] at two-years follow-up, with respective FAOS domain scores (i.e. Symptoms, Pain, Activities of Daily Living (ADL), Sports and Quality of Life (QoL)) serving as the primary outcome of the current study.

Predictors of outcome. Potential predictors of outcome that were analysed in this current study were: patient demographics, postoperative two-dimensional CT variables, and quantitative 3D computed tomography (Q3DCT) variables.[19]

Patient demographics included: sex, age at surgery, side of injury and smoking history. The postoperative 2DCT variables were: PMAF classification based on fracture morphology according to Haraguchi[17] (Types I-III) and Bartoníček[18] (Types I to IV). The presence of fracture comminution and impaction of the tibial plafond and the quality of syndesmotic reduction were based on postoperative 2DCT scans. Two independent observers (JND, RPB) quantified the quality of syndesmotic reduction (satisfactory or unsatisfactory) with the use of standardized axial, sagittal and coronal postoperative CT reconstructions based on the presence or absence of one of the following criteria:[39,40] anterior or posterior translation (AP-translation) of the fibula relative to the tibia, based on the anterior tibiofibular distance and the posterior tibiofibular distance; lateral translation of the fibula relative to the tibia or over-compression of the syndesmosis, based on the distance between the tibia and fibula in the middle of the incisura; internal or external rotation of the fibula relative to the tibia; presence of fracture fragments in the distal tibiofibular syndesmosis; and presence of osteosynthesis material in the distal tibiofibular syndesmosis.

Examples of an unsatisfactory quality of syndesmotic reduction were: syndesmotic malreduction (i.e. extreme anterior or posterior translation) of the fibula relative to the tibia;[41] overcompression of the syndesmosis,[42] and the presence of intrasyndesmotic hardware.

Diastasis or over-compression of the syndesmosis is a medial or lateral translation of the fibula relative to the tibia and was measured as the distance between the lateral cortex of the tibia and the medial cortex of the fibula. AP-translation was measured as the distance between the most anterior cortex of the fibula and the most anterior part of the incisura fibulae. For both measurements we used an axial reconstruction at the level of the physeal scar of the distal tibia which is 1 cm above the level of the tibial plafond and is the deepest part of the incisura fibulae of the distal tibiofibular syndesmosis.

We did not use cut-off values for ‘extreme’ fibular AP-translation or ‘over-compression’ of the syndesmosis, but our current method is based on a previously validated postoperative CT-measurement protocol described Prior et al.[43]

Q3DCT modelling. Previously validated Q3DCT techniques were used to quantify the quality of fracture reduction in intra-articular PMAFs.[44,45] The current Q3DCT technique involved the following steps: anonymous DICOM files were loaded into 3DSlicer (open source software; https://www.slicer.org) and were segmented using thresholding segmentation followed by manual corrections and the created 3D models were exported as STL files and loaded into Meshmixer (open source software: https://www.meshmixer.com). Meshmixer was used to extract the articular surfaces of the PMAF fragment(s), the remaining intact tibial plafond, and the gap(s) in the tibial articular surface. Finally, if displaced PMAF fragments were present, the PMAF fragments were manually moved into their (virtually) optimal reduced or anatomical position using the transform command. Two authors (RPB, BH) checked this virtual reduction, to reach consensus on the optimal virtual reduction of the PMAF fragments into their anatomical position. Subsequently, all articular surfaces, gaps, and original and virtually reduced fragments were exported as separate STL files for the final step of analysis in Matlab (Mathworks, Nathick, Massachusetts, USA).

A custom Matlab script was developed that automatically defined an anatomical coordinate system of the distal tibia such that the positive x-, y- and z-axis were aligned with the lateral, posterior, and inferior directions of the tibia (Figure 2); calculated the area of the articular surfaces (in mm^2) of the total intact tibial plafond, the PMAF fragment(s) and the total surface of the intra-articular gap(s); and applied a rigid iterative closest point (ICP) algorithm[46] to calculate the different displacements of the PMAF fragment(s) in the anatomical coordinate system (translations along the x, y, and z-axes).

Evaluation of the Q3DCT variables. Q3DCT models (Figure 3) were subsequently used to quantify postoperative residual articular congruity at the level of the tibial plafond as well as the fibular notch, respectively: a) articular involvement of the PMAF fragment(s), described as percentage of the total articular surface of the tibial plafond (in case of the two-part PMAF, the total articular surface was given (i.e. the articular surfaces of both the posterolateral and posteromedial fragment combined)); b) ‘classic’ residual intra-articular tibial gap, as displacement along the anteroposterior or y-axis in mm; c) ‘classic’ residual intra-articular tibial step-off, as displacement along the superior-inferior or z-axis in mm; d) 3D multidirectional displacement of the PMAF fragment in mm, described as a vector of the combined displacements along the x-, y-, and z-axes, i.e. $\sqrt{(\Delta x^2+\Delta y^2+\Delta z^2)}$; and e) total surface of the gap(s) between the PMAF fragment and the remaining intact tibial plafond in mm^2. In case of multiple PMAF fragments and intra-articular gaps, for example in the two-part PMAFs, the accumulated surface area of the intra-articular gaps was given (Figure 4).

