In-vivo impact testing on a lengthened femur with external fixation: A future option for non-invasive fracture healing monitoring?

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Abstract

The demand for non-invasive methods for fracture healing assessment has been a constant input for biomedical engineers in the last decades. In this study, the approach based on mechanical vibration, abandoned in the late 90ies, is reproposed. As case study, a femur lengthening procedure treated with external fixator was considered and monitored with impact tests, performed every 3-4 weeks for five months. Unfortunately, after 7 weeks some pins were removed due to infection. Thus, two configurations were considered for the complete fixator and an additional one for the last phase with only pins in the bone. The evolutions of the frequency response function and of the resonant frequencies of the thigh were analysed. Their indications were corroborated with X-rays evidences. Results showed that the callus evolution from the soft phase to the woven bone, affected the resonant frequencies of the system that increased of about 2-3% per week. The major increment (22% ca) was observed for the first resonant frequency. After the formation of the woven bone, the vibratory response remained almost the same, suggesting that the healing assessment could be related to the relative variation of the resonant frequencies. The presented results foster the application of impact testing to fracture healing assessment.

Keywords: *biomechanics, vibration analysis, fracture healing, non-invasive testing, external fixation, bone lengthening.*

Introduction

The assessment of bone fracture healing is currently based on radiographic images and manipulation, resulting invasive and strongly dependent on the operator experience. This explains the strong clinical demand for alternative diagnostic tools to monitor accurately and safely the fracture status. In the 90ies, the impact testing (IT) approach was proposed for the first time as a non-invasive and quantitative method to assess bone healing. The idea behind this approach is that as the bone heals, it gets stiffer and stiffer thus its resonant frequencies increase. The first applications of the IT to *in-vivo* monitoring of tibial fractures can be found in (Cunningham et al. 1990, Benirschke et al. 1993, Tower et al. 1993) with promising results. Nonetheless, the method was soon abandoned and never transferred into clinical practice, probably because of the limitations due to the signal damping caused by soft tissues.

Recently, the technological progress and the development of novel and fast algorithms for vibrational data processing have renewed the interest in this approach. The same authors have evaluated the reliability of IT to the assessment of fractures healing in cases treated with external fixation. This application was chosen for a double reason: first, the healing monitoring is fundamental in presence of external fixators to define a safe time for device

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dynamization and removal. Secondly, excitation and vibration measurements thorough fixator pins screwed into the bone allow overcoming the problem of tissue damping. Initially, a wide campaign of *in-vitro* tests on a tibia phantom was carried out to outline the impact testing procedure and to prove the feasibility of the method, even in presence of external fixators (Di Puccio et al. 2017, Mattei et al. 2017). Later, an *in-vivo* case study of fractured tibia externally fixed was examined with encouraging results (Mattei et al. 2017). Indeed, an increase of the low resonant frequencies was observed, up to 4% per week.

The aim of the present study is to go further in the evaluation of the impact testing as a future option for non-invasive healing monitoring applying the procedure to another clinical case, which is a lengthened femur with external fixation. For the first time, *in-vivo* impact test was performed during the whole fracture healing process: from the end of the lengthening procedure to the bone remodelling phase, after the removal of the fixator.

Materials and Methods

Case study

The case study was a 19 year old female, who underwent to a pediatric femoral fracture, on the right side. The fracture healed with a malunion, that left the shaft with 25° of varus deformity and 25° of procurvatum. Overall, the right limb appeared to be 40 mm shorter than the left leg. Consequently, a correction of the bone deformity was performed using a biplanar closed wedge osteotomy and then applying a carbon made monoaxial external fixator (LRS Orthofix®). Ten days after the intervention, the patient started the lengthening procedure, 1 mm per day for 15 days. Initially, the fixator was assembled using six pins (OsteoTite Bone Screws, Orthofix®) although two of them were removed after about 3 months because of infection and listeresys. The fixator was removed after 4 months, whilst the pins were left for an additional month for an eventual re-operation.

The patient gave informed consent to this research.

Test set up and procedure

The experimental set-up and procedure described by the authors in (Di Puccio et al. 2017, Mattei et al. 2017, Mattei et al. 2017) were adopted in this study. Impact excitation was performed using an instrumented microhammer (5800SL, Dytran®) while vibrations were measured through three accelerometers, two of which were monoaxial (4507, Brüel & Kjær®) and one triaxial (3133A1, Dytran®). Data were acquired and processed using LMS® hardware (LMS scadas mobile 01) and software (Test.Lab). Signals were acquired in the bandwidth 0-4096 Hz, with a frequency resolution of 2 Hz, and each measurement was obtained averaging 10 trials. The identification of the resonant frequencies (frequency analysis) was performed using the Polymax plus algorithm available in the Modal Analysis package of Test.Lab. Based on previous results, only the frequencies within the bandwidth 0-1000 Hz were estimated.

