Minimally Invasive Fixation Techniques of Sacral Bone Fractures

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Abstract: The study focuses on minimally invasive fixation techniques of sacral bone fractures by means of the transiliac internal fixator (TIFI). Several implementations of TIFI for unilateral transforaminal fracture treatment are studied both experimentally and computationally. The comparison of fixation techniques is performed on the basis of the calculated stiffness ratio, which is determined from the displacement of the sacrum and the applied external load. The results of the experimental measurements are compared with numerical simulations while a very good agreement is achieved.

Keywords: biomechanics; pelvis; injury; osteosynthesis; transiliac internal fixator, iliosacral screw.

1 Introduction

Pelvic bone fractures account for about 2 % of all fractures of the human musculoskeletal system. In patients without osteoporosis, most common causes of pelvic fractures are impacts during traffic accidents or falls from large heights. Unstable fractures in pelvic area are often associated with polytraumatic injuries and a high risk of post-operative complications. A selection of the most appropriate fixation technique is one of the key factors for successful medical treatment and minimization of potential negative consequences of the fracture. Either external or internal fixators may be applied [1–3].

The presented study focuses solely on a treatment of a unilateral transforaminal fracture which belongs to group C, subgroup 1 of Tile's classification (i.e. C1 type fracture) [4]. No other affiliated injuries are considered. In the following, minimally invasive fixation techniques are of interest. A special attention is paid to several types of treatment by the transiliac internal fixator (TIFI) [5] and a possible combination of TIFI with the illiosacral screw (ISS) [6].

The TIFI fixator consists of two polyaxial screws, a single polyaxial screw is inserted in the wing of each ilium, while the two screws are interconnected with a subfascial transverse connector rod, Fig. 1 (left), thus forming a stable metal structure which constrains relative motion of the iliac bones [7]. The head of the polyaxial screw is stored in a ball housing which allows an attachment of the transverse connector rod at an arbitrary spatial angle. This simplifies positioning of the TIFI fixation during surgical treatment.

The ISS fixator is a long threaded screw, Fig. 1 (right), which ties the sacral bone fragments together. In most cases, the ISS is inserted through ala of ilium into the first sacral vertebra (S1) [6].

In the following, four fixation techniques are analysed: the classic TIFI, the supraacetabular TIFI, the dual TIFI and the combination of supraacetabular TIFI with ISS (TIFI+ISS). When the classically positioned TIFI is utilised, the polyaxial screws are inserted near the posterior superior iliac spine parallelly to the superior gluteal line [8]. During the supraacetabular insertion of TIFI, the polyaxial screws are inserted within the supraacetabular corridor, i.e. inferior to the classic TIFI [9]. The dual TIFI employs both the classic TIFI and the supraacetabular TIFI in order to fix the sacral fracture [10]. The TIFI+ISS technique combines the supraacetabular TIFI with the ISS, which is inserted into the S1 vertebra.

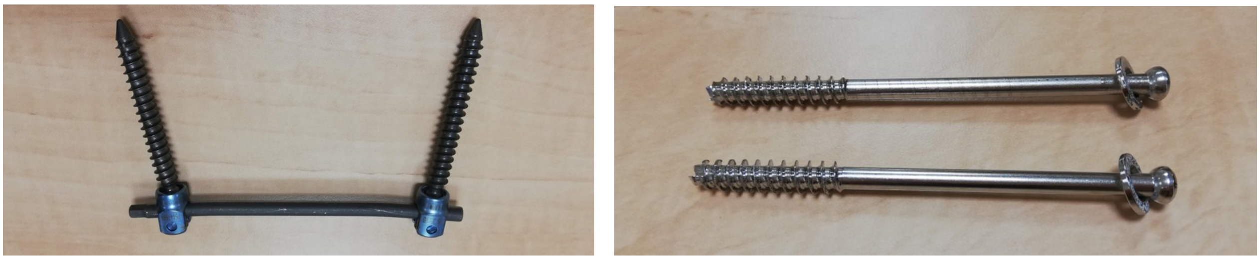

Fig. 1: Transiliac internal fixator (left), iliosacral screws (right).

