Biomechanical behavior of retrograde intramedullary nails in distal femoral fractures

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Abstract

Fractures of the distal femur affect to three different groups of individuals: younger people suffering high-energy trauma, elderly people with fragile bones and people with periprosthetic fractures around previous total knee arthroplasty. Main indications of intramedullary nailing are for supracondylar fractures type A or type C of the AO classification.

The main objective of the present work is to analyze, by means of FE simulation, the influence of retrograde nail length, considering different blocking configurations and fracture gaps, on the biomechanical behavior of supracondylar fractures of A type.

A three dimensional (3D) finite element model of the femur from 55-year-old male donor was developed, and then a stability analysis was performed for the fixation provided by the retrograde nail at a distal fracture with different fracture gaps: 0.5 mm, 3 mm y 20 mm, respectively. Besides, for each gap, three nail lengths were studied with a general extent (320 mm, 280 mm and 240 mm), considering two transversal screws (M/L) at the distal part and different screw combinations above the fracture. The study was focused on the immediately post-operative stage, without any biological healing process.

In view of the obtained results, it has been demonstrated new possibilities of blocking configuration in addition to the usual ones, which allows establishing recommendations for nail design and clinical practice, avoiding excessive stress concentrations both in screws, with the problem of rupture and loss of blocking, and in the contact of nail tip with cortical bone, with the problem of a new stress fracture.

Key words

Intramedullary nail, Retrograde reamed nail, Femoral fracture, Osteosynthesis, Finite element analysis.

Highlights

- Biomechanical behavior of supracondylar fractures depends on nailing configuration.
- Stability in the immediately post-operative is essential for fracture consolidation.
- New nail lengths/blocking configuration were validated in addition to the usual ones.
- Excessive stress concentrations in screws might cause rupture and loss of blocking.
- Excessive contact stress between nail tip and bone might cause a new stress fracture.

Introduction

Fractures of the distal femur represent between 4 and 6% of femoral fractures [1] and about 0.4% of adult fractures [2]. Fractures of the distal femur typically occur in two groups of individuals: younger people suffering high-energy trauma, or elderly people with bones that are more fragile due to osteoporosis, mainly women. Eighty-five per cent of distal femoral fractures occur in older adults [3] with a trend of increase in the percentage of these elderly patients with osteoporosis [4].

However, over recent decades, a third group has emerged: people with periprosthetic fractures occurring around previous total knee arthroplasty. These fractures have a reported incidence of 0.6% of primary and 1.7% of revision knee arthroplasties at five years postoperatively [5], also with percentage increase due to the large number of knee replacements in elderly patients [6]. The fundamental goal of surgical treatment in these patients should be considered similar to those with a proximal femur fracture, which is a rapid surgical procedure that allows weight support and early mobilization to prevent complications in these patients.

Different surgical devices have been used for the treatment of these fractures: buttress condylar plate, angled blade plate, locked plate, polyaxial plates, dynamic condylar screw, external fixation, and anterograde and retrograde locked intramedullary nail are commonly used for treatment of supracondylar femoral fractures [7].

Possibly today the two most commonly used procedures are angular stability lateral plates, implanted by mini-invasive technique, and retrograde intramedullary (IM) nails. Starting from Moed's work in 1995 [8], retrograde intramedullary nails have been accepted as a usual technique. The current designs with multiple holes in the lateral and anteroposterior directions allow the placement of locking screws in different planes and contribute to the mounting stability.

The retrograde IM nailing has specific indications for polytraumatized patients with ipsilateral fracture of the femur and tibia, obese with femoral diaphyseal fractures, fractures of the lower third of the femur, in periprosthetic fractures after implantation of knee prosthesis and pregnant women. Nonetheless, we believe that its main indication is for supracondylar fractures type A or type C of the AO classification, provided that the fracture in type C traces allow the placement of two distal screws, to ensure the stability of the mounting.

A few works on finite element (FE) simulation of retrograde intramedullary nails have been published. Chen et al. [9] employed both mechanical testing and finite element analysis to compare the stiffness variations among different intramedullary nail constructs used in the treatment of distal femoral fractures, focused on screw behavior. They concluded that extra screw holes on the nail provided flexibility during surgery, but yielding to a potential risk of nail fracture under torsion load on these unused screw holes.

Moreover, the screws at the fracture site have been more effective if only it passed through the fracture gap to integrate the separated femoral pieces. The stress around the screw holes of the metaphyseal region abruptly increased and the distal screw around the metaphyseal region had a more important stabilizing effect in the femur–nail construct than does the proximal screw. However, the length of the screw was not analysed. On the other hand, Chantarapanich et al. [10] compared the biomechanical performance of retrograde nail used to stabilize supracondylar fracture (three different levels) by means of finite element analysis, using three different nail lengths (200, 260, and 300 mm) of stainless steel and titanium. In conclusion, purchasing proximal locking screw in the bowing region of the femur may be pose a risk due to the high stresses at the implant and bone. Moreover, there were no differences in stress level, elastic strain at a fracture gap, and bone stress between stainless

steel and titanium implant and since the intramedullary channel requires reaming to accommodate the retrograde nail, the length of retrograde nail should be as long as necessary. To the best of our knowledge, there are no studies focused on all the aspects related to the appropriate nail election that guarantees the best surgical indication (fracture stabilization, relative mobility between femoral pieces above and under fracture site, stress in bone at the nail point level, stress in the nail and stress in the locking screws), depending on the influence of retrograde nail length and different blocking configurations.

On the grounds of this, the main objective of the present work is to analyze, by means of FE simulation, the influence of retrograde nail length, considering different blocking configurations and fracture gaps, on the biomechanical behavior of supracondylar fractures of A type. The issue is to establish which are the nail length and blocking configuration more appropriate for every fracture type. To this, several aspects are analyzed in detail: fracture stabilization by measuring the local micromovements between fracture edges, relative mobility between femoral pieces above and under fracture site, stress in bone at the nail point level, stress in the nail and stress in the locking screws.

Methods

Modeling of the femur and implants

A three dimensional (3D) finite element model of the femur from 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 scanner Roland3D Roland® PICZA (Irvine, California) scanner, whereas a set of computed tomography (CT) of the donor’s femur were treated using Mimics®

Software (Materialise, Leuven). Once the inner interface between cortical and trabecular bone was delimited by means of an in-house algorithm material properties were assigned to the FE model in I-Deas [11], using the same workflow of previous studies [12].

Meshing and material properties

Nail surgery was reproduced in I-Deas in a virtual way, inserting the nail into the femur with the corresponding screws. Subsequently the assembly of the computer aided design (CAD) model was performed under surgeon supervision. Bone, nail and screws were meshed with linear tetrahedra. They were assumed for the bone linear elastic isotropic properties ($E_{Cortical}$=20000 MPa, ν=0.3; $E_{Trabecular}$=959 MPa, ν=0.3 [13], as reference), with variable values related to the processed CT images. The metallic nail and screws were made of 316 LVM steel (E=192.36 GPa, ν=0.3), assumed to be a linear elastic isotropic material.

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.

