Preliminary work on the potential of extending structural health monitoring concepts for healing assessment

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Abstract

External fixations are used to treat skeletal fractures. Patients are required to be immobilized for up to 12 weeks to allow the fracture to heal. This paper presents some preliminary finite element findings to highlight the potential of attaching sensing elements on the fixation to monitor the progression of healing of the fracture. This work paves the way for the extension of structural health monitoring concepts for orthopaedic devices.

Keywords: Structural health monitoring, bone healing assessment, bone fracture

Introduction

Musculoskeletal injuries are often associated with traumas. One of the associated effects of these injuries is bone fracture which is a complete or incomplete breakage of a bone, as a result of excessive force or trauma to the site. Following a fracture, there are a variety of treatment choices, most commonly internal and external fixation, should operative methods be chosen. In general, intermedullary nailing, a type of internal fixation, is chosen, as it has been associated with decreased complications such as pin tract sepsis and joint stiffness (Wu, 2006). However, as noted by Ingari and Powell (2007), temporary external fixation has been indicated in situations where temporary fixation is necessary and risks of infection high, such as in combat. In these circumstances after a short period of time it is possible to convert to internal fixation, but in these cases risks of infection are high, and often the temporary fixation is modified to be permanent. The objectives of orthopaedic injury management are to prevent infection, promote fracture healing and restore function.

The healing process of fractures is a complicated procedure, on both a macroscopic and microscopic level. Due to the precise balance required between anabolic and catabolic phases, delayed unions, mal-unions and non-unions are common, occurring in 5-10% of all long bone fractures (Griffin et al, 2011). Hernigou et al (2005) define a delayed union as a fracture site continuing to sustain clinical and radiological signs of fracture outside of the expected healing time, or the absence of signs of progressive repair between the 3rd and 6th month of repair following a fracture. Mal-unions are defined as a pathological union of a fracture, usually involving shortening and rotational or angular deformity (Wu, 2006), while non-unions are defined as a lack of union within the expected healing time (Griffin et al, 2011). Although there is a lack of a standardised definition of these pathologies, they are clinically significant and have an impact on quality of life.

In the above studies, it is evident that an ability of assess the degree of union of the fixated fracture is of fundamental importance. It is needed to (1) determine if a re-operation is required, and (2) to assess the effectiveness of the external fixation as a definitive treatment. The most common method of determining state of union, following clinical data collected, is a plain radiograph or a CT scan. Unfortunately, both have significant drawbacks to the patient, primarily exposure to radiation, and both are fundamentally inconclusive in determining state of union. Progesses in Engineering research has led to a significant advancement in Structural Health Monitoring (SHM) which have been shown to offer the prospect of a quantum gain in performance and efficiency for the structural integrity management of expensive assets such as aircraft and infrastructure. The key enabling technologies for this revolution include primarily the rapid and continuing advances that have been made in the past three decades in the development of miniaturised sensors, actuators, and of various multifunctional materials and structural concepts Srinivasan, A.V. and D.M. McFarland (2001).

For the purpose of this paper, a fixated femur will be used to outline this potential. A saw-bone femur fixated with a Hoffmann II external fixator was used. This paper will present a set of results that will establish the fundamentals required to underpin the ability to integrate sensing into an external fixator for union and healing assessment. It will be shown that the modal response of a fixated femur is sensitive to the state of union of the fractured region.

Finite element analysis

The aims of this part of the work are to:

1. Determine the potential of locating sensing devices on the external fixation to determine the state of healing of the fractured femur.
2. Qualitatively identify suitable sensor placement locations on the fixation and the appropriate frequency bandwidth that will facilitate the monitoring of the healing of the fracture femur.

