Human SHM –
Healing Assessment of an Externally Fixated Fractured Femur

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Abstract
The application of significant research outcomes in the field of Structural Health Monitoring (SHM) has led to the application and demonstration of related technologies in the field of aerospace, marine, civil and structural engineering. Recently, there are research efforts towards the extension of the SHM concepts to the biomedical area. This aim of this paper is to provide an overview of some of these recent advances. This paper will provide an overview of the potential of using the global dynamic response of an externally fixated fractured femur to establish its state of healing [1-4]. These results show that the assessment of the state of union of the fixated femur can be achieved by analysing its dynamic response.

1 INTRODUCTION

The vibration response of human femur is akin to the transverse vibration of an engineering beam-like structure [5]. Thomas et al utilised the resonant vibration of the femur to promote the flow of femoral cement into the structure during hip replacement procedure. The application of the vibration response for determining the fracture healing was reported by Flint et al [6]. They found that fracture healing can be assessed using a response ratio from transverse vibration response of the femur. Their work questioned the use of transverse vibration of long bone for healing assessment. Indeed they postulated that the analyses of the longitudinal wave propagation may be an alternative.

The use of impulse response method to determine the state of union of a fractured tibia was reported by Nakatsuchi et al [7]. In their experiment, the tibia was supported in a free-free state. They found that the vibrational response of the tibia is affected by the state of healing of the tibia. The work presented only dealt with a fractured tibia that is not subjected to any fixation treatment. This work is further supported by results from Maslov [8] who confirmed the theoretical relationship between the eigenfrequencies and bending stiffness as a means of assessing the tibial fracture healing.
Bone fracture 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 some instances, external fixation can be used as a definitive treatment [9]. Whilst work done to date have shown that the vibration response of a fractured long bone can be used to assess the state of union, this paper seek to integrate the sensing elements into an external fixation for this assessment. In this regard, the externally fixated femur will be the engineering system to be analysed. Integrating the sensing elements into the external fixation is akin to the extending structural health monitoring concepts for the assessment of the state of union of the fractured long bone.

Publications by Chiu et al [1] & Ong et al [2-4] have shown that the progress in Structural Health Monitoring (SHM) can offer the prospect for the healing assessment of an externally fixated fractured long bone. SHM is recognised to offer 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 [10]. Chiu et al [1] & Ong et al [2-4] presented a series of work to demonstrate the extension of an SHM concept to a biomedical application for the assessment of the state of union of a fractured femur. This paper will present some of the experimental tests to show how sensing elements that are attached to an external fixation can be used for assessing the state of union of the fixated femur.

2 TEST SPECIMEN AND PREVIOUS FINDINGS

Figure 1 show a 4th generation saw-bone femur was used for this series of investigation. This saw bone is made from glass reinforced epoxy composite and is suitable for biomechanical testing. The test femur was fixated with a Hoffmann II MRI external fixation system. The connecting rods are made from Vectran-coated carbon fibre rods. The fixation was installed onto the femur using 4 stainless steel self-drilling pins.

![Figure 1: Saw-bone femur fixated with Hoffmann II external fixation.](image-url)
A series of finite element analyses of the fixated femur shown in Figure 1 was presented by Chiu et al [1]. Their preliminary work demonstrated the potential in extending SHM concepts for the monitoring and assessment of healing in a fixated femur. Chiu et al [1] showed the sensing element attached to the fixation pins are sensitive to the changing mechanical properties of the fixated femur arising from the healing of the fractured femur. They also found that it is preferred to have these sensing elements to be located in proximity to the drive point of the input excitation. Since the sensing element can be located on the pin of the fixation, it will be located external to the body and does not interfere with the overall construction of the fixation device. Their results can be summarised as follows:

1. The modal response above 200 Hz is sensitive to the state of union of the fractured femur.

2. At frequencies below 150 Hz the response is dominated by the global response of the fixated femur and the modal response at this frequency bandwidth is insensitive to the state of union of the fractured femur.

These observations were indeed confirmed with the results presented by Ong et al [3, 4]. In the work presented in Ong et al [4] it was shown that the effects of damping from the soft tissues need to be considered for the healing assessment of the fractured femur. These results also underscore the significance of the ability to determine the overall stiffness of the fixated femur. This can be achieved by attaching sensing elements to the strategic locations on the fixation. It was found that the dynamic response of the fixated femur was sensitive to the state of healing of the fracture.

3 TEST PROCEDURE

The test set-up and instrumentation used are illustrated in Figures 2(a) and (b). This test set-up was also used in Ong et al [3, 4]. A PVDF film sensor was bonded onto the pin of the fixation (see Figure 2(b)). The excitation input was applied through a solenoid impactor instrumented with a load cell to measure the impact load imparted to the fixated femur. The input signal supplied to the impactor was provided by a MatLab program that was amplified with a B&K Type 2706 power amplifier. The typical spectrum of the force input is shown in Figure 3.
The fixated saw-bone femur was subjected to a through-cut to simulate a fracture (see Figure 4). The saw-cut was filled with epoxy and the curing of this epoxy was used to simulate healing and union of the fractured region. When simulating the process of healing and union, a 30 min cure-time epoxy was used to highlight the significant findings.