Configurations used and contact modeling

All the considered fractures were modeled as transverse by means of an irregular surface developed to represent a closer geometry to the actual fracture. The effect of gap size remains unclear in the literature. Accordingly to this, the majority of the reviewed in vivo studies are referred to a gap size ranging from 0.6 to 6 mm [14, 15] whereas in FE simulation articles it ranged from 0.7 to 10 mm [16, 17].

Resorting to this irregular fracture pattern, three different fracture gaps have been studied: 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 (Table 1). Only distal fractures were considered.

The study was focused on the immediately post-operative stage. Thus, the interaction at the fracture site does not take into account any biological healing process. Contact interaction was assumed between the outer surface of the nail and the inner cortex of the intramedullary channel of the femur (Fig. 1a). Interaction between screws and cortical bone was considered to be bonded, whereas contact between screws a femoral nail was simulated. The selected friction values of bone/nail and nail/screws were 0.1 and 0.15, respectively, in accordance with literature [17-19]. However, other similar studies modelled bone/nail interaction as frictionless [20, 21].

Loads and boundary conditions

This study considered fully constrained conditions at the condyles and a load case associated with an accidental support of the leg at early post-operative (PO) stage (Fig. 1b). This load was quantified to be about 25% the maximum gait load. According to Orthoload's database [22] the hip reaction force and abductor force (as the prime muscle group), referred to the 45% of gait, correspond to the maximum and most representative load. Muscle attachments areas corresponding to abductor group muscle were determined mimicking anatomy atlas, in the same way that in previous works [23, 24].

The studied femoral nail corresponds to the Stryker S2^{TM} design (Stryker, Mahwah, NJ, USA), considering different lengths (180, 200, 240, 280 and 320 mm, respectively), with a wall thickness of 2 mm and an outer diameter of 13 mm. This reamed retrograde nail uses locking screws of 5 mm of outer diameter, which were modeled as cylinders of the same

diameter. In this work, new possibilities of blocking have been explored apart from the usual blocking configurations.

A stability analysis was performed for the fixation provided by the retrograde nail at a distal fracture with different fracture gaps: 0.5 mm, 3 mm y 20 mm, respectively. Besides, for each gap, the influence of the nail length was examined together with the type of screw fixation. In this way, three nail lengths were studied with a general extent (320 mm, 280 mm and 240 mm, respectively), considering two transversal medial/lateral (M/L) screws at the distal part and different screw combinations above the fracture. For the reference fixation system #1 (the most common in the surgical practice) two additional nail lengths were considered (180 and 200 mm). Considering this fixation system the landmark/reference, the screw systems included in Table 1 have been simulated by means of Abaqus software [25]. Proximal screw, if present, is always anterior/posterior (A/P). The screws below and above the fracture site were placed at the same distance from the fracture (5 cm, approximately). The screw above the fracture site can be either medial/lateral or anterior/posterior.

Results

The FE simulations allowed obtaining the mobility and stress results for the different cases analyzed. The different resulting trends are detailed hereafter.

Stability trends at the fracture site

The complete results are exhibited at the charts of the Figures 2-4.

Regarding fracture gap of 0.5 mm, the screw configurations #1, #3 and #5 exhibit a similar behavior with a slight progress for #3 at the 280 mm nail. Screw configurations 2 and 4 show poorer results with the 240 mm nail, whereas for longer nails from 280 to 320 mm, its performance is comparable to the reference screw combination #1.

For the fracture gap of 3 mm, fixation systems #2 and #4 exhibited worse results for the 240 mm nail, whereas for the lengths of 280 and 320 mm yield to a behavior comparable to the screw system #1. Systems #3 and 5 produce poorer results compared to the first system at nails 240 and 280 mm long, and maintaining the same performance for the 320 mm nail.

When analysing the comminute fracture (20 mm gap) all the screw combinations give poorer results with the 240 mm nail compared to the fixation system #1. There is an improvement for the 280 mm nail except for the #5 screw combination that produces similar behavior and for the 320 mm nail the performance is enhanced.

In conclusion, screw combinations #2 and #4 exhibit a patent improvement on the fracture gap stability compared with the standard screw system #1, for the 20 mm fracture gap and longer nails (280 and 320 mm). At shorter gaps of 0.5 and 3 mm, the behavior for longer nails (280 and 320 mm) is comparable to screw fixation #1. Analysing shorter nails (240 mm) the results are poorer at every fracture gap.

Considering the shortest gap of 0.5 mm, screw combination #5 has similar behavior to #1, whereas #3 improves the stability for the 280 mm. Regarding the 3 mm gap, a similar behavior is observed for longer nails (320 mm), with a marked worse results for the shorter nails (240 mm and 280 mm). At the 20 mm fracture gap, #3 and #5 improve stability compared to #1 for longer nails (320 mm), they exhibit a worse behavior at the shortest nail 240 mm. Concerning the intermediate 280 mm nail, screw system #3 give better results, whereas #5 produces a similar performance to screw system #1.

Two additional nail lengths of 200 and 180 mm were simulated. These nails are only compatible with screw configuration #1 as the antero-posterior screw would be at almost the same position of the screw just above the fracture gap. The observed micromovements' tendencies at the fracture gap for these two lengths are very similar to those for the 240 mm nail, with a slight improvement the shorter the nail is, as it is shown in Table 2 and Figs. 2-4.

In the same way, considering the 320 mm nail as reference, it can be observed that for the combination #1 the shorter nail provides the best results for all the gaps (Table 3).

Trends of the global movement at the femoral head

Table 4 and Fig. 5 exhibit the global movement of the femoral head for the different fracture gap and nail lengths that were simulated. A higher mobility is produced the shorter the nails are, and for higher fracture gaps. This result is inherently related to the global stability that decreases when the fracture gap increases.

Figure 6 shows a scheme of the bearing nail-bone mechanism. When an eccentric load is applied (the imposed load as the hip reaction force is applied at a distance of the physiological femoral axis), a moment is generated at the nail. Consequently, at the higher part of the femur, just above the fracture gap, the femur rotates as a rigid body until the nail is blocked by contact at the intramedullary channel. After, this load is transmitted to the lower part. The longer the nail it is, the higher load from the hip it will support, yielding to smaller loads for the cortical bone at the top part of the nail.

Nonetheless, in order to justify the effect of fracture gap size on the global movement of the ensemble a closer look must be taken at the Fig 7. The nail can be considered as a cantilever beam which resists the same load, but in which the exempt length (part of nail outside intramedullary channel) increases inasmuch as the fracture gap is greater. Consequently, when the exempt part of the nail length increases, the curvature due to bending increases, which induces a higher motion at the higher part of the femur as the results from Table 3 and Fig 5 show.

232 *Trends of cortical stress at the top part of the nail*

233 Table 5 and Fig. 8 gather the results of the stress for the cortical bone at the top part of the
234 nail. An increase in stress is observed as the nail length decreases.