To address the quality of PMAF reduction at the level of the fibular notch, Q3DCT measurements on postoperative residual articular congruity at the level of the fibular notch were

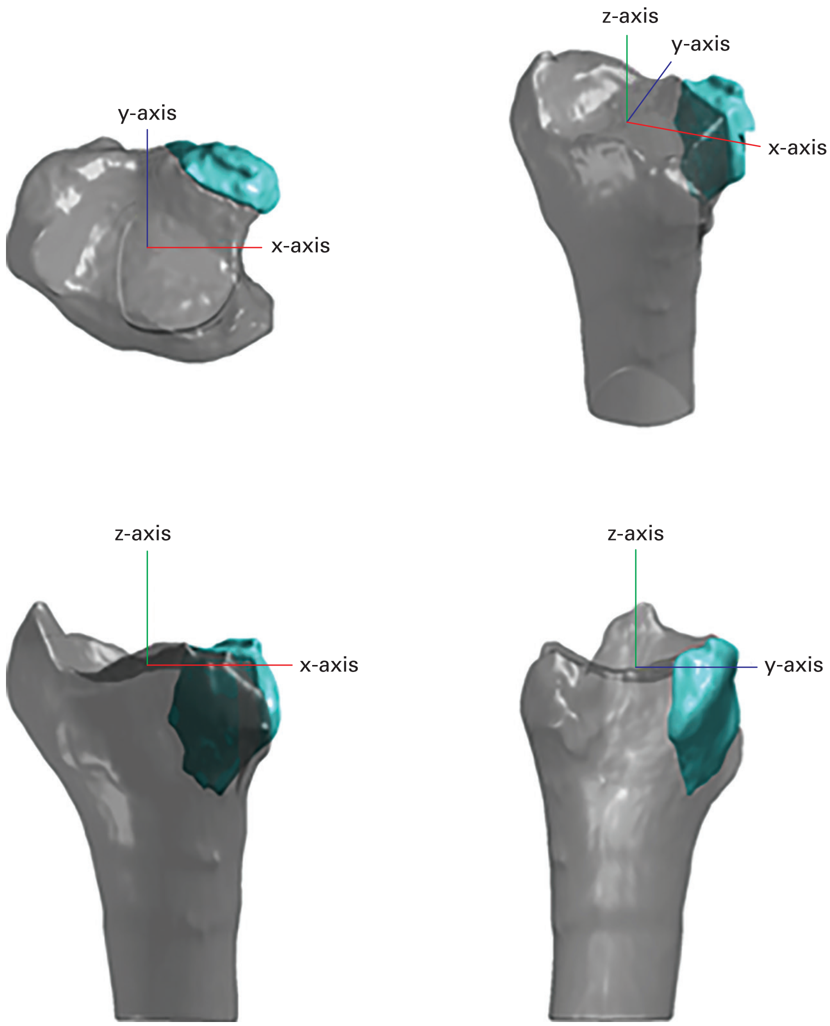


Fig. 2

The anatomical coordinate system of the distal tibia with the positive x-, y-, and z-axes that were created by a custom Matlab script to calculate the different displacements of the PMAF fragments.

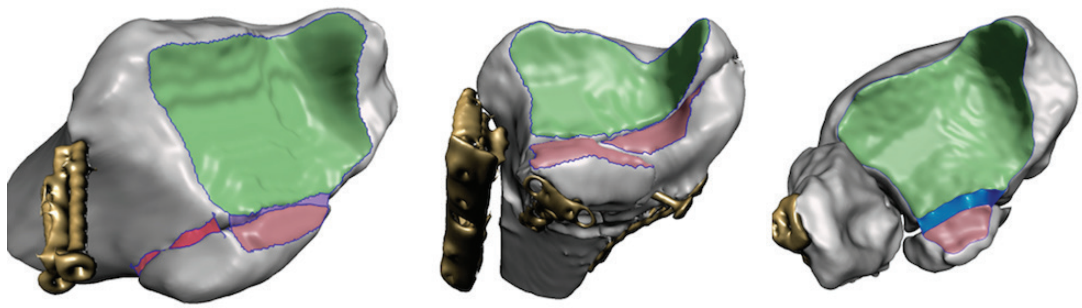
calculated: f) total surface of the residual gap in the fibular incisura of the tibia in mm^2; g) residual step-off in the fibular incisura of the tibia, defined as displacement along the medial-lateral or x-axis in mm (Figure 5).

Statistical analysis. Statistical analysis was performed using IBM SPSS for Mac, v. 25.0 (Armonk, New York, USA). Patients' baseline characteristics were presented as frequencies and percentages in case of categorical variables and as means and SDs in case of continuous variables. Bivariate regression analysis was used to identify the association between the potential clinically important predictors and the outcome, as quantified by FAOS domain scores at two years follow-up. A one-way analysis of variance (ANOVA) test was performed and, in the case of non-normally distributed data, a Kruskal-Wallis test was performed. Where significance (with adjusted significance level of 0.1) was found, the predictors were entered in a multivariate linear regression model with backward stepwise selection procedure to identify the remaining significant predictive factors for the FAOS domain scores. A p-value < 0.05 was considered statistically significant.