Tests plan

The fracture healing was monitored every 3-4 weeks from the end of the bone lengthening phase, considered the time-zero, to the fixator and pins removal (after about 5 months), for a total of six sessions. All details are summarized in Tab.1. During the monitoring period, some changes occurred to the external fixator system, thus three different configurations were studied (Fig.1(a)): C_1, with fixator and 6 pins; C_2, with fixator and 4 pins, i.e. after the removal of the infected pins 3 and 4; C_3, with only pins, after fixator body removal. Since each configuration corresponds to a different mechanical system with its own vibratory response and resonant frequencies, only results obtained for a specific configuration were compared.

Three different boundary conditions for the leg were used during the tests, shown in Fig.1(b). In the first one, labelled l_1, assumed for C_1 and C_2, the patient was lying down with a rubber cylinder under her ankle. In l_2, used for all configurations, the patient was still lying but with a second rubber cylinder positioned under the knee. In the third condition labelled *st*, adopted only for C_3, the patient was standing on the healthy leg with the fractured leg freely hanging.

For each impact tests, multiple input/output (IO) points and directions were used, as detailed in Fig.1(c). In particular, accelerometers were mounted on cubic supports, whilst the excitation was given both on supports and on pin extremities. Local frames were defined to specify directions with x almost parallel to femur axis, y corresponding to pin axis and z normal to support face. Support and pin points are labelled respectively as S_i^d and P_i^d, with i=1-6 corresponding to the pin number and d=x, y, z to the direction.