235 This result is explained in biomechanical terms by the lever arm effect produced by blocking
236 the nail at the inner part of the medullary (Fig. 6)

237

238 *Stress trends at the nail*

239 In order to understand the biomechanics of the ensemble, von Mises stress of the nail have
240 been post-processed at the fracture site. Consequently, it can be observed how is transmitted
241 the load from the upper part of the femur to the lower part, as results in Table 6 and Fig. 9
242 present.

243 Table 6 and Fig.9 exhibit a decrease in the nail stress for shorter lengths. Analogously when
244 comparing different fracture gaps, it is observed that for the same nail length nail stress are
245 reduce for smaller fracture gaps.

246

247 *Stress trends at the fixating screw*

248 Finally, von Mises stresses values of the screws are shown in Table 7 and Figs 10 to 12.

249 Regarding the A/P proximal nail, the stress tendency increases for longer nails at every
250 fracture gap.

251 In relation to M/L superior distal screw, the stress increases when the nail length diminishes
252 henceforth the 240 mm nail at every fracture gap. Stresses remain similar for all fracture gaps
253 for longer nails (320 mm and 280 mm).

254

Finally, von Mises stress decreases for the M/L inferior distal screw as the nail length is shorter from the 240 mm nail at all fracture gaps. Stresses remain similar for all fracture gaps for longer nails (320 mm and 280 mm).

Discussion

As it has been said, few works on FE simulation of retrograde intramedullary nails have been published with a lack of studies focused on the influence of retrograde nail length, considering different blocking configurations, on all the aspects related to an appropriate nail election in order to guarantee the best surgical indication. The combination of nail length and blocking system is an essential factor for primary stability, avoiding excessive stress concentrations both in screws, with the problem of rupture and loss of blocking, and in the contact of nail tip with cortical bone, with the problem of a new stress fracture.

In this work, a complete FE study with respect to the biomechanical behavior of supracondylar fractures of A type, considering the influence of retrograde nail length, different blocking configurations and fracture gaps, is presented. In order to provide clinical recommendations, this study aims to establish the most suitable blocking configuration and optimizes the nail length for every type of fracture. This is performed by the analysis in detail of fracture stabilization by means of local micromovements between fracture edges, relative mobility between femoral pieces above and under fracture site, stress in bone at the nail point level, stress in the nail and stress in the locking screws.

Regardless of FE studies, other experimental biomechanical studies have demonstrated that IM nailing and side plate constructs have similar axial strength [26, 27]. However, a recent cadaveric study of supracondylar fracture fixation showed that IM nailing had 47.5% greater axial stiffness than a dynamic condylar screw and 77% greater axial stiffness than a locking condylar plate. Nailing was also associated with less micromotion than were the other

constructs [28]. A recent study in cadaver has shown that the blocked retrograde nail has better stiffness and fatigue life than locking plates, and superior fatigue life to non-locking nails, which is fundamental for its indication in fractures of osteoporotic aetiology [29]. On the other hand, several authors have pointed out that the high rigidity of the locked plate suppresses callus formation in simple fractures [30-33].

Since the work of Moed published in 1995 [8] about retrograde intramedullary nails without reaming, the surgical technique and the design of nails have improved, what allows us to achieve greater stability of the focus of fracture. From surgical technical point of view the entry point in the intercondylar area is carried out more anterior for allowing a perfect alignment of nail in the two planes, and two distal screws should always be placed in the latero-medial direction that prevent their telescoping in the joint [34]. It is very important that the distal end of the nail must be located below the subchondral bone to avoid damage to the patella with the flexion movements of the knee [35]. Other technical and design improvements (reaming, larger diameter nails and locking screws) in addition to respecting the focus hematoma and less bleeding in surgery, represent advantages in favor of retrograde nailing [36, 37].

Other advantages of the intramedullary retrograde nailing are the high percentages of fracture consolidation achieved with this technique [34, 36, 38], as well as the excellent results in elderly patients [4, 39]. Other authors have demonstrated shorter fracture consolidation times with intramedullary nailing compared to other systems [40]. With respect to the complications reported on the loss of mobility in the knee joint, numerous works corroborate the opposite [34, 38, 41], which coincides with our own clinical experience.

In comparative studies between LISS plate (Less Invasive Stabilization System) and intramedullary nailing, similar fracture consolidation percentages were found, but with fewer complications in the intramedullary nailing [42]. On the other hand, in comparative studies

between traditional open reduction internal fixation (ORIF) and intramedullary retrograde nailing [43], better results concerning consolidation percentages were reported with intramedullary nailing, and no infections [43]. Concerning periprosthetic fractures, the published results for intramedullary nailing are excellent [44-46].

On the other hand, there are authors who after an exhaustive meta-analysis of the published works on the different methods of treatment of distal femur fractures, do not recommend a specific technique, due to the lack "of multicenter randomized controlled clinical trials comparing contemporary treatments such as locked plates and intramedullary nails" [47].

In this work, in addition to the usual blocking configurations new possibilities of blocking have been analyzed, which allows stablishing new criteria for future retrograde intramedullary nail design in order to provide the best solution for every type of distal femoral fracture.

As main limitations of the study, it can be pointed out that the consideration of only one type of fracture (i.e., transverse) could limit the generalization of the conclusions; additionally, the comparison with other surgical techniques (i.e., locking plates) could provide further valuable information.

Conclusions

In view of the obtained results, intramedullary retrograde nailing show technical advantages with respect to other surgical indications, provided that the appropriate nail length and blocking system are selected according to fracture type. Regardless the above considerations, distal blocking screws are always necessary. Finding the optimal solution, focused on the nail length and appropriate blocking system, for every type of fracture would be of great help to clinical practice.

List of abbreviations

IM: Intramedullary nailing

FE: Finite Elements

3D: Three-Dimensional

CT: Computed Tomography

CAD: Computer Aided Design

PO: Post-operative

M/L: Medial/Lateral

A/P: Anterior/Posterior

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Authors' contributions

AH, JA and LG conceived the design of study. LG, SG, EI and SP conceived and developed the finite element models and carried out all the simulations. AH, JA, JM and JG realized the medical supervision of models. All authors participated in the drawing up of the manuscript, and read and approved the final manuscript.

Conflict of interest statement

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

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Tables

Table 1. Different configurations considered in the FE simulation.

Blocking system	Proximal screw (4)	Above fracture site (3)	Distal screws (1, 2)	Fracture type	Gap size	Nail lengths (mm)	Screw configuration
#1	1 A/P	None	2 M/L	Distal	0.5 mm	180, 200, 240, 280, 320	
					3 mm	180, 200, 240, 280, 320	
					20 mm	180, 200, 240, 280, 320	
#2	1 A/P	1 A/P	2 M/L	Distal	0.5 mm	240, 280, 320	
					3 mm	240, 280, 320	
					20 mm	240, 280, 320	
#3	1 A/P	1 M/L	2 M/L	Distal	0.5 mm	240, 280, 320	
					3 mm	240, 280, 320	
					20 mm	240, 280, 320	
#4	None	1 A/P	2 M/L	Distal	0.5 mm	240, 280, 320	
					3 mm	240, 280, 320	
					20 mm	240, 280, 320	
#5	None	1 M/L	2 M/L	Distal	0.5 mm	240, 280, 320	
					3 mm	240, 280, 320	
					20 mm	240, 280, 320	

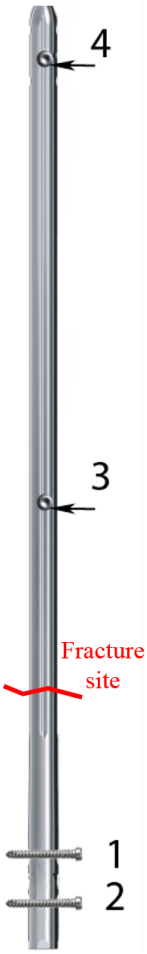


Table 2. Variations in the range of micromovements [%] of the shorter nails compared to the 240 mm nail.

