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Comparison of Modified Transiliac Internal Fixators: Mechanical Testing on Pelvic Models

Srovnání modifikovaných transiliakálních vnitřních fixátorů: mechanické testování na modelech pánve

M. SALÁŠEK, L. LOBOVSKÝ, J. HLUCHÁ, J. KRYSTEK, J. KŘEN

NTIS – New Technologies for the Information Society, Faculty of Applied Sciences, University of West Bohemia, Plzeň, Czech Republic

ABSTRACT

PURPOSE OF THE STUDY

Vertically unstable transforaminal sacral fractures can be stabilized with several types of transiliac internal fixators (TIFI): the classical one (TIFI-C), the supraacetabular one (TIFI-A) and by dual application of TIFI (DTIFI).

MATERIAL AND METHODS

Pelvic models made of solid foam (Sawbones 1301) were used in the study. Mechanical loading tests were performed in order to assess the stiffness of the studied pelvic structures. The stiffness of the intact model was approximated as the slope of load/displacement curve. Then vertically unstable right-sided linear transforaminal fracture was created and subsequently fixed by TIFI-C, TIFI-A and DTIFI (each fixator for a separate model). The fixation techniques were compared based on the ratio between the stiffness of the treated and of the intact pelvis. Motion of the posterior pelvic structures and their deformations were measured using a photogrammetric system with four synchronous cameras. Loads applied at the base of sacrum and sacral base displacements were recorded by the testing device and used to assess the stiffness of the model structure. A dedicated load cell and a monoaxial extensometer were utilised. Every measurement was repeated at least 10 times. Obtained data were analysed by one way ANOVA test with post hoc comparison by Tukey HSD test.

RESULTS

Mean stiffness ratio (±1SD) of pelvic structure was 0.638 ± 0.005 for TIFI-C, 0.722 ± 0.014 for TIFI-A and 0.720 ± 0.008 for DTIFI. Dual transiliac internal fixation and supraacetabular fixation were superior to the classical one ($p < 0.0001$), but DTIFI and TIFI-A stiffness ratios were statistically equivalent ($p = 0.9112$).

CONCLUSIONS

Results of the mechanical analysis using pelvic models indicate that for linear vertical transforaminal sacral fracture without comminuted zone, an application of either TIFI-A or DTIFI provides significantly higher stiffness of the lateral pelvic segment than application of TIFI-C.

Key words: transforaminal sacral fracture, transiliac internal fixator, dual TIFI, stability, biomechanics, digital image correlation.

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INTRODUCTION

Transforaminal vertically unstable sacral fractures are ranked among serious injuries regardless of age (1, 2). In patients with a normal bone structure, a high-energy impact is required for their occurrence (e.g. during motor vehicle accidents or fall from large heights). However in patients with osteoporosis, these fractures can also be caused by a low-energy impact (e.g. fall from a stance height, abrupt sitting on a chair) (6, 12, 14). The Open Reduction Internal Fixation (ORIF) techniques such as spinopelvic fixation or plates for local osteosynthesis are not suitable for higher surgical risk during the acute phase of treatment (13). The ORIF is also contraindicated in case of significant contusion of soft tissues at the location of approach or in case of borderline patient hemodynamic stability (8, 9). In the acute phase of treatment, it is advantageous to use techniques of minimally invasive osteosynthesis. For transforaminal fractures, implants that allow fixation without excessive compression of the posterior pelvic segment are preferred (3–5, 15). Decreasing level of compression reduces the risk of iatrogenic neurovascular injuries. To stabilize the posterior pelvic segment, it is possible to use the transiliac internal fixator (TIFI) in classical insertion technique (TIFI-C) (3, 5) and its modifications – supraacetabularly inserted TIFI (TIFI-A) (8, 20) and dual TIFI (DTIFI) (16–18). All TIFI techniques employ polyaxial screws which are inserted into both iliac bones near the posterior superior iliac spine and stabilize the sacral fracture by interconnecting the polyaxial screws using a subfascial transverse connector rod (5). This study compares the mechanical parameters of TIFI-C, TIFI-A and DTIFI in stabilization of unilateral transforaminal vertically unstable sacral fractures.

MATERIAL AND METHODS

Orthopaedic models of male pelvis made of solid foam, i.e. of a homogeneous isotropic material, were used for the study (7). In these models, the internal structure of the pelvic bones was not respected, i.e. the cortical shell and the trabecular bone were made of the same homogenous material.