Results

CT to classify PM fracture morphology. CT was used to classify PMAF morphology according to the Haraguchi PMAF classification system:[17] 23 patients (36%) had a large posterolateral-oblique PMAF fragment (Haraguchi Type I); 22 patients (28%) had a two-part (posterolateral and posteromedial fragment) PMAF with the transverse fracture line extending into the medial malleolus (Haraguchi Type II); and 25 (36%) patients had a small-shell avulsion-type PMAF (Haraguchi Type III) (Table I).

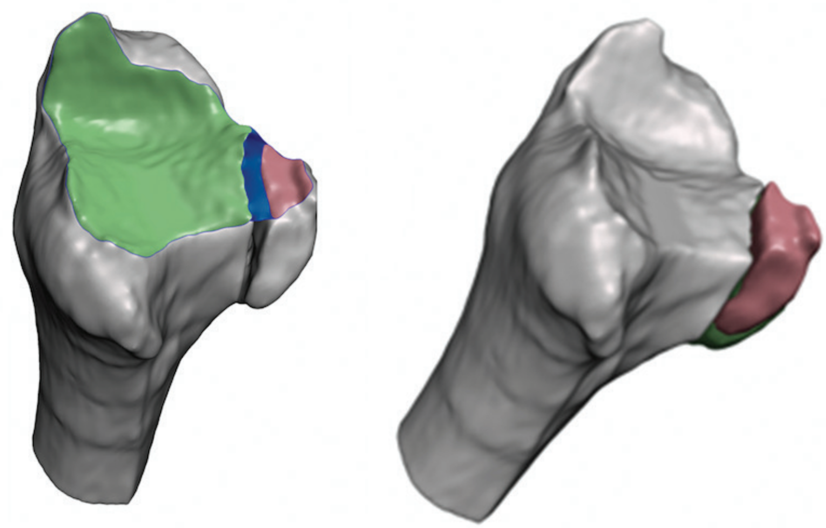
In addition to PMAF morphology according to Haraguchi,[17] the extent of the fracture involvement of the fibular notch according to Bartoníček[18] was assessed: 16 patients (23%) had an extra-incisural fragment with an intact fibular notch (Bartoníček Type I); 30 patients (46%) had a posterolateral PMAF extending into the fibular notch (Bartoníček Type II); 22



a b c

Fig. 3

3D CT (Q3DCT) reconstructions of the three different posterior malleolar ankle fractures (PMAF) according to the fracture classification system of Haraguchi et al,[17] which is based on posterior malleolar fracture morphology. a) A large posterolateral-oblique PMAF fragment (Haraguchi Type I), b) a two-part (posterolateral and posteromedial fragment) PMAF fragment with the transverse fracture line extending into the medial malleolus (Haraguchi Type II), c) a small-shell avulsion-type PMAF fragment (Haraguchi Type III).



a b

Fig. 4

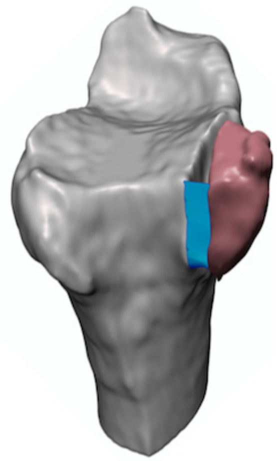
3D CT (Q3DCT) reconstructions of the distal tibia with a posterior malleolar fragment. a) A posterior malleolar fragment (grey) with an example of the surface of the intact tibial plafond (green), surface of the posterior malleolar fragment (pink) and surface of the residual intra-articular surface of the gap (blue). b) A distal tibia (grey) and posterior malleolar fragment with an example of the residual intra-articular step-off at the level of the tibial plafond (pink) and the virtually reduced posterior malleolar fragment into the anatomical position (green).

patients (28%) had a two-part (posterolateral and posteromedial fragment) PMAF with the transverse fracture line extending into the medial malleolus (Bartoníček Type III); and 2 (3%) patients had a large posterolateral triangular PMAF fragment (Bartoníček Type IV).

All patients were treated according to the conventional AO principles of open reduction and internal fixation at our Level-I trauma centre. The methods of fracture fixation are listed in Table II.

Rotational type ankle fractures with an associated PM fragment. In bivariate analyses, PMAF morphology ($p = 0.039$) as well as the percentage of articular involvement of the PMAF ($p = 0.007$) was significantly associated with outcome at two-years follow-up for all FAOS domain scores in the entire cohort of 70 patients with rotational type PMAFs. Sex was also a predictor of outcome for all FAOS domain scores in bivariate analyses. Finally, the total residual postoperative intra-articular gap(s) at the level of the tibial plafond was a predictor of outcome for three out of five FAOS domains (Pain, ADL, and QoL) (Table III).

However, when these significant predictors of outcome were entered in a multivariate analysis, PMAF morphology, but not fragment size as percentage of tibial articular surface, was found to be an independent predictor of all FAOS domain scores at



a

b

Fig. 5

3D CT (Q3DCT) reconstructions of the distal tibia (grey) with a posterior malleolar fragment. a) A distal tibia (grey) and posterior malleolar fragment (pink) with an example of the residual surface of the gap at the level of the fibular notch (blue). b) A distal tibia and fibula (grey) with an example of the residual step-off at the level of the fibular notch (transparent light pink) and the virtually reduced posterior malleolar fragment into the anatomical position (green).

Table I. Baseline demographics and fracture characteristics.

