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Article

The Mechanism of Posterior Malleolar Fracture: A Finite Element Study

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Abstract: Background: Good reduction of the articular surface and restoration of the congruent joint space are crucial for promoting positive outcomes in ankle fracture treatment. A good understanding of the mechanism of ankle fractures is indispensable to achieve these goals. Unfortunately, until now, the mechanism has still not been fully elucidated, particularly regarding the posterior malleolar fractures (PMFs). This study aims to provide insight into the mechanism of PMFs, thereby grasping the key to proceeding with PMFs reduction and fixation. **Methods:** An FE model of a normal ankle in tiptoe posture with 9 collateral ligaments was constructed from CT images. On the model, lateral malleolar fractures were made below, through, and above the syndesmosis; the medial malleolus was broken at its base; and ligaments were suppressed to simulate ligament rupture. A force of 1000 Newtons was applied on the talus head along talus axis. The posterior malleolar fragment (PMF) displacement, whether the talus impacts the posterior malleolus, and the initial mechanism displacing the PMF, were recorded. **Results:** A total of 15 tests were conducted. The tests, 'all collateral ligaments rupture', 'LMFB', 'LMFC+AITFL rupture', 'ATFL+CFL+PTFL rupture', 'ATTL+PTTL+TCL rupture', 'MMF', and 'MMF+AITFL rupture', presented significant PMF displacement. In tests 'MMF' and 'ATTL+PTTL+TCL rupture', the talus hit the medial edge of the PMF; but in tests 'ATFL+CFL+PTFL rupture' and 'all collateral ligaments rupture', the talus impacted the center part of the PMF. Except tests 'all collateral ligaments rupture' and 'ATFL+CFL+PTFL rupture', where PMF displacement was initially caused by talus impact, the other tests demonstrated PMF displaced following PITFL drag. **Conclusions:** This research discovered that rotation is the initial and major mechanism causing PMF displacement. The subsequent impact of the talus on the posterior malleolus may be the reason for large/blocky PMF. The talus impacting the posterior malleolus is always combined with talus rotation. Without the medial ankle structure being broken, big/blocky PMF may not occur. These findings suggest that, in clinical practice, reconstructing both the medial and lateral ankle structures is critical for achieving ankle stability, and this procedure even takes precedence over posterior malleolar fracture fixation itself.

Keywords: ankle fractures; posterior malleolar fractures; mechanism; stability; reduction; fixation; finite element analysis

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Background

Ankle fractures are known as one of the most common fractures in the lower extremity, present in 9% of all fractures, mostly caused by rotation mechanism. Ankle fractures usually cause medial malleolar, lateral malleolar, and sometimes posterior malleolar. Besides bone break, ligament rupture can also occur. However, posterior malleolar fractures (PMFs) are noticed as related to ankle dislocation and some of them seem to correlate with vertical compression, those are also called the posterior Pilon fractures. To achieve excellent functional outcomes following ankle fracture, perfect reduction of the articular surface and restoring congruent joint are necessary. It is generally accepted

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that intra-articular step-off of more than 2 mm is an independent risk factor for an inferior outcome and the development of post-traumatic arthritis, irrespective of the fragment size[1]. Therefore, understanding the mechanism of PMFs and concomitant damages associated with this injury can be particularly significant in ankle fracture treatment.

Previously, many studies were conducted to explore the nosogenesis of ankle fractures, like Lauge-Hanson, Haraguchi, Bartonicek, etc. Those respected investigators revealed some great parts of the procedure, how this kind of fracture happened. Based on the study results, a comparatively maneuverable strategy was set up to deal with the ankle fractures. Even so, there are more and more debates on syndesmosis injury and PMFs in recent years, on account of inconsistent sequence to place back posterior malleolar fragment (PMF) and neglect of PMFs. To better understand the mechanism of PMFs, a finite element study was performed to investigate the role of different parts of the ankle participating in such fractures, especially when the talus head was under anteroinferior compression. Thereby, the key to proceeding with PMFs reduction and fixation could be grasped.

Methods

To study the role of different parts of the ankle (medial malleolus, distal fibula, medial collateral ligaments, lateral collateral ligaments and syndesmosis) in PMFs, ankle FE models in tiptoe posture were created. Collateral ligament rupture and malleolar fracture were modeled respectively. After that, 1000 Newtons were loaded on the talus head along talus axis. The contact between the posterior malleolus and the talus, the posterior malleolus displacement, the initial mechanism displacing the PMF, as well as the location of the highest stress were investigated.

