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An intact fibula may contribute to allow early weight bearing in surgically treated tibial plateau fractures

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Abstract
Purpose The role of the proximal tibiofibular joint (PTFJ) in tibial plateau fractures is unknown. The purpose of this study was to assess, with finite-element (FE) calculations, differences in interfragmentary movement (IFM) in a split fracture of lateral tibial plateau, with and without intact fibula. It was hypothesized that an intact fibula could positively contribute to the mechanical stabilization of surgically reduced lateral tibial plateau fractures.
Methods A split fracture of the lateral tibial plateau was recreated in an FE model of a human tibia. A three-dimensional FE model geometry of a human femur–tibia system was obtained from the VAKHUM project database, and was built from CT images from a subject with normal bone morphologies and normal alignment. The mesh of the tibia was reconverted into a geometry of NURBS surfaces. The fracture was reproduced using geometrical data from patient radiographs, and two models were created: one with intact fibula and other without fibula. A locking screw plate and cannulated screw systems were modelled to virtually reduce the fracture, and 80 kg static body weight was simulated.
Results Under mechanical loads, the maximum interfragmentary movement achieved with the fibula was about 30% lower than without fibula, with both the cannulated screws and the locking plate. When the locking plate model was loaded, intact fibula contributed to lateromedial forces on the fractured fragments, which would be clinically translated into increased normal compression forces in the fractured plane. The intact fibula also reduced the mediolateral forces with the cannulated screws, contributing to stability of the construct.
Conclusion This FE model showed that an intact fibula contributes to the mechanical stability of the lateral tibial plateau. In combination with a locking plate fixation, early weight bearing may be allowed without significant IFM, contributing to an early clinical and functional recovery of the patient.

Keywords Fibula fracture · Tibial plateau fracture · Finite element · Weight bearing · Interfragmentary motion · Bone fixation · Fracture fixation

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Introduction

The proximal tibiofibular joint (PTFJ) mechanics and its role in tibial plateau fractures have been largely overlooked by both the clinicians and the anatomists, and remain poorly known [11]. In vitro tests on human knee joint cadaveric specimens revealed that the PTFJ deforms under mechanical loads representative of physiological knee flexion during motion, pointing out a role in the functional redistribution of the internal loads in the joint [12]. Although resection of the proximal fibula in patients with intact tibial plateau was deemed to have no clinically significant impact on motion biomechanics, it affected the mediolateral ground reaction force component [5]. Actually, patients surgically treated for lateral tibial plateau fracture showed better clinical outcomes when the fibula was intact, in contrast to patients with concomitant fibular fractures of different types [2]. There is also a lack of information in the literature about the incidence of fibula fractures associated with tibial plateau fractures.

Recent finite-element (FE) simulations [4] suggested that immediate postoperative load bearing of a Schatzker I tibial plateau fracture could threaten the integrity of fixations accomplished with cannulated screws, due to possible local bone damage around the screw. Conversely, locking plate systems might protect the bone around the implant thanks to an improved caudo-lateral support of the lateral fragment. There is no clear information or recent studies about the mechanical support that the fibula offers to the tibial plateau. This insight raises the question wether an intact fibula would add to the load-bearing capacity of surgically treated tibial plateau fractures short after surgery.

The aim of the study was to determine whether an intact fibula could positively contribute to the mechanical stabilization of surgically reduced lateral tibial plateau fractures, increasing the load-bearing capacity of the tibia–fragment system, allowing immediate weight bearing after surgery. The rationale that underlies this hypothesis was explored through FE simulations that compared models with and without fibula and considered virtual fracture reduction with Cannulated screws and locking plate systems, as the two major surgical stabilization techniques.

Materials and methods

A matching set of tibia, fibula, and femur bone models from the VAKHUM project database was used (http://www.ulb.ac.be/project/vakhum). Models were built from computerized tomography images of a 99-year-old female of 155 cm and 55 kg, with normal bone morphologies and alignments. No bone density or stiffness information was taken from the patient; only the bone geometries were used from the donor, and both dimensions and shapes were deemed normal. Informed consent was obtained from the patient to use the radiological data for study purposes. Bone stiffness was obtained from experimental measurements on healthy human tissues. For the trabecular bone, tissue average material properties were directly derived from in vitro mechanical tests of proximal tibia bone specimens [7]. As for the cortical bone, an average stiffness was adopted from several experimental measurements that involved various orientations of the internal loads in the cortical layer of tibia specimens. Cortical bone specimens came from 59- to 60-year-old healthy males [7, 10], and trabecular bone specimens were obtained from 50- to 70-year-old male and female donors with no apparent arthritic pathology or osteopenia [7].