Characteristic	Total
Sex, n (%)	
Male	30 (43)
Female	40 (57)
Side of ankle fracture, n (%)	
Left	30 (43)
Right	40 (57)
Mean age at surgery, yrs (SD)	47 (15)
Smoking, n (%)	
Yes	16 (23)
No	54 (77)
Trauma mechanism, n (%)	
Fall/slipped while walking	39 (56)
Fall from bicycle	10 (14)
Accident during sports activities	7 (10)
Fall from height	5 (7)
Other or unknown	9 (13)
Haraguchi classification,[17] n (%)	
Type I	23 (33)
Type II	22 (31)
Type III	25 (36)
Bartoníček classification,[18] n (%)	
Type I	16 (23)
Type II	30 (43)
Type III	22 (31)
Type IV	2 (3)
Tibial plafond communition, n (%)	
Yes	20 (29)
No	50 (71)
Tibial plafond impaction, n (%)	
Yes	52 (74)
No	18 (26)

two-years follow-up. The postoperative residual intra-articular surface of the gap was found to be an independent predictor of the FAOS domains Pain and QoL (Table IV).

Foot and Ankle Outcome Score (FAOS) domain scores. As shown in Table V, there were significant differences in patient-reported outcome measures between patients with respective Haraguchi[17] Types I, II and III PMAFs at two-years follow-up (Table V). Patients with a Type II PMAF (i.e. two-part posterolateral and posteromedial with the fracture line extending into the medial malleolus) had significantly worse outcomes as quantified by FAOS domain scores. Patients with Type II PMAFs had poorer outcome scores on all FAOS domains compared to patients with avulsion-type Type III PMAFs, and did worse compared to patients with large posterolateral Type I PMAFs in terms of Pain and Activities of Daily Living.

Articular involvement or PMAF size. Articular involvement of the PMAF as percentage of the total articular surface of the tibial plafond was found to be a mean of 15.9% (95% confidence interval (CI) 12.9% to 18.8%) for the entire cohort of rotational type PMAFs. Two-part Types II had the largest articular fracture involvement with a mean of 24.2% (95% CI 18.9% to 29.6%), compared with the 'large' posterolateral Types I ($p = 0.019$, one-way ANOVA) with a mean 18.1% of the total tibial plafond (95% CI 13.3% to 22.8%). Avulsion-type Types III, by definition, the least articular involvement of mean 6.4% (95% CI 3.5% to 9.4%; $p = 0.008$, one-way ANOVA) (Table VI).

'Classical' measures of PMAF reduction. The quality of posterior malleolar fracture reduction was described by the residual intra-articular gap and step-off at the level of the tibial plafond. The 'classical' (maximum) gap between the reduced PM fragment and remaining intact tibial plafond was a mean of 0.5 mm (95% CI 0.3 mm to 0.6 mm) for all 70 patients in the current study.

Table II. Methods of fixation.

Method	Haraguchi type I[17] (n = 23)	Haraguchi type II[17] (n = 22)		Haraguchi type III[17] (n = 25)
		Posterolateral fragment	Posteromedial fragment	
Direct fixation, n (%)	10 (44)	7 (32)	3 (14)	1 (4)
Antiglide plate	6 (26)	6 (27)	3 (14)	0 (0)
AP screw	2 (9)	1 (5)	0 (0)	0 (0)
PA screw	2 (9)	0 (0)	0 (0)	1 (0)
Additional syndesmotic screw	3 (13)	2 (10)	2 (10)	0 (0)
Both fragments	N/A	6 (27)		N/A
Non-direct fixation, n (%)	7 (30)	1 (4)		20 (80)
Single syndesmotic fixation	4 (17)	0		15 (60)
Two syndesmotic screws	3 (13)	1 (5)		5 (20)
No fixation at all, n (%)	6 (26)	5 (23)		4 (16)
Fibula fixation, n (%)				
One-third tubular plate	23 (100)	19 (86)		25 (100)

AP, anterior to posterior directed; N/A, not applicable; PA, posterior to anterior directed.

Table III. Bivariate regression analyses of the potential predictors of outcome in rotational type intra-articular ankle fractures with involvement of the posterior malleolus. The outcome is defined as the Foot and Ankle Outcome Score[38] (FAOS) domain scores at two-years follow-up.

Characteristics	FAOS symptoms	FAOS pain	FAOS ADL	FAOS sports	FAOS QoL
Baseline characteristics					
Sex	0.018*	0.045*	0.049*	0.011*	0.040*
Age at surgery	0.582	0.424	0.647	0.453	0.539
Smoking	0.821	0.717	0.600	0.589	0.936
2DCT fracture characteristics					
Haraguchi classification[17]	0.042*	0.039*	0.040*	0.048*	0.050*
Bartoníček classification[18]	0.019*	0.001*	0.001*	0.010*	0.010*
Tibial plafond communition	0.846	0.093	0.162	0.479	0.126
Tibial plafond impaction	0.885	0.679	0.654	0.732	0.577
Quality of syndesmotic reduction	0.965	0.793	0.831	0.980	0.638
Q3DCT on the residual postoperative articular congruity					
Articular involvement (% of total tibial plafond)	0.025*	0.007*	0.007*	0.012*	0.003*
Congruity tibial plafond					
'Classic' gap, mm	0.624	0.833	0.767	0.773	0.873
'Classic' step-off, mm	0.851	0.737	0.769	0.608	0.629
Total 3D displacement, mm	0.755	0.642	0.438	0.670	0.875
Total surface of the gap, mm^2	0.108	0.002*	0.012*	0.125	0.005*
Congruity fibular notch					
Step-off, mm	0.480	0.171	0.108	0.736	0.493
Total surface of the gap, mm^2	0.762	0.649	0.649	0.886	0.901

