Further development of our finite element pelvic model to compare fixation methods for pelvic fractures

Pelvis kırıklarında tespit yöntemlerinin karşılaştırılmasında sonlu eleman pelvis modelinin geliştirilmesi

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Objectives: In this study, we aimed to create a realistic model which is suitable for computerized simulation of any kind of fractures and provides reliable results.

Patients and methods: We used a plastic pelvic model to construct advanced specimens. The data were retrieved from the computed tomography scans of a healthy pelvis. A geometrically exact model by the means of three-dimensional scanning of the plastic pelvis was obtained. The material properties of the bony parts based on the data retrieved from the computed tomography scans were modified. The pelvis was divided into distinct segments and the proportion of the cortical and cancellous bone substance in each segment were determined to make the material properties accurate. In the validation of the pelvic model, a type C pelvic injury was simulated and the fracture of the sacrum and the symphyseolysis were stabilized with plates. These data were compared with those of previously performed cadaver experiments.

Results: Based on the simulation performed on the new model, the shift values between the fragments of the broken sacrum approximated the reported values of our cadaver experiments and also arising strains remained in the tolerable interval.

Conclusion: Our new finite element pelvic model represents the pelvis more accurately than the former one. As the validation of the model was successful, it is suitable for computerized simulation of any kind of fractures offering reliable results.

Key words: Finite element analysis; fracture fixation; pelvic bone.

Amaç: Bu çalışmada her türlü kırığın bilgisayarlı simülasyonuna uygun olan ve güvenilir sonuçlar veren gerçekçi bir model yaratıldı.

Hastalar ve yöntemler: İleri numune elde edebilmek için plastik bir pelvis modeli kullanıldı. Veriler sağlıklı bir pelvisin bilgisayarlı tomografi taramasından elde edildi. Üç boyutlu plastik pelvis taraması ile geometrik olarak kesin bir model oluşturuldu. Bilgisayarlı tomografi taramalarından elde edilen verilere göre kemikli kısımların materyal özellikleri modifiye edildi. Pelvis farklı segmentlere ayrıldı ve materyal özelliklerinin doğru olması için her segmentte kortikal ve kansellöz kemik maddesinin oranı tayin edildi. Pelvis modelinin doğrulanmasında, tip C pelvis hasarının simülasyonu yapıldı ve sakrum kırığı ve semfizyoliz plaklar ile stabilize edildi. Bu veriler daha önceki kadavra deneylerinden elde edilen veriler ile karşılaştırıldı.

Bulgular: Yeni model üzerinde yapılan simülasyona göre, sakrum kırığının fragmanları arasındaki kayma değerleri, kadavra deneylerinde bildirilen değerlere yakındı ve artan gerilme tolere edilebilir aralıkta kaldı.

Sonuç: Yeni sonlu eleman pelvis modelimiz, eski modele göre, pelvisi daha doğru yansıtmaktadır. Modelin doğrulaması başarılı olduğundan, güvenilir sonuçlar ile bu yöntem her türlü kırığın bilgisayarlı simülasyonu için uygundur.

Anahtar sözcükler: Sonlu eleman analizi; kırık tespiti; pelvis kemiği.

High-energy pelvic ring injuries frequently occurring in polytrauma patients pose one of the greatest challenges in trauma patient care. Primary stabilization of pelvic injuries is a life-saving intervention and it aims to stabilize the patient's vital parameters. These surgeries are performed often as temporary interventions, in case of severe injuries, particularly.[1,2]

As soon as the patient's condition allows definitive treatment, we should choose one of the possible ways of fixing methods. Results of several fixation methods are available in the literature. Plate fixation, trans-sacral plating, iliosacral screwing are the most common methods.[3-7]

For the selection of the ideal method, it would be useful to be able to compare the stability of certain osteosyntheses based not only on empiric experiences, but also validated results retrieved from scientific experiments.

In addition, comparative studies would be feasible on cadaver pelvis specimens, however, this type of models pose numerous technical, organizational and ethical difficulties in addition to the limited number of specimens.[8-10]

Although several finite element pelvic models were created in the past, they modelled either just the hemi pelvic bone, or albeit a whole one. They did not include the possible fracture types and fixation techniques.[9-12]

In this study, we aimed to create a finite element pelvic model, which not only shows the whole pelvic ring, but also enables us to compare the stability of different fixation techniques applied in certain types of fractures.

In the past, we already created a pelvic model for the same purpose,[13] however, that model became outdated, partly due to its simplified geometrical characteristics, partly due to its unrealistic and misleading material properties, which were based on a homogeneous 10%: 90%, cortical: cancellous bone ratio in all of the bony elements of the model.

