INFLUENCE OF PLATE SIZE AND SCREW DISTRIBUTION ON THE BIOMECHANICAL BEHAVIOUR OF OSTEOSYNTHESES BY MEANS OF LATERAL PLATES IN FEMORAL FRACTURES

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ABSTRACT

Distal femoral fractures are fractures associated with high rates of morbidity and mortality, affecting 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. They have been classically treated with conventional plates and intramedullary nails and more recently with locked plates that have increased their indications to more types of fractures.

The main objective of the present work is the biomechanical study, by means of finite element simulation, of the stability achieved in the osteosynthesis of femoral fractures in zones 4 and 5 of Wiss, by using locked plates with different plate lengths and different screw configurations, and analysing the effect of screw proximity to the fracture site.
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 Osteosynthesis System LOQTEC® Lateral Distal Femur Plate in two different fracture zones corresponding to the zones 4 and 5 according to the Wiss fracture classification. The study was focused on the immediately post-operative stage, without any biological healing process.
The obtained results show that more stable osteosyntheses were obtained by using shorter plates. In the cases of longer plates, it results more convenient disposing screws in a way that the upper ones are closer to fracture site. The obtained results can support surgeons to understand the biomechanics of fracture stability, and then to guide them towards the more appropriate osteosynthesis depending on the fracture type and location.

KEY WORDS

Lateral plates, Femoral fractures, Osteosynthesis, Biomechanical behavior, Finite element analysis.

HIGHLIGHTS

Biomechanical behavior of supracondylar fractures depends on plate length and screw configuration.

Shorter plates provide more stable osteosyntheses than longer plates.

For longer plates, it is more convenient disposing screws in a way that the upper ones are closer to fracture site.

Stability in the immediately post-operative is essential for fracture consolidation.

The study can help surgeons to find the most appropriate osteosynthesis depending on the fracture type.

INTRODUCTION

Distal femoral fractures are fractures associated with high rates of morbidity and mortality. Although they can occur in young patients due to a high-energy trauma, currently 85% of patients are elderly, mainly women with osteoporotic bone [1], which entails an increase in the therapeutic complexity that these fractures always present. They have been classically treated with conventional plates and intramedullary nails and more recently with locked plates that increase their indications to more types of fractures [2, 3], and present biomechanical advantages in the osteosynthesis of osteoporotic bone [4] reducing the number of failures in varus, so common in conventional plates [5]. They can be implanted percutaneously, indirectly reducing the fracture, thus reducing soft tissue disruption and devascularisation of the fracture focus [1]. However, these plates are not exempt from complications, presenting consolidation problems in up to 34% of cases [2, 6, 7], material breakage and osteosynthesis failure may also occur, related to fracture comminution and early weight bearing [8, 9]. There is no clear scientific evidence on the results obtained, most of the different results published depend on the plate length and the number of screws and their location, since all these variables produce a different stabilization of the fracture by varying the stiffness and elasticity achieved in the fracture focus [10, 11]. The excess of both rigidity and elasticity in the focus impair the fracture consolidation, not knowing what the ideal plate length for the osteosynthesis is and what is the adequate distance of the screws to the fracture focus, as well as their number, especially in comminute fractures in which osteosynthesis is performed by bridging the fracture site with the plate

[2, 12]. Recent studies indicate that increasing the length of the plate and increasing the distance of the screws to the fracture focus decrease the stiffness at the focus and produce better fracture consolidation [13, 14]. Harvin et al., in a clinical study of 96 patients with distal femoral fracture in advanced ages, in which they studied the length of the plate and the number of screws in relation to the consolidation of the fracture, they found that the placement of all the proximal screws in the plate used as a bridge, hinder the consolidation, but the results are not conclusive since the placement of a more flexible osteosynthesis, reducing the number of proximal screws and moving them away from the fracture focus, does not necessarily imply better consolidation [7]. Kiyono et al. [2], in a clinical study on the consolidation of distal femoral fractures, found that the characteristics of the fracture are more important than the length of the plate, the number of implanted screws and their distance from the fracture focus. The clinical studies obtained mixed and inconclusive results, possibly due to the high number of variables in the fracture types and types of osteosynthesis, for which biomechanical studies are necessary to simulate all the possible options and allow obtaining the necessary information applicable to clinical practice.

The aim of this work is the biomechanical study, by means of finite element simulation, of the stability achieved in the osteosynthesis of femoral fractures in zones 4 and 5 of Wiss, by using locked plates with different plate lengths and different screw configurations, and analysing the effect of screw proximity to the fracture site.

MATERIAL AND METHODS

Modeling of the femur and plates

The 3D geometrical model of the femur was developed using a replica of a healthy femur from 55-years-old male a donor. The geometry was obtained by means of 3D Laser Scanner Roland® PICZA (Irvine, California), using the same methodology of previous studies [15, 16]. The geometrical model of the plate was created in NX I-Deas software [17] using the real implant (Osteosynthesis System LOQTEC® Lateral Distal Femur Plate [18]) as reference. The plate thickness is 6 mm, and its length has been varied from the shortest 5 holes (171 mm) to the longest 11 holes (279 mm), depending on the fracture location and the parameters analyzed. The plate uses locking screws of 5 mm of outer diameter, geometrically modelled as cylinders. The fracture was performed in the geometrical model of the femur with three different gap sizes, 0.5, 3.0 and 20.0 mm.

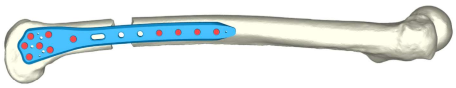
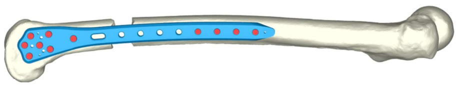
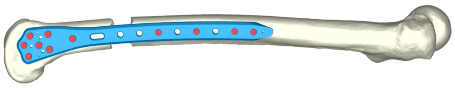
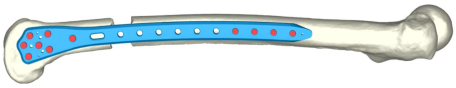
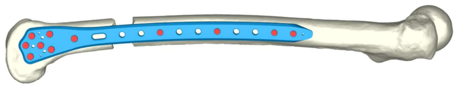
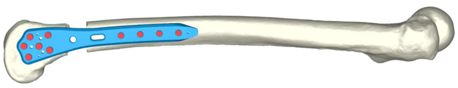
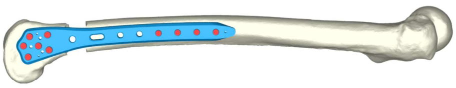
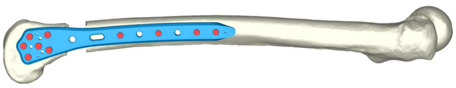
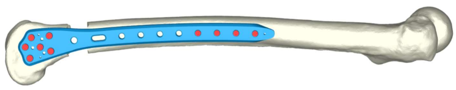
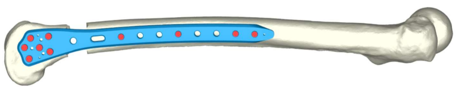
Once the geometrical models were created, the surgery was reproduced virtually with the NX I-Deas software, aligning the lateral plate with femur, and inserting the screws in the desired positions locking the osteosynthesis, under the supervision of orthopedic surgeons.

Configurations simulated

The principal parameters analyzed are the zone of fracture, the plate length, the screws distribution, and the fracture gap. There are 2 different fracture zones analyzed that correspond to the zones 4 and 5 according to the Wiss fracture classification [19]. Wiss zone 4 corresponds to a fracture located in the distal part of the femur diaphysis, while zone 5 of Wiss corresponds to a distal extraarticular femoral fracture. It has been taken into account 3 different plate lengths for each fracture zone. For the Wiss zone 4 fracture, the selected plates were a 7 holes-207 mm long plate, a 9 holes-243 mm long plate, and a 11 holes-279 mm long plate; the plates selected for the fracture in zone 5 were a 5 holes-171 mm long plate, a 7 holes-207 mm long plate, a 9 holes-243 mm long plate. Therefore, for the medium and the longest plates size in each fracture zone two types of screws distribution were analyzed (the 9 holes-243 mm and 11 holes-279 mm plates for zone 4; and the 9 holes-243 mm and 11 holes-279 mm plates for zone 5). Distribution 1 concentrates the 4 proximal screws in the farthest possible part of the plate with respect to the fracture focus; in the distribution 2, the 4 proximal screws are distributed along the proximal part of the plate, placing one in the closest possible position to the fracture focus, two in the final part of the plate and the fourth screw between. The shortest plate for each fracture zone only has one distribution possible since it only has 4 holes available in the proximal part of the plate above the fracture focus.

