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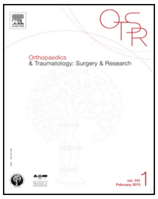

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A numerical model to reproduce squeaking of ceramic-on-ceramic total hip arthroplasty. Influence of design and material

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ABSTRACT

Background: Modern ceramic (CoC) bearings for hip arthroplasty (THA) have been used in younger patients who expect improved survivorship. However, audible squeaking produced by the implant is an annoying complication. Previous numerical simulations were not able to accurately reproduce in vitro and in vivo observations. Therefore, we developed a finite element model to: (1) reproduce in vitro squeaking and validate the model by comparing it with in vivo recordings, (2) determine why there are differences between in vivo and in vitro squeaking frequencies, (3) identify the stem's role in this squeaking, (4) predict which designs and materials are more likely to produce squeaking.
Hypothesis: A CoC THA numerical model can be developed that reproduces the squeaking frequencies observed in vivo.
Material and methods: Numerical methods (finite element analysis [ANSYS]) and experimental methods (using a non-lubricated simulated hip with a cementless 32 mm CoC THA) were developed to reproduce squeaking. Numerical analysis was performed to identify the frequencies that cause vibrations perceived as an acoustic emission. The finite element analysis (FEA) model was enhanced by adjusting periprosthetic bone and soft tissue elements in order to reproduce the squeaking frequencies recorded in vivo. A numerical method (complex eigenvalue analysis) was used to find the acoustic frequencies of the squeaking noise. The frequencies obtained from the model and the hip simulator were compared to those recorded in vivo.
Results: The numerical results were validated by experiments with the laboratory hip simulator. The frequencies obtained (mean 2790 Hz with FEA, 2755 Hz with simulator, decreasing to 1759 Hz when bone and soft tissue were included in the FEA) were consistent with those of squeaking hips recorded in vivo (1521 Hz). The cup and ceramic insert were the source of the vibration, but had little influence on the diffusion of the noise required to make the squeaking audible to the human ear. The FEA showed that diffusion of squeaking was due to an unstable vibration of the stem during frictional contact. The FEA predicted a higher rate of squeaking (at a lower coefficient of friction) when TZMF^{TM} alloy is used instead of Ti6Al4V and when an anatomic press-fit stem is used instead of straight self-locking designs.
Discussion: The current FEA model is reliable; it can be used to assess various stem designs and alloys to predict the different rates of squeaking that certain stems will likely produce.
Level of evidence: Level IV in vitro study.

1. Introduction

The longevity of total hip arthroplasty (THA) has become a prime goal of implant designers, particularly as it becomes a routine procedure in young and active patients [1,2]. In recent years, development strategies have focused on improving alternative bearing surfaces in order to decrease wear and osteolysis [3].

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Ceramic-on-ceramic (CoC) bearings have low wear rates [4], excellent biocompatibility and good tribological properties [5]. They have a low coefficient of friction in lubricated conditions, resulting in excellent wear resistance and less bioactive particulate debris than metal or polyethylene [6]. Because of these qualities, the ceramic hip prosthesis is frequently used throughout the world, especially for young and active patients [1–7]. Enthusiasm for CoC bearings has been tempered recently by reports of disturbing squeaking noises [8]. Squeaking is primarily a problem of hard-on-hard bearings, and has been increasingly reported as a complication of modern CoC bearings [9]. It becomes a real social problem for patients [10]. The reported clinical incidence of squeaking with CoC hip bearings varies between 0.7% and 20.9% [11–16], and can be qualified as worrisome.

The precise etiology of squeaking remains unknown, but most recent studies concur that it is multifactorial [17,18], with three principal contributing factors: (a) patient demographics, including age, sex, height, weight, body mass index (BMI) [8,9,19] and type of activity [12]; (b) surgical technique, especially implant mal-positioning (acetabular anteversion and inclination) leading to impingement and generation of wear particles [9,20], micro-separation (due to joint laxity) leading to edge-loading [21] and mismatched ceramic bearings [22]; and (c) outcome and numerical analyses related to implant type or design, including femoral neck length and diameter (metal deposition/metallosis on bearing surfaces), elasticity and stiffness of metal femoral stems and acetabular shells (metal components frequencies) [23–27].

