CLINICAL ARTICLE

Investigation of the Characteristics and Mechanism of Interosseous Membrane Injuries in Typical Maisonneuve Fracture

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Objectives: Previous studies on the mechanism and scope of interosseous membrane injury in Maisonneuve fractures have been inconsistent. In order to better guide clinical treatment, the characteristics and mechanism of interosseous membrane injuries and proximal 1/3 fibular fracture in typical Maisonneuve fracture were investigated.

Methods: The study comprised 15 patients between January 2019 and June 2021 with Maisonneuve fracture. All patients received X-ray and MRI examination of the calf and ankle joint, and CT scanning of the ankle joint. The injuries of medial structure, inferior tibiofibular syndesmosis, fibula, posterior malleolus, and interosseous membrane were evaluated.

Results: MR images of the calf showed that the injury of interosseous membrane (IOM) was from the syndesmosis to the proximal fibular fracture site in two patients, with a range of 32.3 and 29.8 cm, respectively. In the other 13 patients, the IOM rupture was not only confined to the distal third of the calf, but also close to the fibula fracture, and the IOM was intact between the two fracture sites. The range of distal IOM rupture was 3.7–12.2 cm, with an average of 8.06 ± 2.35 cm. The proximal IOM was completely ruptured from the fibular side at the site of the fibular fracture and the range was 4.1–9.1 (average: 6.75 ± 1.64) cm. The average length of the integrate middle segment of the IOM was 14.55 ± 4.11 (5.6–20.3) cm. MR images of the calf also showed partial rupture of the posterior tibial muscle at the ending point on the fibula in 15 cases, partial rupture of soleus muscle and flexor hallucis longus in seven cases.

Conclusions: The rupture of the IOM was caused by a combination of abduction and external rotation violence. It was manifested in two forms, most of which was not only distal end but also near fibular fracture site ruptures with the middle part intact, and a few were ruptures of the IOM from the ankle to the near fibular fracture site. The tibialis posterior muscle may be related to the location of the fibular fracture.

Key words: Injury Mechanism; Interosseous Membrane; Maisonneuve; Proximal Fibula; Syndesmosis

Introduction

Maisonneuve fracture was first reported in 1840 by the surgeon Jules Germain Francois Maisonneuve.[1] Previous studies showed that Maisonneuve fracture is mainly manifested by proximal 1/3 fibular fracture, separation of the inferior tibiofibular syndesmosis, and deltoid ligament injury or medial malleolus fracture.[2–6] It is rare in clinical practice and accounts for about 5% of all ankle fractures.[7]

Several studies have investigated the mechanisms of Maisonneuve fracture for many years. Imaging manifestations constitute the leading evidence for such investigations. Especially magnetic resonance imaging (MRI)-based studies

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have advanced with respect to the mechanisms underlying Maisonneuve fracture, negating several previous speculations. For instance, previous opinions suggested that the proximal fibular fracture was caused by the transduction of force of outward extortion through the interosseous membrane, and the range of interosseous membrane tearing was between the distal ending point and the fracture site of the fibula.[8–10] However, by MRI examination, Manyi et al.[4] found that the interosseous membrane tearing was only restricted in the distal 1/3 of the calf in patients with Maisonneuve fracture, while the proximal interosseous membrane was still intact.

Most studies suggested that typical Maisonneuve fracture is a specific pronation external rotation (PER) ankle fracture.[11,12] According to the Langue–Hansen classification criteria,[8] Maisonneuve fracture is a pronation external rotation stage III or IV ankle fracture. During the injury, first, the medial structures are damaged, and deltoid ligament rupture or medial malleolus fracture occurs, followed by the avulsion fracture of the attachment point or the rupture of the anterior inferior tibiofibular ligament, interosseous ligament injury, interosseous membrane tearing, and proximal fibular fracture. If the force continues, rupture of the posterior inferior tibiofibular ligament or avulsion fracture of the posterior tubercle of the tibia might occur. Hitherto, only a few MRI-based studies investigated the mechanisms and features of interosseous membrane injuries. Some studies mainly focused on the injuries of ligaments surrounding the ankle joint but ignored the injuries of the muscles. Moreover, there is no plausible explanation for the reason that the fibular fracture usually occurs at the proximal 1/3 segment.