To ensure the accuracy of the FE calculations, the simulation of the fracture, and the mesh coherence of the models with implant, the tibia was remeshed, leading to a structured mesh of hexahedral elements, as previously described [4, 7]. The simulated locking plate corresponded to a Polyax® tibial locked plating system (Biomet Inc, IN, USA), and the cannulated screws (Biomet Inc, IN, USA) consisted of in two titanium 6.5 mm cancellous bone screws. The devices were modelled and virtually implanted, according to metrology data acquisition and to the dimensions reported by the manufacturer (Fig. 1).

Interactions between tibia and fibula were treated as a tied contact, meaning that no relative movements were allowed within the PTFJ. The fracture plane simulated a split fracture of the lateral tibial plateau (Fig. 1). In the absence of any modelled implant, the fragment could move relatively to the tibia, and a finite sliding contact model measured this relative motion while preventing any non-physical penetration of the points of the fragment model into the tibia model. Frictions were neglected, so that the tibia–fragment interactions produced only perpendicular reaction forces. To simulate fracture reduction with the cannulated screws or the locking plate system, tied contacts were defined between the nodes of the bone and the screws that were adjacent to each other.

All the materials of the model were considered isotropic elastic (Table 1). A 400 N axial force (80 kg static body weight in bipedal standing) was applied on the head of the femur model, and force transmission to the tibial plateau was measured by the interaction between the femoral condyles and tibial plateau geometries through another contact

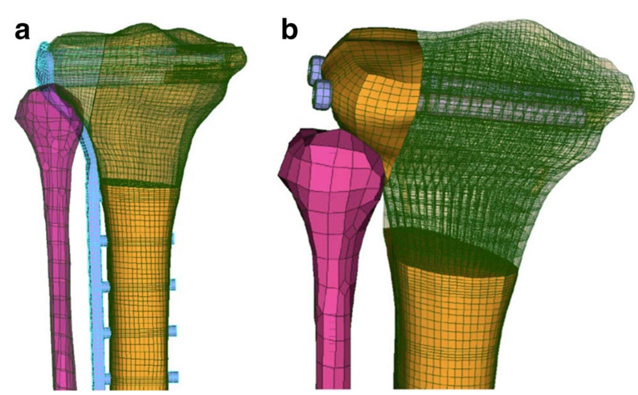

Fig. 1 Posterior view of the fibula and fractured tibia models with the virtually implanted LPS (**a**) and CSS (**b**). In specific zones, the volumetric mesh is represented as partially transparent so as to show the detail of all device components

Table 1 Summary of the material parameter properties used in the model

	Bone		Implanted parts		
	Trabecular	Cortical	Cannulated screws	Polyax	LPS screws
Young's modulus (MPa)	126 [7]	13,000 [7]	114,000 (ASTM F136)		
Poisson's ratio (–)	0.3	0.3	0.34		