A solid object vibrates in response to excitation (e.g. impact, motion, friction, etc.) at a specific set of frequencies that depend on its physical properties (e.g. material, density, dimensions and boundary conditions). The vibration frequencies are unique for each solid object (e.g. the acoustic resonance of a tuning fork at 440 Hz) and are hence termed "characteristic frequencies" or "eigenfrequencies". These characteristic frequencies represent the object's acoustic signature. Identifying the characteristic frequencies of the various components in the prosthesis was an important part of dealing with squeaking as a vibration phenomenon.

Reproducing the dynamic behavior of implant components could help us to understand the mechanical factors that cause squeaking, provide an accurate explanation to surgeons and find the appropriate solution. To investigate and understand this phenomenon, we used numerical and experimental approaches to reproduce squeaking. This method has been used to analyze the squeal sound emitted during automotive braking [28]. In vivo measurements of the squeaking sound reported in the literature or recorded on patients were used to validate the model.

The goals of the current study were to:

- reproduce in vitro squeaking and validate the model by comparing it with in vivo recordings;
- determine why the squeaking frequencies are different between in vivo and in vitro conditions;
- identify the stem's role in this squeaking;
- predict which designs and materials are more likely to produce squeaking. Our hypothesis was that a numerical model could be developed that reproduces the squeaking frequencies observed in vivo.

2. Material and methods

2.1. Materials

In the numerical portion of the study, a finite element model (Fig. 1a) was developed using commercial finite element analysis (FEA) software (ANSYS Workbench, Swanson Analysis Systems, Canonsburg, USA). The hip replacement system consisted of four components: Dynacup^{TM} 52 mm acetabular shell with three screw holes, Meije^{TM} 4L stem (both made of Ti6A14V alloy), 12/14 mm taper with CoC Delta^{TM} 32 mm head and Delta^{TM} insert (outer ceramic liner diameter of 44 mm) (Tornier SA, Montbonnot, France). The material parameters used in the FEA model are listed in Table 1. In order to generate acoustic squeaking emissions, this model does not include synovial fluid (high coefficient of friction condition); this reproduces scenarios when the lubricant synovial film is broken in specific conditions such as impingement, stripe wear, edge-loading [29], and metal transfer [27]. The stem was loaded by applying a force at the top of its taper and along its axis of rotation. The acetabular components (liner and shell) were allowed to rotate around the axis of symmetry of the ceramic part. A numerical method called "complex eigenvalue analysis" [24,30] was used to find the acoustic frequency of the squeaking of the hip replacement system and identify the mechanical state of the acoustic phenomenon.

Table 1
Material parameters of the prosthetic components.

Materials	Density (kg/m^3)	Young's modulus (Pa)	Poisson ratio
Ti6A14V	4420	1.05×10^{11}	0.31
Ceramic	4370	3.58×10^{11}	0.23
Simulated bone	1932	2.0×10^{10}	0.3
Simulated muscle	1000	1.0×10^{6}	0.47

A laboratory hip simulator was used to reproduce the squeaking experimentally (Fig. 1b) to validate the numerical results. The experimental simulator used the same type and size of prosthetic components as the FEA model. The experimental approach used a simplified test set-up providing rotational motion of the metal-back shell and a contact load at the end of the stem. This set-up was designed to reproduce squeaking noises in dry (non-lubricated) conditions without the influence of bone or soft tissues. The acoustic frequency of the emitted sounds was measured using an accelerometer (PCB Piezotronics, Depew, NY 14043, USA) with a 16-channel acquisition system (OROS SA, Meylan, France) associated to NVgate analyzer software.

2.2. Assessment methods

To validate the model in vivo, two concentric cylinders were added to the assembled system to simulate bones and muscles (Fig. 2). This more closely approximates the in vivo conditions for the hip prosthesis and makes it possible evaluate the effects of bone and soft tissues on the squeaking frequency. Clinical squeaking frequencies were recorded in patients to provide a reference value for in vivo squeaking frequencies (Table 2).

The results of the numerical model were compared to the in vitro frequencies reported in the literature that were measured experimentally on implants placed in a hip simulator. They were also compared to in vivo frequencies recorded on patients by the authors or reported in the literature (Table 2). Finally, various stem designs and materials were tested in the FEA model to determine how these parameters influence the likelihood of squeaking.

