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Can You Hear The Femur Play?
Bone audio speakers at the nano scale

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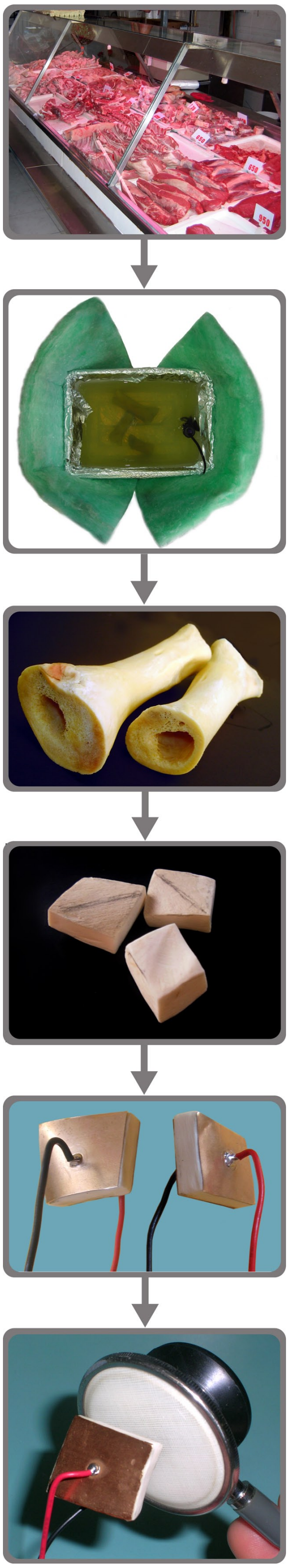


Abstract

This paper describes the research process involved in making audio speakers out of cow bone. The paper begins by discussing the conceptual basis of the work. It goes on explain the piezoelectric nature of the bone matrix and how this makes it possible for bone to operate as an audio speaker. Following this, it chronicles the process of working through from a theoretical possibility to a functional speaker. In the concluding section of the paper, the final artifacts and conceptual oucomes of the process are discussed.

Frame

This paper is framed as a discussion of practice based research. It addresses a process of working with scientific techniques and practices towards an artistic end. In doing so, it focuses on what was learnt in the process of making the work in order to understand how the initial intentions behind the work were modulated through their encounter with materials. Thus, it constructs a narrative that consciously mediates between the technical details and the conceptual concerns of the project, in order to demonstrate how they have informed each other.

The conceptual framework that I bring to bear on this discussion is one that places emphasis on the act of 'making strange', an idea that originates from the writing of the Russian Formalist, Viktor Schlovsky. Schlovsky described the act of 'making strange', or defamiliarisation, thus:

> "The purpose of art is to impart the sensation of things as they are perceived and not as they are known. The technique of art is to make objects "unfamiliar," to make forms difficult, to increase the difficulty and length of perception because the process of perception is an aesthetic end in itself and must be prolonged." (Schlovsky: p13)

For Schlovsky, the aim of 'making strange' was to deconstruct habits of perception so as to enable familiar things to be re-experienced in a new way. Hence, while some of the observations that I make in the course of this paper may seem obvious to someone familiar with the territory, I am interested in foregrounding how these relationships are *experienced* not abstractly understood. Furthermore, I am not only interested in 'making strange' with the materials, but also the actions involved in constructing the artifact and the narrative relationships that they enact. Thus, the experience of making the work becomes an important factor in considering how it will eventually be presented.

Concept

Over the past three years I have been working on a project, now nearing completion, to make audio speakers out of bone. This work has been motivated by a desire to investigate phenomena occurring beyond our human capacity to sense, at the nano scale, and to amplify these interactions in such a way that they are able to be affectively experienced at the human scale. It also references the increasing convergence of life and device that is currently taking place in biotechnical research and practice at the level of the cell, the protein, and beyond and works to 'make strange' the capacities of biological materials existing within our own bodies. Practically, the project has involved working with the piezoelectric nature of the bone matrix in order to cause the bone to vibrate in such a way as to generate audible sound. The quality, or fidelity, of this sound has not been an important consideration.