According to the relevant literature,[10,11,14] it is the proportion of the cortical part, which can be evaluated based on the computed tomography (CT)-scan images, which mainly determines the characteristics of the model. The most commonly used method is determination of the elasticity from the density,[10,15-18] although such a value explicitly for the pelvis bone has not been determined to date. Recommendations for the most feasible density-elasticity relationship are already available.[10,15]

In our study, we chose a simply method by measuring the cortical: cancellous bone ratio on the CT image slices in a given area and then using material properties taken from the literature,[19] and we calculated the material properties specific to the examined regions. As the aim of our study was to compare different fixation techniques used in the therapy of fractures, the amount of details obtained with this method was satisfactory. We did not change the loading and boundary conditions, or the models for the fixations, compared to our previous study.[13] We slightly improved the modelling of the fractures.

Finally, in the validation of our results, we compared the dislocations and tensions we registered on our new model in case of a specific pelvic fracture (Denis C) fixed with a given technique, to the same data gained from a cadaver model, which suffered the same injury and was fixed with the same technique.[8]
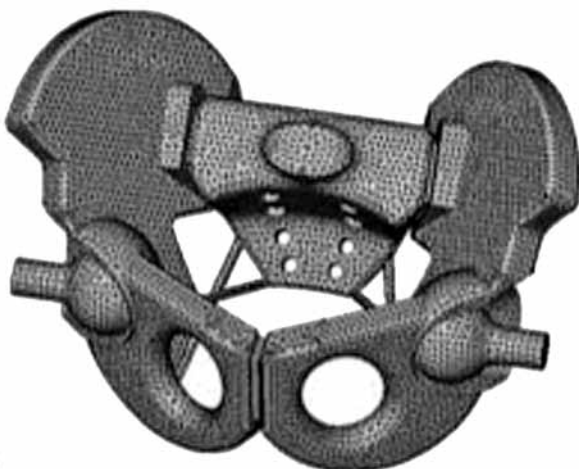

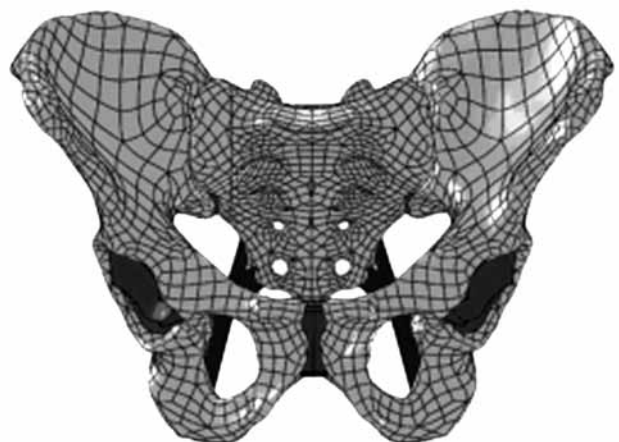**Figure 1.** Our previous pelvic model.[13]

Figure 2. The new model based on three dimensional scans of a plastic pelvis.

TABLE I

Applied material properties

Material properties	Elastic modulus	Poisson's ratio	Maximal allowed tension
Bones			
Cortical	17000 MPa	0.3	70 MPa
Cancellous	400 MPa	0.2	15 MPa
Joints			
Sacroiliac joint	68 MPa	0.2	
Symphysis	50 MPa	0.2	
Ligaments			
Ligamentum sacrospinosum	355 MPa	0.2	
Ligamentum sacrotuberosum	355 MPa	0.2	
Plates			
Dynamic compresson plate	200000 MPa	0.28	800 MPa
Reconstruction plate	200000 MPa	0.28	800 MPa

PATIENTS AND METHODS

Geometrical changes

Our previous model was constructed with simplified geometry (Figure 1).[13]

There were two options: creating a model on the basis of CT-scans requiring special software or scanning a plastic model using a three-dimensional measuring device. The second option was favored by the fact that connection with the computer of the CT required special software, and the model created in this way basically would not be compatible with the software developed for technical purposes. Furthermore, the special software would demonstrate all bones of the pelvis as a uniform unit, and modeling of the joints among them would result in additional difficulties.

Using in this way created computer-aided design (CAD) (Figure 2), we made our finite element pelvic model with the aid of the software "Solid Works 2013". The finite element net applied for the measurements, consists of hexahedron elements. The previous model consisted of approximately 90,000 elements (Figure 1); the new one consists of approximately 140,000 elements (Figure 2).

