Ultrasonic monitoring of the structural integrity of hip replacements

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Medical background

Within the ageing population a growing number of people face structural integrity problems with their hip replacements. There is need for an objective and acurate method of evaluating the results of hip arthroplasty. Radiographic criteria for mechanical loosening are not well-defined. Confusion arises also from the fact that only some of these hip problems are painful. Consequences of loosening of the prosthesis are huge, both from a patient (major re-operation) and societal perspective (costs). Roentgen stereophotogrammetric analysis (RSA), using tantalum bone markers, makes it possible to detect movement between body segments with a high degree of accuracy and thus at an early stage detect prosthetic loosening defined as migration. However, RSA is very costly and also labour intensive. The development of a rapid, non-invasive and cheap monitoring device/procedure therefore constitutes an appealing prospective.

To prolong the effective use of the hip replacement, currently patients often take anti-inflammatory medication, sometimes over extended periods of time. Such medication may may have considerable side effects. Moreover, as monitoring is rather indirect and infrequent, the detection of inflammation allows to pick up problems only at a rather late stage.

In Figure 1 an X-ray image is shown of a hip replacement. A rather long metal pin is inserted in the upper-leg bone. At the other end of the pin a half sphere ball is visible which is placed in a cup-formed plastic component which in its place is put in the hip bone. The connection between the metal pin and the bone can become affected as a result of inflammatory responses, creating thin pockets of fluid between remaining bone and the metal pin. Over time such reaction can lead to serious degradation of the hip replacement system. The development of a rapid, non-invasive and cheap monitoring device/procedure therefore constitutes an appealing prospective.

Figure 1: Medical image of hip replacement on the right-hand of the patient. The cup-formed component that is placed in the hip bone and the metal pin placed in the upper leg bone are clearly visible.

Ultrasound oscillatory transfer

In order to detect early signs of loss of structural integrity due to loosening of the connection between the replacement components and the remaining skeletal structures, we propose to exploit the mechanism of ultrasound transfer. Specifically, by measuring the frequency dependent transfer function of the hip-and-upper-leg system, one may obtain a patient-specific pattern associated with the actual condition of the integration of the prosthesis in the upper-leg bone. The response due to an oscillatory input at designated 'inlets' can be measured at selected 'outlets'.

At sufficiently high frequencies the contribution of the surrounding nearby tissue to the transfer function becomes negligible and mainly characteristics of the bone and prosthesis are measured. By measuring the transfer function at regular instants in time, it is expected that even very subtle changes can be observed and an early detection of any gradual changes can be quantified. An illustration of the concept is given in Figure 2. As the ultrasound agitation and monitoring can be realised non-invasively and potentially at low cost, this basic concept appears a viable option that deserves further research.

Approach

The final goal is to develop a device with which routinely frequency dependent transfer functions can be recorded on a patient-specific basis. To initiate the development of

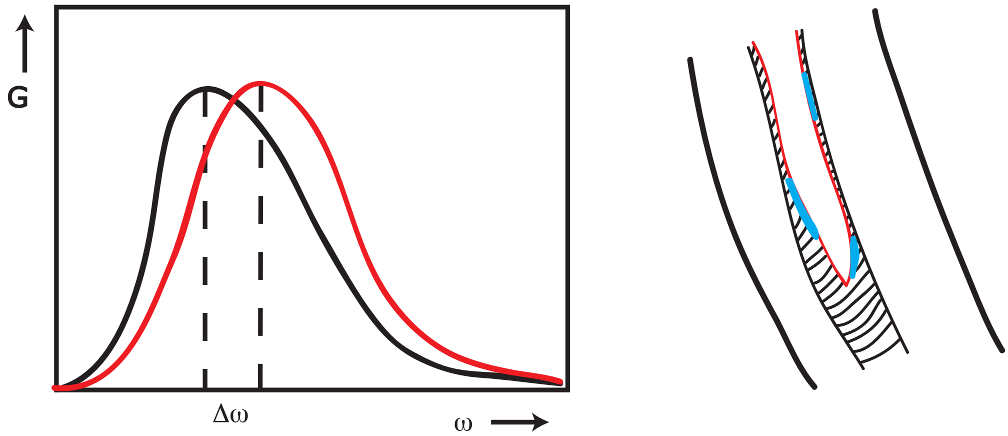

Figure 2: Indication of a shift $\Delta\omega$ in the frequency dependency of the transfer function G in case of an affected hip replacement (red curve) compared to the desired situation (black curve). On the right a sketch is given of part of the upper leg with a metal pin (red) inserted in the remaining bone (hatched area). In blue an indication of affected bone tissue is given arising from inflammation, causing the differences in frequency response.

such a device, a mathematical model will be formulated with which the concept can be underpinned. In a later stage this work will be complemented with the exploration toward a prototype and clinical testing.

To develop a model for patient-specific recording of the frequency dependence of the transfer function we envisage three main steps:

1. a mathematical model will be formulated for the propagation of oscillatory patterns in composite tissues in a grossly simplified cylindrical geometry. For a system of concentric material components an analytical solution will be found and the main sensitivity of the frequency response to changes in the tissue material will be quantified

2. in a follow-up step the mathematical model will be extended to more general curved geometries and heterogeneous tissue components. This will be the basis for the development of a numerical method with which wave-propagation in complex domains can be simulated in detail

3. a final step towards a model for the ultrasound monitoring prototype will be the translation of patient-specific medical imagery into a detailed geometric model of bone and tissue with which the wave propagation and the complete transfer function can be predicted.