*Statistically significant.
ADL, activities of daily living; Q3DCT, quantitative 3D CT; QoL, quality of life

The 'classical' residual (maximum) intra-articular step-off at the level of the tibial plafond was a mean of 0.5 mm (95% CI 0.3 mm to 0.7 mm) for all 70 patients. Overall, there were no differences in postoperative quality of reduction between the three Haraguchi Types of PMAF, in terms of the 'classical' measures of gap and step-off.

'Contemporary' measures of PM fracture reduction. Quality of posterior malleolar fracture reduction as measured by 'contemporary' measures of total surface of the intra-articular residual gap(s) at the level of the tibial plafond was a mean 43.4 mm^2 (95% CI 32.6 mm^2 to 54.2 mm^2) for all PMAFs; with Haraguchi Type II (i.e. two-part PM fracture extending into the medial malleolus) having the largest postoperative residual gap surface between the PM fragment and intact tibial plafond (mean 65.3 mm^2; 95% CI 41.7 mm^2 to 88.9 mm^2); followed by large posterolateral Type I (mean 53.3 mm^2 (95% CI 34.6 mm^2 to 72.0 mm^2); and small avulsion-type. Type III had the smallest residual intra-articular surface of the gap (mean 15.0 mm^2; (95% CI 6.9 mm^2 to 23.1 mm^2; p = 0.007, one-way ANOVA)).

Quality of reduction quantified as postoperative residual 3D displacement of the posterior malleolar fragment was a mean 0.9 mm (95% CI 0.7 mm to 1.2 mm). Again, there were no differences between the three Haraguchi Types of PMAFs.

Q3DCT measurements showed significant differences in quality of fibular notch restoration. Type II PMAFs were significantly better reduced (p = 0.018, one-way ANOVA) than Types I, with the residual step-off at the level of the fibular notch on average 0.4 mm (95% CI 0.1 mm to 0.8 mm) in Types II and 0.7

Table IV. Multivariate regression analyses of the potential predictors of outcome in rotational type intra-articular ankle fractures with involvement of the posterior malleolus. The outcome is defined as the Foot and Ankle Outcome Score[38] (FAOS) domain scores at two-years follow-up.

Characteristic	FAOS symptoms	FAOS pain	FAOS ADL	FAOS sports	FAOS QoL
Baseline characteristics					
Sex	0.454	0.632	0.681	0.309	0.492
2DCT fracture characteristics					
Haraguchi classification[17]	0.002*	0.001*	0.001*	0.001*	0.001*
Bartoníček classification[18]	0.004*	0.001*	0.001*	0.001*	0.001*
Q3DCT on the residual postoperative articular congruity					
Articular involvement (% of total tibial plafond)	0.588	0.432	0.448	0.532	0.493
Congruity tibial plafond					
Total surface of the gap, mm^2	N/A	0.009*	0.162	N/A	0.008*

*Statistically significant.
ADL, activities of daily living; N/A, not applicable; Q3DCT, quantitative 3D CT; QoL, quality of life

Table V. The Foot and Ankle Outcome Scores (FAOS) for the total study cohort and each respective Haraguchi[17] type of posterior malleolar ankle fractures.

FAOS domain	Total, mean (95% CI)	Haraguchi Type I, mean (95% CI)	Haraguchi Type II, mean (95% CI)	Haraguchi Type III, mean (95% CI	p-value* (Type II vs I)	p-value* (Type II vs III)
Symptoms	59.0 (54.1 to 63.8)	61.7 (53.8 to 69.5)	50.3 (41.4 to 59.3)	65.5 (57.7 to 73.4)	0.151	0.021†
Pain	71.7 (64.9 to 78.4)	75.2 (63.1 to 87.2)	54.8 (43.6 to 66.0)	86.3 (77.8 to 94.7)	0.021†	0.011†
Activities of daily living	78.4 (72.3 to 84.5)	82.6 (72.0 to 93.2)	62.4 (51.0 to 73.8)	91.4 (85.5 to 97.3)	0.009†	0.012†
Sports	61.7 (53.9 to 69.5)	61.9 (47.1 to 76.8)	44.3 (31.1 to 57.5)	79.8 (70.5 to 89.0)	0.129	0.010†
Quality of life	62.5 (56.4 to 68.6)	63.2 (51.1 to 75.3)	48.2 (40.1 to 56.4)	76.9 (67.8 to 86.0)	0.079	0.009†

*One-way analysis of variance.
†Statistically significant.