This will be conducted with a series of finite element analyses of the fixated femur. The geometry of the fixated femur shown in Figure 1 was digitally scanned using structured light 3D scanning technology. A finite element model was created from the scanned geometry as shown in Figure . Due to its complex geometry, it was meshed using tetrahedral elements set to a spacing of 2mm. This resulted in 345,966 elements and 79,793 nodes as shown in Figure 2. The fracture was simulated with a 3mm thick slice in the middle of the femur (shown in Figure 3) and was assigned a Young's modulus 1% of the flawless bone. The properties used for the fixation and the saw-bone are shown in Table 1. The unlabeled fixation components in Figure were assigned titanium material properties. A constant 1% viscous damping was used in the simulation. In this respect, the finite element analyses reported in this section is use for qualitative purposes.

Table 1 Material properties used in simulations (Rudman et al, 2006).

Material	**Density (kg/m^3)**	**Young's Modulus (GPa)**	**Poisson's Ratio**
Cortical bone	1500	17	0.3
Stainless steel pin	7817	198	0.272
Composite rod	1500	134	0.3
Titanium	4430	121	0.34

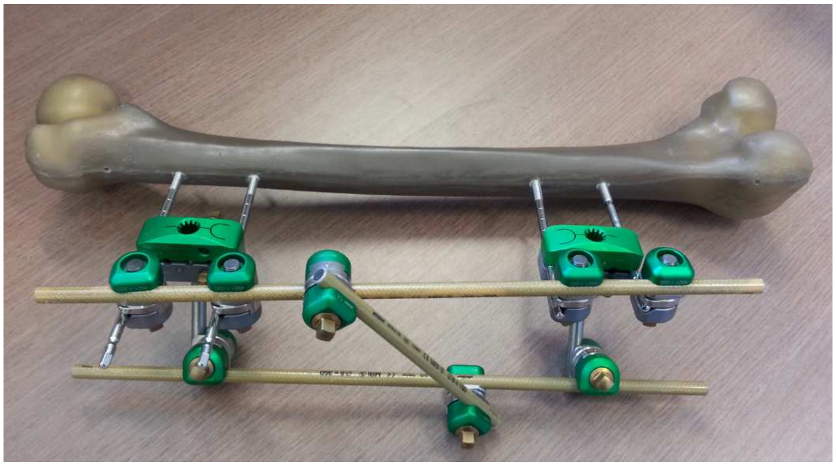


Figure 1: Saw-bone femur fixated with Hoffmann II external fixation.

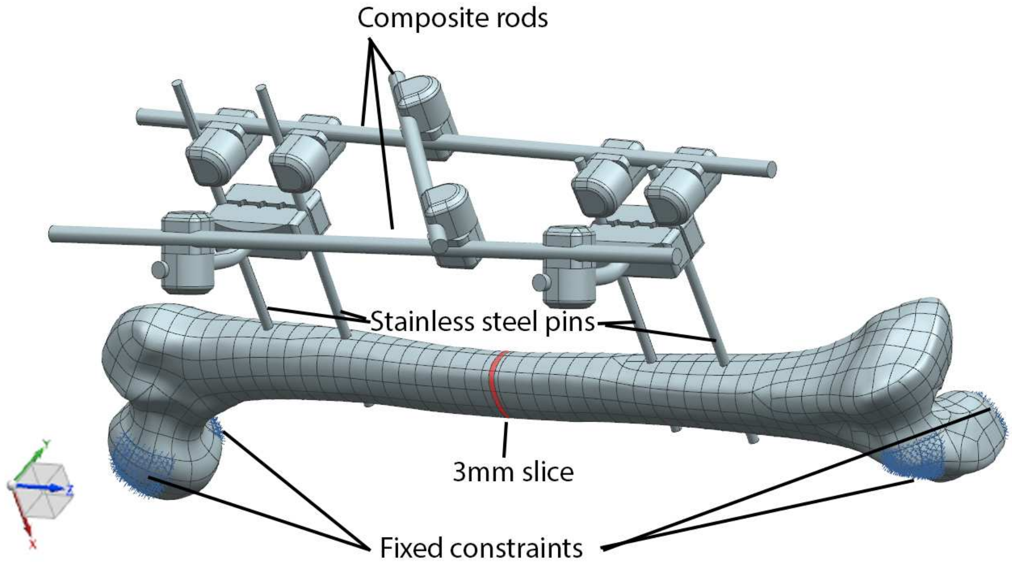


Figure 2: 3D model of fixated saw-bone specimen.