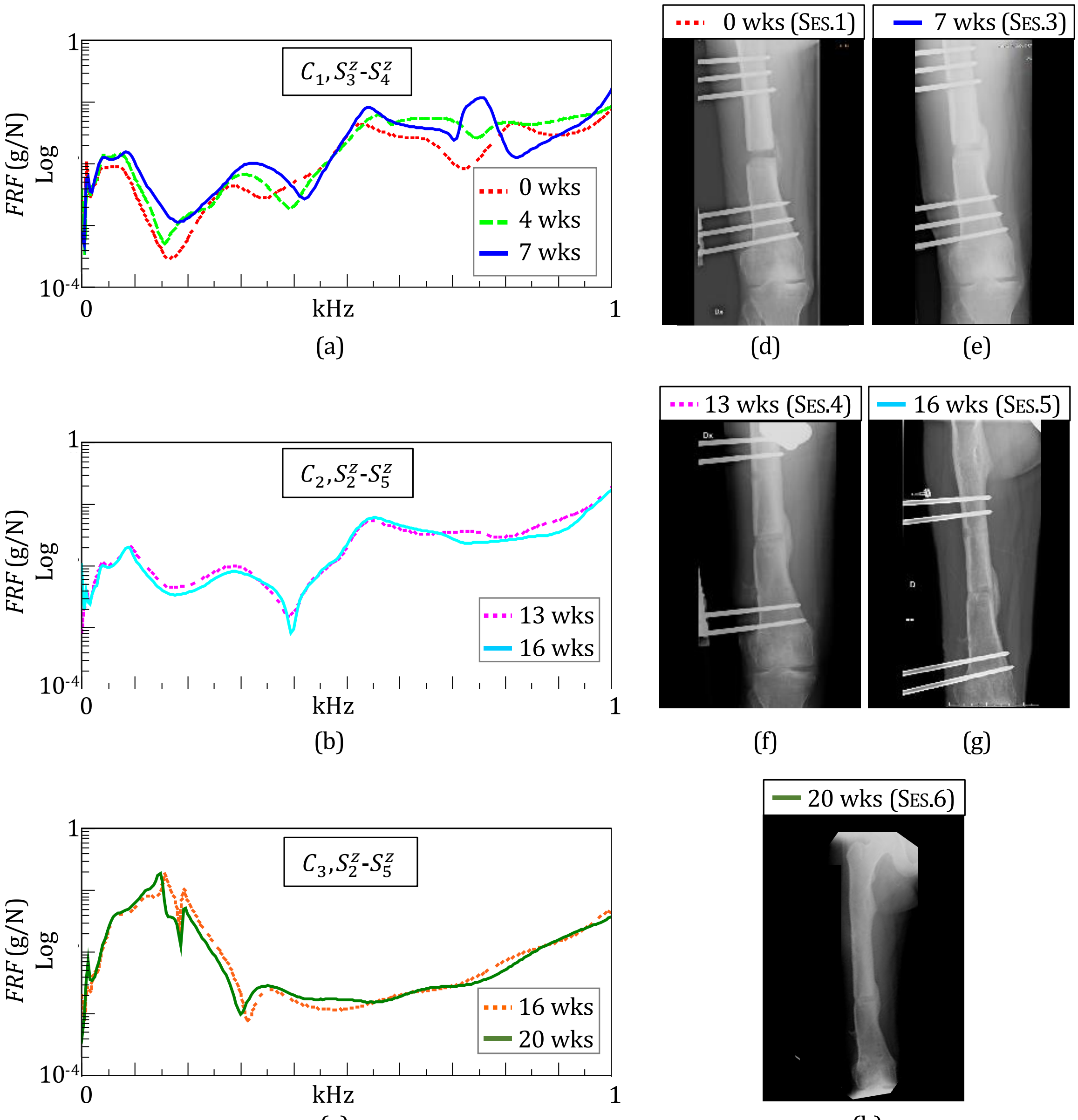

Fig. 1 Test configurations $C_{1\text{-}3}$ *(a) and boundary conditions* $l_{1,2}$ *and s (b). Points and directions used to excite and measure vibrations (c).*

Table 1 Test plan: time from the end of the lengthening phase (t), system configuration, boundary conditions (BCs) and input-output points and directions (see Fig.1).

<table>
<tr><th>Ses.</th><th>t (wks)</th><th>Config.</th><th>BCs</th><th>Input</th><th>Output</th></tr>
<tr><td>1</td><td>0</td><td rowspan="3">C_1</td><td>l_1, l_2</td><td>S_3^z, S_4^z, S_6^z</td><td rowspan="3">$S_2^z, S_3^{x,y,z}, S_4^z$</td></tr>
<tr><td>2</td><td>4</td><td>l_2</td><td>$S_3^z, S_4^{x,z}, S_6^{x,z}, P_3^y$</td></tr>
<tr><td>3</td><td>7</td><td>l_2</td><td>$S_3^z, S_4^{x,z}, S_6^{x,z}, P_3^y$</td></tr>
<tr><td>4</td><td>13</td><td rowspan="2">C_2</td><td rowspan="2">l_2</td><td rowspan="2">$S_1^z, S_2^z, S_5^z, S_6^z$</td><td rowspan="2">$S_1^z, S_2^{x,y,z}, S_6^z$</td></tr>
<tr><td rowspan="3">5</td><td rowspan="3">16</td></tr>
<tr><td rowspan="4">C_3</td><td>l_2</td><td>$S_1^z, S_2^z, S_5^z, S_6^z$</td><td rowspan="4">$S_1^z, S_2^{x,y,z}, S_6^z$</td></tr>
<tr><td>s</td><td>S_1^z, S_2^z, S_6^z</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">20</td><td>l_2</td><td>$S_1^z, S_2^z, S_5^z, S_6^z$</td></tr>
<tr><td>s</td><td>S_1^z, S_2^z, S_6^z</td></tr>
</table>

Results and discussion

The main results of this study are presented in two ways: the graphical evolution of the frequency response function (FRF) and the numerical estimation of its resonant frequencies, reported in Fig.2 and Tab.2, respectively.

Preliminarily, the quality of measurements was assessed by verifying the system reciprocity, i.e. same FRFs by exchanging IO points and directions, and by the goodness of the coherence function, close to unit.

The effect of the BCs was investigated both with and without fixator, by comparing results obtained for l_1 and l_2 and for l_2 and s, respectively. The number of rubber cylinders did not introduce any difference in results, though l_2 conditions was more repeatable and comfortable for the patient. On the other hand, the FRFs and the resonant frequencies estimated in the standing and lying-down conditions were slightly different, probably due to muscle contractions necessary to maintain the balance in the first case. Following results were obtained in l_2 BCs.

Another investigated crucial point was the relevance of the IO points and directions. All points and directions were able to excite most of the vibrational modes of interest. Measurements with input on supports were much better than those with input on pins. In fact, the pin surface was small and curved, causing a limited repeatability of the impact point and direction and consequently a low coherence (<0.85).

The use of IO points on supports closer to the fracture site generally allowed to capture a higher number of resonant frequencies. Moreover, excitation/response in the x or y directions did not added any information on the healing process with respect to z direction. Thus, the FRFs were compared only for IO points closer to the fracture site and with excitation/response in the z direction, as depicted in Fig.2(a-c). On the other hand, resonant frequencies were estimated from all measurements (i.e. all IO points and directions). Table 2 describes the average values and the standard deviation of the resonant frequencies obtained for each configuration. The columns correspond to the vibrational modes. It is worth noting that standard deviation values ranged in the interval 0-5 Hz, with an average value of 2 Hz that corresponds to measurements acquisition resolution, thus confirming the data quality.