Fig. 1 AP radiograph of calf showing the medial malleolus fracture, proximal one-third of the fibular fracture without coronal displacement and separation of inferior tibiofibular syndesmosis (red arrow: medial malleolus fracture; blue arrow: proximal one-third of the fibular fracture)

In the present study, the imaging data and medical records of the patients with typical Maisonneuve fractures were reviewed, and the X-ray, computed tomography (CT), and MRI images were analyzed. Thus, this study aimed to (i) summarize the characteristics of interosseous membrane tear in Maisonneuve fracture; (ii) explore the mechanisms underlying the interosseous membrane injuries; (iii) guide the diagnosis accurately and the choice of treatment strategies of Maisonneuve fracture.

Patients and Methods

Inclusion and Exclusion Criteria

The inclusion criteria were as follows: (1) fracture of proximal 1/3 fibular fracture, separation of the inferior tibiofibular syndesmosis and deltoid ligament injury or medial malleolus fracture; (2) BMI < 25 kg/m^2; (3) received X-ray and MRI examination of the calf and ankle joint, and CT scan of the ankle joint; (4) MRI examination within 3 days after the injury. The exclusion criteria were as follows: (1) history of the previous ankle joint injuries or surgeries; (2) age < 18 years; (3) accompanied with other traumas; (4) open fracture; (5) the medial ankle joint structures were intact; (6) the posterior malleolar fracture was type II Haraguchi fracture.[13]

X-Ray, CT, and MR Scanning of the Patients

Subsequently, data of 15 eligible patients with Maisonneuve fracture, treated in the Department of Foot and Ankle Surgery I of Tianjin Hospital between January 2019 and June 2021, were analyzed in this retrospective study. The Ethical Committee of Tianjin Hospital approved this study (IRB No. 2021-170). All the patients received imaging examinations within 3 days after the injury, including the anteroposterior and lateral X-ray imaging of the ankle joint and calf, which were used to evaluate the fractures of the medial malleolus, fibula, and posterior malleolus. In addition, the distances in the medial clear space and inferior tibiofibular space were measured to assess the injuries of deltoid ligament and inferior tibiofibular syndesmosis. The CT scanning of the ankle joint was performed to confirm the non-displacement fractures and avulsion fractures that could not have been identified by X-ray imaging and provided axial images to evaluate the morphological features of the posterior malleolar fracture (Figures 1, 2, 3, 4, 5, 6).

The MRI of the ankle joint and calf was performed using the Discovery MR 750 (GE Healthcare, Milwaukee, WI, USA). Briefly, patients were placed in a supine position, with the affected knee joint extended and the ankle joint in the natural neutral plantar flexion positions. The MR

Fig. 2 Lateral radiograph of calf showing the posterior malleolar fracture and proximal one-third of the fibular fracture with the fracture line extended from the anterior-superior edge in a posterior-inferior direction (red arrow: posterior malleolar fracture; blue arrow: proximal one-third of the fibular fracture)

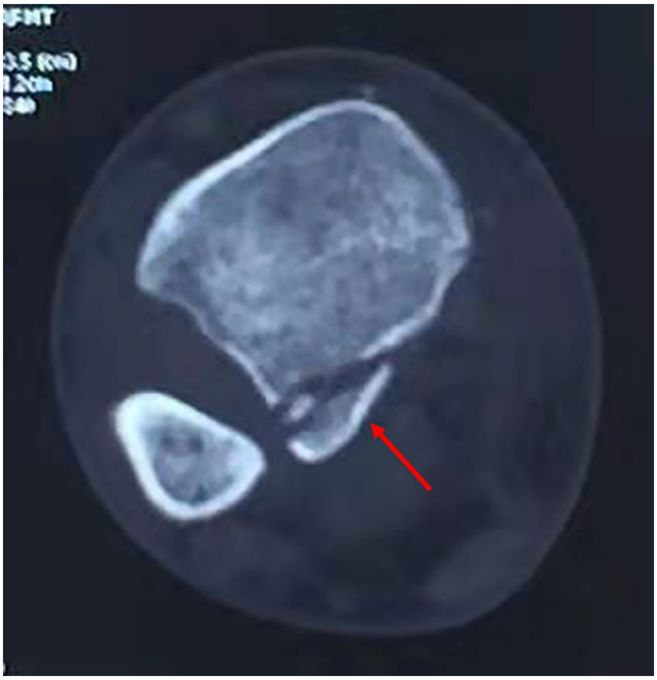

Fig. 3 The CT scanning of the ankle joint showing the type I (posterolateral oblique) fracture according to the Haraguchi classification of posterior malleolus fracture (red arrow: type I posterior malleolus fracture)