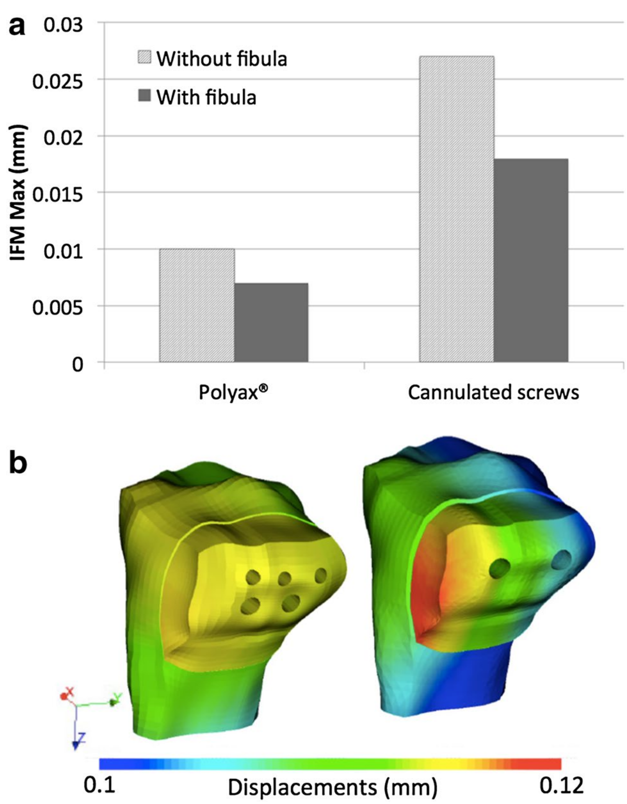

Fig. 2 **a** Maximum IFM obtained in each implanted model, with and without fibula. **b** Mapping of the displacement fields calculated in the proximal implanted tibia models with fibula (deformations magnified × 100 – fibula not represented for the sake of graphical clarity)

problem. The displacements at the distal ends of both the fibula and the tibia model were restricted in all directions. The stress fields in the bone and the devices were calculated, as well as the interfragmentary movement, defined as the average distance of node separation in the fracture plane. The results obtained without the fibula were compared to those obtained with the fibula.

Results

Under mechanical loads, the maximum interfragmentary movement achieved with the fibula was about 30% lower than without fibula, with both the cannulated screws and the locking plate. It ranged from 7 to 18 µm (Fig. 2a). The displacement fields obtained in the proximal tibia model with the locking plate were relatively homogeneous along the sagittal plane. In contrast, the anterior displacements calculated with the cannulated screws were larger than the posterior ones, by about 10% in the tibia and by about 20% in the fragment (Fig. 2b). In general, the anterior tilt of the fragment led to an increased anterolateral tilt of the lateral plateau surgically reduced with the cannulated screws.

As for the calculated reaction forces, the presence of the fibula, respectively, decreased and increased the total force resultant on the medial and lateral plateau (Fig. 3a). Interfragmentary reaction forces (FIRF) were lateromedial with the locking plate and mediolateral with the cannulated screws. Lateromedial interfragmentary reaction forces (i.e., along the *X* direction in Fig. 3c) reveal a compression of the fragment against the tibia at the fracture site, whereas mediolateral interfragmentary reaction forces would be interpreted as distraction forces at the fracture site. The intact fibula increased the magnitude of the lateromedial FIRF component with the locking plate, and it reduced the mediolateral FIRF magnitude by 66% with the cannulated screws. Reaction forces at the PTFJ were mostly axial and were about 16% lower with the cannulated screws than with the locking plate (Table 2).

Discussion

The most important finding of this study was that the fibula contributes to mechanical stability of the simulated lateral tibial plateau fractures. Tibial plateau fractures account for 1% of all fractures in adults. Unicondylar fractures contribute 60% of cases and usually involve the lateral plateau (90%) [3]. This FE analysis explores the possible role of the fibula in the mechanical stabilization of surgically fixed tibial plateau fractures. As reported previously, accurate validation of the implanted model is difficult to achieve because of the lack of matching data in the experimental literature [4]. Yet, the overall axial stiffness of the intact tibia model without fibula was at least 3700 N/mm, which matched with the measurements of 4000 and 4700 N/mm reported for the proximal tibia [8]. The presence of the fibula tended to increase by about 15% the overall axial stiffness of the system, which was translated into a reduction of the calculated interfragmentary movement in the two implanted models. The load-bearing capacity of the fibula improved the stability