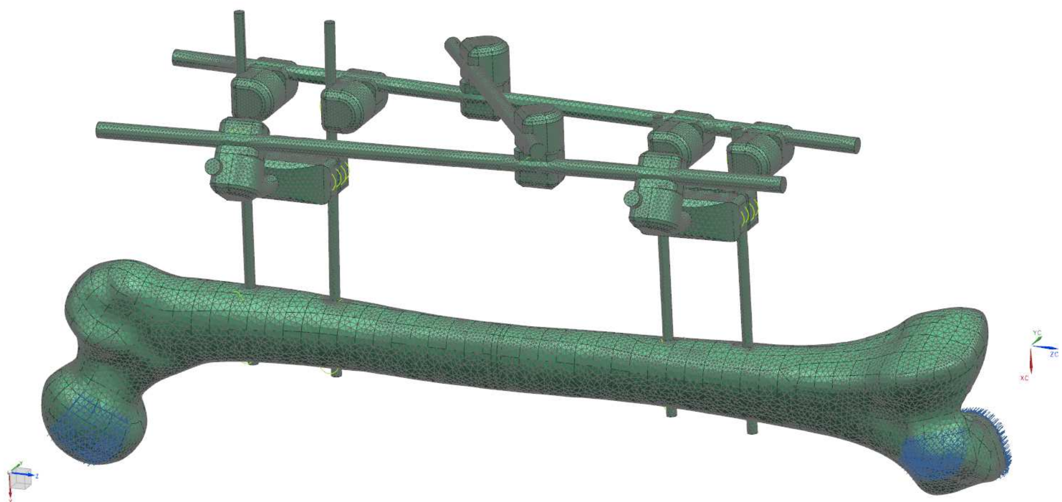


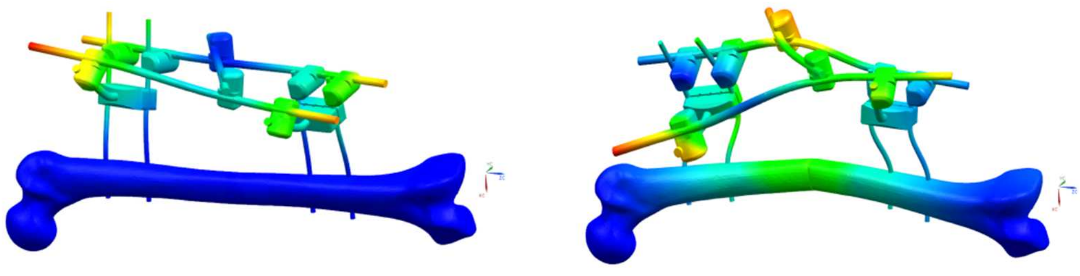
Figure 3: 3D model illustrating mesh density.

The fixed constraints applied to the fixated femur are shown in Figure 3. The dynamic response of the model was solved using NX Nastran. The mode shapes and natural frequencies of the fixated femur were first analysed. To facilitate the assessment of the healing and union of the fracture femur, it is important that the desired mode must include significant deformation of the femur.

Identification of sensing location

Figures 4(a) and (b) show two typical mode shapes that were calculated. They were selected to highlight the significance of using the appropriate modes for monitoring of the union and healing of the fracture femur. It was found that the lower modes are likely to be insensitive to the presence of the fracture because it is dominated by the deformation of the fixation (see Figure 4a). However, the higher mode (e.g. the 6th mode) shown in Figure 4b shows the deformation of the femur. Therefore, it is expected that the higher order resonant behaviour of the femur is likely to be affected by the changing material properties of the femur in the fractured region that is representative of the state of healing and/or union.