Fracture gap	Variation 200 mm vs 240 mm [%]	Variation 180 mm vs 240 mm [%]
0.5 mm	-2.00	-2.41
3 mm	-1.40	-0.58
20 mm	-1.24	-5.03

Table 3. Variations [%] of micromovement range with respect to the longest nail (320 mm)

Fracture gap	Nail length			
	280 mm [%]	240 mm [%]	200 mm [%]	180 mm [%]
0.5 mm	-1.94	-10.41	-12.20	-12.58
3 mm	-0.99	-10.65	-11.90	-11.16
20 mm	-0.05	-12.47	-13.55	-16.88

Table 4. Global displacement at the femoral head

Fracture gap	Nail length				
	320 mm	280 mm	240 mm	200 mm	180 mm
0.5 mm	2.58	2.62	2.62	2.72	2.79
3 mm	2.62	2.67	2.64	2.76	2.80
20 mm	2.93	2.98	2.88	2.99	3.02

Table 5. Von Mises stress of the cortical bone at the top part of the nail

Fracture gap	Nail length				
	320 mm	280 mm	240 mm	200 mm	180 mm
0.5 mm	10.03	11.87	13.38	13.06	13.28
3 mm	10.09	12.62	12.64	12.81	12.57
20 mm	10.42	11.67	12.85	13.10	13.08

Table 6. Von Mises stress of the nail at the fracture gap (MPa)

Fracture gap	Nail length				
	320 mm	280 mm	240 mm	200 mm	180 mm
0.5 mm	80.45	78.08	77.60	77.85	76.54
3 mm	81.84	79.34	78.04	79.70	78.26
20 mm	84.80	83.07	83.41	82.74	81.27

Table 7. Von Mises stress at screws for the system #1 (MPa)

320 mm	0.5 mm	3 mm	20 mm
A/P Proximal	28.44	28.27	29.02
M/L distal superior	57.46	54.2	57.9
M/L distal inferior	80.69	84.58	85.4
280 mm	0.5 mm	3 mm	20 mm
A/P Proximal	30.79	31.56	31.05
M/L distal superior	57.88	54.88	57.59
M/L distal inferior	89.99	84.19	85.49
240 mm	0.5 mm	3 mm	20 mm
A/P Proximal	32.95	32.2	32.75
M/L distal superior	61.93	62.09	67.7
M/L distal inferior	63.04	64.17	61.81
200 mm	0.5 mm	3 mm	20 mm
A/P Proximal	32.81	33.36	34.08
M/L distal superior	63.23	64.07	66.02
M/L distal inferior	57.75	58.83	60.47
180 mm	0.5 mm	3 mm	20 mm
A/P Proximal	40.23	40.25	39.44
M/L distal superior	66.41	67.55	68.67
M/L distal inferior	57.29	58.16	60.12

Figure legends

Figure 1. Geometrical and FE model of the osteosynthesis: a) Contact interaction between the outer surface of the nail and the inner cortex of the intramedullary channel; b) Loads and boundary conditions

Figure 2. Range of micromovements for the 5 screw combinations for different nail lengths and fracture gap of 0.5 mm

Figure 3. Range of micromovements for the 5 screw combinations for different nail lengths and fracture gap of 3.0 mm

Figure 4. Range of micromovements for the 5 screw combinations for different nail lengths and fracture gap of 20.0 mm

Figure 5. Global displacement at the femoral head depending on nail lengths and fracture gaps

Figure 6. Schematic figure concerning mechanical blocking of the nail at the top part of the fracture

Figure 7. Schematic figure of the nail working as a cantilever beam with different fracture gaps.

Figure 8. Von Mises stress in the cortical bone at the top part of the nail for the simulated nail lengths and fracture gaps

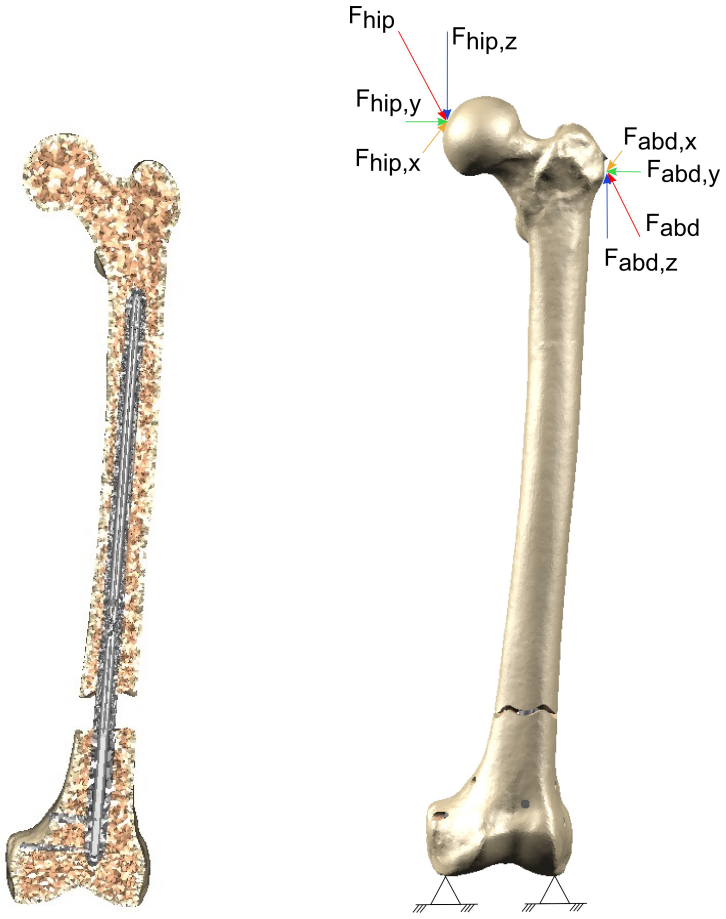
Figure 9. Stress in the nail at the fracture gap exempt zone for the simulated nail lengths and fracture gaps

Figure 10. Stress in the A/P proximal screw (fixation system #1) for the simulated nail lengths and fracture gaps

Figure 11. Stress in the M/L superior distal screw (fixation system #1) for the simulated nail lengths and fracture gaps

Figure 12. Stress in the M/L inferior distal screw (fixation system #1) for the simulated nail lengths and fracture gaps

Figures



(a) (b)