Modeling of Normal Ankle

The three-dimensional digital model of the ankle in this study was generated from the computed tomography (CT) data of a 39-year-old female, height 160cm and weight 60kg. The patient underwent CT scan to rule out fracture after slipping and bruising the left knee. During the CT scan, the patient's lower extremity was put in a neutral rotation position, the foot dropped relaxedly, and slice thicknesses of 1 mm, and a resolution of 512×512 pixels per image were applied. For easy use of data management and subsequent analyses, images were archived in DICOM format. There were no signs of fracture nor dislocation around the ankle presented after examination. According to the patient history, no osteoporosis, tumors, tuberculosis, endocrine system diseases, or other destructive diseases around the ankle were noticed.

The CT images were imported into Materialise Mimics Medical software (Version 21.0, Materialise NV, Leuven, Belgium) to generate a skeletal ankle model in STL format. Then, the STL ankle model was transformed into CAD model in STP format based on NURBS surfaces by Magic Studio 2013 software (version 2012, North Carolina, USA). Additionally, surface optimization and smoothing were generated. After that, Rhino software (Rhino 6, Robert McNeel & Associates, Seattle, Washington, USA) was used. Ligaments around the ankle were created and attached to bones. The morphology of ankle ligaments was referred to previous study. Syndesmosis was referred to Andrew's study[2], ligaments were referred to Golanó's research[3]. The ligaments were as follows: anterior talofibular ligament (ATFL), posterior talofibular ligament (PTFL), calcaneofibular ligament (CFL), anterior tibiotalar ligament (ATTL), posterior tibiotalar ligament (PTTL), tibiocalcaneal ligament (TCL), anterior inferior tibiofibular ligament (AITFL), posterior inferior tibiofibular ligament (PITFL) and posterior intermalleolar ligament (PIML). To simplify the model, CFL and TCL were attached to the talus (Figure 1).

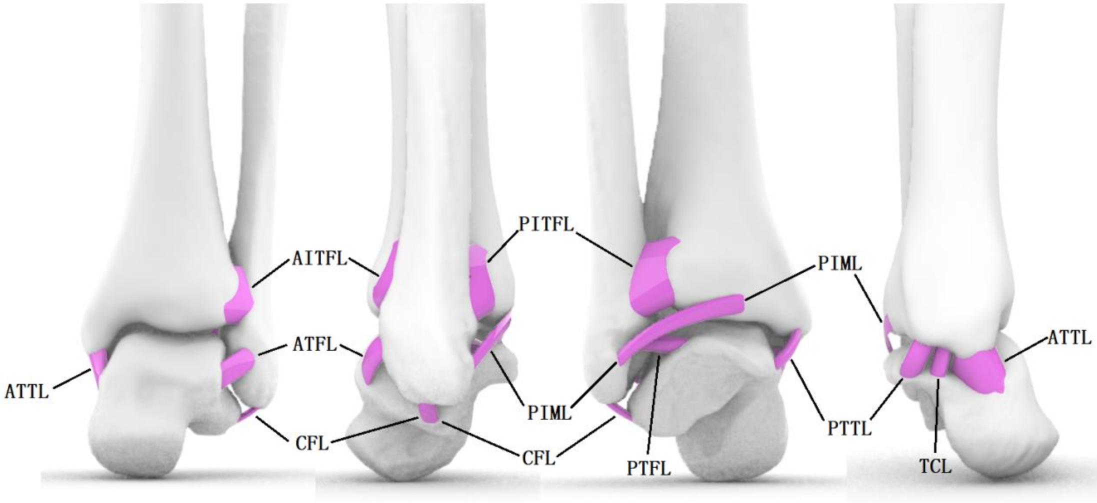

Figure 1. Ankle model. To simplify the model, the CFL and TCL were attached to talus.

Breaking the Posterior Malleolus, Distal Fibula, Medial Malleolus and Ligaments

According to the discovery of Quan Y[4], Su QH, Yao L[5], Haraguchi N[6] and Li Yongqi[7], the fracture line was set to split the posterior malleolus curved from the middle of fibula notch towards the lateral part of groove for tibialis posterior, and the angel between fracture plane and horizontal plane was 70°[8]. The gap of fracture was 0.5mm (Figure 2).

