Effect of callus development on the deformation of external fixation frames

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Received: 6 September 2012 / Accepted: 28 September 2012 / Published online: 17 October 2012
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Abstract

Purpose We designed a sensor that measures the bending moments at the articulations and the torque of the rod of a Hoffmann II® external fixation. We considered the effect of the callus formation in the stabilisation of a “fracture-fixation system.”

Methods Four Hoffmann II® frame configurations were mechanically tested. Two carbon fibre tubes represent the bone fragments (length 180 mm, outer diameter 25 mm, inner diameter 19 mm). The callus is represented by the interposition of springs of different rigidity (10–405 N/mm) in the fracture gap between the tubes.

Results The deformation of the frame is in inverse proportion to the stiffness of the callus; the slope of the curve drops rapidly during early development of the callus, to reach a plateau after some 50 % of recovery of the normal mechanical characteristics of the bone. This simulation supports the theoretical approach, i.e. the external frame resists larger stresses at the start of the fracture healing. Over a callus stiffness of some 200 N/mm the pattern of the curves remains similar, regardless of the frame configuration.

Conclusion An optimisation of the frame is possible, adapted to the actual mechanical situation of the callus. A monitoring system is deemed reliable after making sure that the elementary components behave the same way in the clinical condition as in the laboratory. In an experimental set up we confirmed its reliability in a clinical-like situation.

Introduction

We propose to verify the relative independence of the frame deformation of Hoffmann II® external fixation frames, regardless of the configuration, for increasing values of callus stiffness. We assume that callus rigidity is directly related to the mechanical behaviour (i.e. stiffness and strength) of a healing fracture and therefore is useful to monitor. Improvement of the callus mechanical characteristics increases the load transmission at the fracture site that increasingly contributes to the stability of the system.

Knowing the elementary mechanical characteristics of the Hoffmann II® components (individually tested in optimal in vitro situation), is it possible to validate those characteristics from an in vitro destructive test, performed on different frame configurations?

Material and methods

We designed a sensor that measures the bending moments at the articulations and the torque of the rod of a Hoffmann II® external fixation. It consists of two regular stainless steel rods instrumented with strain gauges (Fig. 1). The geometrical parameters to orient the sensor against the fixation hardware need to be introduced into the system:

- The distance from the gauge to the articulations, proximal and distal
- The orientation of the instrumented rod against the posts (rod-post angle, proximal and distal)
- The orientation of the instrumented rod against the pins (rod-clamp angle, proximal and distal)

Once this is achieved the measurements are performed and the calculation is straightforward with real time monitoring of the torque applied to the rod(s) and the moments at the articulations recorded.

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Fig. 1 Ideal frame configuration, with two sensing rods and four points of measurement (A1, B1, A2, B2)

The stability of an osteosynthesis relies upon fracture configuration and mechanical strength of individual elements of fixation to avoid any failure of the frame when loaded. The mechanical characterisation of the elementary components has been provided by Stryker. The articulation coupling with the weakest characteristics is only of interest as we are concerned by the torque around the axis A (or B, 16.2 ± 2.9 Nm, Fig. 2).

Four Hoffmann II® configurations have been tested to failure in axial compression (Schenck Hydropulse PSA 10 K® machine, electronically controlled). Two carbon fibre tubes represent the bone fragments (length 180 mm, outer diameter 25 mm, inner diameter 19 mm). The callus is represented by the interposition of springs of different rigidity (10 to 405 N/mm), in the fracture gap, between the two tubes fixed by a frame. The frames are manually constructed and the alignment of fragments visually assessed. The characteristics of the frame are (Fig. 3): Apex® 5 mm half pins in position 1–5, in each multi-pin clamp, two multi-pin clamps (bone clamp separation: 35 mm); four stainless steel, 30° posts; four rod-to-rod articulations, two stainless steel fixation rods (8 mm); articulation tightened at 11 Nm.

Fig. 2 Mechanical configuration of a Hoffmann II® articulation rod coupling

We recorded the load deformation curves for each configuration and for different values of stiffness of the “callus model”.

To assess the reliability of the proposed monitoring system we compared the mechanical limits of a complex frame configuration to that expected from the measurements by Stryker. The four frame configurations (Fig. 3) have been tested with one (or two) instrumented rods with reasonable alignment of the fragments (simulating a surgical procedure). The axial load is increased until frame collapse. The moments are recorded at all articulations (A1 to B2, Fig. 1) and the maximum retained as the frame strength (that should be close to 16.2 Nm).

