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Hybrid solution combining osteosynthesis and endoprosthesis for double column acetabular fractures in the elderly provide more stability with finite element model

Yaşlılarda çift kolon asetabuler kırıklar için osteosentez ve endoprotez hibrid kombinasyonu "finite element" yöntemi ile daha çok stabilite sağlar

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ABSTRACT

Objectives: This study aims to compare mechanical stability of osteosynthesis (plate and screw fixation) alone versus the same method supplemented with hip arthroplasty (hybrid solution) for double column fractures in elderly.

Patients and methods: Mechanical investigations were performed on an advanced finite element pelvis model developed for double column fractures. The following simulated implant combinations were analyzed: modular acetabular basket with a ring with polyaxial screws and U-plate; plates with polyaxial screws placed on the medial-horizontal (linea terminalis) and quadrilateral bone surfaces; modular acetabular cup with U-plates; and polyaxial screws in sizes optimized based on a finite element model (FEM). Using the models, the possible shifts in peak load positions arising in different movement patterns caused by load and tension and implant deformation were measured.

Results: Hybrid systems resulted in minimal deformation of the implants already available on the market. We observed less possible shifts and greater stability in the acetabular fracture zones, compared to conventional osteosynthesis alone. Optimization with available and compatible implant sizes led to a further significant increase in stability.

Conclusion: Hybrid method combining osteosynthesis and prosthesis implantation provide more stability in biomechanical models in the treatment of double column fractures in elderly.

Keywords: Acetabular fracture, acetabulum, finite element model, pelvic trauma, plate osteosynthesis, total hip replacement.

ÖZ

Amaç: Bu çalışmada yaşlılarda çift kolon kırıklarında osteosenteze (plak ve vida tespiti) kıyasla kalça artroplastisi ile desteklenen aynı yöntemin (hibrid çözüm) mekanik stabilitesi karşılaştırıldı.

Hastalar ve yöntemler: Çift kolon kırıkları için geliştirilen ileri sonlu eleman pelvis modelinde mekanik araştırmalar yapıldı. İncelenen simüle edilen implant kombinasyonları şunlardı: poliaksiyel vidalı ve U plaklı, halkalı, modüler asetabüler sepet; medial horizontal (linea terminalis) ve kuadrilateral kemik yüzeylerine yerleştirilen poliaksiyel vidalı plaklar; U plaklı, modüler asetabüler kap ve çeşitli ebatlarda sonlu eleman modeline (FEM) göre optimize edilen poliaksiyel vidalar. Bu modellerde yük, gerilim ve implant deformasyonuna bağlı farklı hareket paternlerinden doğan pik yük pozisyonlarındaki muhtemel kaymalar ölçüldü.

Bulgular: Hibrid sistemler, piyasada bulunan implantlarda minimum deformasyona neden oldu. Tek başına konvansiyonel osteosenteze kıyasla, asetabüler kırık bölgelerinde daha az muhtemel kayma ve daha yüksek stabilite gözlendi. Mevcut ve uygun implant ebatlarına göre optimizasyon yapıldığında, stabilitede anlamlı düzeyde ilave bir artış izlendi.

Sonuç: Yaşlılarda çift kolon kırıklarının tedavisinde biyomekanik modellerde osteosentez ve protez implantasyonunu içeren hibrid yöntem daha fazla stabilite sağlamaktadır.

Anahtar sözcükler: Asetabüler kırık, asetabulum, sonlu eleman modeli, pelvik travma, plak osteostentezi, total kalça replasmanı.

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The annual increase of the incidence of acetabular fractures still follows a bimodal pattern. The first spike is represented by pelvic and acetabular fractures in young individuals caused by high-energy impacts, and the second by injuries of the elderly combined with pelvic fractures due to low-energy traumas (>65 years, household accidents).