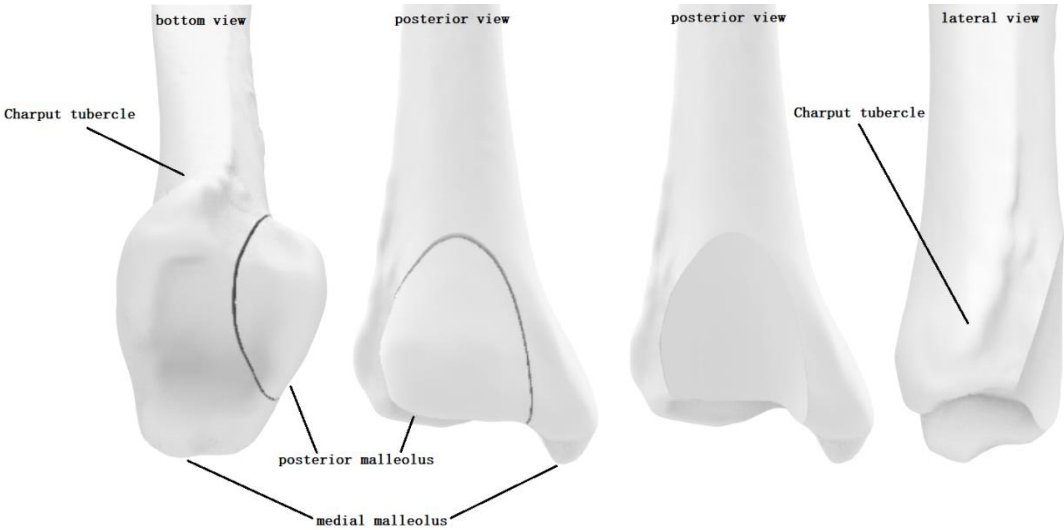

Figure 2. Posterior malleolar fragment.The posterior malleolus was broken curvedly from the middle of fibular notch to the medial of groove of tibialis posterior. The angle between fracture plane and horizontal plane was 70°.

The distal fibular fracture was set on three levels: below syndesmosis, through syndesmosis and above syndesmosis, corresponding to Danis-Weber classification type A, B and C. The shape of the fracture referenced previous research work[9]. The gap of fracture was also 0.5mm (Figure 3).

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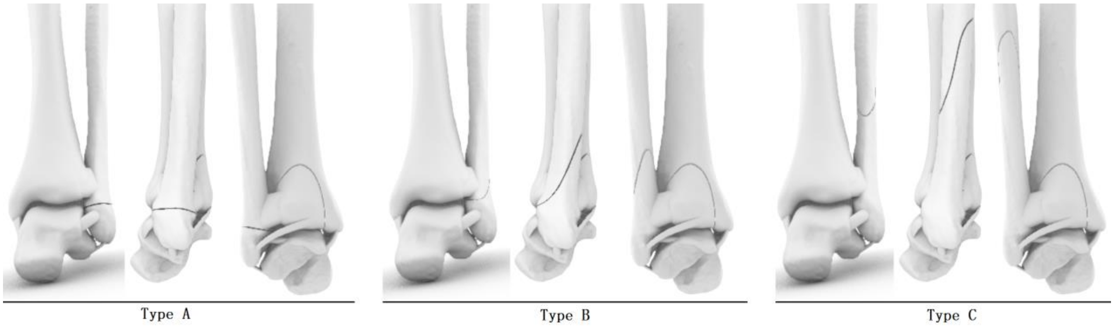

Figure 3. Lateral malleolar fracture. Type A, B and C respectively correspond to Danis-Weber classification type A, B and C.

Medial malleolus was broken at the base level referencing the discovery of Liu and Lu[10, 11]. The angle between the fracture plane and the horizontal plane was 60°. The gap of fracture was 0.5mm too (Figure 4).

Figure 4. Medial malleolar fracture. The fracture was set at the medial malleolus base.

The ligaments were suppressed to simulate ligament rupture (Figure 5).

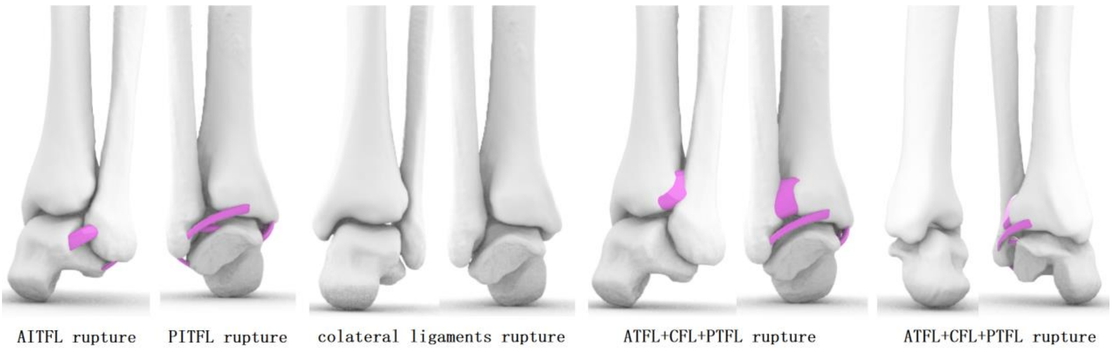

Figure 5. The ligaments were suppressed to simulate ligament rupture.