Figure 1. Geometrical and FE model of the osteosynthesis: a) Contact interaction between the outer surface of the nail and the inner cortex of the intramedullary channel; b) Loads and boundary conditions

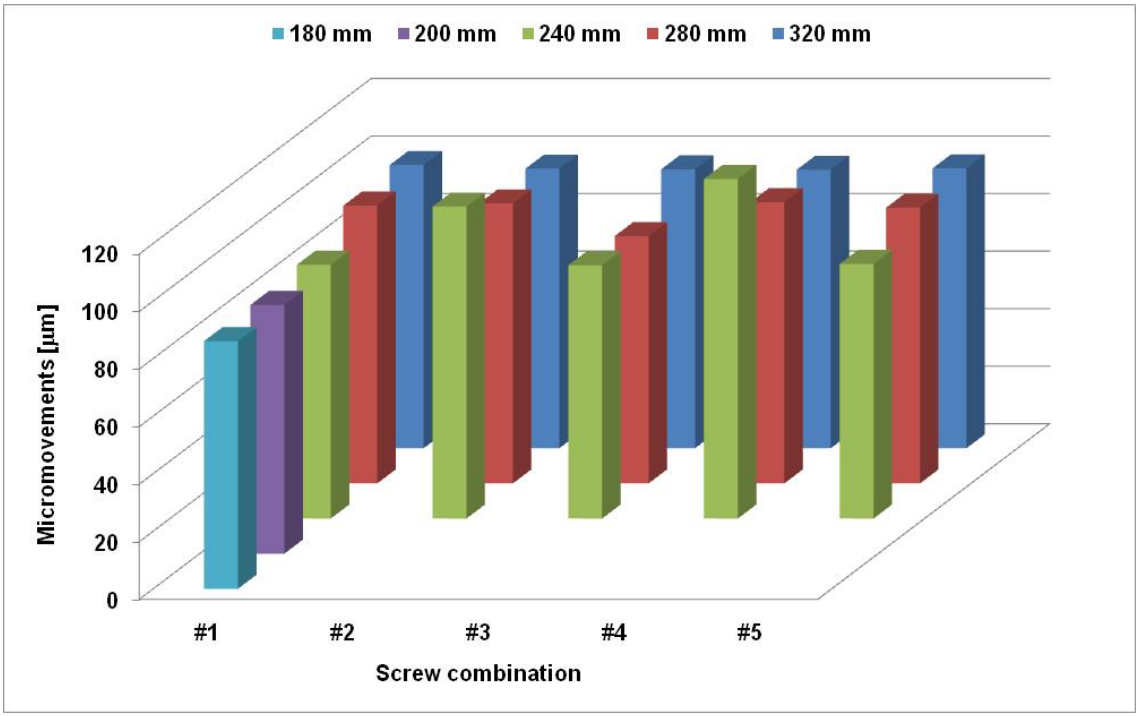


Figure 2. Range of micromovements for the 5 screw combinations for different nail lengths and fracture gap of 0.5 mm

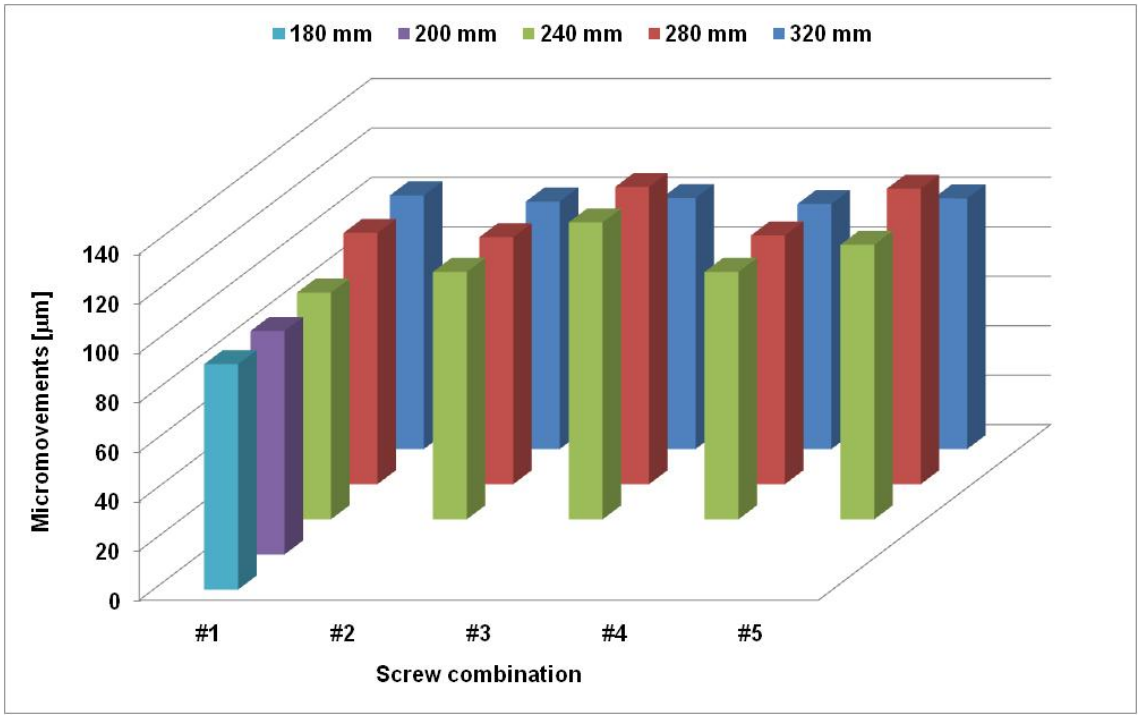


Figure 3. Range of micromovements for the 5 screw combinations for different nail lengths and fracture gap of 3.0 mm