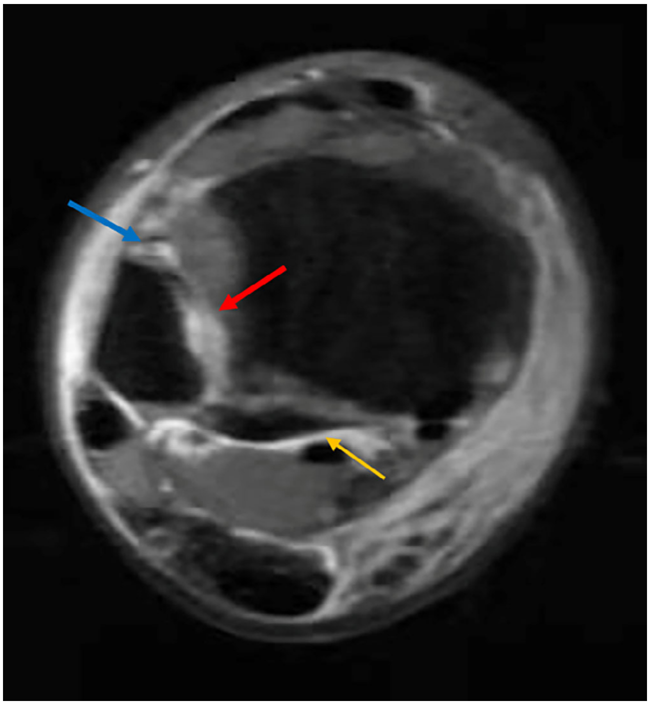

Fig. 4 The axial MRI (cross-sectional FS T2WI images) of the ankle joint showing complete rupture of the anterior inferior tibiofibular ligament (AITFL) and interosseous ligament and fracture of the posterior malleolus (red arrow: complete rupture of interosseous ligament; blue arrow: complete rupture of AITFL; yellow arrow: posterior malleolar fracture)

scanning of the ankle joint covered from at least 6 cm proximal to the distal articular surface of the tibia to the subtalar joint. The ankle coil was used for imaging, and spin-echo or fast spin-echo was used for all the patients. The routine scanning sequences included T1-weighted imaging (T1WI) and fat-suppression proton density-weighted imaging (FS PDWI) on sagittal view, fat-suppression T2 weighted imaging (FS T2WI) on axial view, and FS PDWI on coronal view. The parameters for sagittal T1WI were as follows: TR 400–500 ms, TE 15–25 ms, matrix 256 × 256, FOV 160–200 mm, layer thickness 3.8 mm, and inter-layer space 0.5 mm. The parameters for sagittal FS PDWI were as follows: TR 1800–2800 ms, TE 25–50 ms, matrix 256 × 256, FOV 160–200 mm, layer thickness 3.8–4.0 mm, and inter-layer space 0.5–1 mm. The parameters for axial FS T2WI were as follows: TR 4000–5000 ms, TE 70–100 ms, matrix 256 × 256, FOV 140–210 mm, layer thickness 3.5–4.5 mm, and inter-layer space 1 mm. The parameters for coronal FS PDWI were as follows: TR 1700–2500 ms, TE 30–50 ms, FOV 140–220 mm, matrix 256 × 256, layer thickness 3.8 mm, and inter-layer space 0.5 mm. The axial FS T2WI images were used to assess the injuries of the anterior inferior tibiofibular ligament, interosseous ligament, interosseous membrane, and posterior inferior tibiofibular ligament. The coronal FS PDWI images were used to assess the injuries of the deltoid ligament (Table 1).