There are 3 different gaps of fracture and all of them correspond to a transverse fracture with an irregular fracture surface pattern. The 0.5 mm gap is considered as a non-comminuted fracture, the 3 mm gap represents a mid-value between non-comminuted and comminuted fractures, being this gap the most referenced in the literature, and the 20 mm gap that represents a fracture with a high degree of comminution. The 2 different zones of fracture, the 5 different combinations of plate length and screw distribution, and the 3 gap fractures result in 30 different FE models (Table 1).

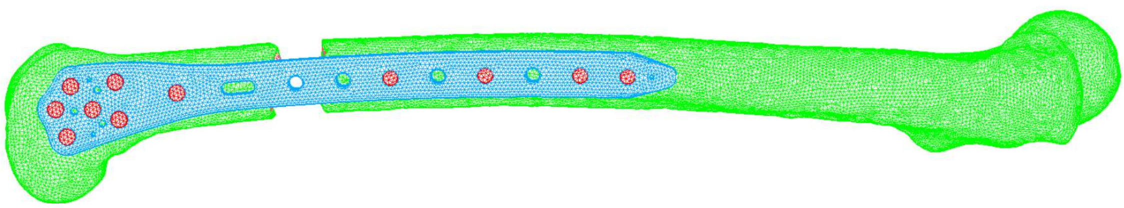
Table 1. Description of the different models

Zone	Figures (20 mm gap)	Number of holes	Upper screws	Gap (mm)
4		7	4-7	0.5
				3.0
				20.0
		9	6-9	0.5
				3.0
				20.0
		9	4, 6, 8, 9	0.5
				3.0
				20.0
		11	8-11	0.5
				3.0
				20.0
		11	4, 7, 10, 11	0.5
				3.0
				20.0
5		5	2-5	0.5
				3.0
				20.0
		7	4-7	0.5
				3.0
				20.0
		7	2, 4, 6, 7	0.5
				3.0
				20.0
		9	6-9	0.5
				3.0
				20.0
		9	2, 5, 8, 9	0.5
				3.0
				20.0

Meshing and material properties

The final osteosynthesis model was meshed, part by part, creating independent meshes for the two geometrical parts of the femur, the lateral plate, and each screw individually, using linear tetrahedral elements. A sensitivity analysis was previously performed to determine the minimal mesh size required for an accurate and precise 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 osteosynthesis models had an average mesh size about 1.5 mm, with about 350.000 nodes and 1.100.000 elements. Figure 1 shows different details of the mesh for one of the implemented models.

The differentiation between the cortical and trabecular bone was done after the meshing process. This differentiation was done by providing different mechanical properties to each bone layer, respecting the anatomical distribution of the cortical and trabecular bone along the length of the femur. The mechanical behavior (linear elastic) for the different components was defined by the Young's modulus and the Poisson's ratio. The mechanical properties for the cortical and trabecular bone, respectively, were: $E_{Cortical}$=20000 MPa and $v_{Cortical}$=0.3; $E_{Trabecular}$=959 MPa and $v_{Trabecular}$=0.3. The plate and screws were made of 316LVM steel alloy, and the mechanical properties were E_{316LVM}=192.36 GPa and v_{316LVM}=0.3.



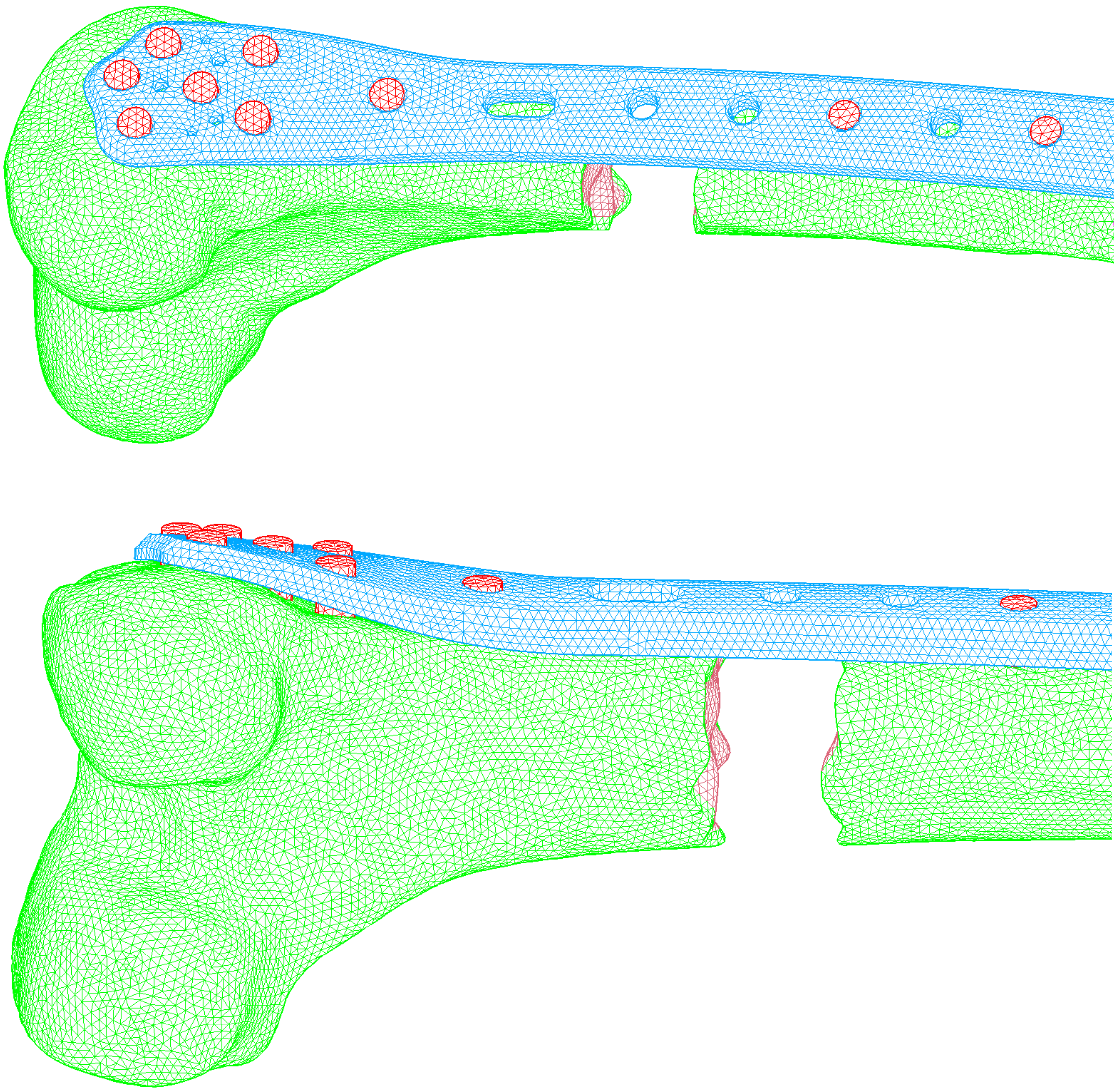


Fig. 1. Details of the mesh for one of the implemented models

Contact modeling

As the meshes created are independent from each part, the contact interactions and its properties must be defined. So, “Tie” interaction was selected for the cortical bone and locking screw contact zones, simulating the rigid union the screw thread provides. “Surface-to-Surface” interaction was defined for the zones were two or more meshes had the possibility to contact during the load application. A 0.15 friction coefficient was used to define contact interaction according to the literature [15, 16] in the contact zones of the screws and trabecular bone, the lateral plate and the cortical bone, and the upper and lower fracture surfaces.