The intact pelvic models were mounted on a steel stand and fixed in both acetabula. In order to fix the pelvic model to the stand, artificial femoral heads made of steel were created as 3D negatives of the acetabula (based on 3D scans of the region from the *fossa acetabuli* to the *limbus acetabuli*). The pelvic model acetabula were glued to their 3D negatives (steel femoral heads) which did not allow any translation or rotation in the acetabular region. No additional screws in the acetabular region nor application of derotational chains (3) was necessary. The pelvic model was mounted on the steel stand such that the base of the sacral bone was oriented horizontally.

Biomechanical tests on the pelvic model were performed using a material testing machine Zwick Roel Z050. The load was applied perpendicular to the sacral base, i.e. in the vertical direction, and was evenly distributed over the entire surface of the base using a steel plate. The experimental setup is shown in Fig. 1.

First, intact pelvic models were tested and loaded with a linearly increasing force from 0 to 300 N (at a constant rate of 2.5 N/s). Experiments on intact models were performed in order to obtain a reference data set and to verify the integrity of the models before starting the measurements of fixators. Then, a right-sided unilateral transforaminal fracture was created on each pelvic model using a fret saw (cut thickness 0.5 mm). The fracture line was simple, vertically oriented and did not interfere

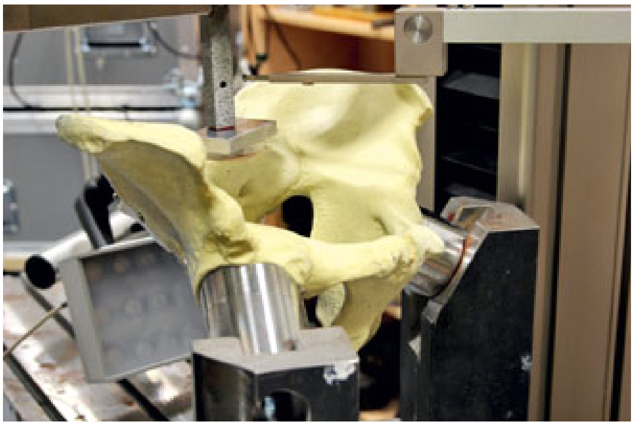

Fig. 1. Pelvic model made of solid foam attached to metal stand and prepared for measurements in material testing machine.

with the intervertebral joint L5 / S1 (AO / OTA 61-C1.3, Denis type 2, Pohlemann type 2, Isler type 1). The fracture is highlighted by the red dashed line in Fig. 2 (left). Each fractured pelvic model was stabilized with one of the three types of TIFI fixation, i.e. TIFI-C, TIFI-A, or DTIFI. Pelvic models with a stabilized fracture using one of the above mentioned fixation types were loaded with a linearly increasing loading force from 0 to 500 N. At the rate of 2.5 N/s, the loading was considered quasi-static and dynamic effects could be neglected.

The TIFI-C fixation was implanted using the technique described by Füchtmeier et al. (5), i.e. the entry points of the polyaxial screws were placed 3 cm cranially from the posterior superior iliac spine and the screws were directed as parallel as possible to the superior gluteal line. The supraacetabular TIFI-A was inserted at the level of the posterior superior iliac spine such that the polyaxial screws targeted towards the anterior inferior iliac spine within the supraacetabular corridor, this technique was first described by Korovessis et al. 2000 (8). The dual DTIFI fixation was a combination of TIFI-C and TIFI-A, as shown in Figure 2 (right), using the technique described