Changing of material properties

Components of the pelvis were considered as a linearly elastic, isotropic material, alike in our previous experiments. Material properties [elastic modulus (Young's modulus), Poisson's ratio] were determined according to the data in the literature[19] (Table I). Separation of the two main bone components of the model, cortical and cancellous layers, would have been preferred, but because of our available computing technology also rather difficult.

Therefore, we decided to use a homogenous bone, whose material properties are derived from the percentage distribution of cancellous and cortical bone substance.

The 2060 megapascal (MPa) elastic modulus of the previous model was calculated with 10% cortical and 90% cancellous bone substance.[13] However, according to the CT scans, and the literature the ratio of the cortical bone is higher.[9,10,14]

We determined the ratio of the cortical and cancellous bone substance based on the CT scans, and the average, common material properties were calculated from this percentual ratio (Figure 3). We performed the measurements on 10 points both on the sacrum and the pelvis, thus we could retrieve
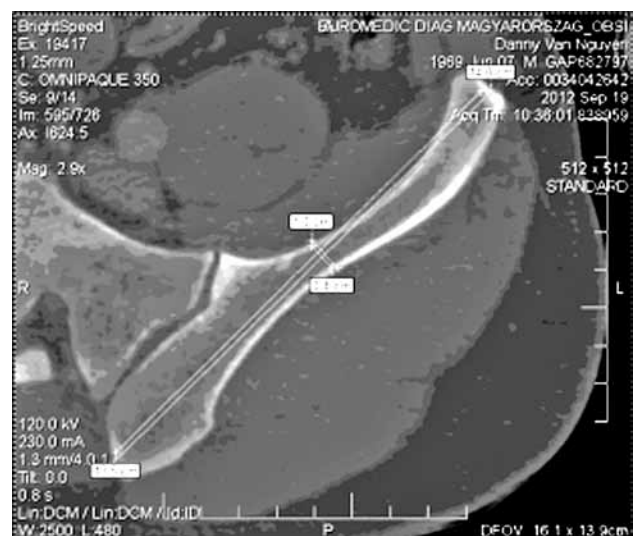

Figure 3. Determination of cancellous/cortical bone substance ratio based on computed tomography scans.
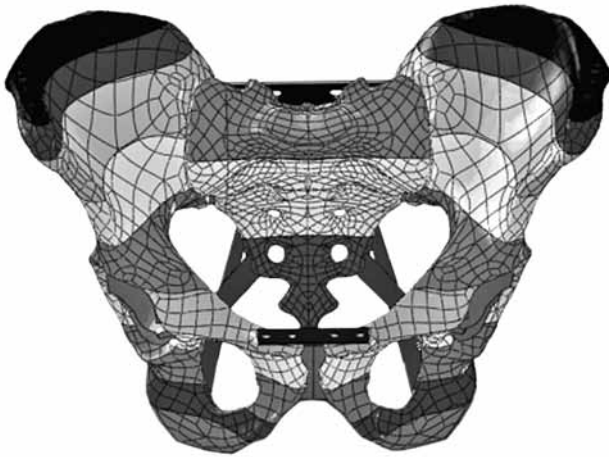
TABLE II

Determination of material properties of the pelvis bone

Slice	A_1	B_1	A_2	B_2	Whole area	Area of the cancellous bone	Cancellous (%)	Cortical (%)	Elastic modulus (MPa)
1	4.2	0.6	3.8	0.4	7.9	4.8	60.32	39.68	6987
2	5.95	0.7	5.65	0.5	13.1	8.9	67.83	32.17	5741
3	7	0.5	6.75	0.4	11.0	8.5	77.14	22.86	4194
4	6.8	0.9	6.65	0.75	19.2	15.7	81.50	18.50	3472
5	3.9	1.35	3.6	1.05	16.5	11.9	71.79	28.21	5082
6	3.75	2.3	3.35	1.95	27.1	20.5	75.74	24.26	4427
7	3.8	1.2	3.55	1.05	14.3	11.7	81.74	18.26	3431
8	5.6	1.05	5.3	0.8	18.5	13.3	72.11	27.89	5030
9	1.8	1.15	1.6	0.9	6.5	4.5	69.57	30.43	5452
10	3.2	0.7	2.9	0.55	7.0	5.0	71.21	28.79	5180
Average:									4900

exact ratio from 10 horizontal slices of these two bones (Table II, III).

Ten slices were created on the pelvis. As the sacrum is smaller in size, we calculated the average of the data retrieved from 10 points and created a sacrum model consisting of four slices. Further measurements were performed on this "sliced" model (Figure 4).