Figure 3: Typical input force spectrum.
During the experiment, the response from PVDF film sensor was connected to a Krohn-Hite 3944 amplifier and acquired by a 6 channel B&K Pulse shown in Figure 2(a). The time-history of the force transducer and the PVDF film sensor were recorded simultaneously. The transfer function between the sensor responses and the force input were calculated with a MATLAB script.

For each of the experiments, the fixated femur was firstly fractured. Upon application of the epoxy, the forced response of the fixated femur was recorded. A total of 10 averages were used for each curing state. The time taken to record the 10 sets of time series was approximately 30 seconds. This is considerably short even when compared with the curing time corresponding to the 5-minute epoxy.

The transfer functions recorded were processed to yield a Healing Index [4] which is defined as follows. Firstly the change in the transfer function is calculated by taking the difference between the magnitude of the transfer function at any time \(T_F(t)\) and that taken at the start of the experiment \(T_F(0)\).

\[
T_F^{\text{change}}(f) = |T_F(0)(f) - T_F(t)(f)|
\]  

In the above equation, \(T_F(0)\) is the transfer function measured at the start of the experiment (i.e. baseline). The transfer function measured at any time \(t\) during the progression of the simulated healing is defined as \(T_F(t)\). The windowed average of \(T_F^{\text{change}}\) is obtained with a 10 Hz window, and the Healing Index is defined as the cumulation of the windowed function:

\[
T_F^{\text{windowed}}(f) = \int_{f_{\min}}^{f_{\max}} T_F^{\text{change}}(f) df
\]

Healing Index = \(\sum T_F^{\text{windowed}}(f)\)
4 SUMMARY OF RESULTS

The experiments were repeated with a 30-minute curing time adhesive. Figure 5 shows the development of the transfer function as a function of time when the 30-minute epoxy. The modal response of the lower modes (up to 70 Hz) is insensitive to union of the fractured region. The magnitude of the transfer function was found to increase in this bandwidth with healing time. This can be attributed to the reduction in the damping as the epoxy cures with time. It may be tempting to use this as an indication of healing. However, damping is affected by soft tissue surround the femur and is therefore not a preferred parameter for healing assessment.

The union of the fractured region is highlighted by the changes in the modal response of the higher modes (200 to 600 Hz). Due to the slower cure-time, the “delayed union” is evident up to approximately 15 minutes from the commencement of the experiment. During this time, there is no significant development in the spectrum. However, as the epoxy cured, the development of the higher modes was observed. This is attributed to the increased structural stiffness as the epoxy cures. This is a preferred parameter to use for healing assessment as the contribution to the structural stiffness from soft tissue is limited. Interestingly, the changes in the modal response are only significant up to 30 minutes into the experiment and is associated with the cure-time of the epoxy used. The increased in the magnitude of the frequency response function of the fixated femur after 30 min is attributed to the changes in damping as the epoxy achieves full cure.

The Healing Index for this set of calculation is shown in Figure 6. The effect of the delayed curing of the epoxy is evident in the Healing Index curve shown in Figure 6. The following characterises the various stage of healing:

a. At the start of the experiment, a region exists where the gradient of the Healing Index curve increases with cure time.

b. A point of inflexion of the Healing Index after which the gradient of the Healing Index curve decreases with cure time.

c. The asymptotic Healing Index is a reflection of the complete union of the fractured region.
Figure 5: Development of transfer function with 30-min cure epoxy
6 DISCUSSIONS

The results described above demonstrate the potential of extending smart structure concepts to an important area of orthopaedics. Given that the objectives of orthopaedic injury management are to prevent infection, promote fracture healing and restore function, the results presented above demonstrates the potential of applying structural health monitoring concepts to determine fracture healing and to ascertain the appropriate time for return to normal duties. It has been shown that integrating sensors into the fixation can potentially be useful in determining the state of union of the fractured femur. The results presented above demonstrated the potential of locating sensing devices on the external fixation to determine the state of healing and the union of the fractured femur. The results show that a rapid union, delayed union and non-union can be assessed readily with an appropriately instrumented external fixation. The ability to assess the state of union is significant because it can be used as part of the management of recovery of the patient. The question of additional and timely medical intervention can be initiated with the knowledge of non-union. Equally as important, a rapid union of the fractured femur can also mean that the person can be potentially be mobilised earlier that can lead to significant savings in economic and social terms.

As described in the Introduction, current methods of assessing union include X-ray and CT scans. The interpretation of union using these techniques is at best qualitative and is highly subjective. The integration of health monitoring concepts into the assessment of state of union provides a quantitative measure that can be used in conjunction with existing techniques. This represents a significant potential of reducing or eliminating the qualitative assessment in the state of union.

7 CONCLUSIONS

The work presented in this paper provides an overview of work that was conducted to highlight the potential of integrating structural health 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.

REFERENCES