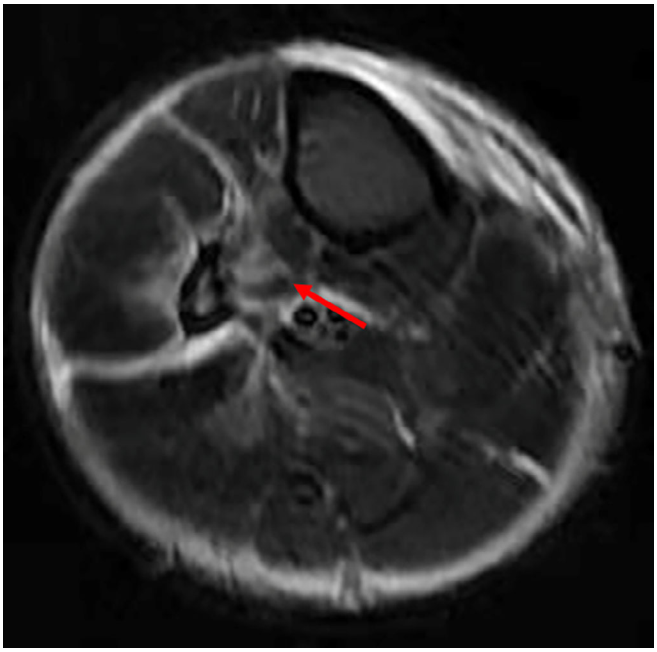

Fig. 5 The axial MRI (cross-sectional FS T2WI images) of the proximal fibular fracture site showing rupture of the interosseous membrane and partial rupture of the posterior tibial muscle (red arrow: rupture of the interosseous membrane and partial rupture of the posterior tibial muscle)

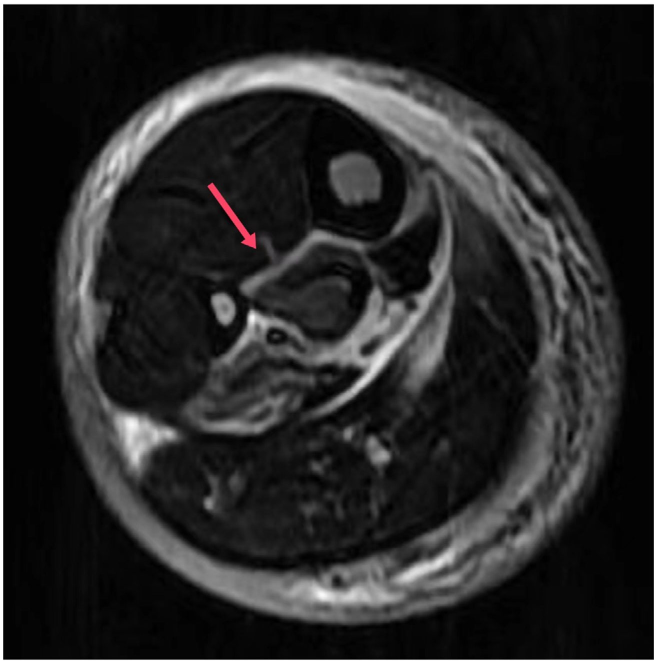

Fig. 6 The axial MRI (cross-sectional FS T2WI images) of the middle calf showing the intact interosseous membrane (red arrow: intact interosseous membrane)

The MR scanning of the calf covered the range from the fibular neck to 3 cm proximal of the distal articular surface of the tibia. The scanning sequences included coronal FS T2WI (TR 3000 ms, TE 50–70 mm, matrix 320 × 192, FOV 370 mm, layer thickness 6 mm, and inter-layer space 1 mm), axial T1WI (TR 400–500, TE 12–20, matrix 320 × 192 or 256 × 256 or 512 × 512, FOV 280 mm, layer thickness 10–14 mm, and inter-layer space 1–2 mm), and axial T2WI/FS T2WI (TR 3000–5000, TE 65–100, matrix 256 × 256 or 512 × 512, FOV 140–280 mm, layer thickness 10–14 mm, and inter-layer space 1 mm). The axial T2WI/FS T2WI was used to assess the injuries of the interosseous membrane, posterior tibial muscles, and flexor hallucis longus.