Piezoelectricity is a characteristic of certain types of crystals and polymers, such that when they are subjected to a mechanical pressure or stress they develop a charge separation, or voltage, across two opposing faces. Conversely, when a voltage is applied to the same material it will, depending on the polarity of the voltage, physically expand or contract at the nanometer scale. It follows that when an oscillating AC voltage is applied to a piezoelectric material it will expand and contract at the same frequency as the AC signal. This principle is used to make piezoelectric buzzers and audio speakers out of industrially manufactured piezo ceramics and I hoped that the same could be achieved with bone[1]. The piezoelectric nature of the bone matrix itself has been documented by a number of different scientists in publications that date back to initial research into the phenomenon by Japanese physicists Fukada and Yasuda in 1957[2]. Orthopedic researchers have applied this knowledge in the design of bone healing devices and some Indian scientists claim to have fabricated an ultrasonic transducer using discs made of dry bone powder[3].

Living bone contains several different types of cells that are housed within the bone matrix and are responsible for constant remodelling of the bone, through reabsorption and secretion of matrix, in response to physical stress. The bone matrix itself is composed of fibres of the protein collagen layered together with hydroxyapatite crystals. However, the piezoelectric nature of bone has been attributed to the collagen rather than the crystaline component of the matrix, which does not posses the correct arrangement and distribution of electrical charges within its molecular structure for the piezoelectric effect to occur. One of the theories as to how physical stress on the bone is communicated to the bone remodelling cells is through the small charges generated by the direct piezoelectric effect of collagen in response to the pressure of walking[4].

What initially interested me about this particular property of bone, was the way in which it speaks to the complex and dynamic entanglements that exist between life and world; to the incredibly fine resolution at which bodies are continually in communication with their physical environment. The problem that I faced as an artist was how to access and express these qualities in an artwork. I was not interested in using scientific visualisation technologies in an exhibition context as I felt that this would become more about the aesthetic and quality of the translation rather than the experience of bone 'made strange' that I hoped to achieve. So I decided to pursue the idea of utilising the converse piezoelectric effect to make bone audio speakers and I did this for two reasons. Firstly, sound is a dynamic and continuous phenomenon. To listen to bone generating sound would thus be to engage in a direct experience of its dynamic material qualities. Secondly, hearing has one of the finest resolutions of all the human senses. "The threshold of [human] hearing corresponds to air vibrations on the order of a tenth of an atomic diameter." (Nave) This would make the smallest movements of air that an ear can respond to somewhere in the order of 0.1 angstroms or 0.000000001 of a millimetre. Thus it would seem that the ear is an appropriate organ through which to experience the intersections of art, life and world at the nano scale.

Paradoxically, in order to utilise the dynamic qualities of bone to make an audio speaker it becomes necessary to remove the bone from its living context. Thus, what was initially an investigation of the electromechanical properties of the living body, becomes a process of material transformation that begins at the butcher and ends with a technological artifact. (See Fig. 1). In a sense, this parallels much of the work that takes place in the life sciences. Living systems are often studied in parts; parts of an organism after it has been killed, or parts of an organism maintained and perpetuated outside of the body through various genetic and laboratory technologies. Increasingly these parts are repurposed towards extra-organismic ends in the biotech and pharmaceutical industries, and in an extension of the traditional terrain of biotechnology, synthetic biology seeks to utilise biological parts at the smallest scale to engineer 'life' from the bottom up. Thus, the process of making the bone speakers, became as much about enacting and reflecting on the use of body parts as technological components, as about 'making strange' certain capacities of the living body.

Process

A large part of the research towards this work has taken place during the course of two residencies at SymbioticA, an art and science collaborative research laboratory at the University of Western Australia. I began the initial reading and practical experiments during a three month residency in 2004 and as part of my year long residency over 2006 I was able to organise a Biomedical Engineering student, William Wong, to undertake the research as an Honours project, partly under my supervision. This lead to a collaboration of sorts in which we both undertook responsibility for particular aspects of the project and worked together through much of the process.