Both surgical and conservative treatment of pelvic fractures in elderly is a significant challenge for the surgeon due to existing osteoporosis and comorbidities.[1] Osteoporosis (i.e., decreased mineral substance of the bone) developing in elderly has a distinct impact both on the primary and long-term stability of the osteosynthesis.[1]

The positioning and stability of any type of implants in the osteoporotic bone is questionable and their long-term anchorage strength is clearly lower, compared to that of the average age population with appropriate bone density.[2] Conservative therapy may fail due to pneumonia, thromboembolism, and mental disorders with frequent occurrence.

In addition to difficulties with reduction and achieving appropriate stability, treatment of acetabular fractures in elderly produce early post-traumatic femoral head necrosis and osteoarthritis of the hip joint, resulting in a considerably compromised walking pattern, and weight-bearing and walking ability. These complications have a significant impact on the short-term results of the osteosynthesis alone procedures.[3,4]

There are antecedent references in the international literature for the so called hybrid procedures (i.e., osteosynthesis combined with joint replacement in a single session). Resch et al.[5] developed a special kind of hybrid intervention taking into consideration the circumstances mentioned above: acetabular fractures in the osteoporotic bones treated in a single session with the so called roof reinforcement plate, applying osteosynthesis and prosthesis implantation in the same session. The main principle of the method is that a custom-made plate is designed and produced based on the computed tomography (CT) scan of the injured acetabulum and the cup is cemented into this plate. The results are improved, compared to osteosynthesis alone. In a case study of 30 patients, 70% of them were able to be mobilized immediately, half of the patients regained their former walking ability very soon and, despite a burdening surgical intervention, the ratio of general surgical complications was not higher than that of patients of similar age treated by osteosynthesis alone.[5]

In the light of literature data, in the present study, we aimed to compare mechanical stability of osteosynthesis (i.e., plate and screw fixation) alone versus the same method supplemented with hip arthroplasty (i.e., hybrid solution) for double column fractures in elderly and to theoretically determine the ideal position and size of the implants.

PATIENTS AND METHODS

The exposition of theory and practice of finite element modelling (FEM) of biomechanical systems is beyond the limits of our publication, thus we delineate its development only schematically.

It is obvious that the accuracy of computed measurements is significantly influenced by the capacity of the system, which is limited also in the 21st century. The main point is to rigorously consider the biomechanical incidences and the constant values observed in real-life setting, as well.

After planning the model, rasterization (i.e., increase of the resolution) is required until the point, after which increase of resolution does not produce any considerable improvement in the results. For the development of a model representing -or at least being similar to- the real biomechanical situation, appropriate and empirically defined material constants are required.

There are no calculation difficulties in cases of implants produced according to licensed manufacturing standards, as the International Organization for Standardization (ISO) standards of the design of the implants and pureness of alloys and basic materials provide a homogenous, exactly definable and traceable static value.

Biological systems pose a harder problem in case of FEM analysis. In the pelvis, the osseous frame (os coxae, i.e. os ilei, ischii, and pubis) and the ligament structures are non-homogeneous systems with several solid-state physics constants, requiring complex calculations or averaging.

However, according to our former calculations and measurements, the system may be properly simplified: the cancellous bone mass with lower stress resistance cannot be considered negligible, compared to the predominant cortical bone substance; however, it may be averaged, and the ligament system not providing any physical stress transmission due to the injury can be neglected.[6] Accordingly, solid-state physics constants applied in our measurements are represented (Table I).

For the simulation, an actual pathological simulation model is required. In our study, we applied

TABLE I

Physical constants of used materials

Part	Elastic modulus [MPa]	Poisson ratio	Yield stress [MPa]
Cortical bone	17	0.3	
Cancellous bone	0.15	0.2	
Acetabular cup (Ti6Al4V)	113.8	0.342	880
Acetabular inlay (UHMWPE)	0.689	0.46	24.1
Acetabular ring (CP titanium grade 2)	103.4	0.33	345
V-shaped plate (CP titanium grade 2)	103.4	0.33	345
Plate fixing screw (Ti6Al4V)	113.8	0.342	880
Angular-stable screw (Ti6Al4V)	113.8	0.342	880

MPa: Megapascal.

a model of a double column fracture combined with a transversal component, as this represents one of the most unstable fracture configurations. The fracture planes were designed to cross each other at the load transmission point of the acetabulum (Figure 1).