The 6th mode shape shown in Figure 4(b) also includes significant deformation of the legs of the fixation. It is inferred from these results that the sensors can suitably be located on the legs of the fixation to determine the state of healing. This is essential as they are easily accessible and are external to the body.



a) **Mode 2, 126Hz** b) **Mode 6, 402 Hz**

Figure 4: Mode shapes.

Forced analyses

To confirm this, a series of forced dynamic response of the fixated femur were conducted with a forced input is applied to the fixation as shown in Figure 5. A unit force is applied over a frequency bandwidth of 1000 Hz. The 4 sensing locations are selected and the transfer functions between the surface stress on these locations and the force input were calculated. Sensing locations 1 and 2 and 3 and 4 were located on the opposite sides of the fracture location. The calculations were conducted with the following femur configurations: (a) no fracture; (b) the fractured femur simulated with the properties at the fractured location reduced to 1% of its original.

The forced responses of the fixated femur with and without the fractured region are shown in Figures 6 and 7. These results shows that the effects of the fractured femur on the transfer function are only evident in the higher modes above 300 Hz. This is because significant deformation of the femur was present only in the higher modes. The results also showed that the sensing location shown in Figure 5 is potentially sensitive to the state of healing and union of the fractured femur.

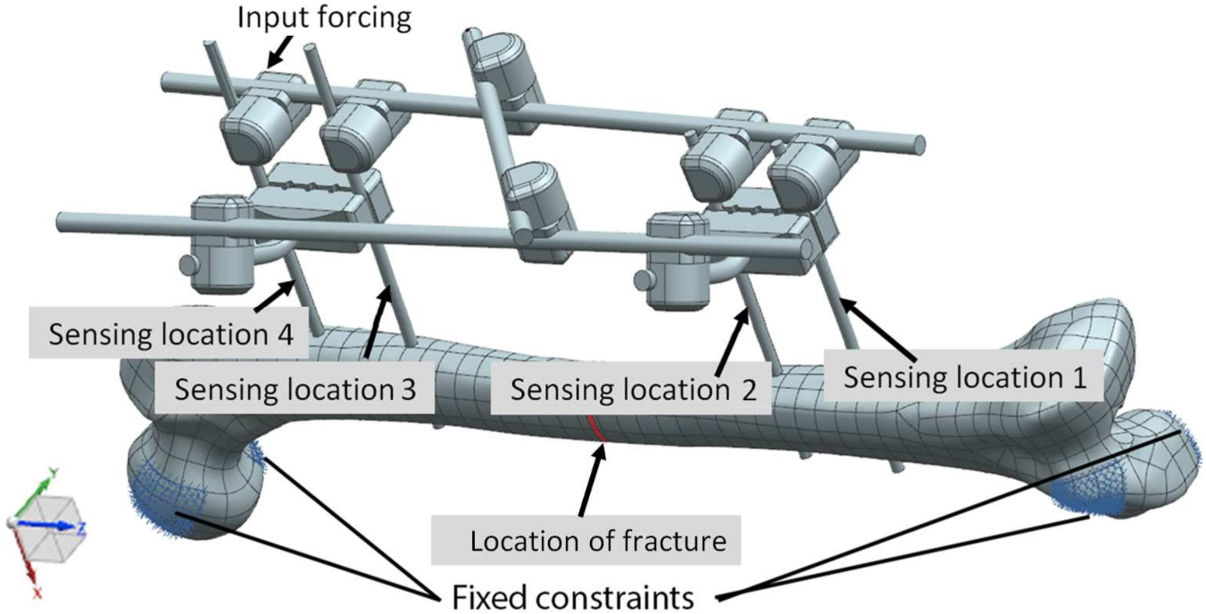


Figure 5: Input and output locations for transfer function calculation.