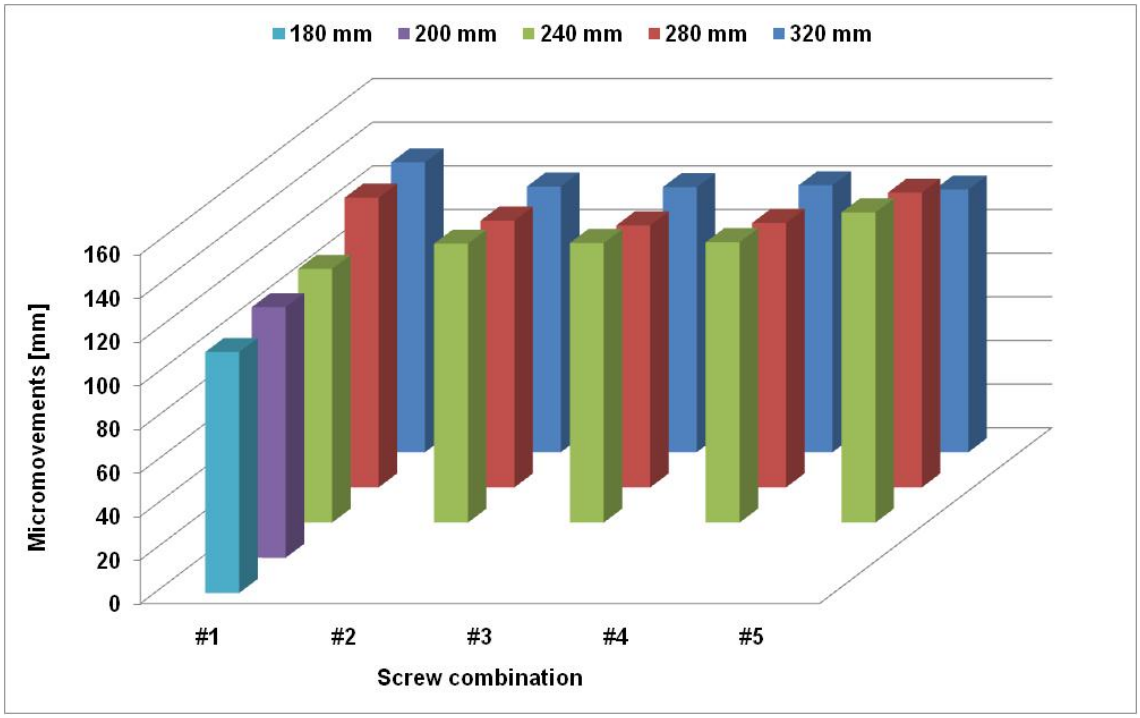


Figure 4. Range of micromovements for the 5 screw combinations for different nail lengths and fracture gap of 20.0 mm

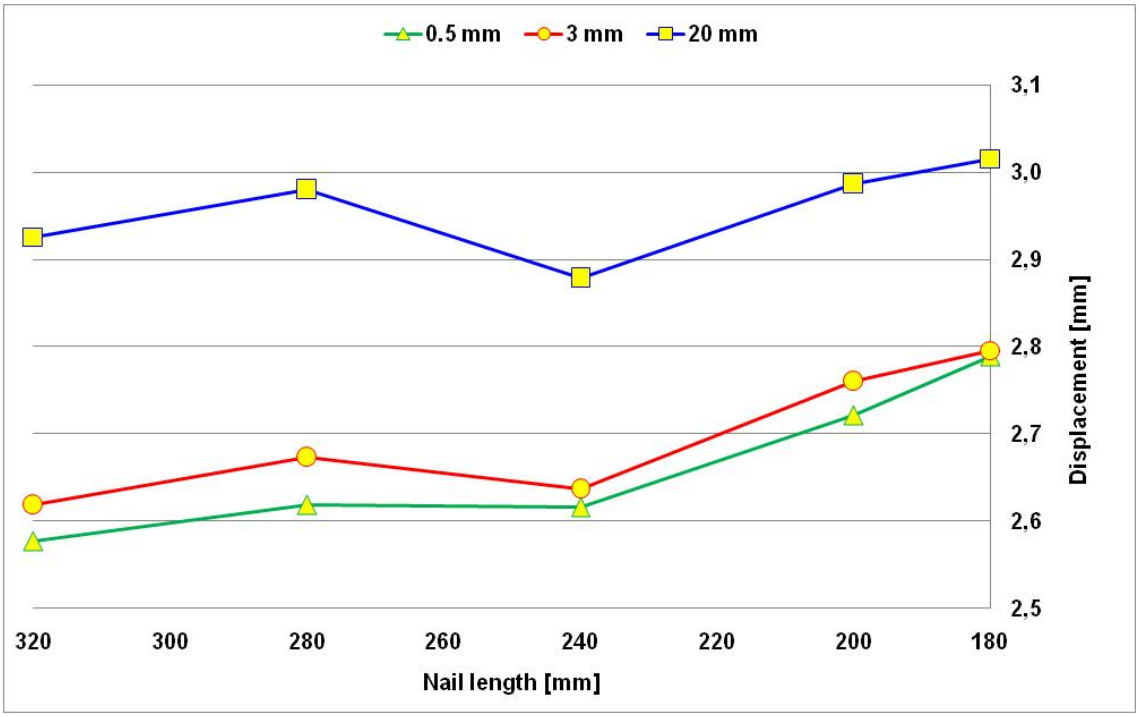


Figure 5. Global displacement at the femoral head depending on nail lengths and fracture gaps

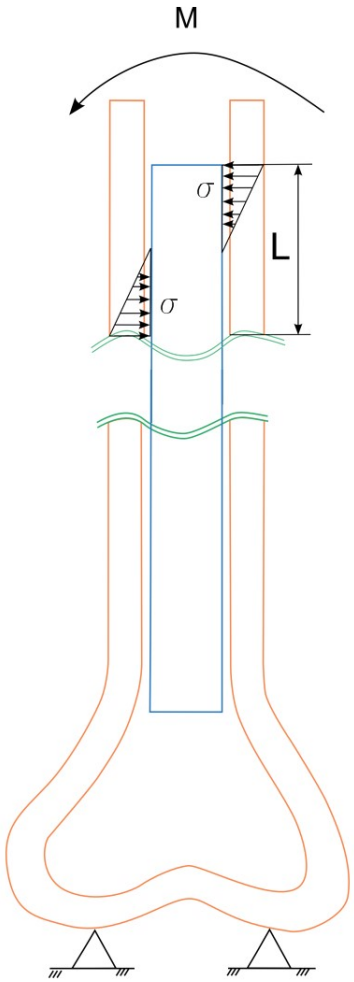


Figure 6. Schematic figure concerning mechanical blocking of the nail at the top part of the fracture

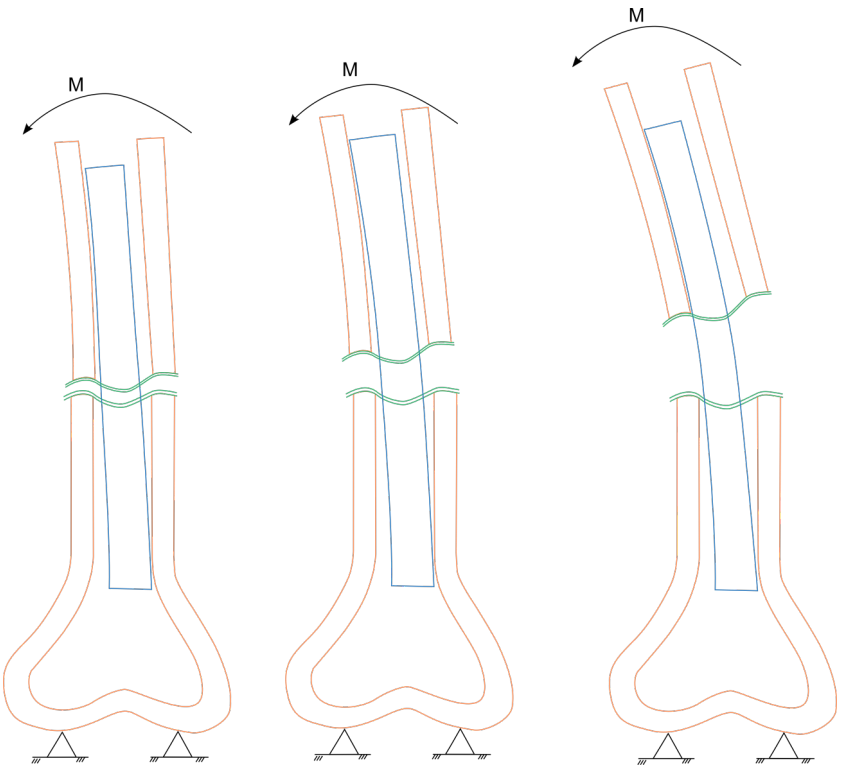


Figure 7. Schematic figure of the nail working as a cantilever beam with different fracture gaps.