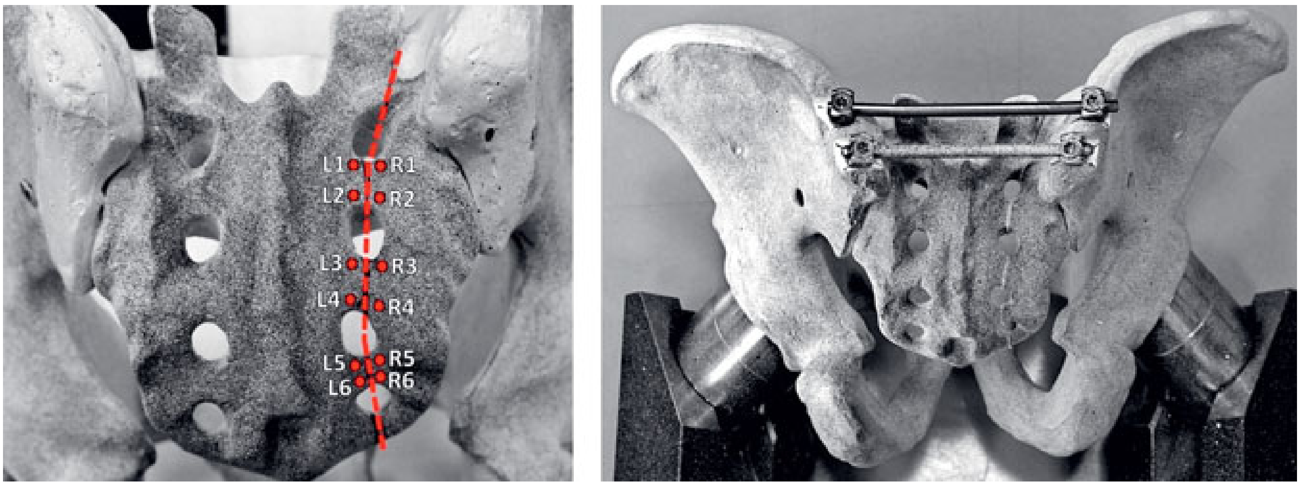

Fig. 2. Dorsal surface of sacral bone covered with black and white pattern for DIC analysis and with highlighted points of interest along fracture line (left), pelvic model fracture treated with DTIFI, the upper TIFI is in standard position of TIFI-C, the lower TIFI is positioned supraacetabularly as TIFI-A (right).

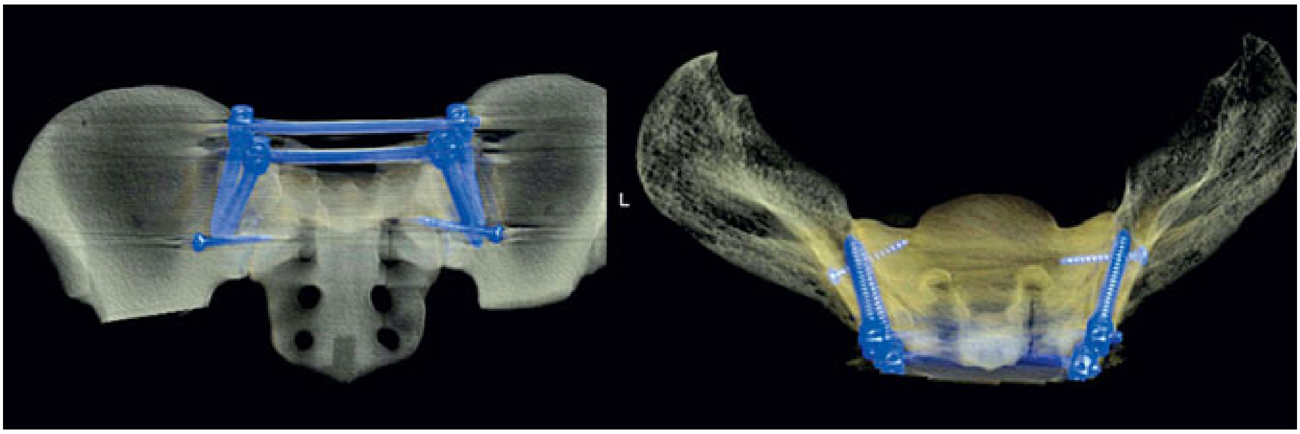

Fig. 3. 3D VRT reconstruction of CT scans of pelvic model with fracture and DTIFI fixation.

by Temperaele et al. (16). The accuracy of implant placement was verified using high-resolution CT scans with 3D VRT reconstruction (volume rendering technique), see Fig. 3. Polyaxial screws with diameter of 7.5 mm and length of 60 mm were used for all types of TIFI. The subfascial transverse connector rods were adjusted according to model size. During the reduction, any kind of compression of the posterior pelvic segment was avoided. All screws were tightened with a torque wrench so as to prevent countersinking of the screw heads.

The vertical load applied at the base of sacral bone was recorded using a dedicated load cell and the vertical displacement of the sacral base, the loading element respectively, was measured using a monoaxial extensometer. These measurements were assessed by the material testing machine. Spatial motion of the sacral bone segments along the fracture line and deformation of their dorsal surface were analyzed using a multicamera stereo-photogrammetric system (ISTRA). This system allowed computer reconstruction of the 3D dorsal surface of the sacral bone using digital image correlation (DIC) of 4 synchronous cameras. The material testing machine and the stereo-photogrammetric system were synchronized with a TTL signal (binary electrical signal) at the beginning and during each measurement.