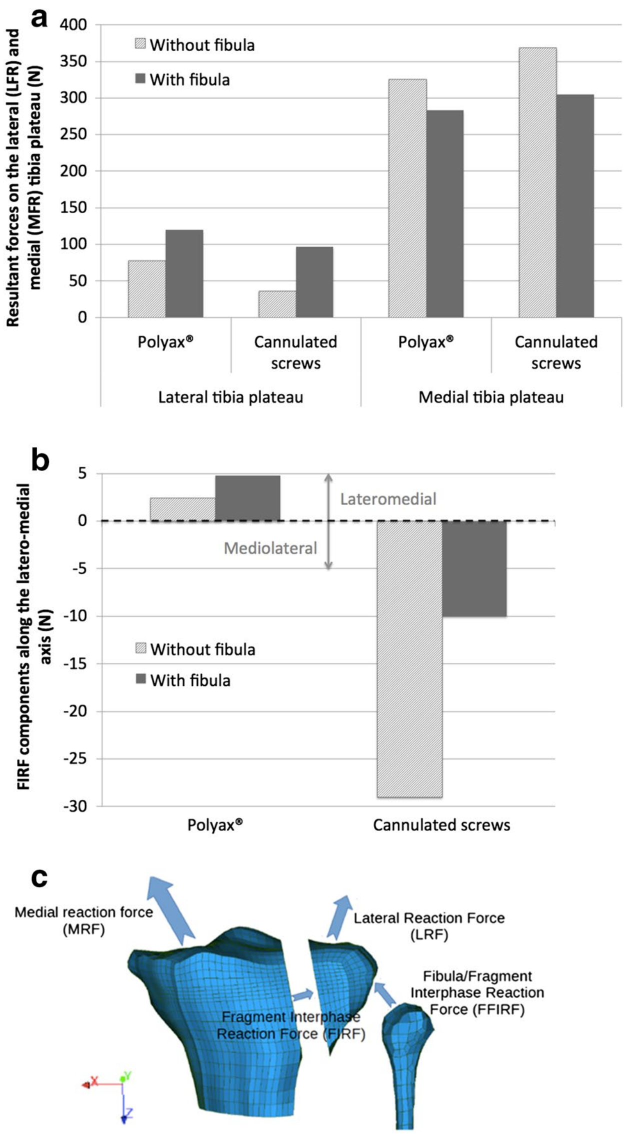

Fig. 3 **a** Lateral and medial total reaction forces between the femoral condyles and the tibial plateau. **b** Reaction force component between the fragment and the tibia along the lateromedial axis (mediolateral direction corresponds to "*x*-axis" in **c**. **c** Graphical representations of the reaction forces in the fractured proximal tibial model

of the lateral plateau, and such improvement was particularly pronounced when the fracture was virtually fixed with the cannulated screws. The analysis of the interfragmentary forces indicates that the larger the proportion of axial load on the lateral plateau is, the more the fragment is pressed against the tibia, or the less the tibia pushes the fragment laterally. Noteworthy, the fragment was always pressed against the tibia with the locking plate, while it was always pushed by the tibia with the cannulated screws. Actually, the cannulated screws led to comparatively larger lateral tilts of the lateral plateau in both the anterior and mid-frontal planes, which made the frontal force components on the medial plateau be mediolateral.

Overall, the fibula contributed to reduce the magnitude of this mediolateral load component and limited the pushing of the fragment by the tibia. Yet, the simulated mechanical support of fibula was geometrically localized, and for the cannulated screws, the posteroanterior gradients of displacement fields with fibula were three times larger than those calculated without fibula. In this sense, a full description of the PTFJ with all the fibular ligaments would probably be necessary. The limited description of the PTFJ in the present model also implied a tied contact between the fibula and the proximal tibia: while this approximation would not be able to capture the behaviour of the joint under lateral or posteroanterior loads, the negligible axial joint deformations registered under several configurations of the knee gives a certain degree of confidence to our contact model hypothesis [12].

The clinical relevance of this study is shown by the mechanical stability that the intact fibula gave to the tibial plateau when axial loading forces were applied. Moreover, when the locking plate model was loaded, intact fibula contributed to lateromedial forces on the fractured fragments, which would be clinically translated into increased normal compression forces in the fractured plane that may help the fracture to heal. Distraction forces would separate fragments altering the healing process in metaphyseal bone, whereas compression forces would help to achieve healing, and for tibial plateau fractures, other intraarticular interfragmentary movement should be avoided as much as posible to prevent joint damage. This model showed that an intact fibula contributes to the mechanical stability of lateral tibial plateau, and in combination with a locking plate fixation, early weight bearing may be allowed contributing to early clinical and functional recovery of the patient. This model also could help the surgeon in decision making, identifying which fractures and constructs are suitable for an early weight bearing physical therapy. Yet, the clinical translation of these simulation results should be carefully addressed. The movement of bony structures and mechanical interactions thereof was studied, but a full understanding of ligamentous and soft-tissue structures remains important to obtain more accurate results.

