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Technical note

Computer-assisted surgery in acetabular fractures: Virtual reduction of acetabular fracture using the first patient-specific biomechanical model simulator

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ABSTRACT

Preoperative planning for the management of acetabular fracture is founded on geometric models allowing virtual repositioning of the bone fragments, but not taking account of soft tissue and the realities of the surgical procedure. The present technical note reports results using the first simulator to be based on a patient-specific biomechanical model, simulating the action of forces on the fragments and also the interactions between soft issue and bone: muscles, capsules, ligaments, and bone contacts. In all 14 cases, biomechanical simulation faithfully reproduced the intraoperative behavior of the various bone fragments and reduction quality. On Matta's criteria, anatomic reduction was achieved in 12 of the 14 patients (86%; 0.25 mm ± 0.45 [range: 0–1]) and in the 12 corresponding simulations (86%; 0.42 mm ± 0.51 [range: 0–1]). Mean semi-automatic segmentation time was 156 min ± 37.9 [range: 120–180]. Mean simulation time was 23 min ± 9 [range: 16–38]. The model needs larger-scale prospective validation, but offers a new tool suitable for teaching purposes and for assessment of surgical results in acetabular fracture.
Level of evidence: IV: retrospective study.

1. Introduction

The development of imaging and information technology has enabled new approaches to acetabular surgery [1]. Virtual preoperative planning is not new in orthopedic surgery [2,3]. Good understanding of the fracture, based on CT scans and 3D reconstruction, is required, especially to decide on the surgical approach and reduction sequences [1,4,5]. Several tools for preoperative planning in acetabular fracture have been presented in the literature [6–9]. Studies report improved understanding and definition of surgical strategy, with operative time-saving, reduced bleeding and improved reduction. Errors in understanding the fracture and in surgical strategy may lead to choosing the wrong approach and to reduction failure [10–12].

Simulators are all based on geometric models for virtual bone fragment repositioning, without taking account of soft tissue or intraoperative reality, such as collision between fragments and the limitations imposed by the surgical environment.

In the light of these limitations, and with a view to making simulation realistic, we developed a patient-specific biomechanical acetabular fracture reduction simulator. The present technical note aims to present results for the first simulator based on a patient-specific biomechanical model.

2. Description of the technique

Between November 2015 and November 2016, 14 patients were operated on for acetabular fracture by the first author in our center. All gave consent. Table 1 shows epidemiological data. Surgery used an anterior (Stoppa-Cole or ilio-inguinal) and/or Kocher-Langenbeck posterior approach [13], depending on strategy. Mean operating time was 150 ± 47 min [range: 90–240 min].

A 3D model of the bone fragments was constructed. Semi-automatic segmentation used the open-source ITK-Snap package (ITK-Snap, Philadelphia, PA). After importation of DICOM images, the region of interest was selected by thresholding bone density so as to segment only bone structures; the software then performed segmentation automatically by region growth. Manual finishing

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Table 1
Main patient characteristics.

Patient characteristics	$n = 14$
Age (years)	39.4 ± 17.7
Gender	
Male	12 (86%)
Female	2 (14%)
Lesion mechanism	
Road accident	6 (43%)
Sports accident	5 (36%)
Work accident	2 (14%)
Low-energy trauma	1 (7%)
Accident-to-surgery time (days)	9 ± 6
Letournel classification [9]	
Simple fracture	
Posterior wall	2 (14%)
Anterior column	3 (21%)
Transverse	2 (14%)
Complex fracture	
T fracture	2 (14%)
Transverse + posterior wall	1 (7%)
Anterior column + posterior hemitransverse	2 (14%)
2-column	2 (14%)
Approach	
Anterior	7 (43%)
Posterior	4 (29%)
Dual	3 (21%)

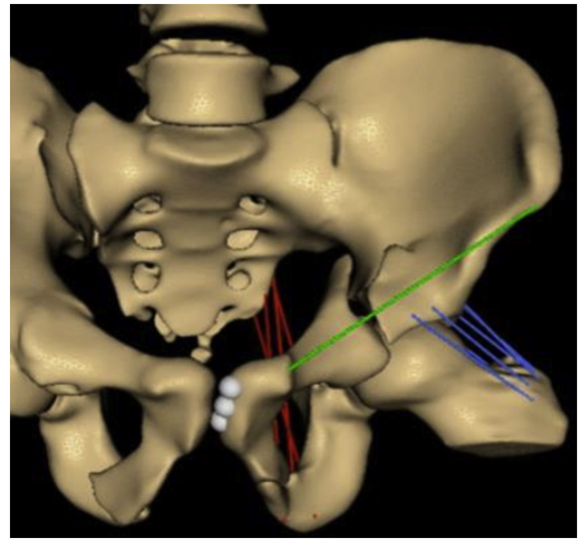

Fig. 1. Biomechanical model of case no. 3 (2-column fracture), with modeled soft tissue: joint capsule (blue), sacrospinous and sacrotuberous ligaments (red), inguinal ligament (green), and pubic symphysis (gray balls).

separated the various fragments in comminuted fractures [14]. Soft tissue was not segmented.

