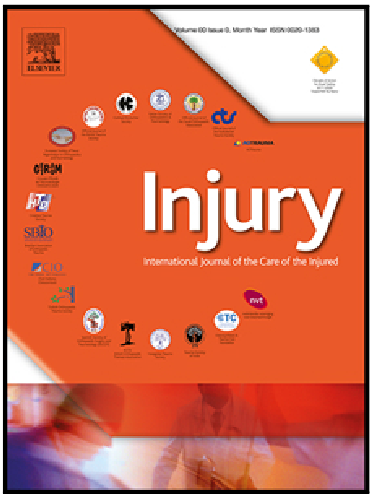

Comparative analysis of the biomechanical behavior of anterograde/retrograde nailing in supracondylar femoral fractures

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Highlights

- Surgical treatment of supracondylar femoral fractures is controversial, with different surgical options.
- Intramedullary nailing has emerged as a new surgical technique in the treatment of that type of fractures.
- A comparative study simulating the biomechanical behavior of anterograde and retorgrade nail is performed.
- Anterograde nailing is an excellent indication in supracondylar fractures of femur type A.
- Anterograde nailing present clear benefits compared to retrograde nailing in the treatment of fractures of femur type A.

Comparative analysis of the biomechanical behavior of anterograde/retrograde nailing in supracondylar femoral fractures

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Abstract

Supracondylar femoral fractures account for a noticeable percentage of the femoral shaft fractures, affecting two etiological groups: high energy trauma in young men, with good bone quality, and older women with osteoporotic femur. Surgical treatment of those kind of fractures remains controversial, with different surgical options such as plate and sliding barrel locking condylar plate, less invasive stabilization system (LISS) or intramedullary nailing, which has emerged as a new fixation choice in the treatment of that type of fractures.

The present work performs a comparative study about the biomechanical behavior of anterograde and retrograde nailing in supracondylar femoral fractures type A, in order to determine the best choice of nailing and locking configuration. A three-dimensional finite element model of the femur was developed, modeling femoral supracondylar fracture and different nailing configurations, both for anterograde and retrograde nails. The study was focused on the immediately post-operative stage, verifying the appropriate stability of the osteosynthesis.

The obtained results show a better biomechanical behavior for anterograde nails, providing a better stability from the point of view of global movements, lower stresses in screws, and less stress concentration in cortical bone. So, for the analyzed fractures and osteosyntheses types, anterograde nailing has demonstrated to be a better surgical option, being an excellent indication in supracondylar fractures of femur, with clear benefits compared to retrograde nailing, providing a better stabilization which enables for a more satisfactory fracture healing.

Key words

Anterograde reamed nail, Retrograde reamed nail, Femoral supracondylar fracture, Osteosynthesis, Finite elements

Introduction

Supracondylar femoral fractures account 3 to 6% of the femoral shaft fractures [1, 2]. Epidemiological studies on these fractures show two basic etiological groups: a) High energy trauma in young men, with good bone quality; b) older women with osteoporotic femur who fall from the same level [3, 4]. According to the AO/OTA classification [5], these fractures are divided into extra-articular (type A) and intra-articular (types B and C).

Surgical treatment of supracondylar femoral fractures is controversial. Since the introduction of fixed-angle blade plates in the 60's, new treatment methods have appeared such as plate and sliding barrel locking condylar plate, which may be used with a large approach to the fracture, or by using the less invasive stabilization system (LISS) technique; when joint involvement is present, a combination of open surgery, for articular reconstruction, and LISS technique may be suitable [6]. Experience and technical skills are required. The mechanical principles and indications of all open reduction and internal fixation (ORIF) techniques must be well understood and reviewed during preoperative planning [7].

Intramedullary nailing (IM) has emerged as a new technical choice in the treatment of that type of fractures. The evolution in the design and materials of the nails has expanded the indications of that technique. In 1953, Modny and Bambara described interlocking nails [8], which were popularized, with the appearance of new models of anterograde blocked intramedullary nails in the 70s [9] and of retrograde ones in the 80s

[10]. Nowadays, modifications in design and materials have allowed intramedullary nailing to become a technical possibility for the treatment of that type of fractures.