In order to enable the DIC analysis, the dorsal surface of sacrum of each pelvic model was covered with a random black and white pattern. This pattern was used to identify the spatial coordinates of a large set of points (on the surface of sacrum) and their displacements at selected instants during the loading process. Several unique points in the vicinity of the fracture line were selected and used to evaluate the dislocation of the fracture during loading. As shown in Fig. 2 (right), points L1 to L6 are located on the left side and points R1 to R6 are located on the right side of the fracture line. The relative motion of the fractured bone segments is quantified by means of the distance between pairs of points L1-R1, L2-R2, …, L6-R6.

The stiffness of the intact pelvic model as well as the stiffness of the fractured model stabilized with one of the above mentioned fixations was evaluated based on the relationship between the loading force exerted on the sacral base and its vertical displacement. Some of the tested models showed a strong nonlinearity of the load curve at the beginning of loading, see Fig. 4. However, at higher loads, the load curve could be well approximated by a linear function in all models. The stiffness of the pelvic structure was determined as a slope of this linear function using a linear regression analysis of the

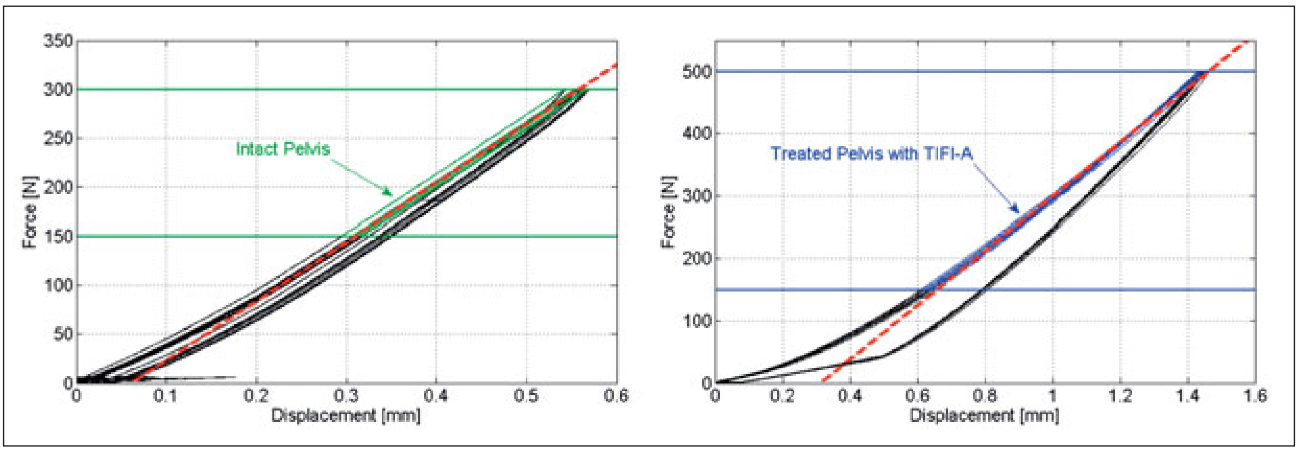

Fig. 4. Load-displacement curves as recorded during testing of intact pelvic model (left) and of pelvic structure treated with TIFI-A (right), red dashed line represents linear approximation of measured data which was used to assess the stiffness of the structure.

measured data. For the intact pelvic model, the stiffness calculation was based on data for loads between 150 and 300 N. For the pelvic model with a fixator-stabilized fracture, this analysis was performed for loads between 150 and 500 N.

The resulting stiffness of individual intact pelvic models differed slightly (in terms of several percents), which could be caused by small variances in between the manufactured pelvic models and due to minor variations in pelvic fixation in the experimental stand. In order to quantify the effectiveness of each fixation technique, the ratio between the stiffness of the fractured model with selected fixation and the stiffness of the intact model was examined. The stiffness ratio *kRi* was defined as:

$$k_{\mathrm{Ri}} = \frac{k_{\mathrm{Fi}}}{k_I}, \; i = 1, \ldots, n,$$

where k_{Fi} is the stiffness of the fractured model with a selected fixation as recorded during the i-th measurement and k_I is the average stiffness of the corresponding intact model.

All measurements were repeated at least 10 times. A separate pelvic model was used for each type of fixation to prevent deterioration of mechanical properties of the model after the tests performed for the previous fixation. In addition, a separate pelvic model was also used to assess the stiffness ratio for the pelvic model with fracture and without any fixation.

The obtained data were statistically analyzed: the normality of the data was evaluated by the Shapiro-Wilk test and the Kolmogorov-Smirnov test, the difference of variances between the data groups was tested by the Brown-Forsythe test. A simple ANOVA was used for the analysis itself, followed by post hoc comparisons using Tukey's HSD test. The test result with $p < 0.05$ was considered statistically significant.