Loads and boundary conditions

The simulations are focused on the immediately post-operative stage. Thus, no type of bone biological healing process had been taken into account. The loads and boundary conditions applied to the osteosynthesis simulate an accidental foot support in the ground, considering 25% of the maximum anatomical load. The condylar zone was fully constrained, preventing it for any type of movement. The loads were extracted from the Orthoload´s database [20]. According to the measurement during the gait cycle, the principal forces acting into the femur are the hip reaction force and the abductor muscles group, referred to the 45% of gait, corresponding to the maximum and most representative load. The hip reaction force was applied on the tip of the femoral head, and the abductor muscles forces group were applied on the muscle attachment areas in the grater trochanter (Fig. 2). The area of application of the forces is carefully created mimicking anatomy atlas, in the same way that in previous works [15, 16].

The different simulations were performed by means of Abaqus software [21].

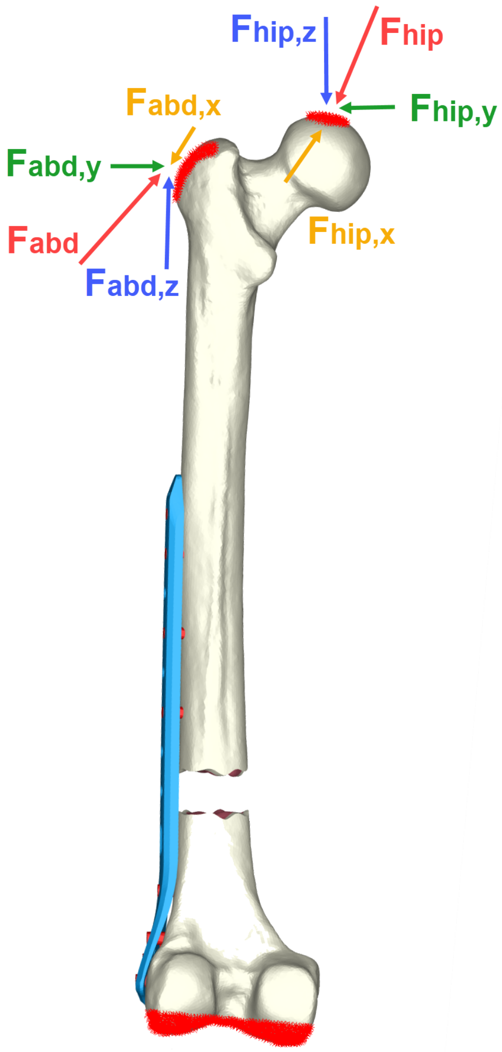


Fig. 2. Details of the mesh for one of the implemented models

RESULTS

The FE simulations allowed obtaining the biomechanical behavior of the different osteosyntheses, and then mobility and stress results for the different cases could be analyzed. The results that characterize the biomechanical behavior of the osteosyntheses are the maximum global displacement at the femoral head, the relative displacement between upper and lower fragments, decomposed into the axial displacement, following the anatomical axis of the femur, and the rotational angle, the maximum von Mises stress in the plate and the maximum von Mises stress in the cortical bone.

The different resulting trends are detailed hereafter. So, in Table 2 are included the complete results obtained for Zone 4 fractures. The same results are depicted in Figs. 3 to 7.

Table 2. Results obtained for Zone 4 fractures

Fracture gap (mm)	Screw distribution	Global disp. at femoral head (mm)	Relative disp. Between fragments (μm)	Rotation between fragments (º)	Maximum stress in plate (MPa)	Maximum stress in cortical bone (MPa)	Contact between fragments
0.5	7 (4-7)	5.13	258	0.139	186.00	21.15	YES
	9 (6-9)	4.96	312	0.210	126.67	29.31	YES
	9 (4,6,8,9)	4.98	265	0.143	185.88	19.33	YES
	11 (8-11)	4.67	312	0.230	112.95	28.13	YES
	11 (4,7,10,11)	4.88	265	0.145	186.51	18.97	YES
3.0	7 (4-7)	5.99	315	0.192	211.18	22.74	NO
	9 (6-9)	8.59	748	0.283	268.17	22.58	NO
	9 (4,6,8,9)	5.89	330	0.201	212.97	18.78	NO
	11 (8-11)	11.51	1800	0.370	310.40	23.10	NO

	11 (4,7,10,11)	5.74	326	0.210	212.77	19.51	NO
20.0	7 (4-7)	5.94	369	0.198	210.03	20.22	NO
	9 (6-9)	8.53	602	0.284	267.15	21.44	NO
	9 (4,6,8,9)	5.85	369	0.205	212.27	19.15	NO
	11 (8-11)	11.50	1497	0.373	310.27	23.36	NO
	11 (4,7,10,11)	5.78	370	0.207	213.97	19.08	NO

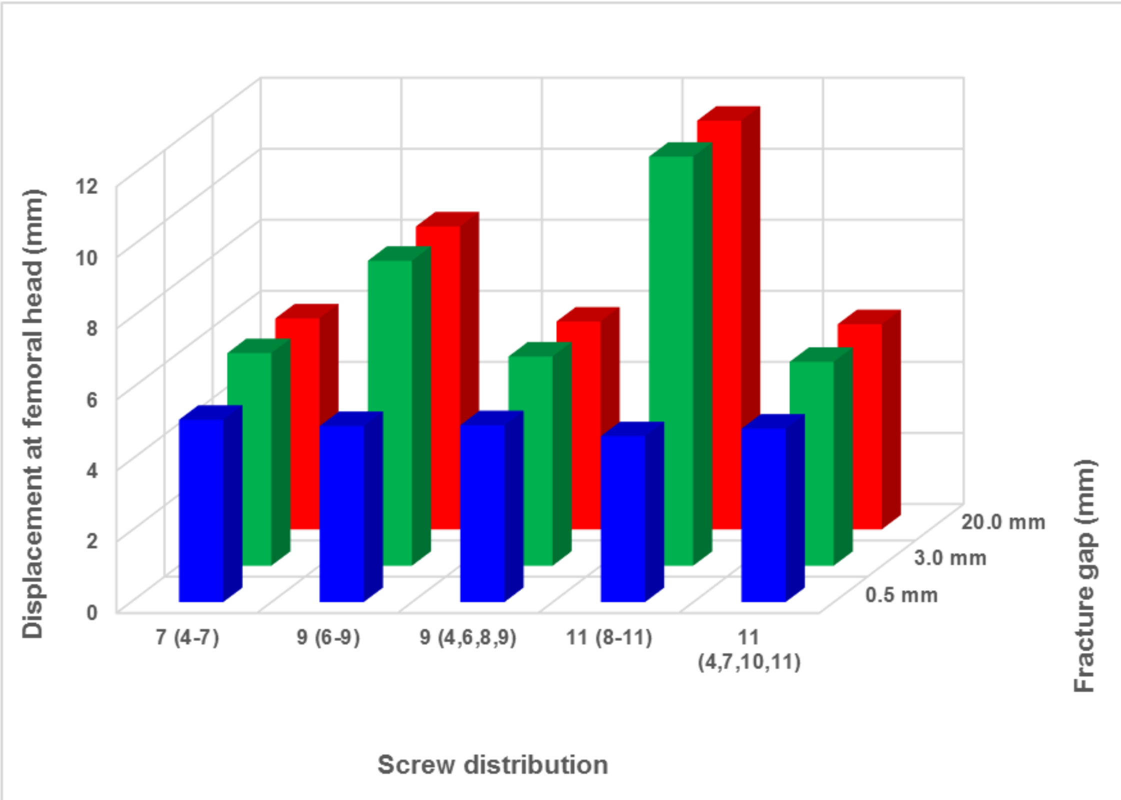


Fig. 3. Displacement at femoral head for Zone 4 fractures

As it can be seen in Fig. 3, the same order of magnitude of displacement at femoral head was obtained for every osteosynthesis for a fracture gap of 0.5 mm. However, for gaps of 3.0 and 20.0 mm the global movement of the femoral head results clearly higher for 9 (6-9) and 11 (8-11) configurations. So, increases of 43.42% and 92.36%, respectively, with respect to 7 (4-7) configuration, were obtained for 3.0 mm gap and 43.59% and 93.67%, respectively, for 20.0 mmm gap. For 9 (4,6,8,9) and 11 (4,7,10,11) configurations the results were similar to 7 (4-7) configuration in all cases, being slightly higher for gaps of 3.0 and 20.0 mm.