The primary goals of the surgical treatment include adequate stability of the fracture site, preserving the length and axis of the leg, a surgery as less aggressive as possible and a good consolidation and functional result [11]. In this regard, intramedullary nailing preserves the hematoma, periosteum and peripheral soft tissues at the fracture site, so it does not interfere in the biological process of consolidation. Retrograde nails can be used in all three types of fractures A, B and C. In addition to ORIF techniques, extra-articular fractures (type A) may be managed with anterograde as well as with retrograde intramedullary nailing. Retrograde nailing has specific indications, either related to approach difficulties in the anterograde nailing (obesity [12], bilateral fracture of femur) or undesirable anterograde approach (floating knee, fracture of pelvis or hip, pregnant women, fractures with knee arthroplasty) [13]. However, the need for an intra-articular approach of the knee is its main disadvantage.

Therefore, in supracondylar type A fractures located in zone 5 of Wiss [14] both anterograde and retrograde nailing are good treatment options. Anterograde nailing is a suitable indication, provided that the situation of the fracture allows us to place the more proximal of the two distal locking screws at least 3 cm distal to the fracture line [15]. Many authors [6, 11, 14-18] point out that the surgical technique of anterograde nailing is extra-articular, remaining the nail easy to remove, and represents a sound alternative for segmental fractures of the femur [13]. In addition, the new designs of nails, with distal holes in two planes, have improved anchorage and stability in the distal fragment. On the other hand, retrograde nailing technique is more demanding. It is hard to achieve an adequate bone reduction and alignment which prevent the shortening, regardless of the problems involved in the placement of the retrograde nail through the knee joint [19].

The development of simulation models using the Finite Element Method (FE) appears as a reliable alternative to in vivo animal experimentation and in vitro studies, because the differences between in vivo humans and in vivo animals or in vitro behavior make difficult the application to humans of such kind of studies. Analysis of osteosynthesis by means of FE models enables the assessment of all critical parameters related to the biomechanical behavior of intramedullary nailing (global stability, local movements at the fracture site and stresses in bone, nail and locking screws), both for anterograde and retrograde nailing.

For anterograde nailing, Shih [20] studied the influence of muscular contractions on stress analysis of distal nail-screw interfaces by means of FE; Montanini [21] combined experimental and numerical methods, concluding that full weight bearing in the immediate post-operating stage should not be allowed since high stress levels reached in cortical bone around screw holes; Shih [22] used FE simulation to compare the conventional static fixation technique and two types of dynamic fixation techniques; finally, Tupis [23] carried out a FE analysis to compare the strain magnitude and distribution resulting from each of two entry points in the proximal femur.

In the case of retrograde nailing, Chen [24] employed both mechanical testing and FE analysis to compare the stiffness variations among different intramedullary nail constructs used in the treatment of distal femoral fractures; Perez [25] analyzed the biomechanical stability of pediatric femur fractures, as measured by gap closure and nail slippage; Salas [26, 27] evaluates biomechanically intramedullary nails vs. locking plates for fixation of femoral fractures in osteoporotic bone by means of the corresponding FE models. Shih [28] studied three types of femoral shaft fractures fixed by three fixation techniques, analyzing the stability achieved; Chantarapanich [29] compared the biomechanical performance of retrograde nail used to stabilize supracondylar fracture for different nail lengths; Chen [30] studied distal femur fractures adjacent to total knee arthroplasty, treated by means of extramedullary locking plate and retrograde intramedullary nail; Bayoglu [31] compared the results obtained from a new approach to more realistic physiological boundary conditions with those of other models employing commonly used boundary and loading conditions in retrograde stabilization of a distal diaphyseal fracture; finally, Bougherara [32] used FE and experimental techniques for analyzing four synthetic femurs fitted with a T2 femoral nailing system, comparing different configurations mimicking post-operative clinical stability at low static axial loads.

Despite the published works, they obtained very mixed results, because of analyzing different situations and configurations. The published results are difficult to compare and lead to controversial conclusions. In view of the existing dispute between the use of anterograde or retrograde nailing for the treatment of supracondylar femoral fractures, the aim of the present work is to carry out a comparative study about the biomechanical behavior of anterograde and retorgrade nailing in that type of fractures, in order to determine the best choice of nailing and locking configuration.

Methods

A three dimensional (3D) finite element model from a femur corresponding to a 55-year-old male donor was developed (the present work is included in the project “Estudio biomecánico y clinico del enclavamiento centromedular en el tratamiento de las fracturas diafisarias de fémur”, which was approved by the Ethics Committee of the Institute of Health Sciences of Aragón, Spain; protocol number C.P.-C.I. PI 15/0214).