2.3. Statistical methods

Non-parametrical tests were applied to compare the in vivo and in vitro frequencies (Table 2), as well as the frequencies recorded in the model. A P-value of less than 0.05 was considered significant. Other results were expressed in a descriptive manner because of the limited number of specimens.

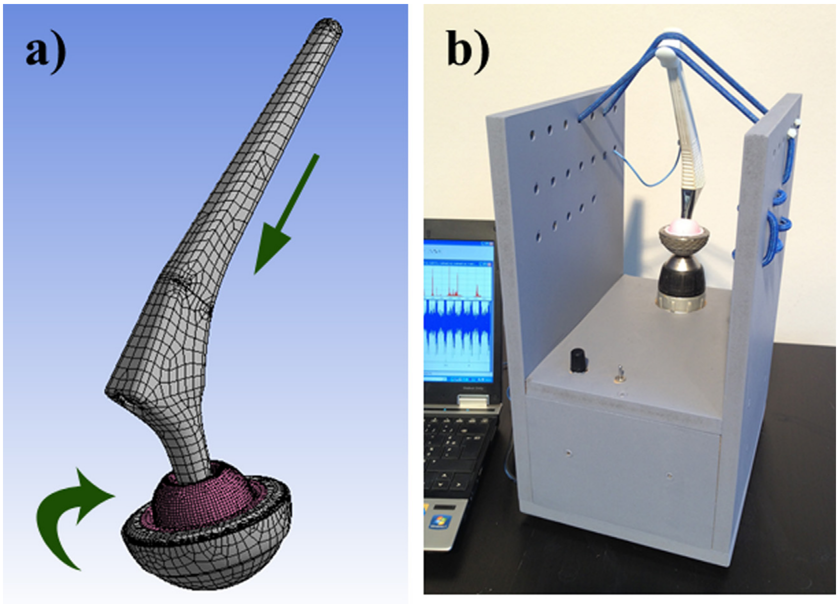

Fig. 1. a: the finite element model with in vitro boundary conditions; b: the experimental setup including the rotation mechanism, a spring applying the load at the upper end of the stem, and a sample prosthesis.

Table 2
Squeaking frequencies reported in literature between 2008 and 2012, recorded directly on patients by the authors, or found on the internet.

N	Origin in vitro	Frequency (Hz)	N	Origin in vivo	Frequency (Hz)
1	Hothan et al. [25]	4350	1	Author recording patient #1 – 2011	1012
2	Hothan et al. [25]	4050	2	Author recording patient #2 – 2011	1200
3	Hothan et al. [25]	3700	3	Author recording patient #3 – 2011	995
4	Hothan et al. [25]	3400	4	Author recording patient #5 – 2010	906
5	Weiss et al. [24]	3400	5	Author recording patient #4 – 2011	1641
6	Sariali et al. [31]	2600	6	E. Belzile – Hip Congress Toulouse 2011 (http://www.chu-toulouse.fr/IMG/pdf/programme_hip.pdf)	550
7	Currier et al. [32]	3617	7	Sariali et al. [31]	2460
8	Currier et al. [32]	2400	8	Sariali et al. [31]	2300
9	Current experimental study (#1)	3972	9	Sariali et al. [31]	2240
10	Current experimental study (#2)	3908	10	Sariali et al. [31]	1450
11	Current experimental study (#3)	3461	11	Currier et al. [32]	2530
12	Current experimental study (#4)	3262	12	Currier et al. [32]	1540
			13	Recording by author on YouTube 1	1791
			14	Recording by author on YouTube 2	1179
			15	Recording by author on YouTube 3	1004
			16	Restrepo et al. [23]	1546
	Minimum (Hz)	2400		Minimum (Hz)	550
	Maximum (Hz)	4350		Maximum (Hz)	2530
	Average in vitro frequency (Hz)	3510		Average in vivo frequency (Hz)	1521

3. Results

The FEA model shows that friction between the ceramic parts induced vibrations that correspond to periodical deformations of the system, which is composed of a stem with a ceramic head that interacts with the ceramic acetabular component (Fig. 3). As the coefficient of friction increases and reaches a critical value (equal to 0.5), the two stem deformations (along two different planes) combine and give rise to an unstable audible vibration that is perceived as squeaking. By increasing the coefficient of friction in the numerical model, the coefficient of friction at which the two vibrations combined was identified, and the frequency of the squeaking was found to be 2790 Hz.

