33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Evaluation of Modal Analysis Techniques using Physical Models to Detect Osseointegration of Implants in Transfemoral Amputees

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Abstract—**Non-invasive vibration analysis has been used extensively to monitor the progression of dental implant healing and stabilization. It is now being considered as a method to monitor femoral implants in transfemoral amputees. This paper evaluates two modal analysis excitation methods and investigates their capabilities in detecting changes at the interface between the implant and the bone that occur during osseointegration. Excitation of bone-implant physical models with the electromagnetic shaker provided higher coherence values and a greater number of modes over the same frequency range when compared to the impact hammer. Differences were detected in the natural frequencies and fundamental mode shape of the model when the fit of the implant was altered in the bone. The ability to detect changes in the model dynamic properties demonstrates the potential of modal analysis in this application and warrants further investigation.**

I. INTRODUCTION

An alternative to the conventional prosthetic socket for above knee (transfemoral) amputees is what is termed transfemoral osseointegration (TFOI) [1]. A titanium implant is inserted into the femur of the residual limb; the implant protrudes through the skin and connects directly to the prosthetic limb without the need for a socket [2].

TFOI has documented advantages over the conventional method in that it eliminates the socket related problems that some amputees experience. These include better control of the prosthetic limb and feedback through the limb, improvements in hip mobility and sitting comfort, fewer dermatological problems on the residual limb and improved quality of life [2], [3]. Consequently TFOI can be an attractive option for amputees who suffer from socket related problems or who have an active lifestyle and require prosthetic limb function to match that lifestyle. However, it can take up to eighteen months after implant insertion for the implant to integrate with the bone and for an amputee to be fully rehabilitated and able to load bear [2]. The long rehabilitation time is a significant disadvantage of TFOI and may be impeding the wider adoption of the technique.

If a non-invasive method of assessing the degree of osseointegration (OI) between the bone and the implant was capable of determining the progression of TFOI and assessing when the implant was able to withstand physiological load it could reduce the overall rehabilitation time. Vibration analysis is a potential method: changes in the dynamic properties of the bone-implant system could be detected as the physical properties at the interface between the bone and the implant change throughout OI progression. Vibration analysis of OI dental implants has demonstrated the potential for the measured dynamic properties of the implant-bone system to indicate the progression of OI [4]-[8], and two commercial devices have been developed based on this approach (Osstell ISQ, Osstell AB, Sweden; Periotest, Medizintechnik Gulden e.K, Germany).

More recently vibration analysis has been extended to TFOI using physical models of the femur-implant system; changes in the physical properties of the interface between the bone and implant were detected as changes in the first natural frequency [9], [10]. The response-only methodology used in [9] and [10] provides information about the structure under the specific test conditions only [11]. Modal analysis, another branch of vibration analysis, uses both excitation and response measurements to develop a model of a structure and provides the natural frequencies, damping ratios and mode shapes. Consequently modal analysis is considered by the authors to be a more versatile vibration analysis methodology to investigate TFOI and to fully characterise the femur-implant system.

This research evaluates two modal analysis excitation methodologies using physical models of the TFOI femur-implant system and establishes if modal analysis is capable of detecting changes at the interface between the implant and the femur.

II. METHODOLOGY

A. Physical Models

Three physical models were developed for evaluating the two excitation methodologies. Full details of the model manufacture are included in [12]. The first model, an unmodified fourth generation large composite femur (Sawbones model 3406, Pacific Research Laboratories Inc, WA, USA), was tested to compare with modal analysis of a previous generation composite femur [13] and to validate the methodology. Composite femurs, of mass 0.52kg, are made

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Manuscript received June 17, 2011. This work was funded by an Australian Government International Postgraduate Research Scholarship. N. J. Cairns was with Queensland University of Technology, Brisbane, Australia. She is now with the Department of Design, Manufacture and Engineering Management, University of Strathclyde, Glasgow, UK (phone: +44141 5482374; fax: +44141 5527986; e-mail: nicola.j.cairns@strath.ac.uk).

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from an inner rigid polyurethane foam core and a short-fibre-filled epoxy outer shell with a hollow canal through the polyurethane foam. A 2.5mm threaded hole was machined in the femur (dashed arrow in Fig. 1(a)) to allow attachment of the excitation hardware.