Definition of Ligament Injury and Interosseous Membrane Injury

The definition of ligament injury was as follows: intact: the ligament structure showed homogenous low signals with no signs of rupture or tissue edema; partial rupture: some of the intact ligament fibers were surrounded by high signals of hemorrhage and edema; complete rupture: the ligament structure was non-continuous and surrounded by edema and hemorrhage.[14]

Definition of interosseous membrane injury was as follows: intact: the tibia and fibular cortex were connected by the continuous low signal band without high signals of hemorrhage or edema; interosseous membrane injury: the low signal band was twisted and circuitous but still continuous and accompanied with high signals; interosseous membrane rupture: the tissue integrity was disrupted, and the signal band of the interosseous membrane was disrupted by high signals of hemorrhage and edema.[4]

Two clinicians evaluated the data independently, and the disagreements were resolved by discussion to reach unanimous conclusions. Intra-group correlation coefficient (ICC) was used to evaluate the degree of consistency.

Observation and Measurement Index

All of the patients' basic clinical information was collected, including age, sex, side and cause of injury. The X-ray manifestations of proximal fibular and medial malleolus fracture were observed. The CT manifestations of medial malleolus fracture, posterior malleolar fracture, and the anterior space of the syndesmosis were observed. The injury condition of ankle ligaments and interosseous ligament were observed, the rupture site and range of interosseous membrane were observed and measured by MRI.

Results

Basic Patient Information

The data of 15 eligible patients (11 males and four females) were included in this study for retrospective analysis. The mean

TABLE 1 Imaging manifestations of the patients with Maisonneuve fractures

Case	Injury of medial structures	Rupture of AITFL	Rupture of OIL	Location of fibular fracture	Posterior malleolar fracture	Rupture of IOM
1	Medial malleolus	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
2	Deltoid ligament	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
3	Medial malleolus	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
4	Medial malleolus	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
5	Medial malleolus	III	III	Proximal 1/3	III	Distal and proximal rupture with the middle part intact
6	Medial malleolus	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
7	Medial malleolus	III	III	Proximal 1/3	0	Distal and proximal rupture with the middle part intact
8	Medial malleolus	III	III	Proximal 1/3	III	Distal and proximal rupture with the middle part intact
9	Deltoid ligament	III	III	Proximal 1/3	0	Distal and proximal rupture with the middle part intact
10	Medial malleolus	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
11	Medial malleolus	III	III	Proximal 1/3	I	Distal and proximal rupture with the middle part intact
12	Medial malleolus	III	III	Proximal 1/3	III	Extensive rupture
13	Deltoid ligament	III	III	Proximal 1/3	III	Distal and proximal rupture with the middle part intact
14	Medial malleolus	III	III	Fibular neck	I	Extensive rupture
15	Deltoid ligament	III	III	Proximal-medial 1/3 junction of the fibula	III	Distal and proximal rupture with the middle part intact

age of the patients was 41.07 (18–70) years. There were six cases of left side injury and nine cases of right-side injury. The cause of injury was fall in nine cases and torsion in six cases.

X-Ray Manifestations of Typical Maisonneuve Fracture

X-ray examination showed that all patients had proximal fibular fracture, fibular neck in one, proximal 1/3 of the shaft in 13, junction of the upper and middle 1/3 of the fibula in one, including spiral fracture in 14 patients, and comminuted fracture in one patient. The anteroposterior X-ray images showed that the fracture line was from laterosuperior to medial inferior in 10 cases, not obvious in four cases, and irregular in one case. The lateral X-ray images showed that the fracture line was from anterior-superior to posterior-inferior in 14 cases and irregular in one case. In the cohort, 11 patients showed medial malleolus fracture and four patients were without medial malleolus fracture, but the medial clear space was >6 mm, indicating the complete rupture of the deltoid ligament; 13 patients also showed posterior malleolar fracture.

CT Manifestations of Typical Maisonneuve Fracture

The CT scanning of the ankle joint showed 11 patients with medial malleolus fracture, and four patients were without medial malleolus fracture, but the medial clear space was >6 mm. Furthermore, 13 patients presented posterior malleolar fracture, including type I and type III fracture in eight and five patients, respectively, according to the Haraguchi classification of posterior malleolus fracture.[13] The axial images of the ankle joint showed external rotation of the distal fibula, while the anterior space of the syndesmosis was increased substantially.

MRI Manifestations of Typical Maisonneuve Fracture

The coronal FS T2WI MR images of the ankle joint showed that four patients had complete rupture of the deltoid ligament. The cross-sectional FS T2WI images of all the patients showed complete rupture of interosseous ligament and anterior inferior tibiofibular ligament (AITFL).