Validation of the models, loading, boundary conditions

In the validation of our model, we simulated a type C pelvis injury for comparison with the results retrieved from our former cadaver experiments.[8]

In our experimental model, the injury of the posterior ring was a Denis I fracture stabilized with a transsacral plate; injury of the anterior ring (symphysiolysis) was fixed with a reconstruction plate.

We applied the same values for the load and boundary conditions as in the previous computerized model.[13] Standing on one foot was simulated by a 500 N downwards vertical load (direction Z) exerted directly onto the sacrum and fixation of the hip joint on the injured side.

Pelvis was dorsally supported against shift into direction Y, and we used "node-node" junction in both hip joints, and "bonded" junction on other surfaces. Compared to our previous model we only modified the modelling of the fracture, which in this case was executed in no penetration" mode. Furthermore, we used an additional 0.6 friction coefficient along the fracture surface, which was obviously an estimated value.

TABLE III

Determination of material properties of the sacrum

Slice	A_1	B_1	A_2	B_2	Whole area	Area of the cancellous bone	Cancellous (%)	Cortical (%)	Elastic modulus (MPa)
1	3.75	2.5	3.55	2.2	29.5	24.5	83.31	16.69	3171
2	2.85	3	2.7	2.75	26.9	23.3	86.84	13.16	2584
3	5.55	2.8	5.35	2.7	48.8	45.4	92.95	7.05	1570
4	5.45	2.25	5.3	2	38.5	33.3	86.44	13.56	2651
5	5	2.05	4.8	1.85	32.2	27.9	86.63	13.37	2619
6	4.25	1.75	4	1.6	23.4	20.1	86.05	13.95	2716
7	4.8	1.35	4.55	1.05	20.4	15.0	73.73	26.27	4761
8	3.15	0.85	3	0.7	8.4	6.6	78.43	21.57	3980
9	2.7	0.45	2.5	0.3	3.8	2.4	61.73	38.27	6753
10	1.55	0.35	1.4	0.25	1.7	1.1	64.52	35.48	6290
Average:									3710

Figure 4. The "sliced" model with new material properties.

Figure 5. Biomechanical model used in the cadaver experiments.

A similar injury was investigated in our cadaver experiments; the specimen was fixed in the same manner (Figure 5).

During the course of the experiments, the shift in the symphysiolysis and between the fragments of the broken sacrum and the arising tensions were measured.

In the experiments performed on the model, we applied 500 N loads in contrast to the cadaver specimens, where we applied 250 N loads. But according to Hooke's law, the results calculated from the double of the shift values obtained from the cadaver experiments are comparable, thus the model is suitable for evaluation.

RESULTS

As both geometry and material properties of the model were involved in the changes, we summarize the results of the changes separately.

Geometrical changes

We obtained the following results after geometrical changes of the model:

The maximal shift between the fragments of the broken sacrum was 3.4 mm, when simulating standing on one foot (Figure 6). We measured 1 mm vertical shift in the anterior ring (symphysiolysis). The maximal tension was 12 MPa in the bones (Figure 7) and 750 MPa in the implants.

It is essential to approximate the values obtained from the cadaver experiments after any changes to preserve the validity of the model. In this case, the necessary data was the shift between the fragments of the broken sacrum. Due to alterations of the load conditions detailed above, we calculated with the double of the shift values retrieved from the cadaver experiments, which was 2.6 mm in this case.

The aim of further modifications was to reduce the difference between these two values.

Material properties

Changing of the material properties was performed in the manner described above. We

Figure 6. Shifts measured on the new model.

Figure 7. Tension distribution on the model: maximum value: 750 MP (deformation magnified 3x).
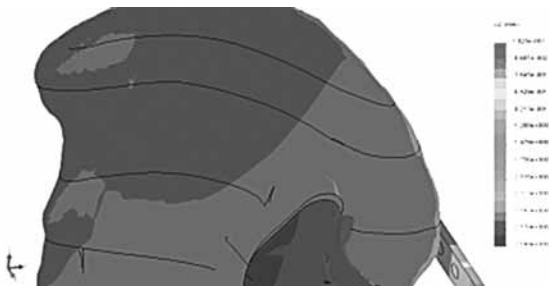
Figure 8. Shift between the fracture surfaces of the sacrum.

Figure 9. Localization of the maximal tension ("sliced" model).

obtained the following results with our model, containing different material properties in all slices. The maximal shift between the fragments of the broken sacrum was 2.9 mm, when simulating standing on one foot (Figure 8).