Two additional composite femurs were cut to a length of 237mm, replicating amputated femurs. The canal of each femur was threaded using a CNC machine to accommodate an implant. Fine adjustments were made iteratively to the female thread pitch of the canals so that one femur required an implant insertion torque of 4Nm and another of 0.5Nm, representing ‘secure’ and ‘loose’ fits of the implant in the femur respectively.

Two implants were machined from commercially pure titanium rod to have a threaded section 80mm long, 19mm outer diameter and 1.75mm male thread pitch. The profile of the implant then changed to a cylindrical section 60mm long, 15mm outer diameter. Flats were machined on the cylindrical section and 2.5mm threaded holes were machined in the flats (dashed arrow in Fig. 1(b)) to allow attachment of the excitation hardware.

The second and third physical models (0.4kg) were completed by inserting the implants into the sectioned composite femurs using a torque wrench. The secure (4Nm insertion torque) and loose (0.5Nm insertion torque) femur-implant systems were designed to represent extremes of the spectrum of implant integration with the bone in order to establish the ability of the modal analysis technique to detect gross changes in the interface between implant and femur.

B. *Experimental Modal Analysis*

Full details of the modal analysis methodology are provided in [12]. Freely supported boundary conditions were used in the modal analysis; the physical models were supported on a soft foam bed. Fig. 1 shows the coordinate system and excitation/response measurement sites identified along the model length. Thirteen and seventeen sites were identified for the unmodified femur and femur-implant models respectively. The specific excitation sites were chosen because they were expected to exhibit a large response during the bending modes.

Two excitation techniques were used; impulse and sinusoidal sweep excitation. Impulse excitation was imparted using a hand-held impact hammer instrumented with a piezoelectric load cell and signal conditioning unit (part numbers 086C03 and 480C02, PCB Piezotronics, Depew, USA). The response of each physical model was measured using a single axis piezoelectric accelerometer (0.002kg) connected to a charge conditioning amplifier (part numbers 4393 and 2692-A-0S2, Bruel&Kjaer, Naerum, Denmark). Each model was impacted twenty times on the excitation site (see Fig. 1) with the accelerometer attached to the first response site. The test was then repeated using the same excitation site but attaching the accelerometer to each response site in turn using beeswax.

After the impact hammer testing was complete, another series of tests were performed using electromagnetic shaker excitation. The electromagnetic shaker was driven by a power amplifier (part numbers 4810 and 2706 Bruel&Kjaer, Naerum, Denmark). A signal generator (33120A, Agilent Technologies, CA, USA) was used to input a sinusoidal sweep signal to the shaker (100Hz-10kHz frequency range, 500mV peak-to-peak amplitude and 5kHz per second sweep rate). Signal amplitude and sweep rate were investigated and optimised so as to adequately excite a broad range of frequencies with satisfactory signal to noise ratio. The excitation signal was measured using a dynamic force transducer (0.028kg) powered by a signal conditioner (part numbers 2311-500 and 4416B, Endevco, CA, USA). The shaker was connected to the force transducer via a Delrin stinger (Bruel&Kjaer, Naerum, Denmark). The force transducer was connected to the model using a screw connection in the 2.5mm threaded hole. Each model was excited ten times by the sinusoidal signal at the excitation site; the placement of the accelerometer on successive response sites was the same as for the hammer excitation.

The excitation and response signals were recorded using a 16-bit resolution data logger (USB-6259, National Instruments, NSW, Australia) connected to a personal computer (HP Intel ® Core™ 2Duo CPU 3.5GB RAM) using data acquisition software (LabVIEW SignalExpress v2.5, National Instruments) and a maximum sampling rate of 50kHz.