Results

We recorded load deformation curves for each configuration and for different values of stiffness of the callus model. The failure of the frame is decided when the curve reaches its elastic limit. In a second experiment the maximum accepted deformation was set to 10 mm for demonstration purpose. The deformation of the four frames, axially loaded respectively at 250 or 500 N, illustrates the significant reduction of the overall deformation when mechanical properties of callus increase (Fig. 4a, b). When the callus stiffness reaches some 200 N/mm no significant difference is observed between the frame configurations. The deformation of the frames B, C, and D, over 10 mm for spring stiffness under 80 N/mm, is not considered (Fig. 4b). The dispersion of the deformation is significantly reduced for higher values of stiffness of the callus (Table 1, Fig. 5).

In a theoretical configuration (Fig. 1), all the articulations should be simultaneously subjected to the same load. In a configuration manually erected, the distribution of moments is not symmetrical. Due to some reorganisation of the frame during loading, it may happen that the maximum computed moment transfers from one articulation to the other. In some experiments the frame collapses early, before reaching the expected strength (100 %, in ordinate).

For low spring (callus) values the variability is greater, which we explain by a higher variability of the alignment of the fragments during the test. The estimated values of the maximum torque at the articulation junction are presented Table 1 and Fig. 5.

The recorded moments at failure (14 Nm) represent 84.7 ± 4 % of the 16.2 Nm experimentally measured for individual testing of the components, close to experimental results. Discrepancies in the results may relate to the early stops of the loading before collapse of the frame; the results however closely correlate to those obtained in individual testing.

Fig. 3 The four Hoffmann II® frame configurations. **a** Unilateral double-rod half-frame. **b** Unilateral single-rod half-frame. **c** Unilateral double-rod, proximal independent pin placement. **d** Unilateral double-rod, proximal independent pin placement, curved rod

Discussion

Some researchers who have investigated the mechanical aspects of external fixation did not consider the development of the callus [3, 6, 16]. They compared devices in an unvarying way that only allows conclusion about their mechanical performance.

The study of the external fixation frame, taking callus into account, raises more interest than does a frame rigidity analysis alone. However, data from mechanical

behaviour, considering callus evolution in external fixation systems, are scarce [1, 2, 4, 5, 7–15, 17–22].

Callus, even with minimal elastic characteristics, causes important variations in load transmission patterns at the bone-callus-fixation structure. Regardless of fixator configuration, callus development is the overriding element for stability of the fixator-bone system [13]. There may be a significant difference between the deformations of frame construction at initial stages of callus development, a factor mostly neglected in the biomechanical evaluation of an external fixation frame. Vera et al. [22] pointed out a significant load transmission through callus even using a highly rigid external fixation system. For Prat et al. [19], rabbit calluses with minimum elastic characteristics (less than 1/100 of those values for normal cortical bone) provide a drastic change on load transmission patterns of healing bone. From an initial situation, when the fixator supports the total applied load, it changes to another in which callus assumes a part of the function. The clinical identification of callus characteristics will support either the process of dynamisation of external fixators or, conversely, reinforcement of the frame.

The stability of an osteosynthesis relies upon fracture configuration and mechanical strength of individual components of the fixation system. The articulation coupling characteristics only are of interest in monitoring the Hoffmann II® ExFix. The torque strength around axis A (or B, 16.2 ± 2.9 Nm) is the weakest element of the system, never to be surpassed. Measurements have been conducted to evaluate the

Fig. 4 **a** Deformation of the frames (load 250 N). **b** Deformation of the frames (load 500 N)

Table 1 Maximum resisting couple of articulations (% of 16.2 Nm)

Spring	N	%
100 N/m	21	78.3
140 N/m	7	79.0
185 N/m	13	96.1
260 N/m	7	82.8
405 N/m	21	92.0

Fig. 5 Maximum bending moments (springs 100–405 N/mm) expressed in % of 16.2 Nm

reliability of the mechanical characterisation of the components of the Hoffmann II® system that were individually tested. The recorded mean moment at failure (14 Nm) represents 84.7±4 % of the 16.2 Nm experimentally measured for individual testing of the components, close to the experimental results.

Conclusion

This simulation is in agreement with the theoretical approach [2], i.e. an external frame is subjected to larger stresses at the beginning of fracture healing. For callus stiffness of some 200 N/mm and over, the pattern of the curves remains similar, whatever the frame configuration. The recorded mean moment at failure (14 Nm) represents 84.7±4 % of the 16.2 Nm experimentally measured for the individual testing.

Clinical relevance

An external fixation frame is, most of the time, constructed in emergency. We demonstrate the possibility of adapting the configuration to actual mechanical characteristics of the system, including callus, by standard stability measurements of critical parameters, during rehabilitation and daily activities.

Conflict of interest The sensor was manufactured by Stryker, following the instructions of the first author. The experiments were conducted using the RD facilities of Stryker, supervised by the first author.

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