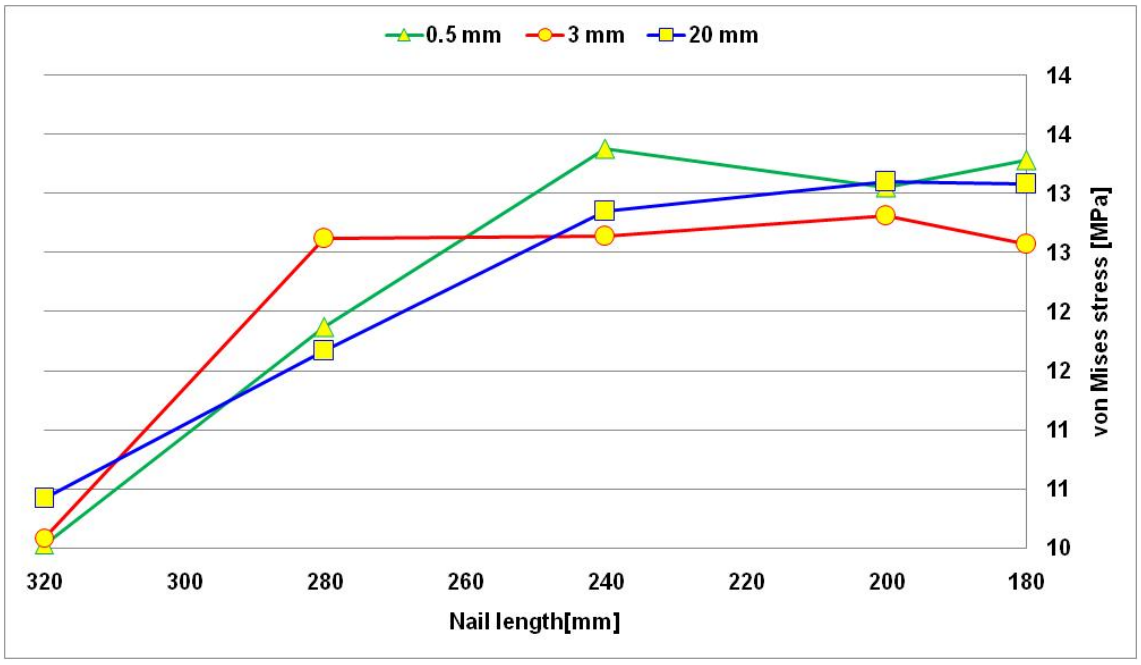


Figure 8. Von Mises stress in the cortical bone at the top part of the nail for the simulated nail lengths and fracture gaps

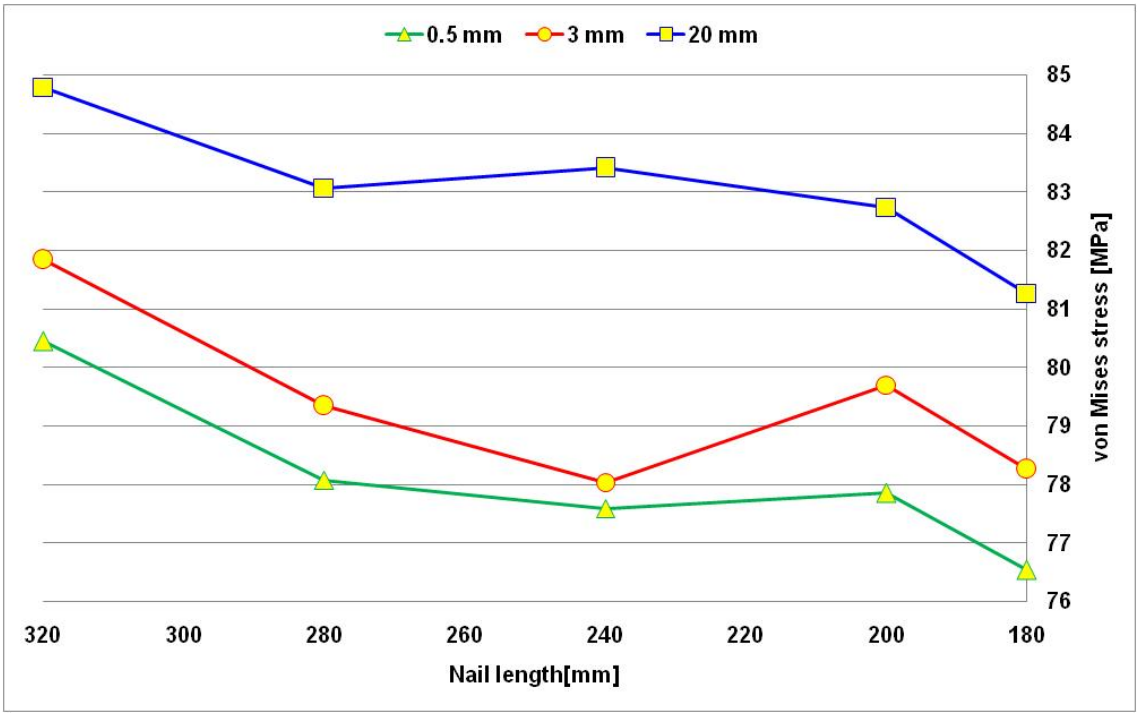


Figure 9. Stress in the nail at the fracture gap exempt zone for the simulated nail lengths and fracture gaps