Imaging of the interaction between the fracture planes rendered calculation more difficult. The friction between the fracture planes was calculated with coefficients applied for rough surfaces.

Our model was boundary; fixation surfaces were modelled according to the following: in regard to the fact that we were unable to analyze sacrum fractures or iliosacral lysis in our model, we considered these contact surfaces as an inertia system, thus our model became defined.

Friction constants used for rough surfaces were applied in the fracture gap and calculated with axial fixation in the case of bone-screw connections (considering the computing capacity). Also, the lamellae of the screws were simplified due to computing capacity and rendering times.

We considered screw-plate connections as bounded due to the principles of angular stable screw heads and absolute stability. The uncemented cup-acetabulum connection was a pure non-friction surface transmitting the radial load direction.

After construction of the static model, only testing of mechanical loads occurring during everyday activities is relevant. Due to limited computing capacity, we simulated exclusively movement patterns indispensable for everyday life, but producing high power transmission (i.e., impulse): standing on two feet, standing up from a chair, climbing stairs, and the force impacts exerted on the femoral head and acetabulum.

We retrieved the resulting data and the occurring torque values from the relevant publication.[7]

In the following part, we described the implant models applied in the FEM. We supplemented the modular revision acetabular cup system (Sanatmetal Conetact R) developed by our team with a U-shaped system bridging the fracture line in the cranial direction. The ring is connected to the plasma-coated acetabular cup with a thread, and the U-shaped plate may be fixed to this with separate screws.

Into the empty grooves in the ring and the grooves of the plate, 3.5-mm and 5.1-mm polyaxial screws can be inserted. The plate can be shaped and shortened by grooves (2×4 grooves) without causing damage. The figure depicts the ideal insertion of the implant system (Figure 2). The design similar to the reconstruction plate allows shortening the plate, although screws may not be inserted into all grooves of the ring due to the absence of periacetabular bone substance suitable for screw anchorage.

Of note, both the anterior and posterior columns can be stabilized thanks to the rotation-centric groove of the ring. According to the options listed above

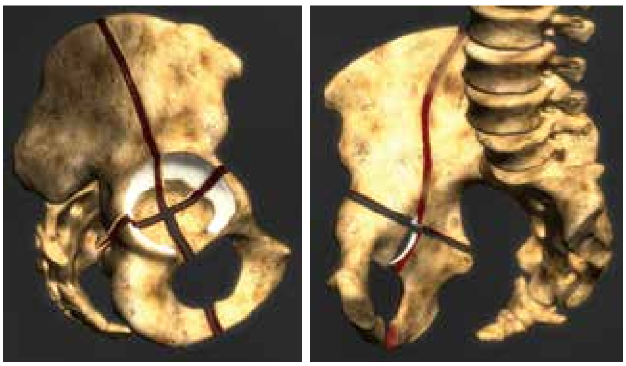

Figure 1. Lateral and internal views of artificial fracture lines.

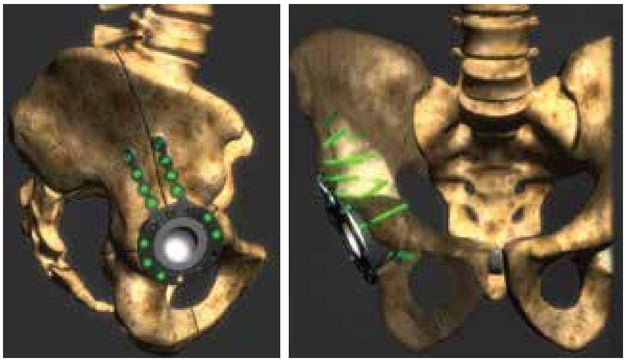

Figure 2. The ideal (full featured) implant use and position.

and the licenses obtained, we also started surgical treatments in addition to biomechanical stability investigations.