As for the bone tissue stiffness, elastic constants were obtained from experimental measurements on cortical bone specimens from 59- to 60-year-old healthy males [10] and on trabecular bone specimens from 50- to 70-year-old male and female donors with no apparent arthritic pathology or osteopenia [7]. Though the quality of the tested bone specimen was deemed normal by the authors of the cited experimental studies, most specimens were representative of middle-aged patients, and might be up to 20% softer than the bone of younger adults [6]. In the absence of more precise

Table 2 Interaction force values calculated throughout the models at the femur–tibia (MRF/LRF), fragment–tibia (FIRF), and fibula–tibia interfaces (see graphical representation in Fig. 3c)

Implanted system	Locking plate system			Cannulated screws		
Force component	*x*	*y*	*z*	*x*	*y*	*z*
	Values without fibula/values with fibula					
MRF (N) Medial Reaction Force	−2.0/1.6	9.0/7.0	325.0/283.0	−33.0/−9.0	8.8/17.0	367.0/304.0
LRF (N) Lateral Reaction Force	−18.0/−23.0	9.0/10.0	75.0/117.0	7.5/−5.4	13.0/11	33.0/96.0
FIRF (N) Fragment Interphase Reaction Force	2.4/4.8	0.0/0.0	0.0/0.0	−29.0/−10.0	0.0/0.0	−4.0/−1.5
FFIRF (N) Fibula Fragment Interphase Reaction Force	–/5.0	–/−1.4	–/97.0	–/3.6	–/0.0	–/82.0

quantitative information about the properties of tibia and fibula bone tissues in adolescents and young adults, this limitation represents a pessimistic estimation of the overall model stiffness which adds to a relatively safe interpretation of the present simulation results.

There are some limitations in this study. Most of the work about the experimental characterization of bone mechanics was reported decades ago when this topic was an active topic of research. In the present study, the trabecular bone stiffness was an average axial stiffness [7], according to the specific boundary load used. As for the cortical bone, the effective simulated stiffness stood for a mean stiffness that takes into account the tissue mechanical response in all directions. Certainly, the stiffness in the longitudinal direction of the haversian structure might be about 20% higher than the mean stiffness used in this study [13], which makes the current model not suitable for quantitative fracture predictions, for example. To this respect, advanced bone models based on micromechanics and calibrated from clinical CT data have been recently proposed and have a great potential [1].

Another limitation was that interactions between tibia and fibula were treated as a tied contact, meaning that no relative movements were allowed within the PTFJ. A sliding contact would have required the additional modelling of the soft tissues of the PTFJ with all the supplementary (and largely uncontrolled) approximations required by such a level of modelling. Nevertheless, only the axial stiffness of the PTFJ was targeted in the present study, and since axial deformations of this joint under physiological compressive loads are expected to be low [12], the tied contact was chosen as an acceptable tradeoff between reasonable model management and significance of the predictions. Yet, the current model would not be valid if rotational boundary loads would have been additionally used. In addition, the study compares a model with an intact fibula and a model without fibula (or a virtually fractured fibula with no axial mechanical resistance) that may not mechanically behave similarly to a model of fractured fibula. However, this model might better represent the time zero situation at which the surfaces of the fractured fibula are not in contact with each other. Nevertheless, this study showed several differences between these two models, and opens the door for future investigations with different types of fibula fractures.

As it was shown in the previous studies, bone quality, fragment size and number, as well as femoro-tibial alignment could be determinant for the choice of a particular implant [8, 14]. In the present theoretical exploration, these parameters were fixed so as to limit the variability of the models and achieve clear interpretations. However, calculations with patient-specific model geometries, as well as population-based statistical explorations should be part of future developments to extrapolate these interpretations to clinical evaluations [9].

Conclusion

In conclusion, this FE model showed that an intact fibula contributes to mechanical stability of lateral tibial plateau fractures, and combined with locking plate system, the mechanical integrity of both the fibula and of the PFTJ may allow an early weight bearing without significant interfragmentary movement.

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