The outer geometry of the femur was obtained by means of 3D Roland3D Roland® PICZA (Irvine, California) scanner, whereas a set of computed tomography (CT) of the femur were treated using Mimics® Software (Materialise, Leuven). The CT scans were obtained by means of a TOSHIBA Aquilion 64 scanner (Toshiba Medical Systems, Zoetermeer, Netherlands) (512x512 acquisition matrix, field of view (FOV)=240 mm, slice thickness=0.5 mm, in plane resolution). Once the inner interface between cortical and trabecular bone was delimited, material properties were assigned to the FE model in I-Deas ® 11 NX Series PLM software (Siemens, Plano, Texas) [33], using the same workflow of previous studies [34].

Nail surgery was virtually reproduced in I-Deas, inserting the nails into the femur with the corresponding screws, being performed the computer aided design (CAD) model under surgeon supervision. In order to cover a broad range of surgical options, the osteosyntheses included in Table 1 (27 FE models, 12 for anterograde an 15 for retrograde nails, respectively) were analyzed. The different gap sizes were simulated: 0.5 mm (considered as a non-comminuted fracture), 3 mm (as the most referenced value found in literature, representing a mid-value) and 20 mm as an example of comminuted fracture (Fig. 1). The used nail was IM Stryker femoral nail S2 (Stryker, Mahwah, NJ, USA), with variable length, wall thickness of 2 mm and outer diameter of 13 mm. This reamed anterograde nail uses locking screws of 5 mm of outer diameter, which were geometrically modeled as cylinders of the same diameter. The type of elements used was linear tetrahedra for bone, nail and screws.

Concerning materials behavior, bone, nail and screws were considered as linear elastic isotropic. For cortical and trabecular bone, the elastic properties were E_{cor}=20000 MPa, ν_{cor}=0.3 and E_{tra}=959 MPa, ν_{tra}=0.3 [35] as reference, with variable values related with the processed CT images. The metallic nail and metallic screws were made of 316 LVM steel (E=192.36 GPa, ν=0.3).

To guarantee the accuracy of the FE results, a sensitivity analysis was performed to determine the minimal size mesh required for an accurate simulation. For this purpose, a mesh refinement was executed in order to achieve a convergence towards a minimum of the potential energy, both for the whole model and for each of its components, with a tolerance of 1% between consecutive meshes. The final models had an average mesh size about 1.5 mm, with about of 240.000 nodes and 1.100.000 elements on average.

Concerning the loads conditions, a load case associated with an accidental support of the leg at early postoperative (PO) stage has been considered. This load was quantified to be about 25% the maximum gait load. According to Orthoload's database, the hip reaction force and abductor force, referred to 45% of the gait, correspond to the maximum and most representative load [36]. Forces generated by the abductor muscles were applied to the proximal area of the greater trochanter, in agreement with most classic authors' opinion [37, 38]. Fully constrained boundary conditions were applied at distal part of the femur (at the condyles). Figure 2 shows both loads and boundary conditions in FE models.

Results

The FE simulations allowed verifying the biomechanical behavior of the different cases, obtaining the mobility and stress results for the different osteosyntheses analyzed. The different behaviors and resulting trends are detailed hereafter.

Trends of the global movement at the femoral head

Global movements of the femoral head for the different osteosyntheses simulated are shown in Table 2 and Fig. 3. A higher mobility is detected, in general, for retrograde nails, increasing as the gap is bigger; on the other hand, every osteosynthesis, depending on the nail length, shows approximately the same level of mobility, with a slight decreasing for longer nails. For anterograde nails, the mobility depending on the gap size exhibits the same trend; in this case, osteosynthesis number 4 presents the lower mobility.

Stability trends at the fracture site

Relative movements at fracture site are processed considering working groups of corresponding nodes located in opposite positions at the fracture focus (Figure 4).

The graphs of relative displacements at fracture site for the different osteosynthesis considered in the study are collected in Table 3 and depicted in Fig. 5.

The micromovements practically reached the same range of values, independently of the type of nail. Concerning gap size, for anterograde nails the micromovements increase as the gap grows for the different osteosyntheses analyzed, obtaining the lower values for the osteosynthesis number 4, except for gap size of 20.0 mm. For retrograde nails, the gap influence is almost non-existent for smaller gaps, significantly increasing for the gap of 20.0 mm.

Stress trends in the nail and locking screws

Tables 4 and 5 include the results corresponding to maximum von Mises stress values in nail and screws, respectively.

Figure 6a shows the maximum values of von Mises stress in the nail for the different fracture gaps and osteosynthesis type that were simulated. The maximum von Mises stress value in the nail increases for higher gap sizes (20.0 mm), both for anterograde and retrograde nailing. The stresses are slightly greater for anterograde nails than for retrograde nails. For retrograde nails, von Mises stresses are higher for osteosyntheses 8 and 9. Any case, the obtained values are well below those corresponding to the yield strength of nails material, which is logical, considering that only a fraction of the physiological load was considered.