A patient-specific biomechanical model was constructed and implemented in the open-source ArtiSynth (ArtiSynth, Vancouver, Canada) simulation environment [15]. Each bone fragment was considered to be an independent rigid body. Bone attached to the sacro-iliac joint was considered to be fixed, whereas the other fragments were considered mobile. Collisions were considered, to ensure against bone fragment interpenetration. The action of the various surgical instruments (clamps, Schanz screws, traction, etc.) was simulated in translation and rotation. To make the simulation realistic, the muscles and their effective action on the bone were simulated by applying global damping on the system, corresponding to a field of viscosity simulating the action of curarized muscles. This simple but effective "trick" avoided any non-anatomic displacement or numerical instability relating to the forces applied on the fragments. The tissues involved in the reduction and balancing of the system (i.e., joint capsule, sacrospinous and sacrotuberous ligaments, inguinal ligament and pubic symphysis) were modeled and set in the model by the surgeon according to the type of fracture (Fig. 1). Each patient-specific model was constructed by the surgeon and adapted to the type of fracture. Real and simulated reduction quality, assessed on postoperative CT scan by an independent observer using Matta's criteria [16], was compared.

Statistical analysis used StatView 5.5 software (SAS Institute, Cary, NC, USA). The non-parametric Mann-Whitney test was used to compare quantitative variables (i.e., reduction, in millimeters). The significance threshold was set at 5%.

3. Results

Fourteen surgeries and 14 simulations were performed. The same reduction sequences as implemented surgically were reproduced on the simulator, and reduction quality was compared between the two. Biomechanical simulation systematically reproduced exactly the bone fragment behavior observed intraoperatively, and the reduction quality. Anatomic reduction was achieved in 12 patients (86%; 0.25 mm ± 0.45 [0–1]) and in the 12 corresponding simulations (86%; 0.42 mm ± 0.51 [0–1]). There was no significant difference in reduction on simulation and after surgery ($p > 0.05$). Results are shown in Table 2. Mean semi-automatic segmentation time was 156 min ± 37.9 [range: 120–180]. Mean simulation time was 23 min ± 9 [range: 16–38]. Fig. 2 shows an example.

4. Discussion

The main interest of this preoperative planning tool derives from the new paradigm according to which it is the actual procedure rather than the desired result that is to be simulated. In the literature, all authors describe geometric models for repositioning each bone fragment by moving them freely in 3 dimensions, in translation and rotation [6–8]. However, this does not match surgical reality: fragments cannot always be considered independent, as they are sometimes connected by elements such as the joint capsule or sacrospinous ligament. The present biomechanical model corresponds to a stable numeric environment comprising bone fragments, soft tissue and their interactions.

The present study involves certain limitations. Firstly, the simulator could not be tested on all possible types of fracture. Secondly, the segmentation process could be improved. The difference in bone density between cancellous and cortical bone within the fracture site and the wide range of fracture types requires time-consuming manual finishing. In our experience, mean segmentation time was 156 minutes, whereas in the literature it varies between 38.7 and 130 minutes [7,8,17]. Semi-automatic segmentation is sometimes imperfect, leading to abnormal collisions that hinder reduction. Body mass index and age did not affect segmentation quality. Lastly, we did not test the simulator under real conditions (i.e., preoperatively), as we wanted to validate it against surgical reality. Now that it has been shown that this patient-specific biomechanical model faithfully reproduces bone fragment behavior with respect to the surgical reduction sequences, a controlled prospective study could confirm these preliminary findings.

Some authors use custom-made plates based on preoperative planning to guide reduction [18]. Another solution uses virtual planning combined to 3D printing [9,19]. The present planning tool could also be used as a teaching aid and for surgeon training in this demanding technique. It could improve understanding of acetabular fractures and treatment, especially for trainee surgeons.