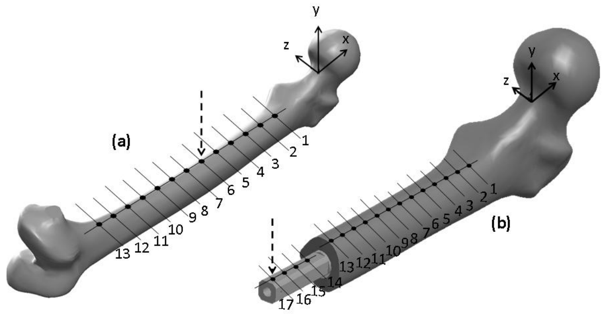

Fig.1. The (a) unmodified femur and (b) sectioned femur-implant physical models, showing coordinate axes, numbered response sites and the single excitation site for each model (dashed arrow).

C. *Data Analysis*

Customized analysis programs were written using MATLAB software (version 2007a, MathWorks Inc, Natick, MA, USA), detailed in [12], to process the input and response signals and compute the frequency response function, accelerance, defined as the ratio of acceleration response to excitation force in the frequency domain.

Plots of accelerance-frequency and corresponding coherence-frequency were generated from the tests performed at each excitation/response site combination. Then a mean accelerance-frequency plot was calculated from all 13 and 17 response sites of the unmodified femur and femur-implant models respectively. The mean accelerance plots were used to identify the natural frequencies. The imaginary components of the accelerance were also used to identify the mode shapes of the model.

III. RESULTS

A. Natural Frequencies of unmodified composite femur

Three natural frequencies of the unmodified composite femur determined using the impact hammer and electromagnetic shaker are presented in Table I alongside the same modes of a previous generation composite femur model reported in [13]. The maximum difference in frequency values obtained between the hammer and shaker was 5% (second bending mode). When comparing the frequencies obtained with the shaker to [13], the largest difference, 16%, was found in the first bending mode.

TABLE I
NATURAL FREQUENCIES OF COMPOSITE FEMUR

Structure	4th gen femur	4th gen femur	Femur in [13]
Excitation device	Impact hammer	Shaker	Shaker
1st bending (Hz)	347	352	295
Torsion (Hz)	634	629	632
2nd bending (Hz)	938	890	809

B. Comparison of Impact Hammer and Shaker

The accelerance-frequency and corresponding coherence-frequency plot obtained for the test at excitation site 17, response site 17 of the secure femur-implant model using the impact hammer and shaker are illustrated in Fig. 2. At the natural frequencies (peaks in the accelerance plot), the corresponding impact hammer excitation coherence was less than 0.8 and for the shaker excitation greater than 0.8. As a coherence value of 1 indicates no noise in the measurement, the signal to noise ratio achieved with the shaker methodology is superior to that of the hammer. Over the frequency range (0-1800Hz), two and three natural frequencies were obtained using the hammer and shaker respectively. The minimum at 550Hz is antiresonance, indicating no motion at the site at this frequency.

C. Comparison of Secure and Loose Femur-Implant Models

The mean accelerance-frequency plots over the range 0-3000Hz for the secure and loose femur-implant models excited using the shaker are compared in Fig. 3. A change in the natural frequencies between the secure and loose implant fit is evident; the fundamental frequency lowers when the implant is loosely fitted and higher frequency modes also change. Antiresonances are not preserved in the computation of the mean accelerance.

The fundamental frequency mode shapes of the secure and loose femur-implant models are illustrated in Fig. 4. With no excitation applied to the model the imaginary accelerance at each site would be zero. Therefore the deformation pattern of the model is illustrated by the positive or negative value of imaginary accelerance, indicating positive or negative displacement at this site. It is evident that the fit of the implant alters the deformation pattern of the model.

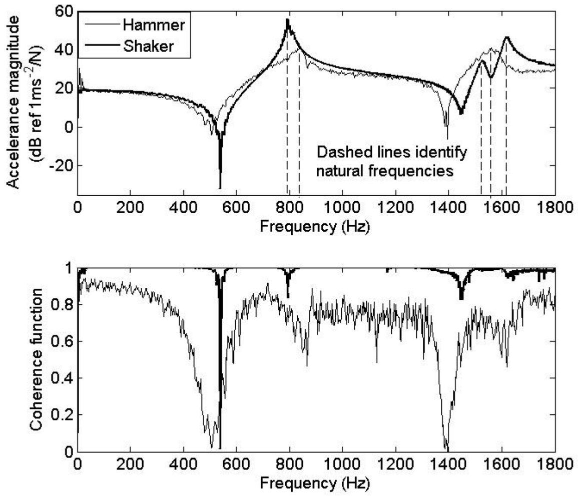

Fig. 2. Accelerance magnitude and corresponding coherence over the frequency range 0-1800Hz of the secure femur-implant model obtained using the impact hammer and shaker (excitation site 17, response site 17). Larger shaker excitation coherence values at natural frequencies (vertical dashed lines) demonstrate superior signal to noise ratio compared to the hammer excitation.