The transfer function obtained for sensing locations 1 and 2 are shown in Figure 6(a) and 6(b). The results obtained from these two sensing locations are similar both in magnitude and in phase. The natural frequencies for the modes above 250 Hz increases when the fracture is totally healed and united. Figure 7(a) and 7(b) shows the transfer function obtained for sensing locations 3 and 4. The healing of the femur can be indicated by the appearance of natural modes at about 300 Hz and 480 Hz.

This set of results clearly demonstrates the significance of locating the sensing element in the proximity of the drive point. It also highlights the potential of integrating structural health monitoring concepts into the orthopaedic devices for the monitoring of healing and union of a fractured femur. An important feature is the possibility of locating sensors external to the human body for healing assessment.

Conclusions

The work presented in this paper described the potential of integrating structural heath monitoring concepts into fixators to determine the state of union of a fractured long bone. The work presented showed how the inclusion of actuation and sensing protocol can be established to assess the state of union of the externally fixated saw-bone femur. This preliminary study highlights the potential of locating sensors external to the human body in assessing the state of healing of a fixated fractured femur.

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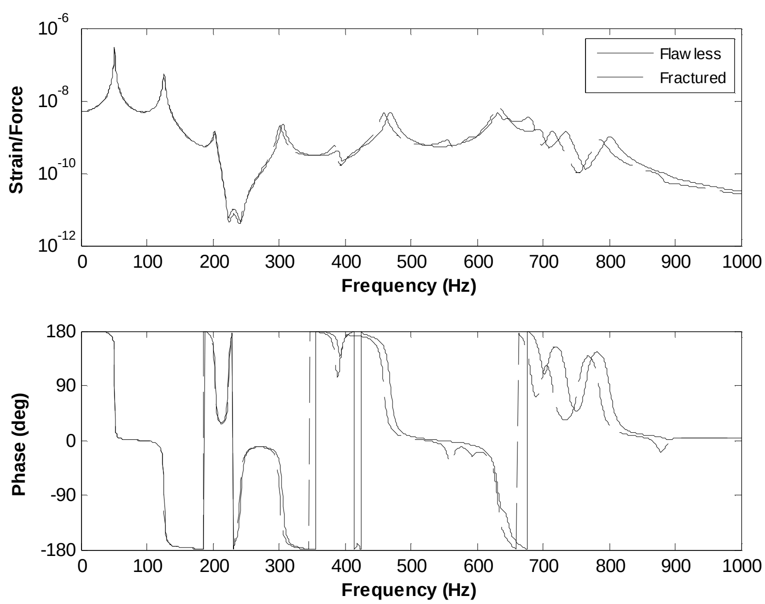

Figure 6(a): Transfer function for a fractured and flawless bone on pin 1.