On the experimental side, the acoustic frequency of the squeaking noise was measured on the hip simulator. The vibration signal corresponded to the recorded noise with a frequency of 2755 Hz (Fig. 4). This frequency is very similar to the numerical simulation result (2790 Hz), confirming the accuracy of the FEA model (relative mismatch of 1.2%).

This frequency corresponds to a periodic deformation of the stem. Additionally, experimental evaluations of each implant component showed that the characteristic frequencies (acoustic signature) of the stem are closer to the measured squeaking frequency (in vitro), while the characteristic frequencies of the metallic shell are higher than 8 KHz and those of the ceramic insert are higher than 20 KHz. This confirms that the shell and ceramic insert have little influence in the diffusion of squeaking. The dynamic numerical analysis confirmed that the squeaking (acoustic emission) is due to unstable friction-induced vibrations, which result in a resonance related to the femoral components [30].

An average frequency of 3510 Hz was found in vitro and an average frequency of 1521 Hz was found in vivo ($P < 0.05$). When pseudo in vivo conditions were evaluated with the FEA model (soft tissues and muscle elements were placed around the femoral stem), the

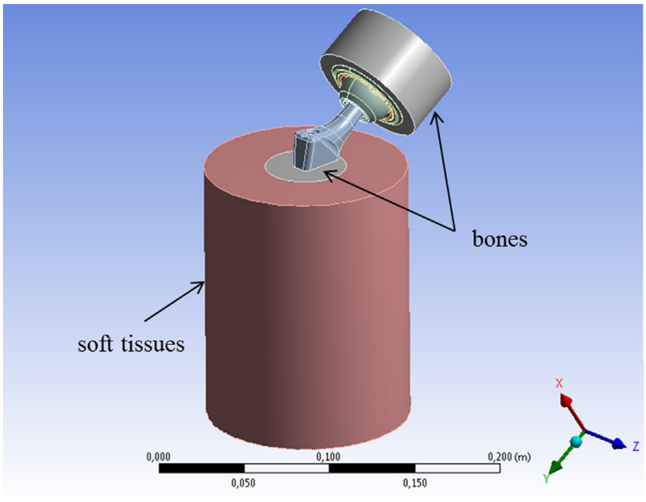

Fig. 2. The numerical model with pseudo in vivo conditions: two concentric cylinders simulating bones and muscles have been added to the assembled system.

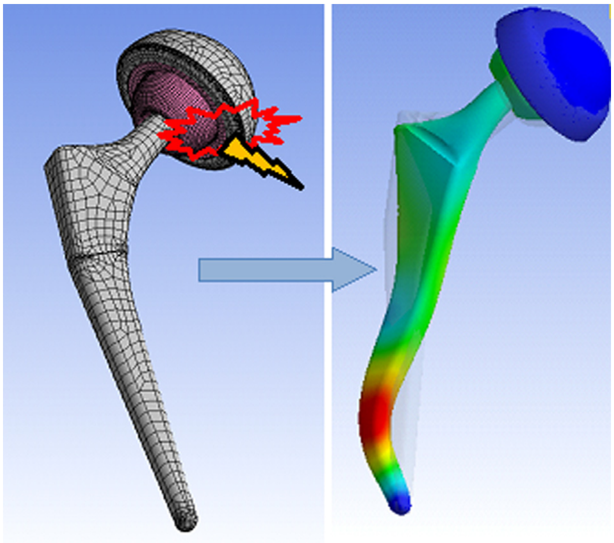

Fig. 3. Displacement graph for one type of prosthesis vibration, a bending vibration in the stem's plane induced by friction between the ceramic parts.