Constructing of FE Models

After fractures and ligament rupture were created, the models were inputted into FEA software Abaqus (Abaqus/CAE 6.14, Dassault Systemes Corp, RI, USA). Material properties applied in this study are detailed in Table 1.

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Table 1. Material Property setting.

Material	Young's modulus (MPa)	Poisson ratio
Skeleton	7300	0.3
ligament	260	0.4

The interaction between normal bone surfaces was set as hard contact, frictionless, including joint surfaces. The interaction of coupling fracture faces was set as a hard contact penalty, with a friction coefficient of 0.2. The contact between matched faces of syndesmosis was also set as a fracture interaction. The end of the ligament was tied to the footprint on bone.

The mesh structure approach was C3D10 Tet. Mesh quality was verified by skewness measure, and high mesh quality was presented for all cases. An average of 581 thousand elements were meshed for each model. There was no analysis error in the mesh quality check.

Boundary conditions were as follows: proximal end of the tibia and fibula were fixed in 6 degrees of freedom; a reference point was coupling to the talus head; 1000 N was loaded at the reference point along talus axis

Coordinate System

The cartesian coordinate system was used to describe the talus movement. The origin was set at the center of distal tibia joint surface, with the X-axis pointing to the left, the Y-axis pointing to the back, and the Z-axis pointing to the head (Figure 6).

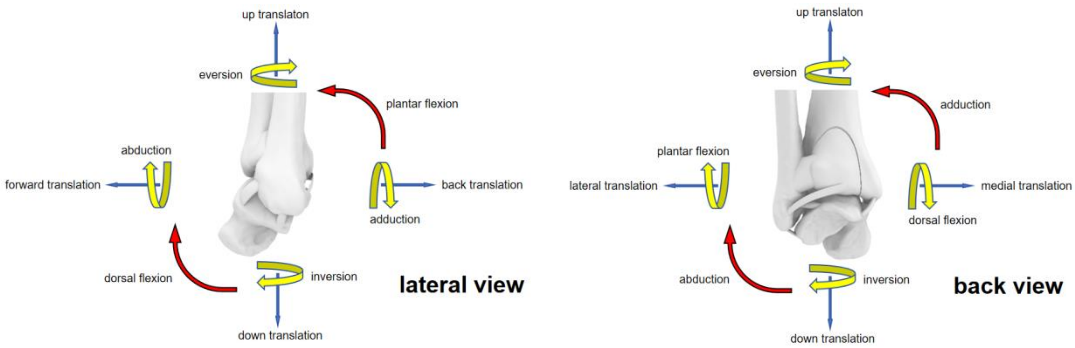

Figure 6. Coordinate system to describe the movement of talus.

Results

A total of 15 models were built to simulate ankle deformation in different situations. After loading 1000 Newtons on the talus head along talus axis, the contact between posterior malleolus and talus was investigated, meanwhile, the displacement of PMF and talus was also recorded (Table 2). Among all models, 7 models (yellow in Table 2) presented significant posterior malleolus displacement, they were 'all collateral ligaments rupture', 'LMFB', 'LMFC+AITFL rupture', 'ATFL+CFL+PTFL rupture', 'ATTL+PTTL+TCL rupture', 'MMF' and 'MMF+AITFL rupture'; 6 models showed no displacement, they were 'intact', 'AITFL rupture', 'PITFL rupture', 'AITFL+PITFL rupture', 'LMFA' and 'MMF+PITFL rupture'. However, 2 models, 'LMFC' and 'LMFC+PITFL rupture', displayed slight or doubtful displacement in the test. Considering no density was assigned to materials and the PMF moved almost synchronously with the proximal fragment, the 'slight' can be treated as 'N' (gray in Table 2). As a consequence, there were totally 8 models with no displaced posterior malleolus. In the displaced group, 4 models demonstrated talus impacted PMF (blue in Table 2): 'all collateral ligaments rupture', "ATFL+CFL+PTFL rupture", 'ATTL+PTTL+TCL rupture' and 'MMF'. In these 4 models, interestingly, 'MMF' and 'ATTL+PTTL+TCL rupture' appeared talus hit the medial edge of PMF, while 'ATFL+CFL+PTFL rupture' and 'all collateral ligaments rupture" showed talus impacted the central part of PMF. The other 3 models in the displaced group, 'LMFB', 'LMFC+AITFL rupture' and 'MMF+AITFL rupture', presented no sign of talus impacting PMF.

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Reviewing the animation of displacement, the initial mechanism that 'talus impact' drove PMF to move was seen in the model 'all collateral ligaments rupture' and 'ATFL+CFL+PTFL rupture' (red in Table 2). However, in models 'ATTL+PTTL+TCL rupture' and 'MMF', the PMF was dragged by PITFL initially. In models 'intact', 'AITFL rupture', PITFL rupture' and 'AITFL+PITFL rupture', talus translation was not observed, there was only rotational movement (pink in Table 2).