Scum on the top of bone rotting tank

The initial stages of the transformation involved a ‘purification’ of the material. After purchasing the bones - large cow femurs - from the local butcher I removed the bone marrow and scraped as much flesh from them as I could. Then I macerated them for several weeks in a rotting tank (see Figs. 1 and 2), consisting of an insulated plastic box filled with water and heated to 37°C using an aquarium heater. This set-up promoted the growth of flesh eating bacteria, which were used to break down any remaining tissue. Once clean, the bones were soaked in 100 percent ethanol for a further 10 days (see Fig. 3) before being placed in a drying oven at 50°C. Care was taken not to heat the bone beyond 60°C at any stage in the process as this would denature the collagen and potentially destroy the piezoelectric responsivity of the matrix.

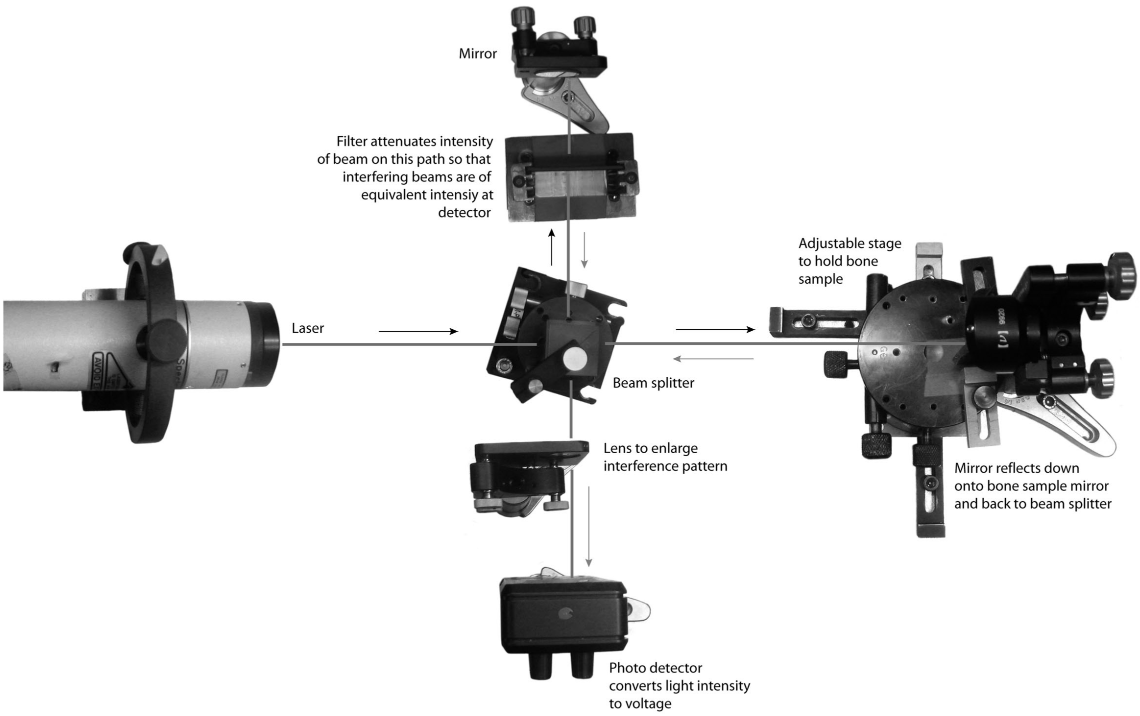
The second part of the process was to construct the transducers. We cut sections approximately 20-30mm square at a 45° angle to the longditudinal axis of the bone using a water cooled bone saw. This was done in accordance with the initial research paper published by Fukada and Yasuda on the subject of bone piezoelectricity. The water cooled bone saw would again protect the collagen from any adverse heating effects and the angle of the cut was crucial to gain the maximum piezoelectric effect. I then glued foil electrodes onto opposing faces of the bone sections and attached electrode wires using conductive silver loaded epoxy.

The third stage of the process involved testing and measuring the responsivity of the speakers. We drove the bone using a variable frequency sine wave generator coupled to a high voltage amplifier and tried a number of different systems to detect the vibration. We had determined that the vibrations should be somewhere in the order of several nanometers and, if they were transmitted well enough through the air, would be within range of human hearing. However, to our disappointment, this was not the case. We tried using a highly sensitive microphone connected to an oscilloscope in order to see the vibrations but the background noise in the lab proved to be too loud. We then tried several types of piezoelectric vibration sensors with the oscilloscope but found that the electromagnetic interference from the charges stored on the electrodes of the bone transducer was too great for a meaningful signal to be achieved. By this stage the challenges of working with materials at such a small scale were becoming evident. Not only were the changes in the bone apparently beyond the scale of human perception but they were also too small to be detected in our acoustically and electromagnetically noisy environment.