RESULTS

Based on the preformed experiments, the pelvic model with fracture without applied fixation had a mean stiffness ratio of 0.4715 (i.e. the stiffness of the fractured pelvis reaches 47.15 % of the stiffness of the intact pelvic structure).

Analysis of the results for the pelvic models with fixation revealed that the mean stiffness ratio (± standard deviation) was 0.638 ± 0.005 for TIFI-C, 0.722 ± 0.014 for TIFI-A, and 0.720 ± 0.008 for DTIFI. In the ANOVA test, the differences between the groups were rated as highly statistically significant ($F = 215.62$; $\mathbf{p < 0.0001}$). A post hoc comparison using Tukey's HSD test showed that DTIFI and TIFI-A showed a significantly higher stiffness ratio than TIFI-C ($\mathbf{p < 0.0001}$), DTIFI and TIFI-A were statistically equivalent ($p = 0.9112$). These data are shown in Tables 1, 2 and Figure 5.

The obtained values of the stiffness ratio were in accordance with the results of DIC analysis of the movement of the fractured parts of the sacrum during loading, i.e. significantly higher displacements of the posterior pelvic segment were recorded with TIFI-C than with TIFI-A or DTIFI. These two types of fixation showed similar displacements. Deformation of the dorsal surface of the sacral bone at maximum load is shown by the color displacement map in Figures 6, 7, 8 for all three fixation techniques. These graphs show that the relative motion around the fracture line is very similar for both DTIFI and TIFI-A techniques. In contrast, TIFI-C shows a significant distraction in the fracture line that was not present in DTIFI or TIFI-A fixation. This was confirmed by quantitative evaluation of relative displacements between pairs of points along the fracture line L1-R1, L2-R2, …, L6-R6, see Fig. 9. The average value of the shift between the L-R points is 43% higher for TIFI-C than for DTIFI and 51% higher than for TIFI-A.

Tab. 1. Resulting stiffness ratio and its confidence interval for each tested fixation technique

Stiffness ratio	k	SD	95% CI	
TIFI-A	0.722	0.014	0.712	0.731
TIFI-C	0.638	0.005	0.635	0.642
DTIFI	0.720	0.008	0.715	0.725

Tab. 2. Results of statistical analysis of recorded experimental data

ANOVA		F = 30.266				p < 0.0001	
Tukey HSD		Mean difference	Q	95% CI		p	Cohen d
TIFI-A	TIFI-C	0.083	25.273	0.072	0.095	**< 0.0001**	8.211
TIFI-A	DTIFI	0.002	0.582	-0.010	0.013	0.9112	0.189
TIFI-C	DTIFI	-0.081	25.367	0.070	0.092	**< 0.0001**	8.022

DISCUSSION

Transforaminal vertically unstable sacral fractures can be stabilized with minimally invasive TIFI (3, 5, 8) and its modification (14, 16–18), or with a transilliac plate (1, 9), iliosacral screws (ISS) (4, 9), a combination of these implants (19), or minimally invasive spin-

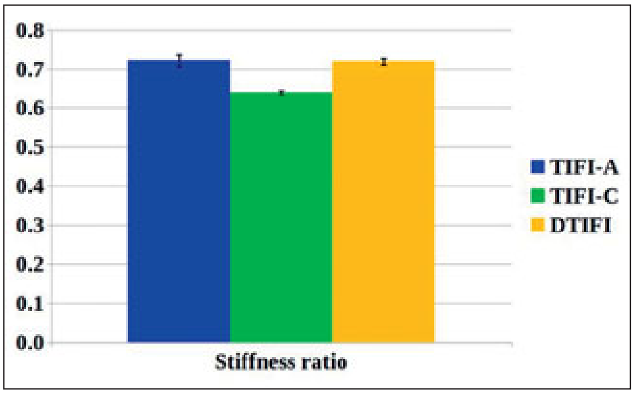

Fig. 5. Visualisation of mean stiffness ratio for TIFI-C, TIFI-A a DTIFI fixation techniques.