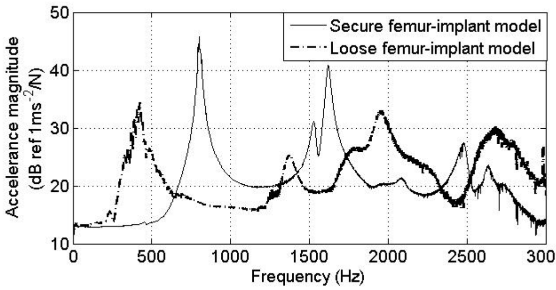

Fig. 3. Mean accelerance magnitude-frequency plot for the secure and loose femur-implant models obtained using shaker excitation. The natural frequencies change with the alteration in implant fit.

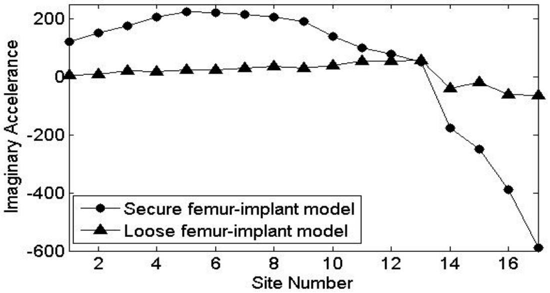

Fig. 4. Imaginary component of accelerance versus site number at the fundamental frequency of the secure and loose femur-implant models obtained using shaker excitation. The mode shape depicted by the value of imaginary accelerance has changed with the alteration in implant fit.

IV. DISCUSSION

The small percentage difference in the natural frequencies of the composite femur obtained using the impact hammer and shaker excitation in the current study indicate that the experimental methodologies, combined with the customised MATLAB programming, provide accurate natural frequencies of the model. The accuracy of the test methodology used is further supported by the agreement between the femur frequencies obtained using the shaker and those reported in [13] using a similar test methodology.

The larger coherence values obtained with the shaker excitation demonstrate that superior signal to noise ratio is achieved compared to the impact hammer, and indicate that the natural frequencies obtained using the shaker are likely to be more accurate. The shaker demonstrated a superior capability at exciting the higher modes of the femur-implant model (1400-1800Hz in Fig. 2). Detection of higher modes may prove useful as it is important to gather as much information as possible about the dynamic properties of the model in order to assess the capabilities of the modal analysis technique in this application.

It was difficult to avoid double impacts with the impact hammer which required repeating the tests. Controlling the alignment of the excitation was also harder with the hammer. These difficulties with the impact hammer, combined with the superior vibration response obtained using the electromagnetic shaker, indicate that use of the shaker is preferred in this application and it should be investigated further to establish the feasibility of modal analysis to detect the progression of OI.

Using shaker excitation the modal analysis identified changes in the natural frequencies between the secure and loose femur-implant models. In addition the mode shape of the fundamental frequency was also different for the secure and loose femur-implant models. The frequency and mode shape changes suggest that the femur-implant model has modes that are influenced by the connection between the implant and the femur and with further investigation may be used to quantify the femur-implant bond.

However, the implant-bone interface changes simulated in this study are gross; the quality of thread mating between the femur and the implant used is not necessarily the most appropriate representation of the mechanical and biological changes that occur at the interface *in vivo*. Further investigation is required to assess if the modal analysis technique can detect more subtle changes at the interface.

The freely supported boundary conditions were used to allow the results to be compared with another modal analysis study [13] and were not considered to accurately represent the boundary conditions of the femur *in vivo*. Investigation of more appropriate boundary conditions is also required.