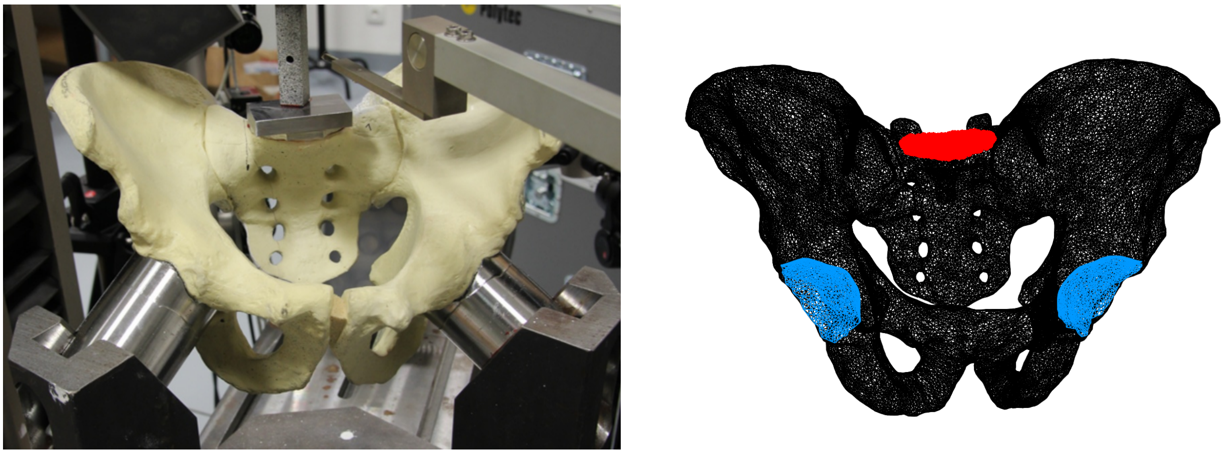

Fig. 2: Orthopaedic model of pelvic structure used during the experimental campaign (left) and FE computational mesh used for numerical simulations (right).

The selected types of fixation techniques are examined for a simplified test case which can be easily controlled within both experimental and computational modelling. This involves a male pelvic ring fixed in both acetabula so that no translations nor rotations in the acetabular region are allowed. The pelvic ring is positioned so that the sacral base is horizontal. The sacral base is loaded by a vertical force which magnitude corresponds to the physiological loading by an upper body weight of an average adult male.

2 Experimental analysis

The experiments were performed on artificial orthopedic models of an adult male pelvis [11]. These models were made of solid polyurethane foam and were mounted on a steel stand which enabled fixing the model in acetabula on steel femoral heads. The femoral heads were manufactured as three-dimensional negatives of acetabula. Thus it was possible to constrain displacements and rotations in the acetabular regions. In order to asses the performance of the selected fixation techniques, the treated pelvic models were subjected to compressive loading in mechanical testing machine, Fig. 2 (left).

On the contrary to cadaveric samples, application of the orthopaedic models enhanced repeatibility of the performed tests as the variations between the models were small. The material properties of the polyurethane foam were determined using a serie of dedicated tensile and compressive test measurements on cuboidal samples of material cut out of the pelvic models. The resulting Young modulus and Poisson ratio of the foam are presented in Tab. 1.

The solid foam, which the pelvic models were made of, was a homogenous isotropic material. Its mechanical response was almost linear while the viscoelastic effects were negligible. This significantly simplified development and verification of the computational model.

The stiffness of the treated pelvic structure was assessed based on the load-displacement curves recorded at the sacral base during the full scale pelvic tests. This data were recorded by the load cell and the extensometer of the mechanical testing machine while the three-dimensional motion of the fractured bone was analysed by digital image correlation of a set of simultaneously captured images. The quality of the pelvic ring fixation was assessed based on ratio between the stiffness of the treated pelvic structure and the stiffness of the intact pelvis. In addition a relative motion of selected points on the fractured bone parts during loading was investigated.