Figure 6b shows the maximum values of von Mises stress in locking screws for the different fracture gaps and osteosynthesis type that were simulated. In this case, higher values of maximum von Mises stress are reached for retrograde nails, independently of fracture gap size and osteosynthesis type. For anterograde nails, stresses in screws are practically identical for every gap size, significantly diminishing for osteosynthesis type 4. This could be due to a local leverage effect, with a greater mechanical arm. For retrograde nails, the higher stresses are produced for osteosyntheses type 8 and 9, i. e., for longer nails, reaching values approximately twice than for anterograde nailing. The obtained values are well below those corresponding to the yield strength of locking screws material.

Trends of stresses in cortical bone

Results corresponding to stresses in cortical bone, for the different osteosyntheses and fracture gap size are presented in Table 6.

Figure 7 shows the maximum values of von Mises stress in the cortical bone for the different fracture gaps and osteosynthesis type that were simulated.

Stresses in cortical bone are lower for anterograde nails, being very similar in this case independently of fracture gap size and osteosynthesis type. For retrograde nails, stresses are almost independent of fracture gap size, but they are significantly lower for longer nails (320 mm). Those stresses appear located at the contact zone around nail tip. The obtained values are sufficiently low to avoid additional fractures.

Discussion

From our knowledge, none of the published papers using the FE method has comparatively studied the complete biomechanical behavior of anterograde vs. retrograde IM nailing in supracondylar fractures of the femur, simulating different types of comminution at the fracture site. Bougherara [32] has studied, by means of experimental techniques, the anterograde or retrograde nailing on synthetic bones, using a nail identical to S2, but of titanium (T2), and without simulating fractures, but comparing stresses in three femoral portions, applying a static load and comparing with the results obtained from a FE model obtained from a cadaveric sample. Other work using FE method has focused on retrograde nailing to check the stress concentrations according to the number of locking screws [39], the biomechanical behavior of the nail [24], retrograde metallic versus composite nails [40], retrograde nail with static or dynamic blocking [28], or retrograde titanium and steel nails [29].

Most of the published works use synthetic bones to compare the retrograde nail with different types of plates [41, 43], or a classical retrograde nail with a new prototype [43], or models in cadaver also comparing plates and nails [44-51]. Other authors have tested the biomechanical behavior of different nail designs [52] or compared plates with retrograde and Roussel-Taylor nails [53].

The main aim of surgical treatment is to use a device which provides adequate stability, preserves the length and alignment of the limb and ensures a good functional result, and all this with a surgical procedure as less aggressive as possible.

In the study carried out in the present work, a 13 mm diameter nail in both anterograde and retrograde approaches was used, simulating the reaming of the medullary cavity, because a good contact between endosteum and nail surface is a key point to achieve the stability of the nail [54, 55]. That choice has also allowed us to avoid fatigue fractures in the holes of the screws [56], and the use of locking screws of 5 mm of diameter.

Among the options of surgical devices for the treatment of fractures of the distal extremity of the femur, the ORIF may be indicated in fractures which involve the joint, but in those located in the supracondylar area, intramedullary nailing is a better option. Blocked plates can prevent callus formation, because of their high stiffness, [57-61]. Although similar resistance to axial load has been described for nails and plates [46-57], it has been recently demonstrated that IM nailing has a 47.5% greater axial stiffness than a dynamic condylar screw, and 77% greater axial stiffness than a locking condylar plate. Other problems of plates are the breaking and implant failure [7, 62-69]. Nailing has also been associated with less micromotion at the fracture site than other devices [42].

The obtained results show the influence of nail type in the biomechanical behavior of the different osteosyntheses analyzed. So, concerning mobility, despite both types of nails provide approximately the same range of micromovements at fracture site, with retrograde nails the global mobility is significantly higher, reaching displacement values as much as 49% greater. Then, anterograde nails provide a better stability from the point of view of global movements. On the other hand, stresses in nail are very similar independently of nail type for different fracture gap sizes and osteosynthesis type, being slightly higher for anterograde nailing; however, stresses in screws are significantly higher for retrograde nailing, reaching values approximately twice in longer nails than for anterograde nailing. Finally, stresses in cortical bone are significantly higher for retrograde nails, especially for shorter nails, appearing at the contact zone corresponding to nail tip. Those concentrated stresses can lead to secondary fractures in the affected zone if load accidentally increases. Definitively, for the analyzed fractures and osteosyntheses types, anterograde nailing has demonstrated to be a better surgical option.