Table 2. The displacement of posterior malleolar fragment.

The displacement of posterior malleolar fragment

model/test*	posterior malleolar fragment displacement(Y/N)	talus impact posterior malleolus(Y/N)	talus movement**	initial mechanism displacing posterior malleolar fragment***	location of the highest stress
intact	N	N	PF+Inv+Ad	/	proximal tibia
all collateral ligaments rupture	Y	Y	BT+UT	talus impact	posteromedial facet of distal tibia
AITFL rupture	N	N	PF+Inv+Ad	/	PTFL
PITFL rupture	N	N	PF+Inv+Ad	/	proximal tibia
AITFL+PITFL rupture	N	N	PF+Inv+Ad	/	PTFL
LMFA	N	N	BT+UT; PF	/	ATTL
LMFB	Y	N	BT+UT; PF+Ev	PITFL traction	anterior process of lateral malleolar fracture
LMFC	slight	N	BT+UT; PF	PITFL traction	proximal tibia
LMFC+AITFL rupture	Y	N	BT+UT; Ab+Ev	PITFL traction	ATTL
LMFC+PITFL rupture	slight	N	BT+UT; PF	PIML traction	proximal tibia
ATFL+CFL+PTFL rupture	Y	Y	BT+UT; PF+Ev+Ab	talus impact	posteromedial facet of distal tibia
ATTL+PTTL+TCL rupture	Y	Y	BT+UT; Ad+Inv	PITFL traction	posteromedial facet of distal tibia
MMF	Y	Y	BT+UT;Ad+Inv	PITFL traction	ATTL
MMF+AITFL rupture	Y	N	BT+UT+MT; Ad+Inv	PITFL traction	ATFL
MMF+PITFL rupture	N	N	BT+UT;Ad+Inv	/	posteromedial facet of distal tibia

Note: * model/test: intact=model with intact ligaments, and medial, lateral malleolus, LMFA=left malleolar fracture type A, LMFB=left malleolar fracture type B, LMFC=left malleolar fracture type C, MMF=medial malleolar fracture. ** talus movement: FT=forward translation, BT=back translation, UT=upward translation, DT= down translation, MT=medial translation, LT=lateral translation, DF=dorsal flexion, PF=plantar flexion, Ev=eversion, Inv=inversion, Ad=adduction, Ab=abduction. *** Animation was investigated to clarify the initial mechanism (traction/impact) that induced posterior malleolar fragment displacement. Y=yes, N=no.

Discussion

The Classification Systems of PMFs

There are several classification systems developed to describe PMFs. Each of them has unique advantages, but none of them perfectly explains the injury mechanism of such kind fractures, especially has a satisfied derivable treatment strategy with regard to outcomes. Haraguchi, Bartoníček and Mason classification system are most frequently used. To evaluate the user reliability of the frequently used classification system for PMFs, Haraguchi classification, Bartoníček classification and Mason classification, Rashid built a team of 9 surgeons to screen the medical images of 60 patients from two hospitals at two separate time points, with each assessment taking place more than 4 months apart. As a result, inter-rater reliability (Fleiss'κ) was rated as 'moderate' for Haraguchi classification and Mason classification, 'substantial' for Bartoníček classification; the intra-rater reliability (Cohen's κ) was rated as 'substantial' for all three classifications[12]. A systematic literature review was also applied to assess these three classifications. In the report, a total of 110 studies with a total of 12614 patients were included, all classifications got a substantial to perfect score regarding the inter- and intra-observer reliability. Bartoníček classification was advised according to its treatment algorithm, and its consistency with predictive values[13]. Li Yongqi et al. classified the PMFs into three types according to the tibial insertion of PIML, PITFL and PTTL. They discovered type II (PITFL) presented in 229 cases (77.4%) out of a total of 296 cases of PMFs. Additionally, they also found the articular surface suffered from fracture, proximal displacement of PMF and posterior extent of talus subluxation increased with the escalation of classification grade[7]. In the present study, the trajectory of posterior malleolar fracture line and the angle of fracture plane were made referencing the classification system and fracture map described previously.