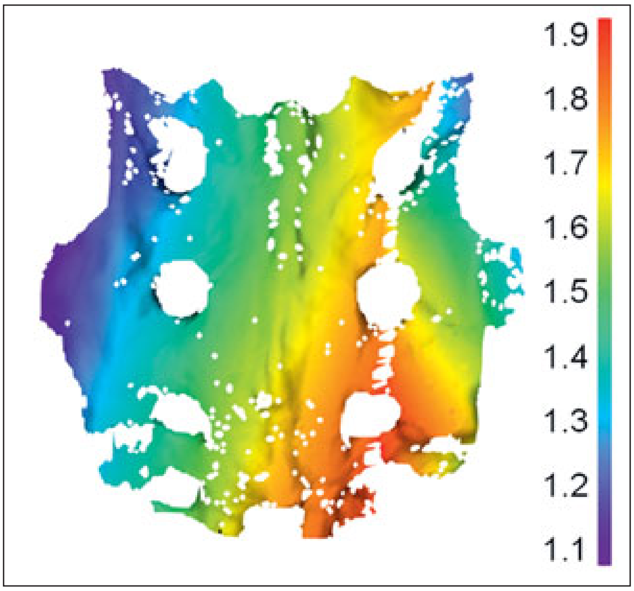

Fig. 6. Contour plot of displacements (in milimetres) at dorsal surface of sacrum for fracture treated with TIFI-C and loading of approx. 500 N.

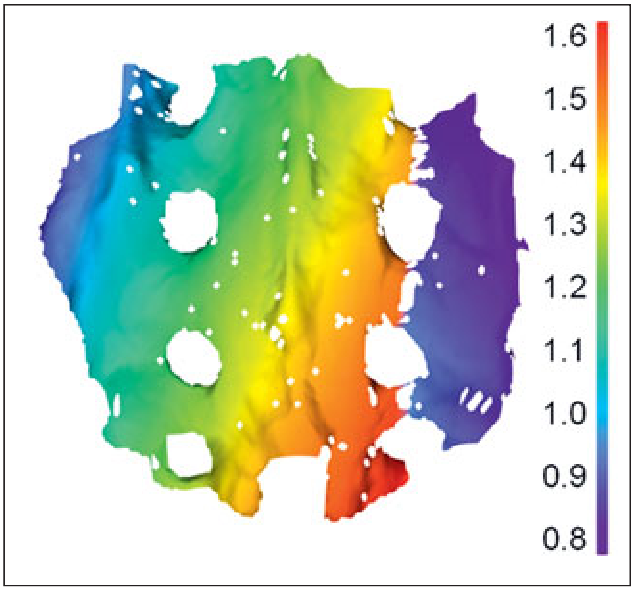

Fig. 7. Contour plot of displacements (in milimetres) at dorsal surface of sacrum for fracture treated with TIFI-A and loading of approx. 500 N.

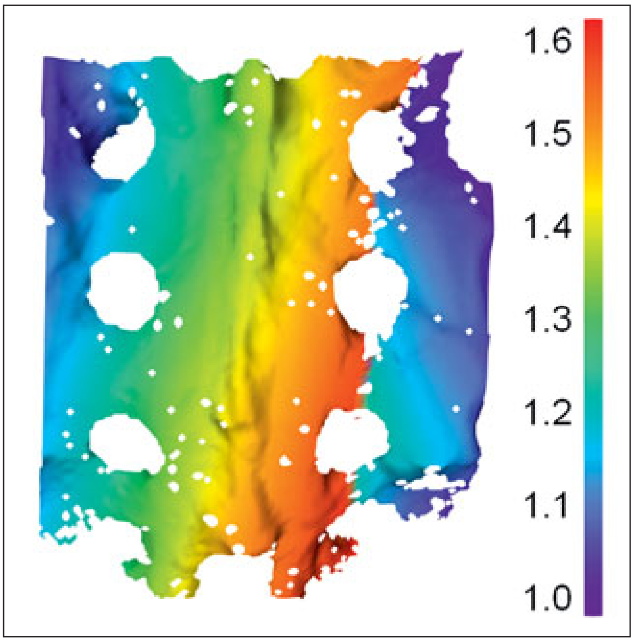

Fig. 8. Contour plot of displacements (in milimetres) at dorsal surface of sacrum for fracture treated with DTIFI and loading of approx. 500 N.

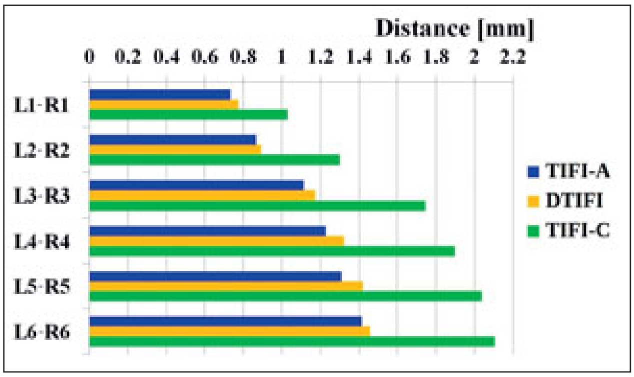

Fig. 9. Comparison of relative displacements (in milimeters) between L-R points along fracture line under loading of approx. 500 N.

opelvic fixation (11, 15). The classical insertion of TIFI (TIFI-C) was described in 2004 by Füchtmeier et al. (5) and the first biomechanical study on TIFI-C was published in 2011 by Dienstknecht et al. (3). This study was performed on an anatomical specimen of the pelvis, two ISSs and two anterior plates for fixation of complete dislocation of the SI joint were compared with TIFI-C. No statistically significant differences were found between the studied implants.