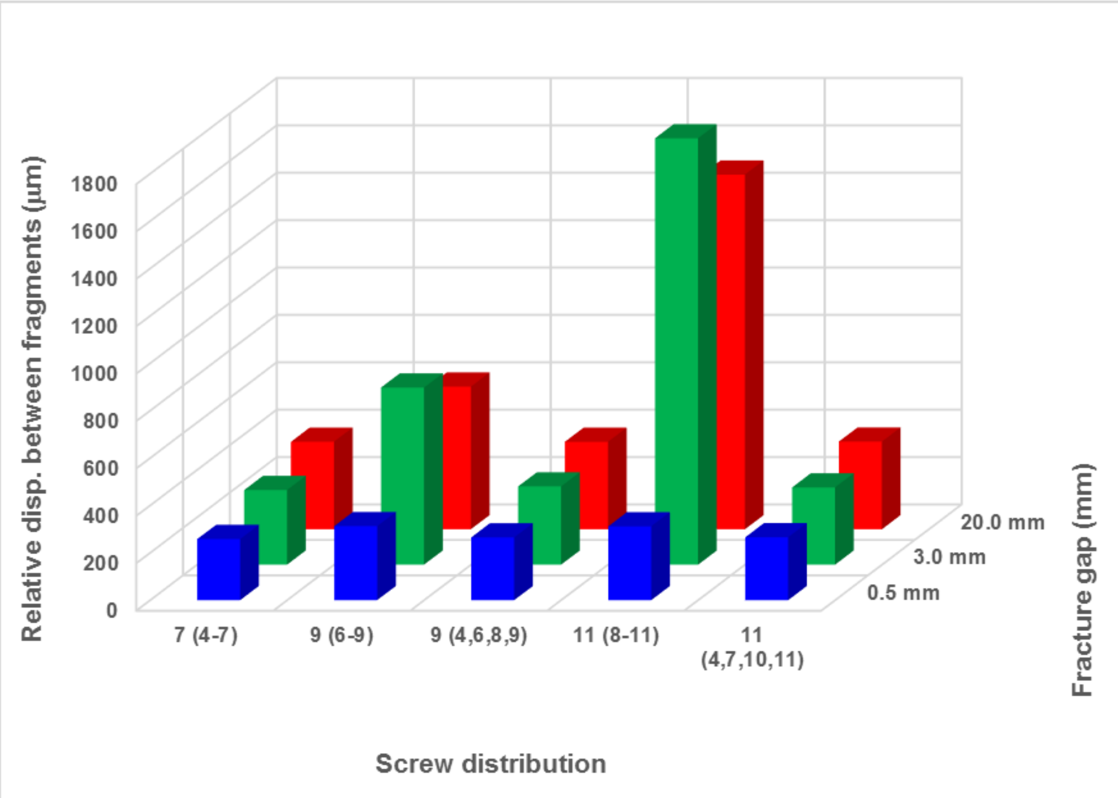


Fig. 4. Relative displacement between fragments for Zone 4 fractures

According Fig. 4, a moderate increase of relative displacement was observed for 9 (6-9) and 11 (8-11) configurations for a fracture gap of 0.5 mm (21.12% and 20.82%, respectively). However, for gaps of 3.0 and 20.0 mm the increase was noticeably higher for 9 (6-9) and 11 (8-11) configurations. Increases of 137.35% and 471.27%, respectively, with respect to 7 (4-7) configuration, were obtained for 3.0 mm gap and 63.05% and 305.39%, respectively, for 20.0 mmm gap. For 9 (4,6,8,9) and 11 (4,7,10,11) configurations the results were similar to 7 (4-7) configuration in all cases, being higher as the gap increases.

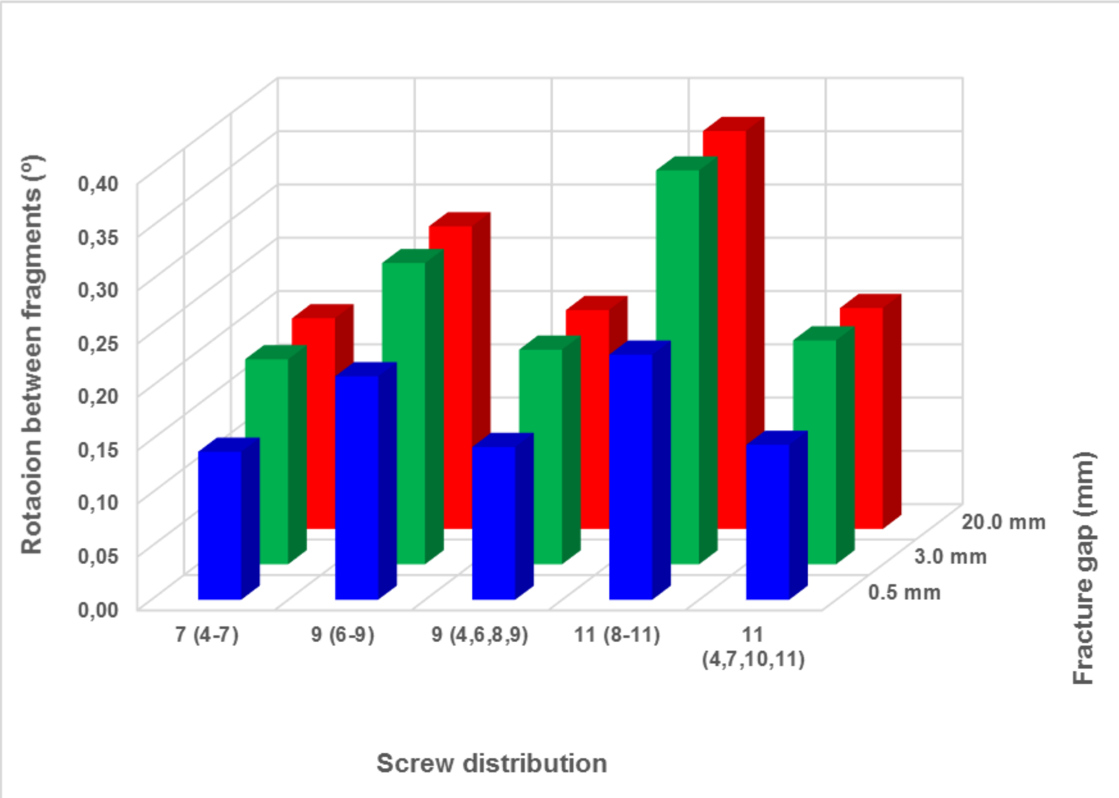


Fig. 5. Rotation between fragments for Zone 4 fractures

In the case of rotation between fragments (Fig. 5), an important increase of relative displacement was observed for 9 (6-9) and 11 (8-11) configurations for every fracture gap. For a gap of 0.5 mm, increases of 50.98% and 65.59%, respectively, with respect to 7 (4-7) configuration, were obtained; for a gap of 3.0 mm increases of 46.95% and 92.14%, respectively, were obtained; finally, for a gap of 20.0 mm increases of 43.66% and 88.90%, respectively, were obtained. For 9 (4,6,8,9) and 11 (4,7,10,11) configurations the results were similar to 7 (4-7) configuration in all cases, being higher for gaps of 3.0 and 20.0 mm.