The cross-sectional FS T2WI MR images of the calf showed that the rupture of IOM was from the syndesmosis to the proximal fibular fracture site in two patients, with a range of 32.3 and 29.8 cm, respectively. In the remaining 13 patients, the IOM rupture was not only confined to the distal third of the calf, but also near the fibula fracture, and the IOM was intact between the two fracture sites (ICC = 0.84). The distance from the rupture area (proximal end of the interosseous membrane with distal rupture) to the ankle plafond was 3.7–12.2 cm, with an average of 8.06 ± 2.35 cm (ICC = 0.91). The proximal IOM was completely ruptured from the fibular side at the site of the fibular fracture and the range was 4.1–9.1 (average: 6.75 ± 1.64) cm (ICC = 0.79). The average length of the integrate middle segment of the IOM was 14.55 ± 4.11 (5.6–20.3) cm (ICC = 0.92) (Table 1).

The cross-sectional FS T2WI MR images of the calf showed patchy hypersignals close to the proximal insertion of the posterior tibial muscle, at the ending point on the fibula in 15 cases, indicating partial rupture of the posterior tibial muscle. Subsequently, seven patients showed patchy high signals close to the proximal ending point of the flexor hallucis longus and soleus, suggesting partial rupture of these muscles.

Discussion

In this study, we investigated the characteristics and mechanism of interosseous membrane injuries and proximal 1/3 fibular fracture in typical Maisonneuve fracture. The results showed that the rupture of the IOM was caused by a combination of abduction and external rotation violence. It was manifested in two forms, most of which was not only distal end but also near fibular fracture site ruptures with the middle part intact, and a few were ruptures of the IOM from the ankle to the near fibular fracture site.

Imaging Manifestations of Maisonneuve Fracture

The imaging manifestations of Maisonneuve fractures are inconsistent. A typical Maisonneuve fracture is a unique pronation-external rotation type injury, manifested by fracture of the proximal 1/3 fibula, inferior tibiofibular syndesmostic lesion, and complete deltoid ligament rupture or medial malleolus fracture. Also, posterior malleolar fracture was detected in several patients, which is mainly Haraguchi type I or III fracture.[13] The supination-external rotation mechanism can also lead to Maisonneuve fracture, but such injuries are rare[15–18] and mainly manifested by varied imaging findings; the mechanisms underlying these injuries exhibit specific features. For instance, Charopoulos et al.[18] reported a case of atypical Maisonneuve fracture, for which the MRI and X-ray examinations confirmed posterior malleolar fracture, fibular neck fracture, and partial rupture of anterior talofibular ligament and anterior inferior tibiofibular ligament, while no medial malleolar fracture or deltoid ligament rupture was found. The study speculated that the injuries could be caused by the plantar flexion and outward extortion or slight plantar flexion accompanied with supination-external rotation of the ankle joint. Hinds et al.[19] reported a case of variated Maisonneuve fracture with hyperplantar flexion; the imaging manifestations included the fractures of proximal 1/3 fibula, medial malleolus, and posterior malleolus, associated with the posterior dislocation of the ankle joint. The fracture of the posterior malleolus consisted of two parts, the posteromedial and posterolateral parts that belonged to Haraguchi type II fracture. The authors speculated that the injuries were caused by the external rotation combined with the following drastic hyperplantar flexion. In this study, one patient with intact medial structures and three patients with Haraguchi type II posterior malleolus fracture were excluded, and all the included patients presented the features of typical Maisonneuve fracture, which favored the investigation of mechanisms underlying the fracture.

Injury Characteristics of Interosseous Membrane and Interosseous Ligament in Maisonneuve Fracture

In this study, ruptures of AITFL and interosseous ligament occurred in all 15 patients, confirming that injury of the ligaments mentioned above was one of the essential characteristics of classical Maisonneuve fracture. External rotation is the most important mechanism for separation of syndesmosis. External foot rotation causes outward rotation and lateral displacement of the fibula, leading to a gradual increase in AITFL and interosseous ligament tension until the ligament breaks. Once the fibula moves outward beyond the scope of the IOM, injury can result in damage to the IOM.