The biomechanics of supraacetabularly inserted TIFI-A was first studied by Vigdorchik et al. (20) in 2015 on a composite model of the pelvis. In this study, the unsuitability of TIFI-A for SI dislocation (a model with complete instability of the sacroiliac joint) was demonstrated. In contrast, transforaminal fractures showed superiority of TIFI-A over one ISS (in segment S1) and superiority of the combination of TIFI-A and one ISS over one TIFI-C.

The clinical results of TIFI-A were published for example by Schmitz et al. (14). Their study focused on osteoporotic fractures of the posterior pelvic segment, cannulated polyaxial screws augmented with bone cement in the supraacetabular corridor were used. A study of the biomechanics of TIFI-A (or augmented TIFI-A) in osteoporotic bone has not yet been performed. TIFI-A was also studied by Wu et al. 2018 who used it in combination with the anterior subcutaneous pelvic internal fixator (ASPIF) (20).

Dual TIFI (DTIFI) was first described by Ueno et al. (18) in 2015, a non-anatomical plastic model was used. The study showed that the mechanical response of the pelvic structure with DTIFI was not affected by the length of the screw heads and that DTIFI provided greater stability than standard fixation with a single TIFI-C. This result was also confirmed in our study. However, the same effect was also achieved by supraacetabular insertion of one TIFI (i.e. TIFI-A). DTIFI could be beneficial for complex fractures, but there are no biomechanical data to support this hypothesis.

A comparison of all three types of TIFI was not included in any of the previous studies.

The subject of this study was not the modification of DTIFI proposed by Toda et al. (17) who used a vertical connector to connect the two DTIFI rods to prevent them from relative moving to each other. This modified DTIFI might be stiffer than insertion without vertical connector, but biomechanical data of this hypothesis are missing In addition to the modifications described above, it is also possible to use dual TIFI with only one bevelled U-shaped rod (U-TIFI). This was described in a clinical study by Zhu et al. 2015 (21), this implant set up might have similar mechanic behavior as the modified DTIFI by Toda et al., but direct biomechanical comparison is still missing.

Our study had several limitations:

1. The hardened foam pelvis model did not have the internal anatomical structure of the pelvic bones and does not consider their movable joint.
2. The mechanical properties of this hardened foam are close to those of cancellous bone.
3. Rotation of individual hemipelvis was prevented due to Bipedal fixation of the model in the area of the both acetabula.
4. The fracture line was created without the use of CNC navigation.

CONCLUSIONS

All three types of TIFI significantly increase the stiffness of the posterior pelvic segment when applied to stabilize unilateral vertical transforaminal fractures without comminuted fracture zone. Within the presented biomechanical study on orthopaedic models of pelvis, the supraacetabularly inserted TIFI and the dual TIFI fixation showed superior results in terms of the stiffness of the posterior pelvic segment compared to the classical TIFI. Verification of these results is a subject of an ongoing comparative clinical study and of a biomechanical study on comminuted sacral fractures.

Conflict of interests

All authors declare that they have no conflict of interest with respect to the published biomechanical study.