Table VI. The Q3DCT characteristics on the residual postoperative quality of fracture reduction for each respective Haraguchi[17] type of posterior malleolar ankle fracture

Variable	Total, mean (95% CI)	Haraguchi Type I, mean (95% CI)	Haraguchi Type II, mean (95% CI)	Haraguchi Type III, mean (95% CI)	p-value (Type I vs II)	p-value (Type II vs III)
Articular involvement of the posterior malleolar fragment(s), %	15.9 (12.9 to 18.8)	18.1 (13.3 to 22.8)	24.2 (18.9 to 29.6)	6.4 (3.5 to 9.4)	0.019*	0.008*
Quality of fracture reduction						
'Classic' residual intra-articular gap, mm	0.5 (0.3 to 0.6)	0.5 (0.3 to 0.8)	0.6 (0.3 to 0.9)	0.3 (0.1 to 0.5)	0.839	0.109
'Classic' residual intra-articular step-off, mm	0.5 (0.3 to 0.7)	0.4 (0.2 to 0.6)	0.8 (0.4 to 1.2)	0.3 (0.1 to 0.6)	0.546	0.122
Total 3D displacement, mm	0.9 (0.7 to 1.2)	1.0 (0.7 to 1.3)	1.2 (0.7 to 1.4)	0.6 (0.3 to 1.0)	0.663	0.152
Total surface of the intra-articular gap, mm^2	43.4 (32.6 to 54.2)	53.3 (34.6 to 72.0)	65.3 (41.7 to 88.9)	15.0 (6.9 to 23.1)	0.564	0.007*
Fibular notch						
Step-off at the fibular notch, mm	0.4 (0.3 to 0.6)	0.7 (0.4 to 0.9)	0.4 (0.1 to 0.8)	N/A	0.018*	N/A
Total surface of the gap at the fibular notch, mm^2	12.7 (7.9 to 17.5)	19.8 (10.0 to 29.6)	15.5 (5.7 to 25.3)	N/A	0.403	N/A
Quality of syndesmotic reduction						
Satisfactory/Unsatisfactory	54/16	18/5	18/4	18/7		
Intrasyndesmotic material						
No/Yes (i.e. debris, metal, fragment)	44/26	13/10	16/6	15/10		

N/A, not applicable.
*Statistically significant.

mm (95% CI 0.4 mm to 0.9 mm; p = 0.018, one-way ANOVA) on average in Types I. Type III PMAFs are by definition extraincisural and therefore do not involve the fibular notch.

Posterior malleolar fracture morphology. Taking posterior malleolar fracture characteristics, as well as measures of postoperative articular congruence, into account, bivariate analyses and subsequent multivariate analyses resulted in the following predictors of patients' outcome in PMAFs (Table VII).

For Haraguchi[17] Type I PMAFs, quality of fracture reduction (as quantified with 3DCT measurement of 'classical' residual step-off) and quality of syndesmotic reduction were predictors of outcome in a bivariate analysis. Multivariate analyses also revealed 'classical' measures of residual intra-articular step-off to be an independent predictor of poor outcome in large posterolateral Types I (Table VIII).

Table VII. Bivariate regression analyses on the postoperative quality of fracture reduction as potential predictors of outcome for each respective Haraguchi[17] type of posterior malleolar ankle fracture. The different Foot and Ankle Outcome Score (FAOS) domains are the respective FAOS domain score at two-years follow-up.

Characteristic	Haraguchi Type I (n = 23)					Haraguchi Type II (n = 22)					Haraguchi Type III (n = 25)				
	Symptoms	Pain	ADL	Sports	QoL	Symptoms	Pain	ADL	Sports	QoL	Symptoms	Pain	ADL	Sports	QoL
Articular involvement of the posterior malleolar fragment(s), %	0.043*	0.132	0.129	0.524	0.120	0.542	0.535	0.623	0.578	0.743	0.447	0.693	0.567	0.649	0.668
Quality of fracture reduction															
'Classical' residual intra-articular gap, mm	0.246	0.132	0.381	0.630	0.446	0.681	0.524	0.648	0.561	0.669	0.373	0.254	0.631	0.573	0.772
'Classical' residual intra-articular step-off, mm	0.041*	0.039*	0.153	0.047*	0.08	0.273	0.532	0.429	0.736	0.662	0.586	0.657	0.541	0.552	0.664
Total 3D displacement, mm	0.273	0.233	0.382	0.488	0.582	0.668	0.548	0.578	0.640	0.743	0.762	0.553	0.661	0.744	0.654
Total surface of the intra-articular gap, mm²	0.197	0.324	0.668	0.346	0.844	0.707	0.191	0.387	0.719	0.185	0.165	0.909	0.964	0.894	0.395
Fibular notch															
Step-off at the fibular notch, mm	0.193	0.186	0.374	0.482	0.172	0.003*	0.103	0.246	0.659	0.158	N/A	N/A	N/A	N/A	N/A
Total surface of the gap at the fibular notch, mm²	0.288	0.187	0.488	0.488	0.182	0.688	0.481	0.386	0.222	0.382	N/A	N/A	N/A	N/A	N/A
Quality of syndesmotic reduction															
Satisfactory/Unsatisfactory	0.212	0.008*	0.047*	0.401	0.049*	0.367	0.434	0.703	0.501	0.902	0.076	0.039*	0.042*	0.206	0.059

*Statistically significant.
ADL, activities of daily living; N/A, not applicable; QoL, quality of life.

Table VIII. Multivariate regression analyses on the postoperative quality of fracture reduction as potential predictors of outcome for each respective Haraguchi[17] type of posterior malleolar ankle fracture. The different Foot and Ankle Outcome Score (FAOS) domains are the respective FAOS domain score at two-years follow-up.