Traditionally, Some authors believed that the IOM of the crural was ruptured to the level of fibular fracture in patients with Maisonneuve fracture.[16,18] The IOM is a fascial membranous structure with a thickness of about 1 mm connecting the interosseous crest of the fibula and tibia in one plane, which is mainly composed of fibrous connective tissue. The function of the IOM is to prevent the lateral displacement rather than the anterior and posterior displacement of the fibula. A study[4] demonstrated that the distal end of the normal interosseous membrane is strained, while the proximal end is relaxed in an arch or S shape. As the IOM linearly connects the tibia and fibula, the function of limiting the rotation of the fibula is almost absent, especially in the relaxed part of the middle and proximal IOM.[2]

The interosseous ligament is the thickened part of the distal IOM, which could rupture upon external rotation force; however, the extent of IOM rupture is not closely associated with the external rotation force. Some studies suggested that the rupture of the IOM was caused by the abduction force; specifically, the IOM could be ruptured when the abduction force was beyond the strength of the IOM. In a study performed by Merrill et al.[2] in autopsy specimens, the superior and inferior syndesmotic ligaments and the articular capsules were completely resected, while only the IOM intact between the tibia and fibula was preserved. The findings showed that the fibula could be easily rotated externally for approximately 150° without rupturing the IOM. However, the application of abduction force on the distal fibula could lead to IOM rupture easily. In another study, Manyi et al.[4] demonstrated that the rupture of the IOM was associated with the diastasis; the more substantial the syndesmotic separation, the larger the range of IOM rupture.

In this research, MRI of two patients showed an extensive rupture of IOM in the lower leg from the syndesmosis to near the proximal fibular fracture, with a range of 32.3 and 29.8 cm, respectively, which was inconsistent with the characteristics of distal and proximal IOM ruptures and integrity of the middle section in the other 13 patients in this study. Both patients had obvious diastasis, we suggested that the mechanism of this type of tear to the IOM is due to the large amount of abducting force during the injury rather than external rotation force transmitted through the IOM.

In the study by Manyi et al.,[4] MRI examination of 12 patients with Maisonneuve fracture proved that the rupture of the IOM only reached the distal 1/3 of the calf, and the average distance from the rupture area to the distal articular surface of the tibia was 79 mm, while the IOM at the proximal segment and the fibular fracture was intact. In this study, all the patients showed complete rupture of the AITFL and the interosseous ligament, and 13 of them had rupture of the distal IOM with an average range of 8.06 ± 2.35 cm. Therefore, we speculated that the rupture of the AITFL and the interosseous ligament could be caused by the external rotation stress, which induced the external rotation and posterolateral displacement of the fibula, while the tearing of the IOM at the distal calf could be caused by the external rotation and abduction stress.

The location of fibular fracture near the proximal 1/3 of the fibula is the most evident difference between Maisonneuve fracture and typical PER ankle fracture. Pankvich[16] demonstrated that when the AITFL was resected, the interosseous ligament rupture and proximal fibular fracture were induced by the external rotation of the foot from the neutral position. Some studies demonstrated that in patients with pronation-external rotation-type fracture (Maisonneuve fracture not included), the range of IOM injury was not at the same level of fibular fracture but possibly lower than the fracture level.[20] These findings suggested that the previous opinion about the mechanism that the force was transmitted along the IOM to the proximal end and induced fibular fracture was not accurate.

One of the typical features of Maisonneuve fracture is proximal 1/3 fibular fracture, and the fracture line was from medial inferio to laterosuperior (anteroposterior image)[4] and from posterior-lower to anterior-upper (lateral image).[4,15,16] Some studies[2,21] suggested that the proximal fibular fracture could be caused by the external rotation stress transmitted along the fibular to the proximal end, which was stopped by the osseous and capsuloligamentous structures of the superior tibiofibular joint. The fracture site of the fibula act as a breakthrough point to release the force.[21] However, the stress of typical pronation-external rotation type fracture is also transmitted along the fibula to the proximal end, while the fracture is mainly occur from 2.5 to 8 cm above the ankle joint.[22] Therefore, we speculated other putative causes involved in the fracture of proximal fibular fracture.