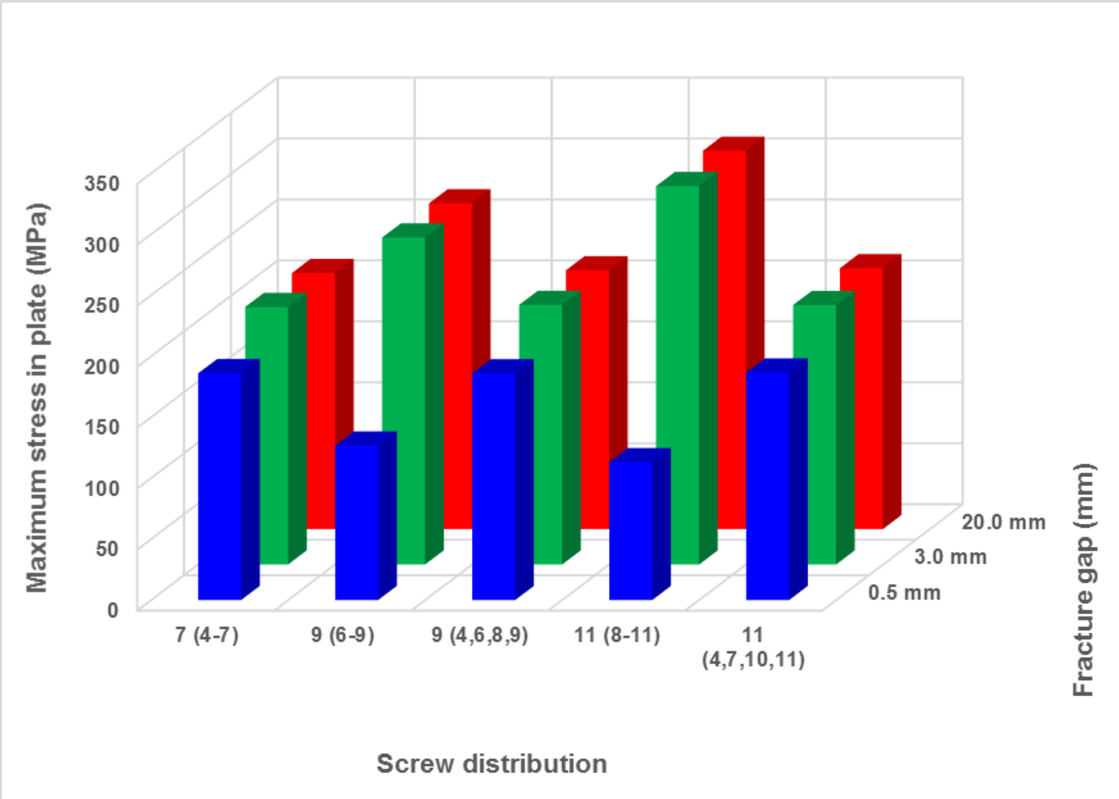


Fig. 6. Maximum stress in plate for Zone 4 fractures

Concerning maximum stress in the plate (Fig. 6), a decrease was observed for 9 (6-9) and 11 (8-11) configurations for 0.5 mm gap with respect to 7 (4-7) configuration (31.90% and 39.28%, respectively). On the contrary, increases of 26.99% and 46.98%, respectively, with respect to 7 (4-7) configuration, were obtained for a gap of 3.0 mm, whereas increases of 27.20% and 47.73%, respectively, were obtained for a gap of 20.0 mm. For 9 (4,6,8,9) and 11 (4,7,10,11) configurations the results were similar to 7 (4-7) configuration in all cases, being slightly higher for gaps of 3.0 and 20.0 mm.

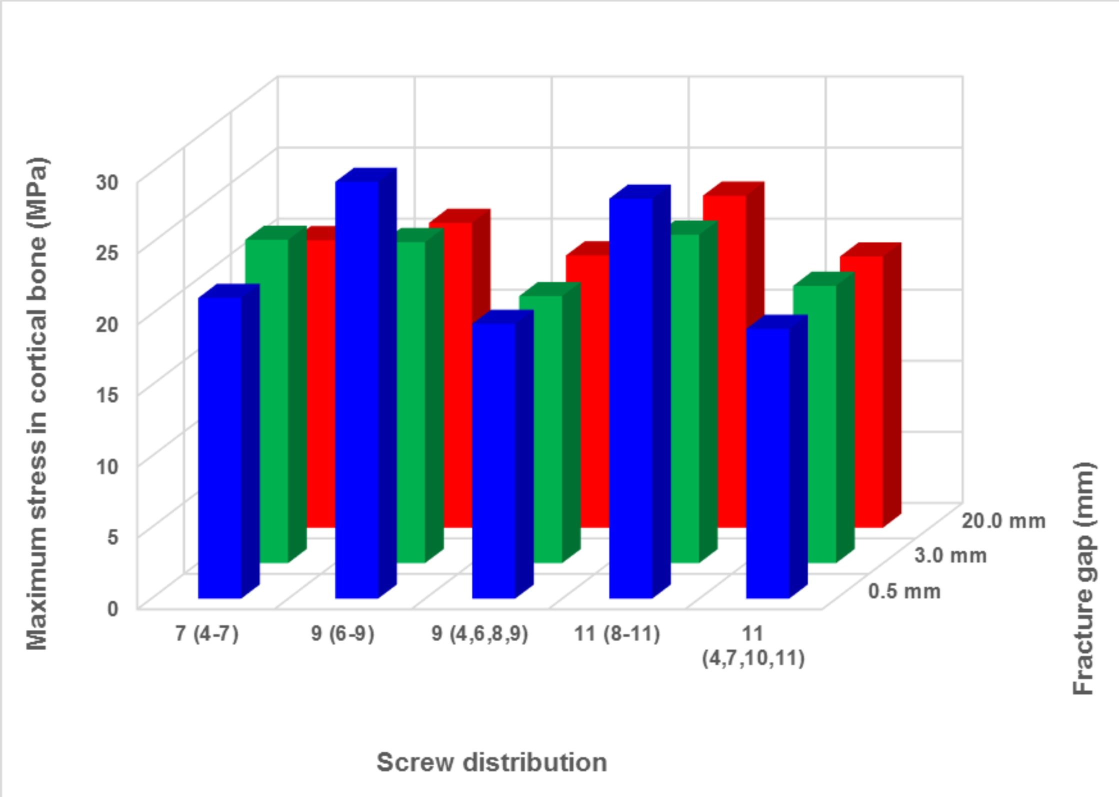


Fig. 7. Maximum stress in cortical bone for Zone 4 fractures

Finally, considering maximum stress in cortical bone (Fig. 7), a moderate increase was observed for 9 (6-9) and 11 (8-11) configurations for 0.5 mm gap with respect to 7 (4-7) configuration (38.59% and 32.97%, respectively), while a slight decrease was detected for 9 (4,6,8,9) and 11 (4,7,10,11) configurations (8.64% and 10.31%, respectively). Decreases of 17.43% and 14.21% for 9 (4,6,8,9) and 11 (4,7,10,11) configurations, respectively, with respect to 7 (4-7) configuration, were obtained for a gap of 3.0 mm; for a gap of 20.0 mm, increases of 6.04% and 15.50%, respectively, were obtained for 9 (6-9) and 11 (8-11) configurations, and decreases of 5.28% and 5.34%, respectively, for 9 (4,6,8,9) and 11 (4,7,10,11) configurations.

The complete results obtained for Zone 5 fractures are included in Table 3. The same results are depicted in Figs. 8 to 12.