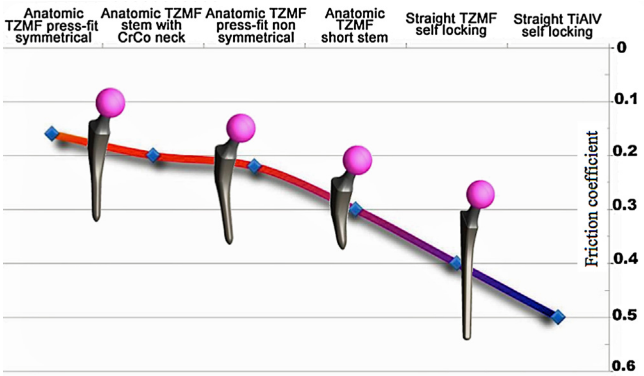

Fig. 5. Different designs and materials were introduced into the FEA model. Use of TZMF^{TM} alloy (instead of Ti6Al4 V) with anatomical stems (instead of straight self-locking stems) produces the highest rate of squeaking at lower coefficients of friction. A self-locking Muller-type stem made of Ti6Al4V (Meije^{TM}, Tornier Montbonnot, France) was used in this study.

squeaking frequency decreased from 2790 Hz (in vitro condition) to 1759 Hz (in vivo condition). These last results compare favorably to the records found in the literature and those measured on patients by the authors (Table 2). This proves that our model is relevant for reproducing in vivo squeaking, since the numerical simulations of in vivo conditions (adding bone and soft tissues) were are within this range ($P > 0.05$). Finally, since squeaking is related mainly to the femoral component, different designs and materials were introduced in the FEA model. This confirmed that anatomical stems and TZMF^{TM} alloys are more susceptible to producing squeaking at low coefficients of friction (Fig. 5).

4. Discussion

A FEA model of a CoC hip replacement system has been developed to reproduce and analyze the squeaking phenomenon. The mechanism of squeaking was investigated using the complex eigenvalue method to identify and predict the vibration frequencies that are the source of the acoustic emission. The numerical model and its results were validated using a simple experimental hip simulator. The results of our study show that the frequencies of unstable vibrations of the prosthetic system are in agreement with the squeaking frequencies measured during experimental tests. The FEA model predicted a squeaking frequency of 2790 Hz and was in agreement with previous studies [25,33]. This result is very close to the squeaking frequency of 2755 Hz measured during the experimental tests, with a mismatch of only 1.2%.

This study has several limitations:

- although this was a mathematical FEA model of THA components, the model was validated by comparing the results with experimental and in vivo data;

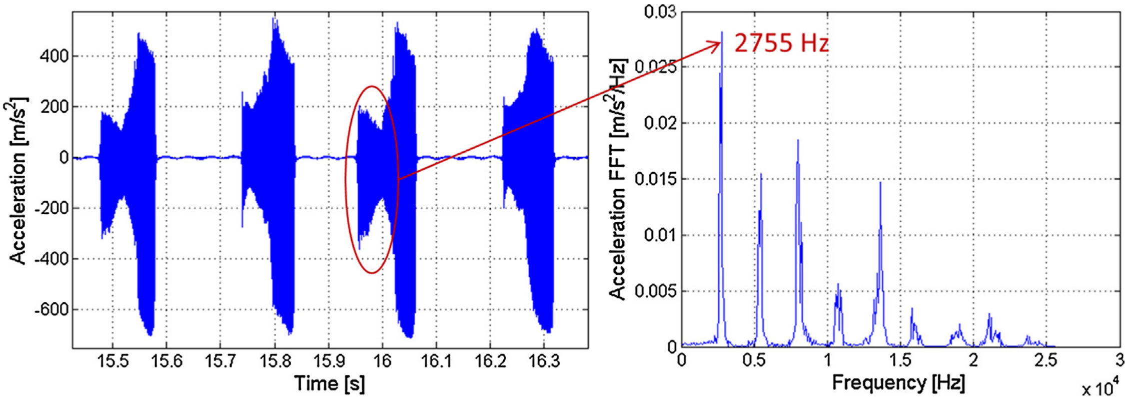

Fig. 4. Analysis of the signal extracted when the setup generates an acoustic emission (squeak): the squeaking frequency is detected using a Fourier transform application.

- lubrication was not introduced in the model or in hip simulator trials. Because loss of lubrication is considered to be the first step in creating squeaking with CoC components [20], the study was designed to use the bearing in the worst case scenario to produce squeaking;
- simulated in vivo squeaking was compared to an average of 16 squeaking records from patients implanted with different hip replacement designs and different morphologies (Table 2). Ideally, the comparison should have been performed with in vivo squeaking using the same Tornier femoral stem as used in the FEA model; however, this stem was not clinically available. This would certainly have improved the in vivo validation of the numerical model.