Possible Mechanism Conjecture

The posterior tibial muscle originates from the posterior side of the proximal half tibia and fibula, as well as the posterior side of the IOM with the function of plantar flexion, adduction, and internal rotation of the ankle joint. In this study, the MRI examination showed that the posterior tibial muscle was torn near the ending point at the proximal fibula, as well as the soleus and flexor hallucis longus. We speculated that when Maisonneuve fracture occurs, the knee joint is slightly bent and the ankle joint is slightly dorsal flexed, the foot is pronation rotated and fixed on the ground, and the tibia and fibula are inward rotated in comparison with astragalus, but the degrees of rotations were different. For instance, the rotation degree of the tibia is relatively lower than fibula, which increased the IOM tension. The posterior tibial muscle contracts intensively due to the passive tractions from the instantaneous powerful force toward the distal and medial-posterior directions, while the stress is focused on some part of the ending point on proximal calf, such as proximal 1/3 fibula in most cases, and fibular neck or middle 1/3 in fewer cases. Under the joint effects of the external rotation force and tractions of the ending point of posterior tibial muscle on fibula and adjacent ending point of the IOM, the fibula proximal to the stress concentration point was fixed by the superior tibiofibular joint and the surrounding ligaments, while the fibula distal to the stress concentration point maintained the trend of external rotation, which consequently led to proximal 1/3 fibular fracture. This fracture is centered by the internal-posterior ending point of the posterior tibial muscle (stress focus), and extended toward the proximal, lateral, and anterior sides. Therefore, the fibular fracture line was from medial inferio to laterosuperior and from posterior-lower to anterior-upper, and the IOM attached at the site of fibular fracture with posterior tibial muscle showed different degrees of tearing.

Previous study[4] demonstrated that the proximal segment to the IOM was intact, and no IOM tearing was observed at the site of fibular fracture. However, the present study showed different findings. For instance, in the fibular fracture in all the patients, different degrees of IOM tearing were found at the site of posterior tibial muscle attachment; it was torn from the fibular side, indicating that the IOM tearing was caused by the passive traction from the posterior tibial muscle.

Recommendation for Treatment Strategies

Restoration of anatomic alignment and stability of the ankle mortise is essential for the management of Maisonneuve fracture. The proximal fibula lies in close association with numerous important ligamentous and neurovascular structures, not the least of which is the common peroneal nerve. For this reason, the open reduction and stabilization of the proximal fibular fracture was not performed. Furthermore, the loss of limitation on fibula due to the rupture of the interosseous ligament and interosseous membrane, the shortening, external rotation and abduction of the distal segment of the fibula in typical Maisonneuve fracture should be precisely reduced and firmly fixed. Therefore, the syndesmosis should be preferably stabilized with syndesmotic screws rather than with dynamic fixation such as suture button.

Limitation and Strengths

The characteristics and possible mechanism of interosseous membrane injury in typical Maisonneuve fracture were studied in this paper, which is helpful to guide the diagnosis accurately and the selection of treatment strategies of Maisonneuve fracture. The current study presents several limitations. First, the sample size was relatively small. Second, we conjecture the mechanism of interosseous membrane injuries and proximal 1/3 fibular fracture in typical Maisonneuve fracture based on the imaging manifestations; however, further experiments on cadavers are needed to confirm this speculation. Third, atypical fractures were not included in this article, which remains to accumulate more cases to explore the injury mechanism.

Conclusion

A typical Maisonneuve fracture includes medial malleolus fracture or deltoid ligament rupture, inferior tibiofibular syndesmosis disruption, and proximal 1/3 fibular fracture. MRI showed the rupture of the AITFL and interosseous ligament in all patients. The rupture of the IOM was caused by a combination of external rotation and abduction violence. It was manifested in two forms, most of which was not only distal end but also near fibular fracture site ruptures with the middle part intact, and a few were ruptures of the IOM from the ankle to the near fibular fracture site. The tibialis posterior muscle may be related to the location of the fibular fracture.

Author Contributions

He JQ, Ma XL, and Hu YC contributed to the conception and design of the study. Wang SL, Li N, and Cao HB contributed to the acquisition of the data. Wang GX, Guo L, and Zhao B contributed to the analysis and interpretation of the data. He JQ, Wang GX, and Zhao B contributed to the drafting of the manuscript. All the authors read and approved the manuscript.

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