Using the current experimental set up it would be problematic to adopt the technique in a clinical setting. The length of time to accurately attach the shaker and the 17 test repeats at each response site make it impractical. The sites located on the femur would need to be measured through the skin of the thigh (how this attenuates the response needs to be investigated) or use the implant sites only. Therefore due consideration is required as to how to implement the technique as a clinical tool should it prove successful at detecting the progression of OI.

V. CONCLUSION

Of the two modal analysis excitation devices evaluated in the study, the shaker was demonstrated to be superior at detecting the natural frequencies of the femur-implant model with better signal to noise ratio and consequently is recommended as the most appropriate method to further investigate the application of modal analysis to TFOI.

Changes in natural frequency and corresponding mode shape as a result of a change in the implant fit within the femur were demonstrated: interfacial changes can be identified using modal analysis techniques and form the basis for further modal analysis testing of more realistic models.

REFERENCES

[1] R. Brånemark, P-I. Brånemark, B. Rydevik, and R. R. Myers, "Osseointegration in skeletal reconstruction and rehabilitation: a review" *Journal of Rehabilitation Research and Development*, vol. 38, pp. 175 –181, March/April 2001.

[2] P-I. Brånemark, *The Osseointegration Book From Calvarium to Calcaneus*. Berlin: Quintessenz Verlags-GmbH, 2005, pp. 463 –487.

[3] K. Hagberg, R. Brånemark, B. Gunterberg, and B. Rydevik, "Osseointegrated trans-femoral amputation prostheses: Prospective results of general and condition-specific quality of life in 18 patients at 2-year follow up." *Prosthetics and Orthotics International*, vol 32, pp. 29 –41, March 2008.

[4] N. Meredith, D. Alleyne, and P. Cawley, "Quantitative determination of the stability of the implant-tissue interface using resonance frequency analysis" *Clinical Oral Implants Research*, vol 7, pp. 261 –7, September 1996.

[5] N Meredith, K. Boo, B. Friberg, T. Jemt, and L. Sennerby, "Resonance frequency measurement of implant stability in vivo" *Clinical Oral Implants Research*, vol 8, pp. 226 –233, June 1997.

[6] P. Cawley, B. Pavlakovic, D. N. Alleyne, R. George, T. Back and N. Meredith, "The design of a vibration transducer to monitor the integrity of dental implants" *Proceedings of the Institution of Mechanical Engineers, Part H*, vol 212, pp. 265 –72, 1998.

[7] S. Lachmann, B. Jager, D. Axmann, G. Gomez-Roman, M. Groten, and H. Weber, "Resonance frequency analysis and damping capacity assessment. Part I: An in vitro study on measurement reliability and a method of comparison in the determination of primary dental implant stability" *Clinical Oral Implants Research*, vol 17, pp. 75 –9, February 2006.

[8] V. Pattijn, *et al*, "Resonance frequency analysis of implants in the guinea pig model: Influence of boundary conditions and orientation of the transducer" *Medical Engineering and Physics*, vol 29, pp. 182 –190, March 2007.

[9] W. Xu, F. Shao, and D. Ewins, "A resonant frequency measurement system for osseointegration trans-femoral implant" *Key Engineering Materials*, vol 295-296, pp. 139 –44, 2005.

[10] F. Shao, W. Xu, A. Crocombe, and D. Ewins, "Natural frequency analysis of osseointegration for trans-femoral implant" *Annals of Biomedical Engineering*, vol 35, pp. 817 –824, May 2007.

[11] *Structural Testing: Part 2 Modal Analysis and Simulation*, Bruel & Kjaer., Naerum, Denmark, 1988, pp.1 –56.

[12] N. J. Cairns, "The feasibility of vibration analysis as a technique to detect osseointegration of transfemoral implants," Ph.D. dissertation, School. Eng. Systems., Queensland University of Technology., Brisbane, Australia, 2010. Available: http://eprints.qut.edu.au/38874/.

[13] J. F. Dias Rodrigues, H. Lopes, F. Q. de Melo, and J. A. Simoes, "Experimental modal analysis of a synthetic composite femur" *Experimental Mechanics*, vol 44, pp. 29 –32, February 2004.