We spent several weeks trying these various different approaches with no success. During this time I began to question my own ready belief in the scientific papers documenting experimental evidence of bone piezoelectricity. I realised how much I had been influenced by the common ellision of science and fact in popular western culture. I was also struck by the tenuous experiential connection afforded by the various translation technologies that we were using to access the world outside our sensory bandwidth. Trying to understand the complex micro-interactions between mechanical and electromagnetic phenomena that we could only capture in fragments using a necessarily limited and target specific technical apparatus, and rationalise within our equally limited theoretical frameworks, felt like stumbling around in the dark. There were moments when we were convinced that there was the solidity of a definite result in front of us only to have it assume an entirely different shape under closer inspection. At one point in the process we were sure that we could hear sound emanating from the bone transducers, but after a few days and some more rigorous examination we realised that the sound was in fact being generated by the foil shielding on the connections resonating with the electromagnetic field generated by the high voltage signal.

Eventually, it became necessary for William to construct a Michaelson laser interferometer (see Fig. 4) that would be immune to electromagnetic interference and more sensitive to specific vibrations than an acoustic microphone. This particular type of interferometer works by directing a laser beam through a beam splitter to create two beams from the original one. One of the two beams is bounced off the subject of examination using a mirror and recombined with the second beam at a detector which measures light intensity. Once the laser and sample are correctly positioned the movement of the sample under the reflected beam will cause the two beams to interfere in such a way as to change the intensity of the light at the detector in time with the sample vibration. This change in intensity is translated into a voltage and fed into the oscilloscope where it can be read as a sinosoidal signal. It sounds fairly straight forward when described in this manner but once again the details of the process reveal the difficulties of coupling our macro sensory realm with the tiny size of the measurements that we were seeking to make.

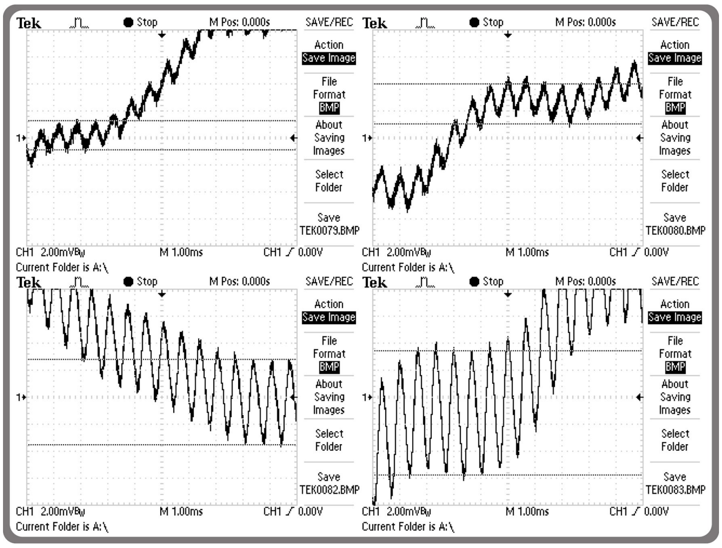
In order to align the interferometer correctly we often spent hours making minute adjustments to the tilt of the different reflective mirrors and the position of the bone speaker in relation to the laser beam. Once this was finally achieved we repeatedly found that the bone itself was slowly shifting position in imperceptible increments, which caused the interferometer to lose its alignment again within minutes. We went through several systems for holding the bone in place but found in the end that it was necessary to leave it to settle overnight before trying to test it. Even then it was not always still in the morning and a bump of the table or a bang of the door could cause it to begin shifting again. I felt like a blind Gulliver clumsily thrashing around in a world whose detail was way too fine to match my motor skills and whose effects I was only able to register second hand.