Tab. 1: Materials parameters.

	Young modulus [GPa]	Poisson ratio [-]
Solid foam	0.194	0.20
Titanium	120	0.33

3 Computational analysis

The experimental data were utilised for validation of the numerical computations based on the finite element (FE) method. The computational mesh is displayed in Fig. 2 (right). The geometry of the computational model was created from CT images of an orthopedic pelvic model [12]. The CT scans were performed in the transversal direction with a distance of $1.2\,\mathrm{mm}$ between two subsequent CT images. The computational model was simplified so that the pelvic ring was considered as a single continuous body, i.e. the cartilage and joints between pelvic bones were neglected.

The computational mesh of the model was created within the HyperMesh software package [13] and consisted of about $300\,000$ volume elements. Specifically, the elements were tetrahedrons with a characteristic edge length of $2.44\,\mathrm{mm}$. Computational simulations were performed in the finite element solver Abaqus [14].

For the purposes of numerical analysis, a homogeneous isotropic linearly elastic model was used for both the polyurethane solid foam and the titanium fixators. The applied material parameters are given in Tab. 1.

The two sets of boundary conditions are highlighted in Fig. 2 (right). The red colour highlights the sacral base region where the static load was applied in cranio-caudal direction. The blue colour depicts the acetabula which were fixed in space, i.e. rotations and displacements in all directions were constrained.

The linear unilateral transforaminal fracture was considered. The direction and the size of the fracture were created in accordance with the experiments. The width of the fracture line was $0.7\,\mathrm{mm}$. A surface to surface contact problem was considered between the surfaces of the fractured bone parts with a friction coefficient of 0.8.

The computational models of the individual fixator screws have been simplified by omitting their threads. Each screw was created as a three-dimensional cylindrical body with volumetric tetrahedral elements and constrained to the surface of the insertion hole within the pelvic bone. The screws and the cylindrical connector rod (also created using volumetric tetrahedral elements) were tied using a constraint.

4 Results and discussion

In order to assess the efficiency of each fixation technique, the stiffness of the entire pelvic structure k was determined for each model as

$$k = \frac{F}{u^B}, \tag{1}$$

where F was the external loading force acting in the cranio-caudal direction (i.e. perpendicular to the sacral base) and u^B was the displacement of the sacral base along the axis parallel to the direction of loading. In the experiments, the stiffness of the fractured pelvis model treated with a selected fixation technique was always compared to the stiffness of the original intact model by a stiffness ratio r_k. The same ratio was also determined during the numerical analysis. It was defined as

$$r_k = \frac{k_F}{k_I}, \tag{2}$$

where k_F corresponded to the stiffness of the fractured pelvis model with a fixation and k_I was the stiffness of the intact pelvis model.

In ordert to assess the stiffness of the intact pelvis, both experimental measurements and computational simulations were performed for the load of $F = 300\,\mathrm{N}$. The computationally predicted vertical displacement of the sacral base subjected to this loading was $u_I^B = 0.419\,\mathrm{mm}$. Thus the resulting stiffness of the intact model was $k_I = 714.6\,\mathrm{N}\cdot\mathrm{mm}^{-1}$. This value was subsequently used as a reference value for the stiffness ratio