Characteristic	Haraguchi Type I (n = 23)					Haraguchi Type II (n = 22)					Haraguchi Type III (n = 25)				
	Symptoms	**Pain**	**ADL**	**Sports**	**QoL**	**Symptoms**	**Pain**	**ADL**	**Sports**	**QoL**	**Symptoms**	**Pain**	**ADL**	**Sports**	**QoL**
Articular involvement of the posterior malleolar fragment(s), mm	0.438	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Quality of fracture reduction															
'Classical' residual intra-articular Step-off, mm	0.029*	0.021*	N/A	0.042*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fibular notch	N/A														
Step-off at the fibular notch, mm	N/A	N/A	N/A	N/A	N/A	0.071	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Quality of syndesmotic reduction	N/A														
Satisfactory/Unsatisfactory	N/A	0.063	0.233	N/A	0.344	N/A	N/A	N/A	N/A	N/A	N/A	0.031*	0.042*	N/A	N/A

*Statistically significant.
ADL, activities of daily living; N/A, not applicable; QoL, quality of life.

For Haraguchi[17] Type II PMAFs (i.e. two-part posterior malleolar fractures extending into the medial malleolus), only residual step-off in the fibular notch (but not residual intra-articular step-off at the tibial plafond) was a predictor for worse scores in the FAOS domain symptoms. There were no other Q3DCT measurements of quality of reduction found to be bivariate predictors of outcome for Types II. In multivariate analysis, none of the 'classic' or 'contemporary' measures of fracture reduction were found to be predictors of outcome for two-part Haraguchi Type II PMAFs.

In small avulsion-type, Haraguchi Type III PMAFs, the quality of syndesmotic reduction was found to be a predictor of the FAOS domain scores Pain and Activities of Daily Living in bivariate analysis. Also, in these Haraguchi Type III PMAFs, the quality of syndesmotic reduction remained an independent predictor for the FAOS domain scores Pain and Activities of Daily Living in multivariate analysis.

Discussion

In PMAFs, posterior malleolar fracture morphology, and not the dogmatic characterization based on posterior malleolar fragment size,[15] is an independent predictor of patient outcomes. Patients with a two-part PMAF extending into the medial malleolus (Haraguchi Type II) have worse outcome scores than patients with either a small avulsion-type (Haraguchi Type III) or larger posterolateral posterior malleolar fragment (Haraguchi Type I). For posterolateral small avulsion-type Haraguchi Type III PMAFs, the quality of syndesmotic reduction is essential, while for larger posterolateral Haraguchi Type I PMAFs the quality of intra-articular reduction at the level of the tibial plafond is an independent predictor of patients' outcome. Interestingly, while patients with two-part Haraguchi Type II PMAFs have the worst functional outcome scores, none of the tested predictors were independently associated with outcome at two-year follow-up. This study contributes to our understanding of rotational type ankle fractures with a concomitant fracture of the posterior malleolus: firstly, PMAF morphology, rather than posterior malleolar fragment size, is predictive of patient outcome, and secondly, these respective posterior malleolar fracture patterns have different respective predictors of patients' outcome suggesting different surgical strategies are needed for each respective PMAF type: posterior malleolar fracture morphology should guide treatment, and not posterior malleolar fragment size.

The current study should be interpreted in the light of its strengths and limitations. The current study is the first study that used postoperative CT images to evaluate quantitative measures of postoperative fracture reduction as potential predictors of outcome in 70 patients with rotational type intra-articular PMAFs at two-years follow-up.

Additionally, postoperative CT imaging allowed for postoperative evaluation of the congruence of the tibial incisura and the quality of syndesmosis reduction (i.e. the orientation of the talus underneath the tibia and the quality of fibular reduction into the fibular notch of the tibia). However, due to the lack of a standardized protocol on surgical decision-making, all patients were treated following surgeons' preference by different respective trauma and orthopaedic surgeons. This resulted in a very heterogeneous group with different PMAF patterns and different techniques (or lack) of fixation of the posterior malleolar fragment(s). However, this could be considered as strength as this 'natural experiment' with postoperative CT and standardized outcome measures, but without a standardized surgical protocol to address the PMAF. It does correspond with actual daily clinical practice for the surgical treatment of PMAFs in a Level-I trauma centre though, and thus helps us understand the potential flaws associated with current clinical practice.

Solan et al[27] have argued that 'all' PMAFs are worth fixing because the posterior malleolus is important and often overlooked in rotational-type ankle fractures. The authors asserted that direct fixation of the PM has several advantages: restoration of the tibial articular surface, the length of the fibula, and (indirectly) the stability of the ankle syndesmosis. However, we concur with White et al[28] that this statement should be adopted in clinical practice with caution and should be nuanced: direct fixation of the posterior malleolus should be undertaken to correct talar subluxation or articular impaction of the tibial plafond. In all other cases, there is insufficient evidence to state that all of the PMAF should be fixed surgically. We feel the current debate has been correctly shifting from surgical decision-making based on PM fragment size to treatment-driven based on PM fracture morphology and overall fracture or injury patterns.