We measured 0.7 mm vertical shift in the symphysiolysis. The maximal tension (717.5 MPa) was detected in the reconstruction plate fixing the symphysis (Figure 9).

In the validation process, we compared the data retrieved from the finite element model, with those that we gained from the cadaver experiments, which were performed within the same conditions.[8] We can conclude that the shift between the fragments of the broken sacrum (2.9 mm) is very close to the doubled value retrieved from the cadaver experiments (2.6 mm) (Figure 10).

Tensions arising under load were less than the maximal allowed, both in the bones and plates (Table I).

DISCUSSION

We conclude that all performed changes were necessary in order to improve our previous model,[13] and validation of the new model was successful
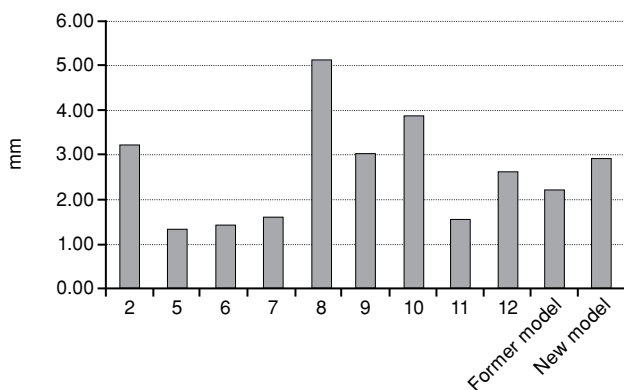

Figure 10. Shift values of the sacrum fragments (mm) obtained from cadaver models (numbered), from the former and the new computerized model.
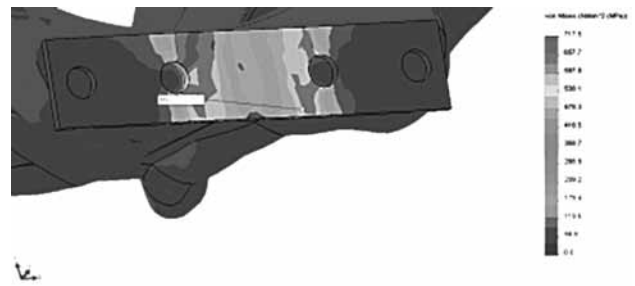
based on the results obtained from the cadaver experiments.[8]

Models which can be found in the literature usually model an intact, uninjured hemipelvis, sometimes an intact whole pelvis.[9-12]

It is widely accepted that in case of a finite element pelvic ring model, it is the rate of the cortical bone that mainly determines the properties of the model.[10,11,14]

That was the main reason, why with the aid of CT images we adjusted our previously used 10%: 90%, cortical-cancellous bone ratio.

In the literature, the mean cortical bone rate in pelvic bone is approximately 20-25%, but obviously it largely depends on the location of the examined area.[12,14] Our calculations of 19.94% (range 7.05-38.27) mean cortical bone rate for the sacrum, and mean 27.1% (range 18.26-39.68) for the pelvis are comparable with those that can be found in the literature, and furthermore it shows that the sacrum is a more cancellous bone.

In the literature, the elastic modulus (Young's modulus) is calculated from the density values gained from the CT-scans.[15-18]

As we already mentioned above, an accurate density-elasticity correlation concerning the pelvic bone is not known yet, it has only been determined with indirect methods.[10,15]

Nevertheless, our mean elastic modulus values (sacrum 3710 MPa, pelvic bone 4900 MPa) calculated from the cortical-cancellous bone ratio nears those, that can be found in the literature.[10,12]

In creating this pelvic model, our aim was not only the modelling of an uninjured pelvis. More importantly, we are able to model the different types of fractures of the pelvis, and their possible fixation techniques. Our primary aim was also the comparison of different surgical methods.

Limitations

In our model, instead of separating the cortical part from the cancellous part, we used mean values.

Considering the whole pelvis, the cortical-cancellous bone ratio was only determined in 10 CT-slices, due to the lack of a more advanced computing technology we could not provide a more detailed model.

Instead of calculating the values of the Young's modulus from the density retrieved from the CT-scans, we used Young's modulus values for the cancellous and cortical part, which was previously reported in the literature.[19]

Conclusion

Compared to the previous one,[13] the new finite element model represents the pelvis more accurately. It can be a more secure tool for the comparison of surgical techniques performed for fixation of different types of fractures in the future.

With the introduction of technological developments in computing science, we would like to improve our model by including more details and so far omitted factors in the future.

Declaration of conflicting interests

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