The Mechanism of PMFs

It is known that deep insight into injury mechanism and focus on the key part of reduction is crucial for rehabilitation of ankle injury. Many biomechanical researches have been done to

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investigate ankle fracture, but the process of PMFs still remains unclear. The supposition has been made that external rotation of talus or axial impact loading is the cause of PMFs. Unfortunately, this hypothesis has not been demonstrably proved. Especially, rotation and impact, which one is more essential remains controversial. Zhang compared two cases that suffered lower tibia spiral fracture combined with lateral malleolar fracture. Case 1 underwent right foot plantar flexion, backward impact and external rotation, while case 2 only underwent right foot external rotation. A big triangle posterolateral malleolar fragment was presented in case 1, but no PMF occurred in case 2. Speculation was made that high-degree ankle plantar flexion induced talus impacting posterior malleolus upward, generated a PMF[14]. The Lauge-Hansen ankle fracture classification system is widely accepted since it is based on the mechanism of injury. Patton reviewed 153 patients who suffered trimalleolar fracture, according to CT scan, there was no significant association between the Lauge-Hansen classification and PMF morphology[15]. Haraguchi investigated 15 cadaver ankles applied by Lauge-Hansen pronation-external rotation loading and axial loading along the tibia, he discovered that posterolateral malleolar avulsion fracture was attributed to PITFL traction following lateral malleolus external rotation, posterior tibial margin consisting of 2 fragments was produced by a combination of the PITFL avulsion and axial loading[6]. Wang reported PMFs generally associated with distal tibia rotation[16]. In order to verify the role of rotation and impact in the displacement of PMF, a plantar flexion ankle model was constructed in the present study; a pre-existing posterior malleolar fracture was created, and density was not assigned to the material to avoid the influences of gravity and inertia on the movement of PMF; a force of 1000 newtons was applied to the talus head along talus axis to simulate a 102 kg person standing on tiptoe with a single foot, thereby, the talus impact or push the PMF directly. Examine the results, test 'all collateral ligaments rupture' and 'ATFL+CFL+PTFL rupture' presented significant talus impacting posterior malleolus and PMF upward displacement. On the other hand, significant lateral rotational displacement of PMF was observed in tests 'LMFB' and 'LMFC+AITFL rupture'. Upon scrutinizing the animation, it was noticed that rotation is the initial and major mechanism causing PMF displacement. Integrating the findings from previous research, it is conjectured that rotation produces avulsion fracture, the fragment is small or shell shape; but rotation combined with strike, generates 'posterior Pilon fracture', the fragment is big or blocky shape.

The Factors That May Affect PMF Morphology

In practice, the central tendency of fracture line or area in ankle fractures is noticed. A major reason for this occurrence has been considered to be the mechanically significant bone architecture features. In Ying's study, the anterolateral tibia, the anteromedial tibia, and the fracture line were identified as the stress concentration zones related to ankle fracture; sagittal fracture angle below 60° may compromise ankle stability[17]. In the present study, posterolateral malleolus and posteromedial malleolus were observed to be the stress concentration area respectively under talus impact load with lateral malleolar structure and medial malleolar structure broken. The predicted fracture line was consistent with previous research. However, reviewing the literature, PMF morphological characteristics was also reported may not connect with posterior malleolar fracture itself or spiral fracture of the middle and lower third of tibia[18]. In the present study, posterolateral malleolus and posteromedial malleolus were observed to be the stress concentration area respectively under talus impact load with lateral malleolar structure and medial malleolar structure broken, the predicted fracture line was consistent with previous research and clinical practice.

Medial Structure Broken Causes the PMF

Posteromedial malleolar fractures are recognized in clinical experience. This kind of fractures have been included in several classification systems, such as Haraguchi classification, Mason classification and Mangnus classification, etc. Hasen reported the posterior Pilon fracture was resulted from vertical strike combined with rotation mechanism in 2000[19]. Coincidentally, Mason, Zhang Jianzheng and other researchers also expressed similar opinions. However, it is still hard to

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say how rotation and/or vertical strike cause PMF. In this study, tests 'ATTL+PTTL+TCL rupture' and 'MMF' demonstrated stress concentration at the medial corner of the PMF, while the other tests did not (Figure 7). Eliminating the influence of pre-existing posterior malleolar fracture line, it is reasonable to suppose deltoid ligament or medial malleolus broken lead to talus inversion, upward and backward movement, which induces the talus strike the posteromedial malleolus, subsequently result the posteromedial malleolar fracture; without talus strike, isolated external rotation hardly cause posteromedial malleolar fracture.