In 2017, Verhage et al[15] designed a randomized controlled trial (POSTFIX) to further advance our understanding whether or not to fix the posterior malleolus in rotational type PMAFs. The authors should be commended for dedicating their resources to help resolve the debate on posterior malleolar fragment fixation. Unfortunately, one can argue that their study design has an important methodological flaw as it included medium-sized (5% to 25%) PMAFs based on review of preoperative plain lateral radiographs. However, nowadays it is well-established that determining PM fragment size based on lateral radiographs is probably imprecise as the plane of the fracture does not correspond to the direction of the X-ray beam.[16] Therefore, it is considered that low-dose preoperative CT scanning of rotational type PMAFs may be indicated similar to most other intra-articular fractures.[13] Moreover, our current study now suggests that posterior malleolar fracture morphology is more important than posterior malleolar fracture size, which is impossible to comprehend on plain lateral radiographs. There will be a potential bias of PMAFs that are 5% to 25% in size as these may include both large Type I posterolateral, two-part Type II with the fracture line extending into the medial malleolus, and even some small-avulsion Type III PMAFs.[19] Therefore, the results of the proposed POSTFIX trial[15] may not give us the answers we need without CT imaging.

Based on the current study, one could propose that patients with large Type I posterolateral PMAFs will benefit from anatomical reduction and fixation as postoperative step-off is a predictor of poor outcome in this particular type of PMAF. This is in accordance with some previous studies that stated that the quantitative measure on congruity of the tibial articular surface, the 'classical' step-off, was associated with clinical outcome in PMAFs. In 2002 Langenhuijsen et al[31] concluded that tibiotalar joint congruity, and not posterior malleolar fragment size, in posterior malleolar PM fragments that involved > 10%

of the tibial articular surface does influence the prognosis in PMAFs. However, it is well-established that determining posterior malleolar fragment size based on lateral radiographs is an unreliable method.[16] Additionally, Berkes et al[33] concluded in 2013 that postoperative tibial articular surface congruity (i.e. a 'classical' intra-articular step-off > 2 mm on postoperative CT) is associated with inferior short-term outcomes in operatively treated type IV Lauge-Hansen[47] supination external rotation (SER IV) ankle fractures.

On the other end of the spectrum are the small avulsion Type III PMAFs, where our data show that good outcomes associated with this specific fracture type are obtained with an adequate reduction of the syndesmosis. In particular for these Type IIIs, the current debate whether or not to fix the posterior malleolus may not apply as a good quality of the syndesmosis can be obtained without a separate posterolateral approach and direct fixation of these small avulsion type posterior malleolar fragments.

Finally, the most challenging PMAF for decision-making are the Type II PMAFs where the posterior-medial fracture line extends into the medial malleolus. These patients do worse,[20] and it remains unclear if they would benefit from direct reduction and fixation. White et al[28] recently suggested that as these types are often associated with tibiotalar dislocation, Type II PMAFs may benefit from direct surgical fixation if it restores the posterior bony buttress in order to obtain a stable ankle joint. Moreover, these PMAF types may be considered inherently unstable as they involve the posterior colliculus of the medial malleolus with the deep deltoid attached. The Type II PMAFs could be associated with more chondral damage and tibial plafond impaction. These 'invisible injuries' may well be important predictors of outcome that have yet to be elucidated in further prospective studies of these complex injuries.

The dogma that all PMAFs involving 25% to 33% or more of the tibial plafond should be operatively fixed has been successfully challenged.[27,28] It is well established that these PMAFs occur in specific fracture patterns with a different overall injury pattern and fracture morphology as evaluated with CT imaging.[20] In conclusion, the current observational prospective cohort study showed that PMAFs are three separate entities based on PM fracture morphology, with different independent predictors of outcome for each respective Haraguchi[17] PMAF Type. This contributes further to the shift away from the current dogma that posterior malleolar fragment size is more important than posterior malleolar fracture morphology. The current debate on whether or not to fix the PMAFs needs to be specified; which morphological subtype benefits from fixation? In PMAFs, fracture morphology should guide treatment instead of fragment size.

Take home message

- Posterior malleolar ankle fractures (PMAFs) are three separate entities based on fracture morphology with different predictors of outcome for each respective PMAF type.
- Posterior malleolar fracture morphology should guide surgical decision-making instead of PM fragment size.

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Funding statement:
No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

ICMJE COI statement:
J.N. Doornberg was supported with an unrestricted research grant from the Marti-Keuning-Eckhardt Foundation. R. P. Blom was supported with unrestricted research grants from ZonMW, Amsterdam Movement Sciences and the Marti-Keuning-Eckhardt Foundation. B. Hayat was supported with a Van Leersum Grant of the Royal Netherlands Academy of Arts and Sciences. For the remaining authors none were declared. No funding was received in direct support of this study.

Acknowledgements:
We gratefully acknowledge the following *EF3X-trial study group collaborators:
M. Suzan H. Beerekamp, Robert-Jan de Muinck Keizer, Marjolein A. M. Mulders, Dirk Th Ubbink, Mario Maas, Jan S. K. Luitse, Peter Kloen, Taco J. M. Blokhuis, Michiel J. M. Segers, Meir Marmor, Marcel G. W. Dijkgraaf and Diederik T. Meijer.

Ethical review statement:
This study did not require ethical approval.

Trial registration number:
Dutch Trial Register: NTR 1902.

This article was primary edited by M. Hossain and first proof edited by G. Scott.