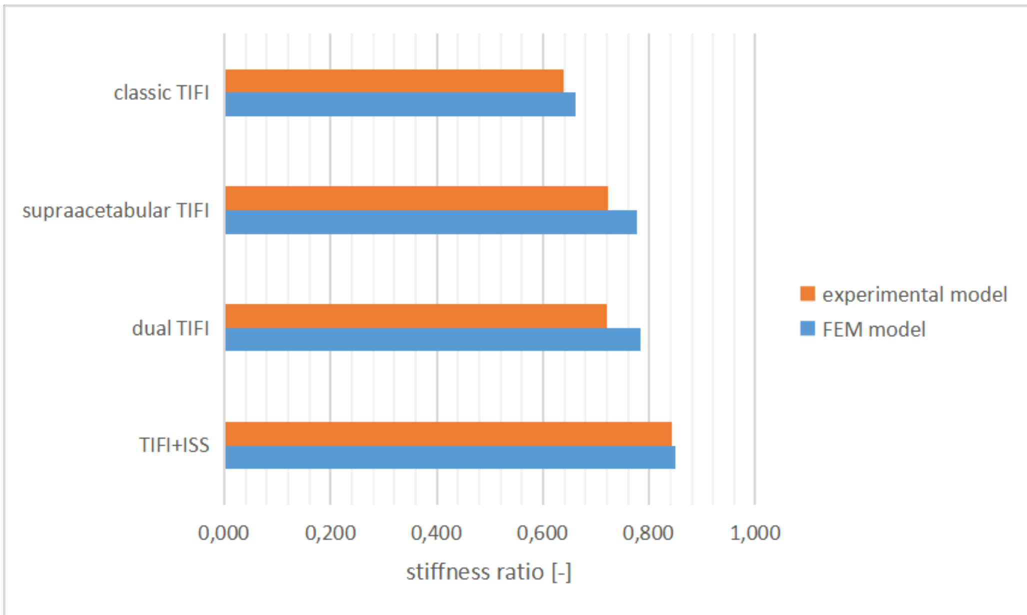

Fig. 3: Comparison of the resulting stiffness ratios obtained experimentally and computationally.

Tab. 2: Resulting stiffness ratios of both experimental and FEM model under load F = 500 N.

	stiffness ratio experiment [-]	stiffness ratio FEM [-]
classic TIFI	0.639	0.660
dual TIFI	0.720	0.785
supraacetabular TIFI	0.722	0.777
TIFI+ISS	0.842	0.849

calculations for all individual fixators within the computational study. The stiffness of the pelvic model treated with a selected fixator was determined using a maximal static load of 500 N.

Within the experimental part of the study, each fixator was tested using a new orthopaedic model of pelvis. Thus the stiffness of the intact pelvis had to be determined for every single pelvic model separately. Then, the fracture was created and a studied fixation technique applied.

The resulting values of stiffness ratio obtained from both experimental tests and numerical simulations are listed in Tab. 2 and graphically visualised in Fig. 3. The results were in good agreement while the computational data predicted slighlty larger values of the stiffness ratio than the measurements. The best results were achieved for the combination of TIFI and ISS which provided the stiffness ratio of about 85 %. Furthermore, results for the dual TIFI and for the supraacetabular TIFI were about identical. Thus applying the dual fixation did not bring any further improvement in the studied case. The computational values indicated the stiffness ratio of roughly 78 % for both techniques. The worst values were achieved by the classic TIFI which provided the stiffness ratio of 66 % within the FE analysis and only 64 % in the experiments.

The maximum deviation of the FE model from the experimental data is about 9 % for the model with dual TIFI fixation. On the contrary, the experimental and computational results differ in less than 1 % for the combination of TIFI and ISS.

5 Conclusion

Within this study, both the experimental and the computational model of the pelvic structure were developed and used to analyze several TIFI techniques. For the studied case of the linear vertical transforaminal sacral fracture without comminuted zone, experimental as well as computational results indicated that supraacetabular insertion of TIFI fixator and dual application of TIFI was superior to the classical TIFI technique and provided significantly higher stiffness of the lateral pelvic segment. However, enhancing the supraacetabularly inserted

TIFI with the second TIFI fixator (forming the dual TIFI) did not provide higher stability of the pelvic structure. For the studied case, the best results in terms of structural stiffness were achieved when the supraacetabular TIFI was combined with the ISS inserted into S1 vertebra. This restored the stiffness of the pelvic structure to almost 85 % of its original value.

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