The stem's characteristic frequencies are close to the observed squeaking frequency. The femoral components and its vibrations were found to have a key role in the occurrence of squeaking, confirming previous scientific and clinical observations [9]. Nevertheless, even though the cup was found to have no resonance in the squeaking frequency range, it influenced the dynamic stability of the whole system by dissipating more or less frictional contact [25,32]. The findings of this analysis confirmed the theory of modal lock-in [24,28,33]: as the coefficient of friction increases, the characteristic frequencies of two adjacent structural deformations of the system (the stem in our case) shift in frequency and approach each other. When the coefficient of friction reaches a critical value, the vibrations in two different planes constructively interfere. They are amplified significantly enough to become audible (unstable vibration with a high amplitude at 2790 Hz).

The unstable vibration of prosthesis components is excited in high coefficient of friction conditions. Part of the energy provided by friction is dissipated or re-introduced in the system in the form of vibrations [33,34]. This result is consistent with clinical results that report stripe wear [12], impingement [19], edge-loading [15] or metal transfer [27] as causes of squeaking; these are all possible pathways to higher friction between the ceramic bearing surfaces. Therefore, when the friction between the contact surfaces increases, the propensity of the ceramic hip prosthesis to become unstable and emit squeaking noise increases. In our numerical simulation, squeaking occurs at extremely high friction levels of 0.5, well above the typical level of less than 0.1 under normal lubrication conditions. Similarly, on the experimental simulator, the squeaking appeared only in the worst, completely dry (non-lubricated) conditions.

In the literature, a mismatch is reported between the squeaking frequencies measured in vitro (average of 3510 Hz) with experimental hip simulators and those measured in vivo (average of 1522 Hz) (Table 2). This difference can be explained using the numerical model described in this study. The simulations show that characteristic frequencies of the system change when periprosthetic bone is included in the model, as this increases stiffness with respect to the mass. Adding muscle, characterized by low stiffness and considerable volume and mass, has the greatest effect on the model and significantly reduces characteristic frequencies to 1759 Hz. These frequencies values are close to squeaking frequencies recorded in vivo.

This validated numerical model, which is based on experience with studies of brake squeal [28,30], confirms the major influence of the femoral component on the transmission of the squeaking sound. Moreover, recent work [31,35] has shown that modal dynamic instability can occur in any mechanical system, including frictional pairs. This model is essential for understanding this phenomenon in depth. Our preliminary results may explain the different rates of squeaking encountered in the literature for femoral stems of different designs and materials (Fig. 5). In the current study, a Muller-type stem (Meije^{TM}) was found to be less sensitive than an anatomic stem. The acetabular cup, with its geometry, metallic rim that creates metal debris [14,29], and its suboptimal positioning, associated with ligament laxity, can be the cause of a breakdown of the lubricant film that causes the stem's excitation and audible vibration. Orthopedic implant manufacturers can only reduce this phenomenon by changing the geometry and material of the implants. The development of new ceramic composites with improved tribological characteristics in dry lubrication conditions would definitely reduce the phenomenon; however, this would require significant development time and a particularly long and expensive clinical validation phase.

5. Conclusion

Having a model that accurately simulates squeaking gives the industry the opportunity to optimize the design of future femoral stems to reduce their sensitivity to high friction conditions. By changing stem geometry or material, selected characteristic frequencies may be altered to prevent them from combining into one unstable frequency when the friction energy increases. Parameters such as stiffness, mass, length, and material could be carefully selected, taking the morphology of the distal and proximal femur into consideration, to control and reduce acoustic emission from the femoral stem.

Disclosure of interest

Philipe Piriou declares no conflict related to this work but declares out of this work consultancy with Biomet, Amplitude, Tornier and Microport and receives royalties from Tornier.

Henri Migaud declares no conflict related to this work but declares out of this work Education and Research consultancy with Tornier and Zimmer.

Eric Renault declares no conflict related to this work but declares out of this work employment by Tornier.

Michel Serrault declares no conflict related to this work but declares out of this work consultancy with Tornier.

Francesco Massi and Ghassene Ouenzerfi declare no direct conflict related to this work, but their research unit (LaMCoS INSA, Lyon, France) received grants from Tornier for this study.

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