The horizontal + quadrilateral surface model using an L-shaped plate (Figure 3) perfectly represents our practical results and, thus, these do not require further explanation.

The results obtained from the biological model were evaluated in the SolidWorks system. We registered predominantly the multidirectional, mostly vertical shifts, tension and deformation arising from the implants in different anatomical regions (i.e., ala, acetabular bottom, anterior column).

Figure 3. An internal view of quadrilateral surface plate.

RESULTS

We analyzed the shifts in a native fracture model (i.e. without implant) mentioned above in the first calculation cycle. For as much as conservative therapy was out of the scope of our investigations, no detail is given here. It is important that shifts close to the acetabulum were larger than 1 mm in the model without implants, which is not compatible either with the biological, or with the mechanical prerequisites of fracture healing.

Osteosynthesis alone (i.e., plate fixation) produced acceptable shift values (considering that we performed a single calculation, not a cyclic one). Another important result is that in the horizontal plate and screws, in cases of minimal shift and any type of load pattern, such a high amount of stress arose which was significantly close to the yield-point of the implant (difference <20%), thus considering the cyclic load and material fatigue, the chance of immediate implant breakage was extremely high. Our self-developed system -even in the case of an idealized model taking into account all fixing options- produced surprising results. The screw fixation of the grooves in the U-shaped plate and in the ring was performed according to the fracture pattern and bone quality.

However, even if we choose the idealized model for the finite element measurements (regardless of surgical exposure and invasiveness), we may draw some essential biomechanical consequences: similarly to the stabilizing pseudopodia or the fixation of a Burch-Schneider basket,[8] the maximal stress was measured in the direction of the screws inserted into the os ischii and ramus ossis pubis (Figure 4).

The screws inserted into the U-shaped plate and the acetabular perimeter zones mentioned above represented only minimal stabilizing factors, despite the fracture gaps running between them. The role of the spherical acetabular cup component

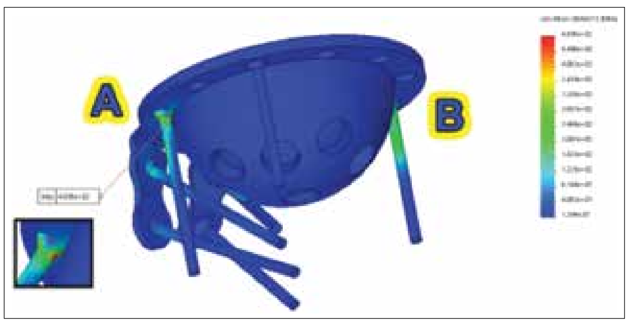

Figure 4. Implant strain during weight-bearing (main load-bearing screws noted with “A” and “B”).

(plasma-coated socket) did not take any part in the load bearing, and this was defined as an advantage, namely this was considered the exact main benefit of the hybrid system.

DISCUSSION

Shift tests performed with the system showed more stability around the acetabulum (i.e., less shift between the fragments). However, computed mechanical experiments verified a larger shift in the region of the iliac bone, probably as the acetabulum was the center of the motion. This might be a considerable factor influencing fracture healing, although we proved in our previous experiments that after fixation of the anterior column (our system is suitable also for this thanks to the grooves), the iliac bone did not require any additional fixation.[6]

As a supplement, we provided CT scans taken under load three months after surgery. According to the results of simulation, the screw exposed to the strongest stress broke. We optimized the implants based on the practical results and in accordance with our primary objectives.

The main point of each FEM is optimization. However, in the case of biomechanical implants, we need to take into consideration the compatibility of the already existing implants and their availability on the market, in addition to optimal mechanical manufacturing. If we perform optimizing measurements on such implants, time-consuming licensing procedures can be avoided.