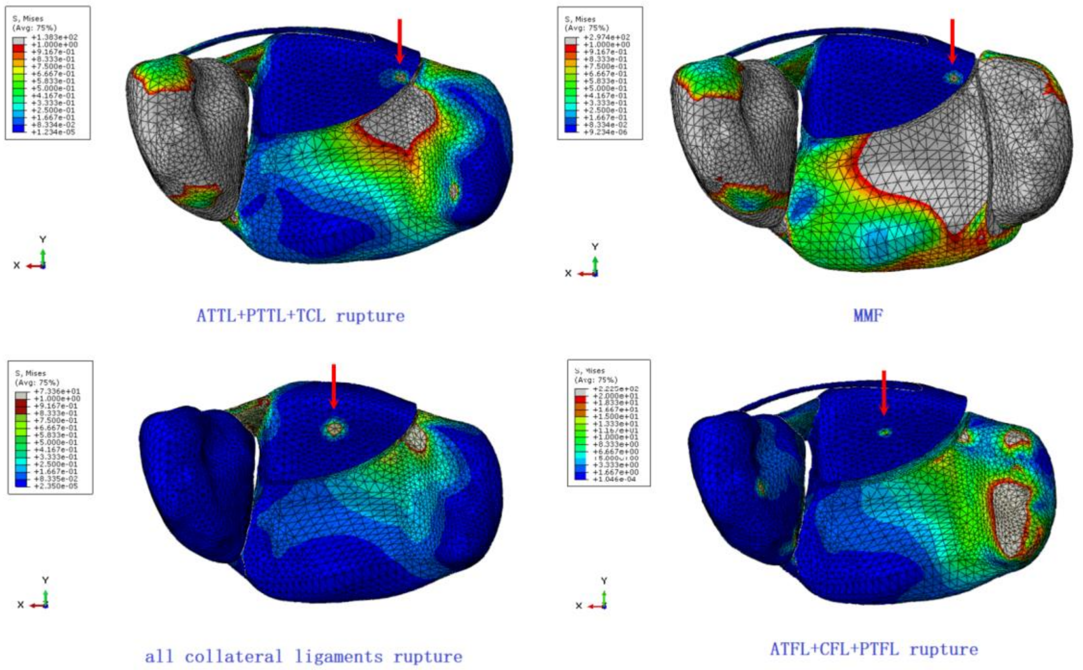

Figure 7. In the tests 'ATTL+PTTL+TCL rupture' and 'MMF', stress concentration presented at the medial corner of the PMF; while in the test 'all collateral ligaments rupture' and 'ATFL+CFL+PTFL rupture', stress concentration presented at the central area of the PMF (as shown by the red arrow).

Isolated 'Talus Impact Posterior Malleolus' Does Not Exit in Practice: Such Movement is Always Combined With Talus Rotation

Posterior Pilon fracture and anterior Pilon fracture have been mentioned in recent years. The feature of these kinds of fractures is the existing of big fragment located at the posterior or anterior malleolus, shifting proximally. Wang noticed the correlation between PMFs and spiral distal tibial fracture. He reported the incidence of PMFs associated with simple spiral distal tibia fracture was 74.0-90.8%, the independent predictors were age, osteoporosis, external rotation of the proximal tibia and spiral fibula fractures[16]. Wang's study underlined the role of rotation mechanism in PMFs. Athmaram reported when the foot was plantar flexed, the talus directly struck the posterior malleolus, pushing it backward; when foot was dorsal flexed, the talus impacted anterior tibial margin; while when foot was in a neutral position, a Y-shaped fracture with large anterior and posterior fragments occurred[20] . In the present study, except test 'all collateral ligaments rupture', all other tests showed no pure translation without talus rotation. Furthermore, investigating the animation of displacement and stress distribution, it looks like rotation always occurred before impact and induced PMF shift primarily, despite the ankle was put in a plantar flexion position with loading on the talus head along talus axis toward rear-up direction.

The Role of Different Part of Ankle in Ankle Stability

The fundamental role of ligaments in maintaining ankle stability is universally acknowledged. Several cadaveric studies have been done to give insight into the function of ankle ligaments. Generally, ATFL restricts talus from forward translation in the early period of ankle plantar flexion