Table 3. Results obtained for Zone 5 fractures

Fracture gap (mm)	Screw distribution	Global disp. at femoral head (mm)	Relative disp. Between fragments (μm)	Rotation between fragments (º)	Maximum stress in plate (MPa)	Maximum stress in cortical bone (MPa)	Contact between fragments
0.5	5 (2-5)	5,28	270	0,114	146,22	16,79	YES
	7 (4-7)	4,78	323	0,177	134,93	16,28	YES
	7 (2,4,6,7)	4,98	265	0,122	149,17	15,35	YES
	9 (6-9)	4,48	351	0,248	122,48	17,41	YES
	9 (2,5,8,9)	4,89	272	0,124	139,71	17,35	YES
3.0	5 (2-5)	5,48	280	0,119	155,66	16,93	NO
	7 (4-7)	6,58	518	0,145	163,54	18,19	NO
	7 (2,4,6,7)	5,36	285	0,124	156,97	16,77	NO
	9 (6-9)	5,92	546	0,159	136,38	17,69	NO
	9 (2,5,8,9)	5,21	296	0,130	150,61	17,44	NO
20.0	5 (2-5)	5,46	248	0,118	154,51	16,98	NO
	7 (4-7)	6,75	449	0,148	167,16	19,18	NO
	7 (2,4,6,7)	5,38	254	0,129	156,58	16,37	NO
	9 (6-9)	6,59	502	0,145	155,58	21,55	NO
	9 (2,5,8,9)	5,26	257	0,131	151,55	16,46	NO

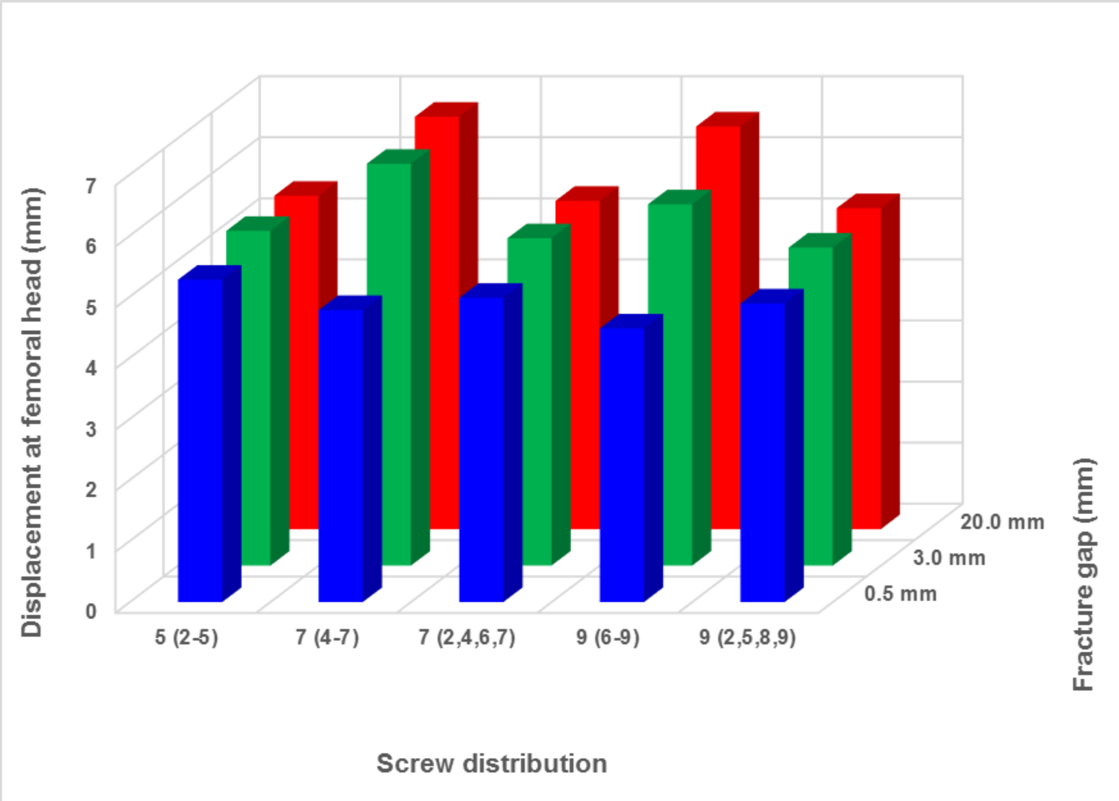


Fig. 8. Displacement at femoral head for Zone 5 fractures

As shown in Fig. 8, considering displacement at femoral head, the same order of magnitude was obtained for every osteosynthesis for a fracture gap of 0.5 mm, with a slight decrease for 7 (4-7) and 9 (6-9) configurations with respect to 5 (2-5) configuration (9.41% and 15.13%, respectively). However, for gaps of 3.0 and 20.0 mm the global movement of the femoral head was higher for 7 (4-7) and 9 (9-9) configurations. So, increases of 20.07% and 7.95%, respectively, with respect to 5 (2-5) configuration, were obtained for 3.0 mm gap and 23.71% and 20.79%, respectively, for 20.0 mmm gap. For 7 (2,4,6,7) and 9 (2,5,8,9) configurations the results were slightly less to 5 (2-5) configuration in all cases.

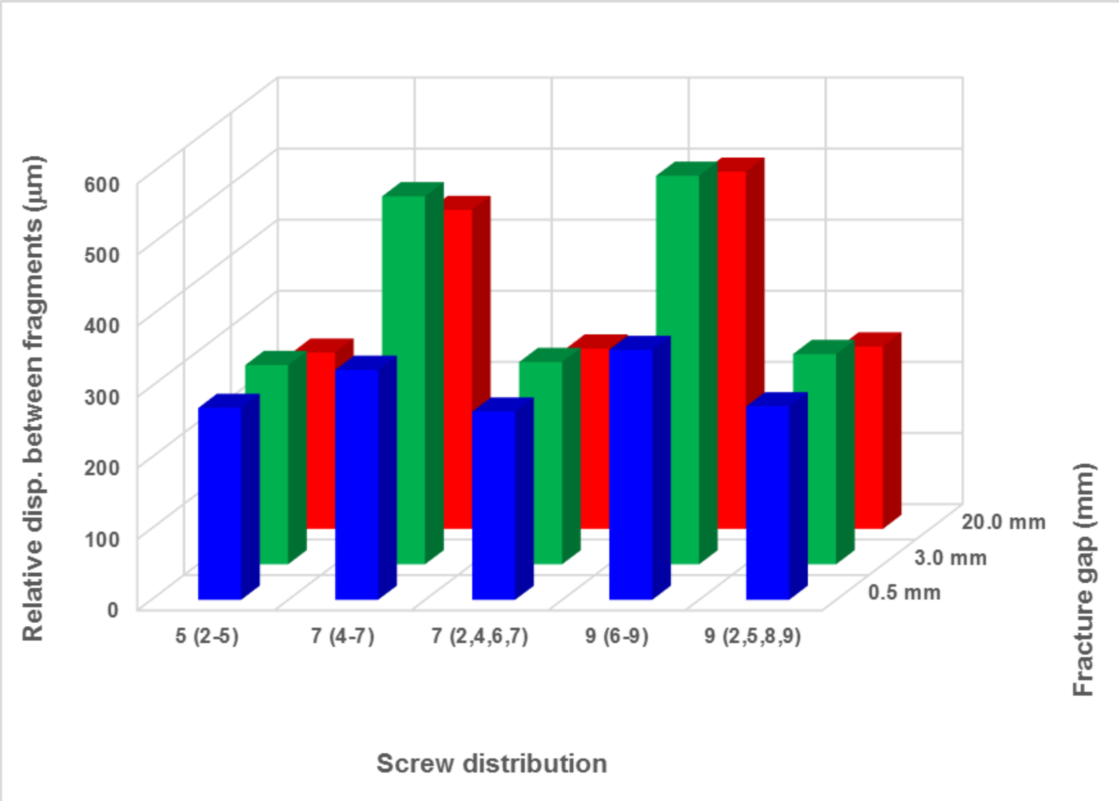


Fig. 9. Relative displacement between fragments for Zone 5 fractures

For relative displacement between fragments (Fig. 9), a moderate increase was observed for 7 (4-7) and 9 (6-9) configurations for a fracture gap of 0.5 mm (19.81% and 30.21%, respectively). However, for gaps of 3.0 and 20.0 mm the increase was noticeably higher for 7 (4-7) and 9 (6-9) configurations. Increases of 84.71% and 95.00%, respectively, with respect to 5 (2-5) configuration, were obtained for 3.0 mm gap and 80.90% and 102.62%, respectively, for 20.0 mmm gap. For 7 (2,4,6,7) and 9 (5,5,8,9) configurations the results were similar to 7 (4-7) configurations in all cases, being slightly higher as the gap increases.