References

1. Boudissa M, Saad M, Kerschbaumer G, Ruatti S, Tonetti J. Posterior transiliac plating in vertically unstable sacral fracture. Orthop Traumatol Surg Res. 2020;106:85–88.
2. Chen H, Wu L, Zheng R, Liu Y, Li Y, Ding Z. Parallel analysis of finite element model controlled trial and retrospective case control study on percutaneous internal fixation for vertical sacral fractures. BMC Musculoskelet Disord. 2013;14:217.
3. Dienstknecht T, Berner A, Lenich A, Zellner J, Mueller M, Nerlich M, Fuechtmeier B. Biomechanical analysis of a transiliac internal fixator. IntOrthop. 2011;35:1863–1868.
4. Eastman JG, Shelton TJ, Routt MLC Jr, Adams MR. Posterior pelvic ring bone density with implications for percutaneous screw fixation. Eur J Orthop Surg Traumatol. 2021;31:383–389.
5. Füchtmeier B, Maghsudi M, Neumann C, Hente R, Roll C, Nerlich M. Die minimal-invasive Stabilisierung des dorsalen Beckenrings mit dem transiliakalen Fixateur interne (TIFI) - operative Technik und erste klinische Ergebnisse. Unfallchirurg. 2004;107:1142–1151.
6. Giráldez-Sánchez MA, Lázaro-Gonzálvez Á, Martínez-Reina J, Serrano-Toledano D, Navarro-Robles A, Cano-Luis P, Fragkakis EM, Giannoudis PV. Percutaneous iliosacral fixation in external rotational pelvic fractures, a biomechanical analysis. Injury. 2015;46:327–332.
7. https://www.sawbones.com/full-male-pelvis-large-solid-foam-w-sacrum-1301.html
8. Korovessis P, Stamatakis M, Baikousis A. Posterior stabilization of unstable sacroiliac injuries with the Texas Scottish Rite Hospital spinal instrumentation. Orthopedics. 2000;23:323–327.
9. Liuzza F, Silluzio N, Florio M, El Ezzo O, Cazzato G, Ciolli G, Perisano C, Maccauro G. Comparison between posterior sacral plate stabilization versus minimally invasive transiliac-transsacral lag-screw fixation in fractures of sacrum: a single-centre experience. Int Orthop. 2019;43:177–185.
10. Osterhoff G, Tiziani S, Hafner C, Ferguson SJ, Simmen HP, Werner CM. Symphyseal internal rod fixation versus standard plate fixation for open book pelvic ring injuries: a biomechanical study. Eur J Trauma Emerg Surg. 2016;42:197–202.
11. Peng Y, Zhang G, Zhang S, Ji X, Li J, Du C, Zhao W, Zhang L. Biomechanical study of transsacral-transiliac screw fixation versus lumbopelvic fixation and bilateral triangular fixation for "H"- and “U”-type sacrum fractures with traumatic spondylopelvic dissociation: a finite element analysis study. J Orthop Surg Res. 2021;16:428.
12. Rommens PM, Wagner D, Hofmann A. Minimal Invasive Surgical Treatment of Fragility Fractures of the Pelvis. Chirurgia (Bucur). 2017;112:524–537.
13. Santolini E, Kanakaris NK, Giannoudis PV. Sacral fractures: issues, challenges, solutions. EFORT Open Rev. 2020;5:299–311.
14. Schmitz P, Baumann F, Grechenig S, Gaensslen A, Nerlich M, Müller MB. The cement-augmented transiliacal internal fixator (caTIFI): an innovative surgical technique for stabilization of fragility fractures of the pelvis. Injury. 2015;46:S114–S120.
15. Song W, Zhou D, He Y. The biomechanical advantages of bilateral lumbo-iliac fixation in unilateral comminuted sacral fractures without sacroiliac screw safe channel: a finite element analysis. Medicine. 2016;95:e5026.
16. Tempelaere C, Vincent C, Court C. Percutaneous posterior fixation for unstable pelvic ring fractures. Orthop Traumatol Surg Res. 2017;103:1169–1171.
17. Toda K, Yagata Y, Kikuchi T, Takigawa T, Ito Y. Minimally invasive surgery for unstable pelvic ring fractures: transiliac rod and screw fixation. Acta Med Okayama. 2020;74:27–32.
18. Ueno FH, Pisani MJ, Machado AN, Rodrigues FL, Fujiki EN, Rodrigues LM. Biomechanical study of the sacroiliac fracture fixation with titanium rods and pedicle screws. Acta Ortop Bras. 2015;23:154–157.
19. Vigdorchik JM, Jin X, Sethi A, Herzog DT, Oliphant BW, Yang KH, Vaidya R. A biomechanical study of standard posterior pelvic ring fixation versus a posterior pedicle screw construct. Injury. 2015;46:1491–1496.
20. Wu XT, Liu ZQ, Fu WQ, Zhao S. Minimally invasive treatment of unstable pelvic ring injuries with modified pedicle screw-rod fixator. J Int Med Res. 2018;46:368–380.
21. Zhu L, Wang L, Shen D, Ye TW, Zhao LY, Chen AM. Treatment of pelvic fractures through a less invasive ilioinguinal approach combined with a minimally invasive posterior approach. BMC Musculoskelet Disord. 2015;16:167.

Korespondující autor:
Ing. Libor Lobovský, Ph.D.
NTIS, Faculty of Applied Sciences
University of West Bohemia
Univerzitní 8, 301 00 Plzeň
E-mail: lobo@kme.zcu.cz