Based on these facts, possible optimization calculations of our hybrid system were determined as follows: Can the length of the U-shaped plate and the number of the 3.5 mm screws be reduced?; Can we increase the size of the screws inserted into the ring; and Does this increase stability? Stability can be increased by the reduction of the length of the plate (decreased invasiveness) and by the increase of the core diameter of the main load bearing screw (Figure 5, 6, and 7).

The stress on the implants is decreased (significantly under the yield-point), the number of required implants is reduced (less invasion and bone loss), and the possible shift is less; therefore, we can achieve higher stability with less invasiveness and bone loss. It is unambiguously proven that the hybrid method of fixation (osteosynthesis + prosthesis) provides fewer shifts (i.e., warrants higher stability) during load patterns, compared to plate osteosynthesis alone.

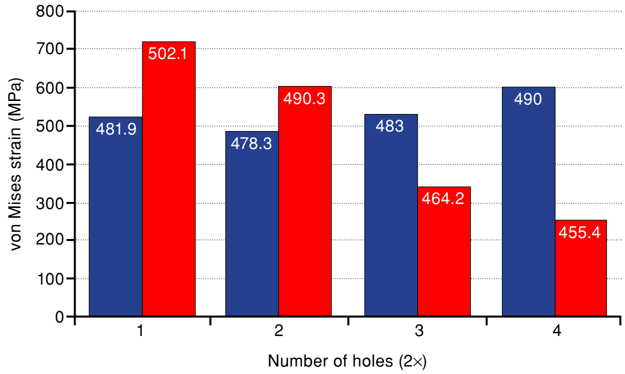

Figure 5. Strain ratio according to plate length (blue: stairs climbing; red: rising from a chair).

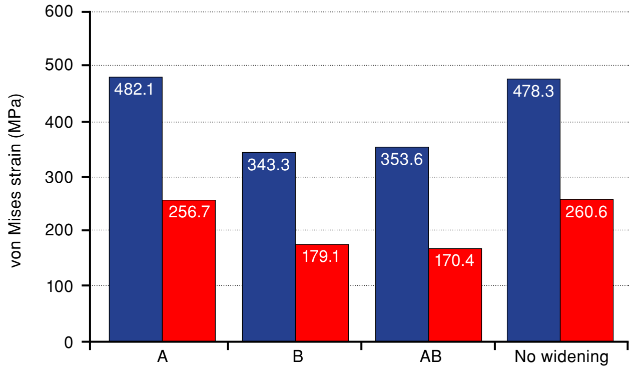

Figure 6. "A" and "B" screw strain during weight-bearing (blue: stair-climbing; red: rising from a chair).

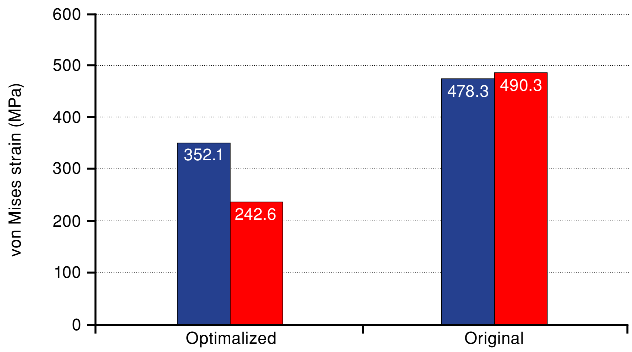

Figure 7. Peak strain comparison between original and optimized implants (blue: stair-climbing; red: rising from a chair).

Our measuring system indicated lower stress and less shifts in the most involved acetabular zone in the hybrid system, compared to those after plate osteosynthesis. The larger shift in the iliac bone had no impact on stability. Furthermore, the optimized implant model did not reach the safety limits of the implanted materials.

In conclusion, based on the results of the biomechanical investigations, hybrid solutions (osteosynthesis + prosthesis) provide higher stability and improved biomechanical results, compared to other surgical procedures for double column fractures in elderly. With regard to the joint replacement, complications such as necrosis of the femoral head and osteoarthritis can be avoided, but cannot be modelled in a FEM.

Declaration of conflicting interests

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