Healing monitoring with complete fixator

The bone healing with the complete fixator assembled on the femur was assessed in configurations C_1 and C_2. During the first 7 weeks after the end of the lengthening phase (C_1), the FRF of the fractured femur showed the typical changes produced by the callus development. As depicted in Fig.2(a), the FRFs at weeks 0, 4 and 7 were characterized by pretty similar trends, though they clearly appear to be shifted towards higher values as the healing advanced. Only at week 7, the FRF showed a marked large peak around 750 Hz, not visible in the previous sessions. This change in the FRF might be due to combined effect of callus stiffening and mass reduction, as well as to a change of the muscular tone. The frequency analysis identified six frequencies between 0-1000 Hz, (Tab.2). During the first four weeks, all the frequencies increased, the first ones more markedly than the others, (2-4% vs. <1% per week). From week 4 to week 7, f_1, f_5 and f_6 kept increasing, even much more than in the previous period (4-5% per week), whilst f_2 remained constant and f_3 decreased of about -1% per week. Consequently, f_1, f_5 and f_6, resulted the best parameters to follow this first phase of the healing. In agreement with (Mattei et al. 2017), the first resonant frequency was affected by the most significant variations passing from 75 Hz to 80 Hz and finally 91 Hz (+22%). This estimated evolution of the fracture healing was corroborated by radiographic images shown in Fig.2(c-d): the soft callus visible at week 0 developed in the stiffer woven bone at week 7.

During weeks 13-16 (C_2) both FRF and frequency analysis demonstrated a negligible variations: the FRFs at week 13 and 16, compared in Fig.2(b), were almost identical and the changes of the resonant frequencies (Tab.2) were lower than 0.3% per week. Accordingly, the radiographic images (Fig.2(f-g)) demonstrated that at week 13 the healing process was advanced given the presence a mix of woven bone that developed in hard callus at week 16, when the fixator was removed. Consequently, results suggests that when the resonant frequencies increments reach a steady condition, the bone can be considered healed and thus (stiff and) strong enough to remove the fixator.

Healing monitoring after fixator removal

The FRF of the thigh was evaluated also after the removal of the fixator body (C_3) at weeks 17 and 20. The completion of the fracture healing was confirmed by almost unvaried FRFs (fig.2(c)) and resonant frequencies (Tab.2). In particular, the patient thigh was characterized by four resonant frequencies in the band 0-1000 Hz: 122, 150, 191 and 321 Hz, at week 7. Only f_2 decreased of -3%, passing from 156 to 150 Hz, probably as a consequence of a different muscle tone and/or thigh mass. X-rays image at week 20 (Fig.2(e)) showed the callus in the remodelling phase, i.e. towards the development of compact bone. The values of the resonant frequencies in this configuration represent a property of the dynamical behaviour of the thigh, which is also characterised by a damping coefficient (for each one of the frequencies).