It is clear that anterograde nailing provides greater fracture stability, from the biomechanical point of view. But it should also be noted that a large proportion of these fractures occur in women with osteoporosis, whose bone structure in the distal femoral metaphysis is weak, causing greater instability in the retrograde nail, despite using screws with condyle washers in the locking holes proximal to the knee to avoid "Bell-Clapper Effect" [70].

On the other hand, bone healing is faster with the anterograde nails [71], and retrograde nails have a higher incidence of angular malalignment [72, 73]. Not should be underestimated the potential morbidity caused by the intra-knee approach, even if the insertion hole was correctly performed. Some authors have found a higher incidence of post-operative knee pain, but suggest that longer-term reviews are necessary to evaluate the possible sequelae [74]. However, a recent meta-analysis insists on postoperative knee problems in retrograde nailing, with a high percentage of knee pain [75]. In addition, a large number of supracondylar fractures occur among elderly population, more prone to knee osteoarthritic changes, which further complicates the problem.

As main limitations of the present study, the consideration of only one type of fracture (i.e., transverse) could limit the generalization of the conclusions. On the other hand, the comparison with other surgical techniques (i.e., locking plates) could provide additional valuable information.

Conclusions

In view of the obtained results, anterograde nailing is an excellent indication in supracondylar fractures of femur type A, according to the AO/OTA classification, with clear benefits compared to retrograde nailing, providing a better stabilization which enables for a more satisfactory fracture healing.

List of abbreviations

OTA: Orthopaedic Trauma Association

ORIF: Open Reduction Internal Fixation

IM: Intramedullary nailing

FE: Finite Elements

3D: Three-Dimensional

CT: Computed Tomography

CAD: Computer Aided Design

PO: Post-operative

Conflict of interest statement

The authors have no professional or financial conflicts of interest to discloser.

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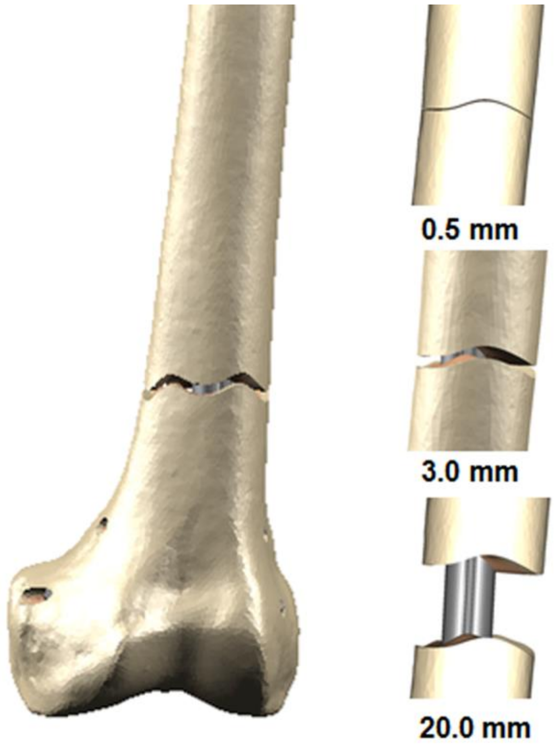

Figure 1. Distal fractures with different gap sizes: 0.5 mm, 3.0 mm and 20.0 mm.