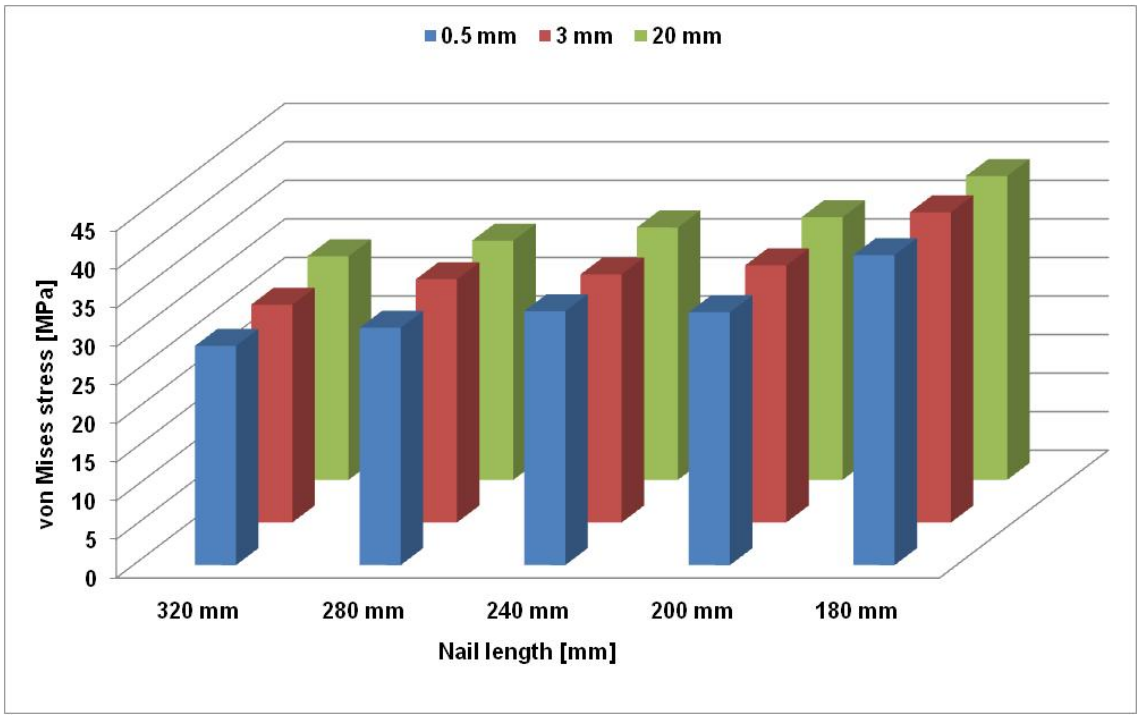


Figure 10. Stress in the A/P proximal screw (fixation system #1) for the simulated nail lengths and fracture gaps

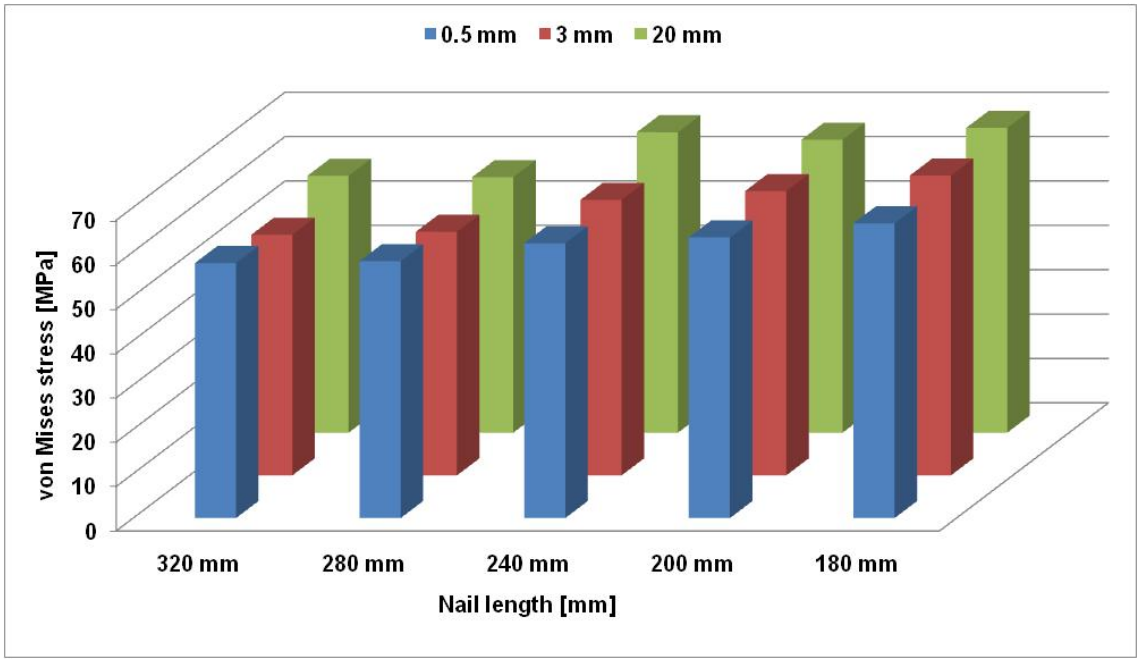


Figure 11. Stress in the M/L superior distal screw (fixation system #1) for the simulated nail lengths and fracture gaps

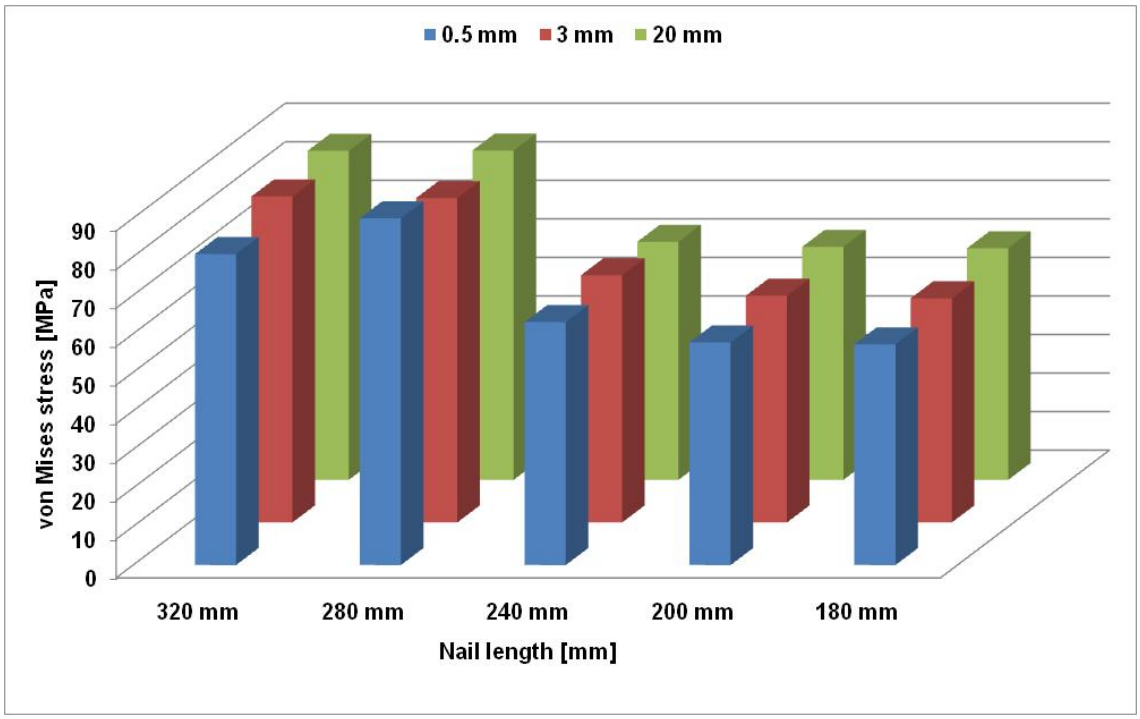


Figure 12. Stress in the M/L inferior distal screw (fixation system #1) for the simulated nail lengths and fracture gaps