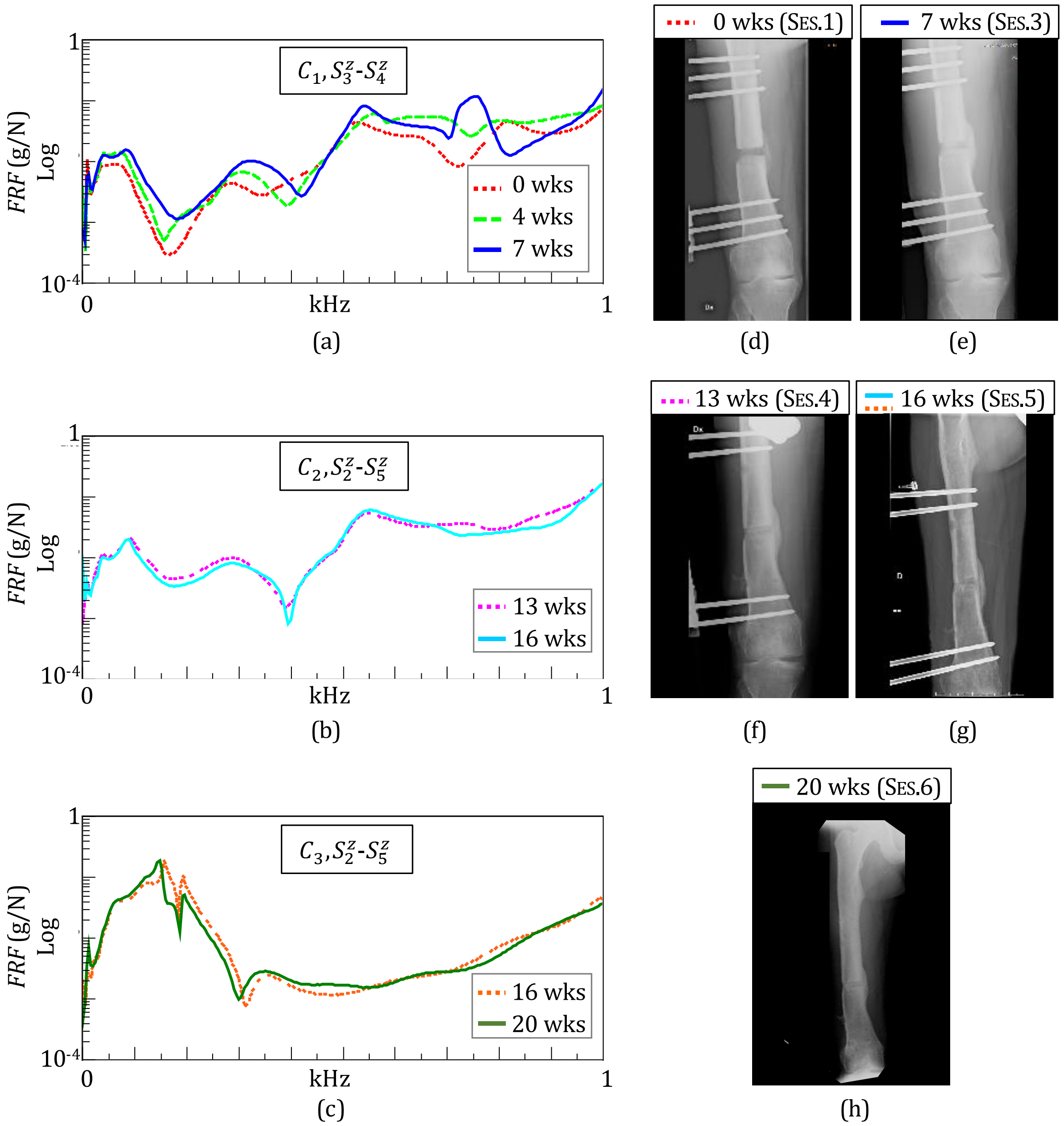

Fig. 2 On the right, evolution of FRFs of the fractured femur during healing, both with fixator (a,b) and with only pins (c) (in l_2). On the left, X-rays images of the fractured femur from the stop of bone lengthening (0 wks) to the beginning of bone remodelling (20 wks).

Table 2 Average values and standard deviations of resonant frequencies of the fractured thigh during healing, evaluated considering all input-output points and directions for each test session. Each column identifies the same vibrational mode for a given configuration.

t (wks)	Config.	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_4 (Hz)	f_5 (Hz)	f_6 (Hz)
0	C_1	75 (2)	277 (4)	523 (4)	689 (4)	761 (3)	812 (1)
4		80 (2)	316 (4)	559 (3)	726 (4)	775 (3)	845 (0)
7		91 (2)	315 (2)	538 (1)	764 (2)	863 (3)	954 (3)
13	C_2	89 (1)	302 (3)	497 (1)	538 (2)	580 (3)	943 (4)
16		89 (1)	298 (5)	495 (2)	545 (2)	587 (5)	937 (2)
16	C_3	128 (2)	155 (1)	189 (0)	317 (1)		
20		129 (3)	151 (1)	191 (1)	322 (3)		

Conclusions

The present study aims to examine the efficacy of the impact testing approach as a future option for non-invasive and quantitative healing monitoring. As case study, the fracture created for lengthening a fractured femur was considered. Results showed that the callus evolution from the soft phase to the woven bone, affected the resonant frequencies of the system that increased of about 2-3% per week. The major increment (22% ca) was observed for the first resonant frequency. After the formation of the woven bone, the vibratory response remained almost the same, suggesting that the healing assessment could be related to the relative variation of the resonant frequencies. The presented results foster the application of impact testing to fracture healing assessment. However, further tests will be necessary for proving its reliability in cases of complex fractures and fixator assemblies. Additionally, future investigations will be focused on discerning the effect of callus stiffening from possible other factors affecting the resonant frequencies, such as mass reduction and muscle tone variation.

Author's contributions

F.D.P. and L.M. conceptualized the study and performed the tests. L.M. processed and interpreted data. F.D.P. supervised the process. S.M. was responsible of the clinical aspects, including X-ray analyses. L.M. and F.D.P. wrote the manuscript. All authors have read and approved the final manuscript.

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