Figure 2. Loads and boundary conditions

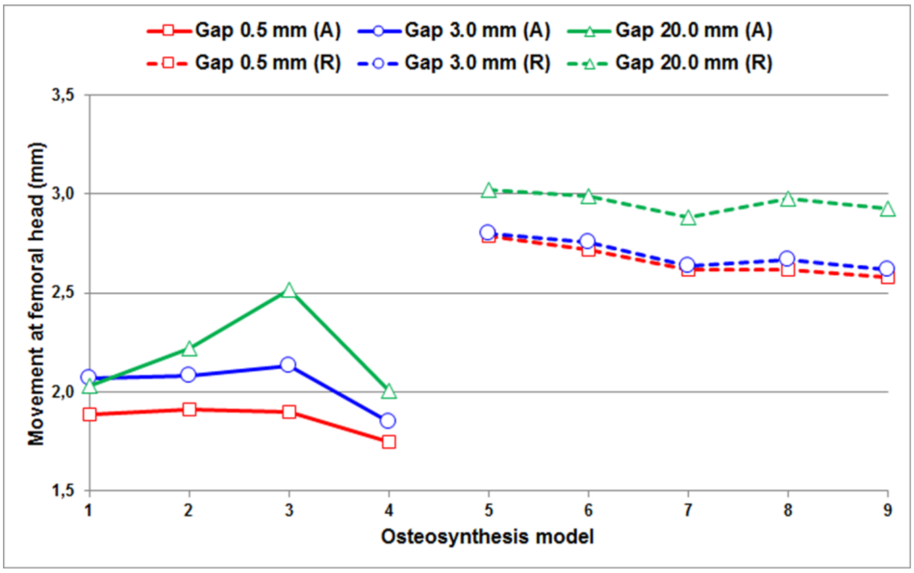

Figure 3. Global movements at femoral head for the different osteosynthesis models (A: anterograde; R: retrograde).

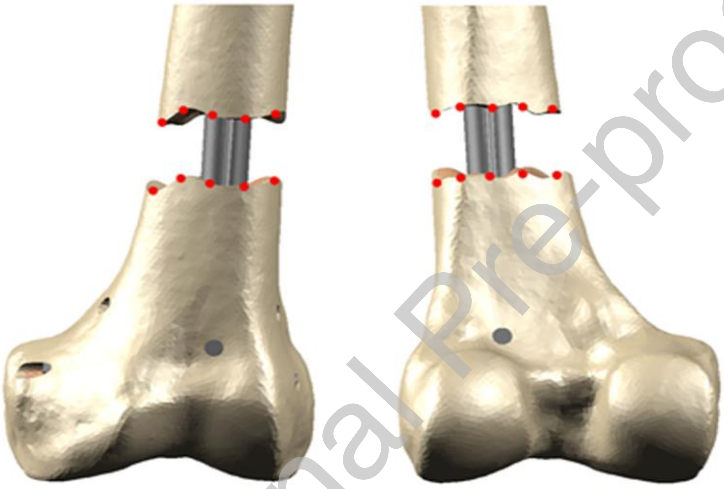

Figure 4. Groups of corresponding points for micromotion processing: anterior and posterior views.

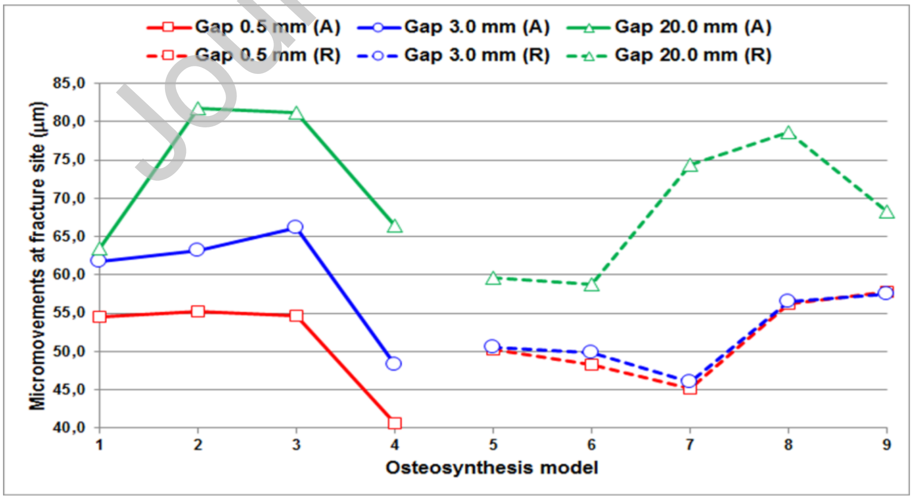

Figure 5. Relative micromovements at fracture site for the different osteosynthesis models (A: anterograde; R: retrograde).