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and internal rotation when the ankle is extremely plantar flexed[21]. The CFL bridges both the talocrural joint and subtalar joint, allowing talocrural joint flexion and extension movements, as well as subtalar joint movement. PTFL restricts talus excessive backward shift and dorsal flexion[3]. Despite much attention has been devoted to ankle lateral ligaments, meaningful research has also stressed the crucial role of the deltoid ligament. Preserving the continuity of medial ankle structure is integral to instantly obtain congruent ankle joint space and normal talus trajectory, only repairing the lateral structure cannot provide sufficient support for ankle stability. Already in 1996, Michelsen et al. discovered complete fibular osteotomy did not cause abnormal motion of ankle in the absence of a medial injury[22]. Following this, several investigations have been done. Sasse et al. reported that in dorsiflexion or plantarflexion position, an intact lateral malleolus was not necessary for physiological talar tracking, injured deltoid ligament healing at its resting length was crucial to restoring physiological talar rotation[23]. Dalen and his team, after cadaver test, declared the significant ankle-stabilizing role of the deep posterior deltoid after Web B ankle fracture and transection of the superficial and anterior deep deltoid ligaments[24]. Gregersen et al. Disclosed that the fixation of fibular fracture primarily improved external rotation stability but did not substantially improve lateral translation, valgus, or internal rotation stability in SER4 ankle fracture[25]. The current study revealed that only AITFL or/and PITFL rupture did not result in talus translation, there was no sign of talus impact posterior malleolus in tests 'AITFL rupture', 'PITFL rupture' and 'AITFL+PITFL rupture'. In this sense, medial or/and lateral ankle structure broken is unavoidable for PMFs. This finding was consistent with Filippi's study. In Filippi's cadaveric test, it was found that without lateral collateral ligament rupture, even complete disruption of syndesmosis ligament did not increase the proximal displacement of fibula[26]. Interestingly, also based on a cadaver test, Sato reported that lateral ankle ligament rupture had no direct effect on the stability of syndesmosis[27]. Soto's findings concurred with the present study. Test 'ATFL+CRL+PTFL rupture' showed no subluxation of syndesmosis but showed talus directly impacted PMF. On the other side, test 'MMF+PITFL rupture' and 'LMFC+PITFL rupture' showed no PMF displacement, while test 'MMF+AITFL rupture', 'LMFC+AITFL rupture' and 'LMFB' displayed PMF shift. This demonstrates that PITFL plays a key role in PMFs, intact PITFL and broken AITFL (the equivalent of test 'LMFB') are crucial for PMFs.

Limitations of the Present Study

The present study has some limitations as well as strengths. Firstly, since pre-existing posterior malleolar fracture was made, the present study did not show the process of big/blocky and small/shell PMF formation, therefore cannot completely interpret the mechanism of PMF morphology. Secondly, the insertion of CFL and TCL was set to talus, not calcaneus, this may ignore the influence of subtalar joint movement on the talocrural joint. Thirdly, the ankle joint capsule was not modeled, the effect of the capsule limits PMF displacement was neglected.

Conclusions

The results of this study provide insight into the mechanism of posterior malleolar fractures. Rotation is the initial and major mechanism causing PMF displacement, even when the talus is pushed directly upward and backward towards the posterior malleolus in the absence of rotational load. The subsequent impact of the talus on the posterior malleolus may be the reason that leads to large/blocky PMF. However, isolated 'talus impacting the posterior malleolus' does not exist in practice, such movement is always accompanied by talus rotation. PITFL plays a key role in PMFs, intact PITFL and broken AITFL (which is equivalent to test 'LMFB') are crucial for PMFs. The medial ankle structures provide strong support for ankle stability. Without the medial ankle structure being broken, big/blocky PMF may not happen. Preserving the continuity of medial ankle structure is essential for immediately achieving congruent ankle joint space and normal talus trajectory, merely repairing the lateral structure cannot provide sufficient support for ankle stability. These findings suggest that, in clinical practice, reconstructing both the medial and lateral ankle structures is critical for achieving ankle stability, and this procedure even takes precedence over posterior malleolar fracture fixation itself.

Authors' contributions: Zhijian Ma and Yichao Ma performed the finite element analysis, both are the major contributor in writing the manuscript. Liping Bai and Zhijian Ma designed the study. Lixian Bai and Liping Bai performed the manuscript redaction and review. Rongjiang Li and Han tang performed the data collection and analysis. The authors have read and approved the final manuscript.

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Data Availability Statement: The datasets used and/or analyzed during the current study are available from the Zhijian Ma on reasonable request.

Institutional Review Board Statement: This study was approved by the Ethics Committee of the Second People's Hospital of Yunnan Province and the First People's Hospital of Kunming.

Conflicts of Interest: The authors declare that they have no competing interests.

Abbreviations

PMFs=posterior malleolar fractures, PMF=posterior malleolar fragment, ATFL=anterior talofibular ligament, PTFL=posterior talofibular ligament, CFL=calcaneofibular ligament, ATTL=anterior tibiotalar ligament, TCL=tibiocalcaneal ligament, PTTL=posterior tibiotalar ligament, AITFL=anterior inferior tibiofibular ligament, PITFL=posterior inferior tibiofibular ligament, PIML=posterior intermalleolar ligament, intact=model with intact ligaments, and medial, lateral malleolus, LMFA=left malleolar fracture type A, LMFB=left malleolar fracture type B, LMFC=left malleolar fracture type C, MMF=medial malleolar fracture, FT=forward translation, BT=back translation, UT=upward translation, DT= down translation, MT=medial translation, LT=lateral translation, DF=dorsal flexion, PF=plantar flexion, Ev=eversion, Inv=inversion, Ad=adduction, Ab=abduction.

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