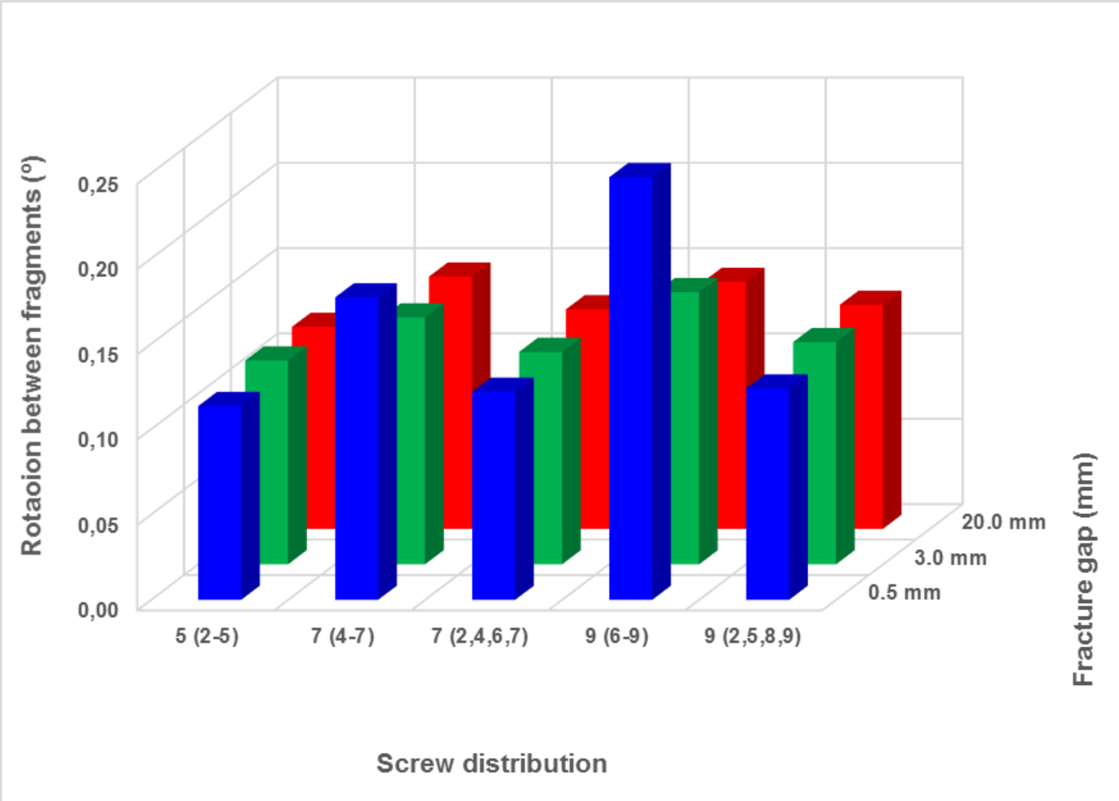


Fig. 10. Rotation between fragments for Zone 5 fractures

With respect to rotation between fragments (Fig. 10), an important increase of relative displacement was observed for 7 (4-7) and 9 (6-9) configurations for a gap of 0.5 mm with respect to 5 (2-5) configuration (56.04% and 118.04%, respectively); for a gap of 3.0 mm increases of 21.13% and 33.51%, respectively, were obtained for the same configurations; finally, for a gap of 20.0 mm increases of 24.86% and 22.25%, respectively, were obtained. For 7 (2,4,6,7) and 9 (2,5,8,9) configurations the results were slightly higher with respect to 5 (2-5) configuration in all cases.

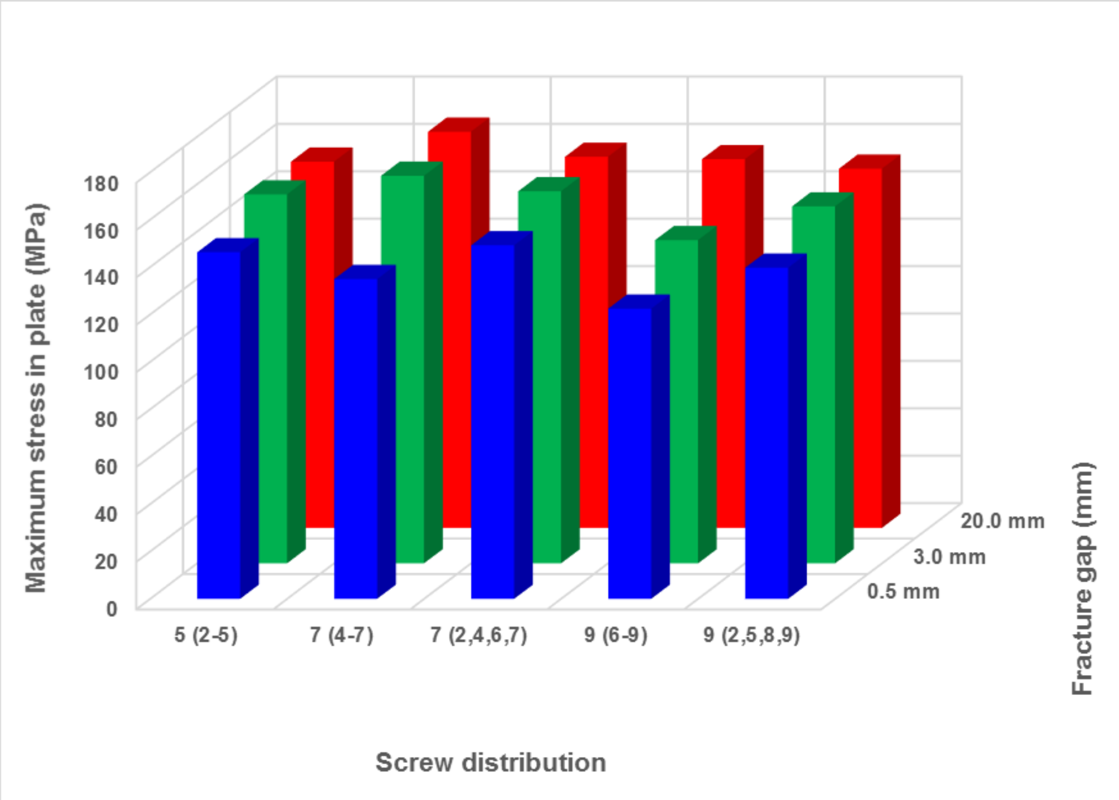


Fig. 11. Maximum stress in plate for Zone 5 fractures

When maximum stress in the plate is considered (Fig. 11), a decrease was observed for 7 (4-7) and 9 (6-9) configurations for 0.5 mm gap with respect to 5 (2-5) configuration (7.73% and 16.29%, respectively). For a gap of 3.0 mm. an increase of 5.06% was obtained for 7 (4-7) configuration, while a decrease of 12.39% was obtained for 9 (6-9) configuration. Finally, increases of 8.19% and 0.69%, respectively, with respect to 5 (2-5) configuration, were obtained for a gap of 20.0 mm. For 7 (2,4,6,7) and 9 (2,5,8,9) configurations the results were similar to 5 (5-5) configuration in all cases.