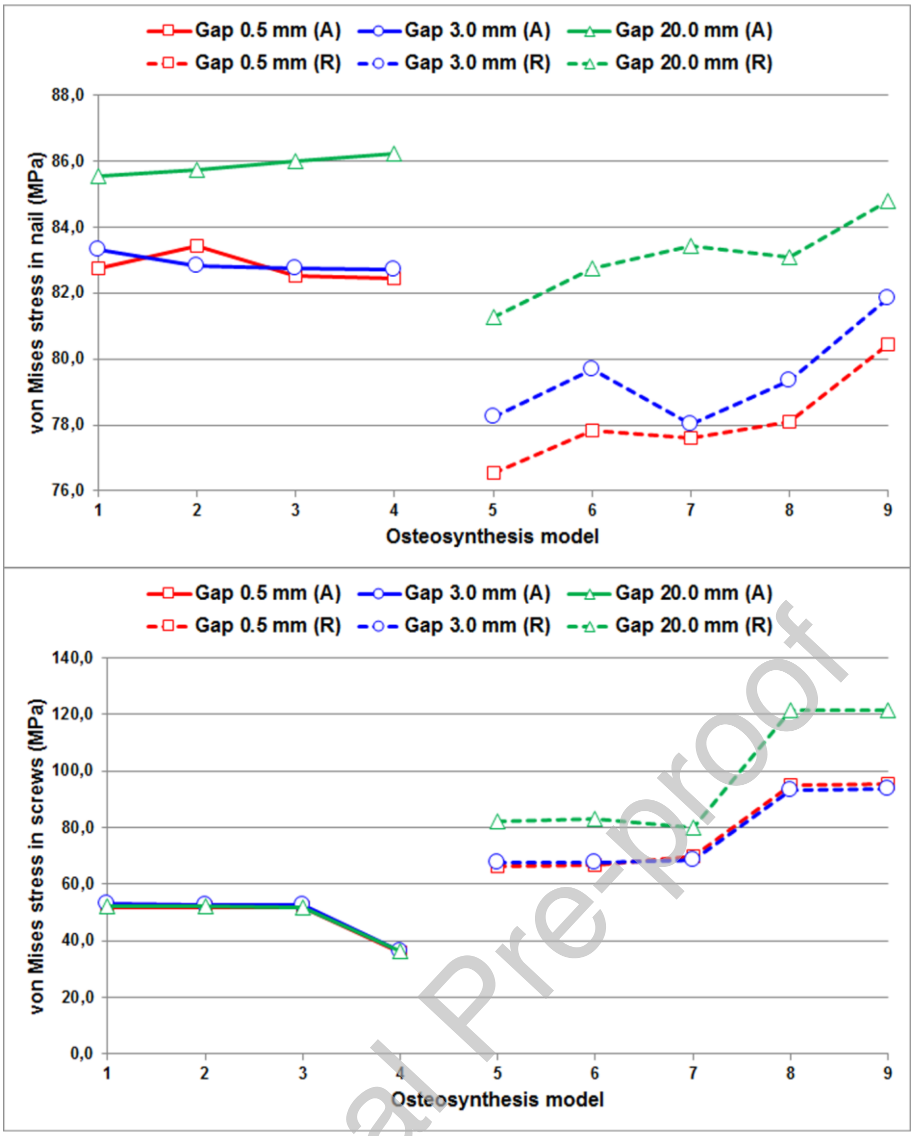

Figure 6. Maximum values of von Mises stress for the different fracture gaps: a) stresses in the nail; b) stresses in the locking screws. (A: anterograde; R: retrograde).

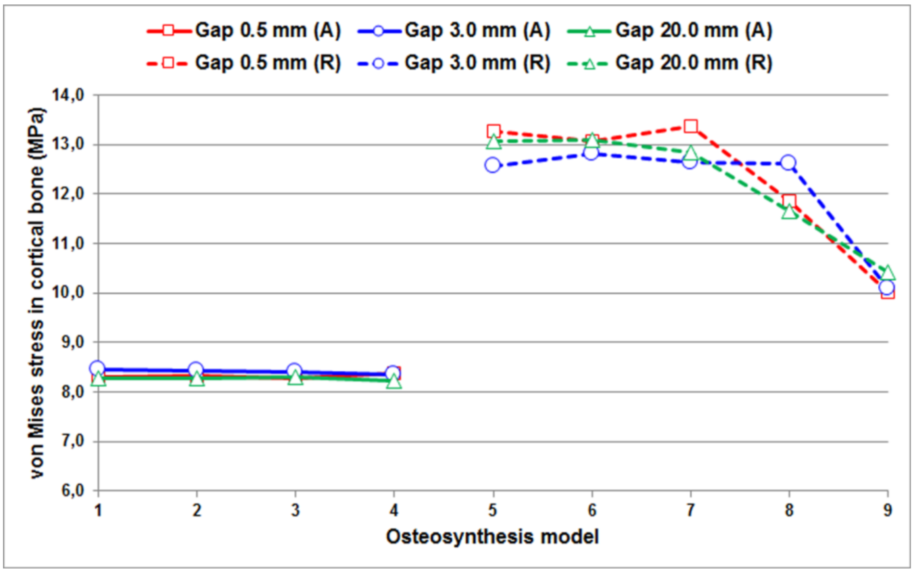

Figure 7. Maximum values of von Mises stress in the cortical bone for the different fracture gaps (A: anterograde; R: retrograde).