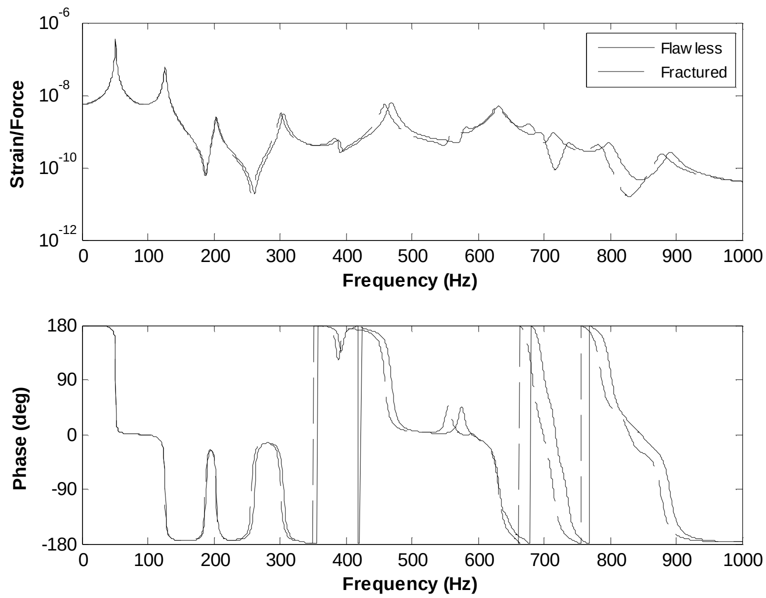

Figure 6(b): Transfer function for a fractured and flawless bone on pin 2.

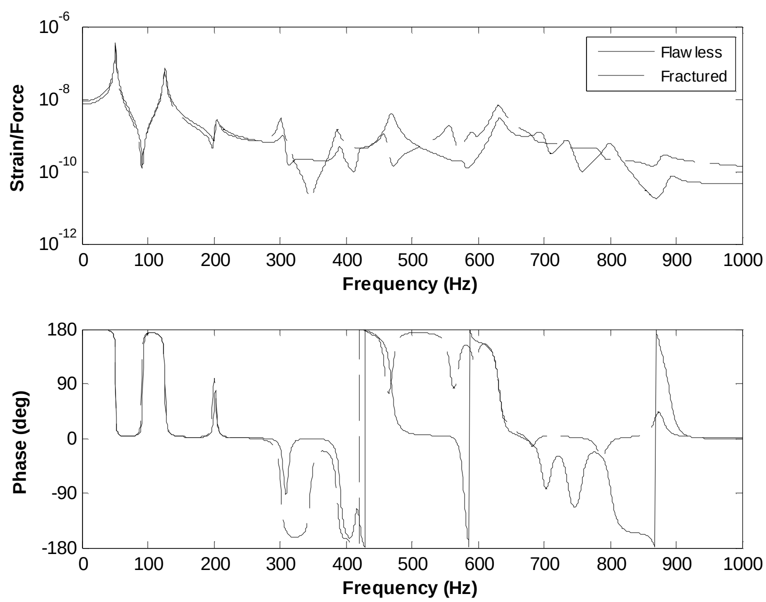

Figure 7(a): Transfer function for a fractured and flawless bone on pin 3.

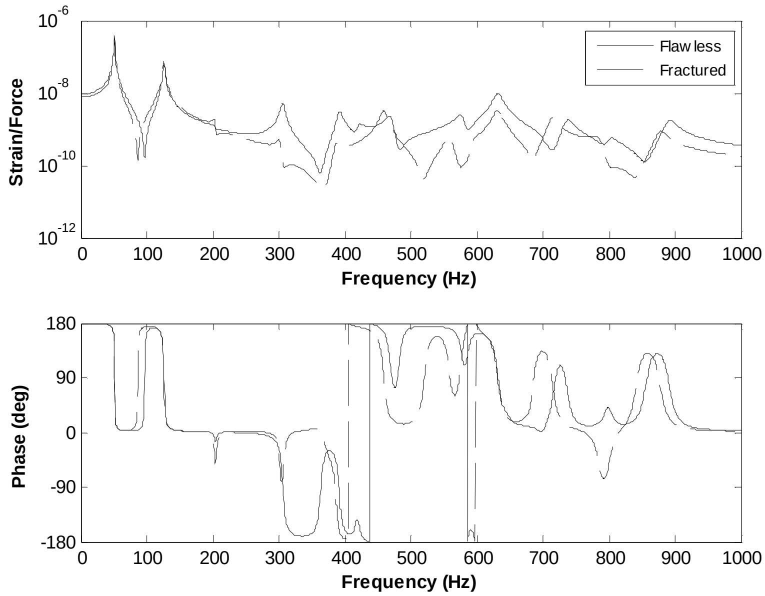

Figure 7(b): Transfer function for a fractured and flawless bone on pin 4.

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