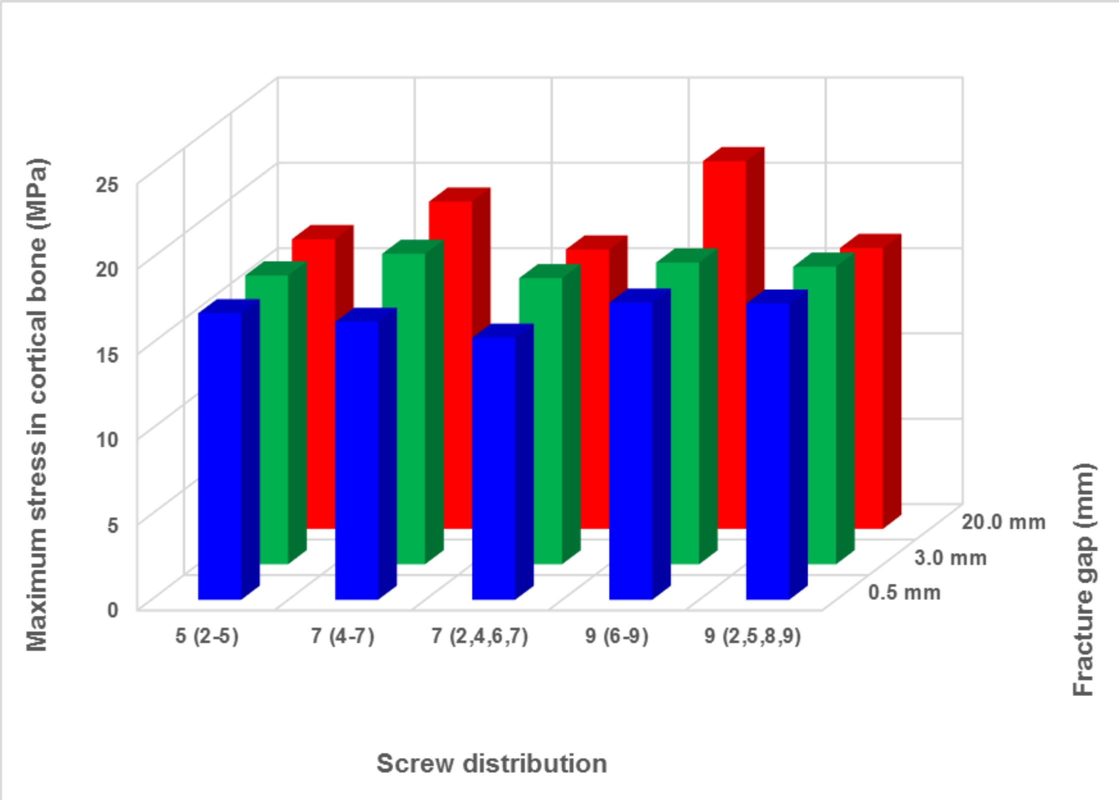


Fig. 12. Maximum stress in cortical bone for Zone 4 fractures

Finally, considering maximum stress in cortical bone (Fig. 12), a similar order of magnitude was obtained for every configuration when gaps of 0.5 mm and 3,0 mm were considered, while moderate increases were observed in the case of 20.0 mm gap for 7 /4-7) and 9 (6-9) configurations with respect to 5 (2-5) configuration (12.96% and 26.92%, respectively). For 7 (2,4,6,7) and 9 (2,5,8,9) configurations and gap of 20.0 mm, similar results as for 0.5 mm and 3.0 mm were obtained.

DISCUSSION

Despite clinical evidence about the influence of material, plate length and number and disposition of screws on the mechanical behavior of femoral fractures osteosyntheses, no consensus was achieved among surgeons, and consequently more biomechanical studies are necessary, in order to help surgeons to find the most appropriate osteosynthesis depending on the fracture type and location and patient conditions.

That is why in this work a biomechanical study about osteosynthesis of femoral fractures in zones 4 and 5 of Wiss. Plate length and number and position of locking screws were considered as factors conditioning the mechanical behavior of the osteossyntheses.

Discrepancies exist about which the more appropriate stability is depending on the fracture type, and does not yet exist scientific evidence on which is the more appropriate osteosynthesis configuration for every fracture type [2, 7, 22]. Due to variation on material, plate length and number and distribution of locking screws, multiple stabilizer assemblies can be performed, providing variable stabilities at the fracture site.

With respect to the material, a higher number of pseudoarthrosis has been reported for steel plates [23], probably related with the greater stiffness. On the contrary, titanium plates cause lower rates of pseudoarthrosis [10, 24]. However, no significant differences were found by other authors [7].

Concerning plate length and screw distribution, there is currently an ongoing debate about the optimal disposition and it is the most controversial aspect. There is a lot of clinical studies [2, 7, 22, 23] that have not reached a definitive conclusion, and very few published studies concerning biomechanical behavior according to the type of mounting [12, 15, 16].

The working length of the plate depends on the distance from the fracture site to the nearest screw, a shorter distance providing a more rigid osteosynthesis, reporting that pseudoarthrosis is 2.9 times more frequent than in the case of more proximal screws are unimplemented [7]. It has been clinically observed that short plates fixing all screws and being placed very close to the fracture site provide a very rigid stabilization, making it difficult the callus formation, with frequent pseudoarthrosis [25]. The trend nowadays is to perform an osteosynthesis using a longer plate as a bridge, with a reduced number of proximal screws and fixing them farthest from the fracture site, allowing micromovements that promote callus formation [2]. Other authors have pointed out that stability depends more on the type of fracture and characteristics of the patient than the osteosynthesis itself [7]. Some authors have stated that plate length in the case of unstable comminuted fractures must be between 2 and 3 times longer than the fracture plot [2, 22], avoiding the arrangement of the 3 more proximal screws to the facture site [2, 26]. However, Stoffel [27] submits that recommendation is only valid for single plot stable fractures, but for unstable comminuted fractures all screws should be implemented as closely as possible to the fracture site in order to improve stability. Finally, Henderson [10] reports a clinical study and found no influence of plate length on fracture healing.

According the obtained results in the present biomechanical study, more stable osteosyntheses were obtained by using shorter plates, i.e., 7 holes plate for

Zone 4 fractures and 5 holes plate for Zone 5 fractures. In the cases of longer plates, it results more convenient disposing screws in a way that the upper ones are closer to fracture site. Any case, shorter plates provide more stable osteosyntheses than longer plates. From a mechanical point of view, this fact could be explaining considering the plate as a cantilever fixed to the lower fragment and supporting the upper fragment; so, as more far from fracture site is the load transmission between upper fragment and plate, higher is the plate deformation, resulting in a higher mobility of the upper fragment with respect to the lower fragment. As consequence, stresses in the plate also grow.

On the other hand, the contact between fragments for a gap of 0.5 mm causes a different load transmission mechanism; while for gaps of 3.0 mm and 20.0 mm the loads are transmitted producing a situation of bending in the plate, the contact between fragments for a gap of 0.5 mm allows the loads being transmitted by means of a global bending moment (tension in the plate and compression in the contact between fragments), producing lower movements and stresses in the plate.

These results corroborate the clinical results stating that the osteosynthesis with short plates and all screws implemented provide greater stability at the fracture site [27]. For its part, Lujan [24] found that the callus was more voluminous in the cortical opposite of the plate; this may be because the contact between fragments seen in this study for small gaps, causing compressive stresses in that zone. Elkins [28], in a biomechanical FE study, detected that longitudinal forces at the fracture site help callus growth while shear forces harm it. Also has been demonstrated by means of animal experimentation that the forces that impacts on the fracture site, below a certain level, promote mesenchymal cells differentiation during the fracture healing process [29]. In the present study, those conclusions are corroborated; so, in unstable fractures with large gaps (20 mm) stabilized by means of a long plate and placing only the more proximal screws, significant displacement and shear forces appears with levels that can be unacceptable for fracture healing.

However, the main limitation of the above conclusions is that the study takes into consideration only the biomechanical aspects of the problem, without taking account of the biological aspects of fracture healing, with the result that a certain level of micromovements at the fracture site could help callus growth, while an excessive stiffness may harm it.

Despite the above limitation, the obtained results can support surgeons to understand the biomechanics of fracture stability, and then to guide them towards the more appropriate osteosynthesis depending on the fracture type and location.

DECLARATIONS OF COMPETING INTEREST

none

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