Table 1. Different configurations considered in the FE simulations.

Model	Nail type	Proximal screw	Distal screws	Fracture type	Gap size (mm)	Nail lengths (mm)	Screw configuration
1	Anterograde	Oblique (#1)	2 L/M (#2, #4) and 1 A/P (#3)	Distal	0.5 3.0 20.0	380	
2	Anterograde	Oblique (#1)	1 L/M (#2) and 1 A/P (#3)	Distal	0.5 3.0 20.0	380	
3	Anterograde	Oblique (#1)	1 L/M (#4) and 1 A/P (#3)	Distal	0.5 3.0 20.0	380	
4	Anterograde	Oblique (#1)	2 L/M (#2, #4)	Distal	0.5 3.0 20.0	380	
5	Retrograde	1 A/P (#3)	2 L/M (#1, #2)	Distal	0.5 3.0 20.0	180	
6	Retrograde	1 A/P (#3)	2 L/M (#1, #2)	Distal	0.5 3.0 20.0	200	
7	Retrograde	1 A/P (#3)	2 L/M (#1, #2)	Distal	0.5 3.0 20.0	240	
8	Retrograde	1 A/P (#3)	2 L/M (#1, #2)	Distal	0.5 3.0 20.0	280	
9	Retrograde	1 A/P (#3)	2 L/M (#1, #2)	Distal	0.5 3.0 20.0	320	

Table 2. Global movement at the top of the nail [mm].

Model	Nail length (mm)	Gap 0.5 mm	Gap 3.0 mm	Gap 20.0 mm
		Anterograde nailing		
1	380	1,89	2,07	2,03
2	380	1,91	2,08	2,22
3	380	1,90	2,13	2,52
4	380	1,75	1,85	2,01
		Retrograde nailing		
5	180	2,79	2,80	3,02
6	200	2,72	2,76	2,99
7	240	2,62	2,64	2,88
8	280	2,62	2,67	2,98
9	320	2,58	2,62	2,93

Table 3. Maximum amplitude of axial micromotions [μm].

Model	Nail length (mm)	Gap 0.5 mm	Gap 3.0 mm	Gap 20.0 mm
		Anterograde nailing		
1	380	54,53	61,73	63,5
2	380	55,26	63,13	81,7
3	380	54,64	66,14	81,24
4	380	40,69	48,33	66,43
		Retrograde nailing		
5	180	50,27	50,62	59,62
6	200	48,22	49,84	58,83
7	240	45,13	46,02	74,31
8	280	56,18	56,46	78,57
9	320	57,85	57,53	68,21

Table 4. Maximum von Mises stress in nail [MPa].

Model	Nail length (mm)	Gap 0.5 mm	Gap 3.0 mm	Gap 20.0 mm
Anterograde nailing				
1	380	82,73	83,31	85,55
2	380	83,44	82,83	82,73
3	380	82,51	82,74	85,99
4	380	82,44	82,70	86,22
Retrograde nailing				
5	180	76,54	78,26	81,27
6	200	77,85	79,70	82,74
7	240	77,60	78,04	83,41
8	280	78,08	79,34	83,07
9	320	80,45	81,84	84,80

Table 5. Maximum von Mises stress in screws [MPa].

Model	Nail length (mm)	Gap 0.5 mm	Gap 3.0 mm	Gap 20.0 mm
Anterograde nailing				
1	380	51,98	53,06	52,08
2	380	51,95	52,85	52,04
3	380	51,93	52,88	52,03
4	380	35,97	36,23	36,57
Retrograde nailing				
5	180	66,41	67,55	82,21
6	200	66,70	67,58	83,35
7	240	69,97	68,79	79,97
8	280	94,92	93,41	121,43
9	320	95,57	93,84	121,30

Table 6. Maximum von Mises stress in cortical bone [MPa].

Model	Nail length (mm)	Gap 0.5 mm	Gap 3.0 mm	Gap 20.0 mm
		Anterograde nailing		
1	380	8,31	8,46	8,28
2	380	8,34	8,43	8,29
3	380	8,29	8,41	8,30
4	380	8,38	8,35	8,23
		Retrograde nailing		
5	180	13,28	12,57	13,08
6	200	13,06	12,81	13,10
7	240	13,38	12,64	12,85
8	280	11,87	12,62	11,67
9	320	10,03	10,09	10,42