Despite our clumsiness the interferometer proved to be the appropriate instrument for the task and we were finally able to detect a vibration in the bone. The bone speakers were, in fact, vibrating at the nano scale just as we had predicted. They had a fairly wide frequency response from around 300Hz up to about 3000Hz, depending on the particular piece of bone, and each transducer had a different resonant frequency, usually sitting somewhere around 2000Hz. (See Fig. 5) So the responsivity of the speakers was well within the range of human hearing[5] and close to the frequencies that are easiest for human ear to detect. But we could not hear anything.

Our assemblage of translation devices produced a map that, while useful, was ‘not the territory’[6] The map was an artifact of the particular series of material interactions through which it was generated. To read the map required a series of contextually specific skills and abstractions that, while allowing the details of the map to be interpreted, took us further away from an experience of the bone and created instead an understanding of the practice of map reading. I was confronted by a fundamental conflict between the intentions of my art practice, which is to create affective experiences of materiality, and the processes of doing scientific research, which are designed to extend the perceptual parameters of a researcher’s body with maps. While these maps signify a great deal about the process of scientific knowledge formation they were not what I had hoped to achieve as an end result.

However, although I was initially frustrated by the tenuous nature of the mapped connection to the vibrating bone, I began to realise that this impeded perception, and the function of belief as a mediating factor in the experience of the nano scale bone oscillations, were an important part of the work. After all, the intention of ‘making strange’ is to “to increase the difficulty and length of perception”. (Schlovsky: p13) Perhaps in doing so, both the object in question, and the limits of our ability to perceive are experienced in a new way. If I could construct the work so that it challenged people to believe in the bone speakers, and in doing so caused them to strain at the limits of their perceptual abilities, then I would have succeeded in making the body doubly strange – both the transductive nature of bone and the bandlimited nature of our perceptual faculties would be experientially revealed.



Oscilliscope trace for a 2kHz bone vibration driven by increasing voltage levels

Artifact

In the final days of William’s Honours year we had a breakthrough. When the bone speakers were placed on or close to the diaphragm of a stethoscope it was possible to hear them through the stethoscope’s ear pieces. This is because the stethoscope tubing contains the air and prevents the sonic vibration picked up by the diaphragm from dissipating before it is directed into the ears. The sound was very soft but clearly audible. As I moved the frequency dial on the function generator I could hear the sweep of the sine tone coming from the bone. By this stage I was suspicious of anything that seemed to be a positive result, so I spent several days testing the set-up before I allowed myself to become excited. At the most basic level I was just happy that we had managed to get it to ‘work’, but I was also pleased with the new dimension that the introduction of the stethoscope brought to the project. By placing the bone on the stethoscope an immediate connection is drawn between the speakers and the bioscientific context in which they were conceived and created. A conceptual bridge is formed between old and new technologies; the stethoscope as an instrument that is nearly two hundred years old and the bone speaker which points to strange new technical interventions into the body. Bone as a material has been used to craft instruments of sound and survival since the beginning of human civilisation. To exhibit the bones using stethoscopes in this manner foregrounds the instrumental quality of the speakers. The stethoscope itself operates both as a translation technology and as a means to gain an analogue experience of the bone sound.

The bone speakers intervene in the feedback loop between metaphor and the experience of materiality that habitually constructs the bone matrix as a static quality[7]. They open up the potential for an experience of the mutable qualities of materials at the nano scale and possibly the realisation that stasis is, in fact, only a function of something that does not appear to change within our time or scale of resolution. This in turn can lead to a radical reappraisal of ones own body as something that is continually informing itself at these scales in ways that are not consciously perceived. This re-evaluation of the intricacy of interactions occurring between phenomena at all times is something that the much heralded coming of the era of nanotechnology already inspires. There is currently significant debate occurring about the threats posed by such technologies and how best to protect ourselves from unintended consequences. Although nanotechnologies are unlikely to produce quite the fantastic results that are both promised and feared, there is no doubt that manipulation of materials at the nano scale will prove to be increasingly important in time to come. Correspondingly, the artistic interrogation of the processes, poetics and politics of these manipulations will also become increasingly important. However, the difficulties of amplifying such material transformations so that they can be perceived within the time and scale of an artwork will continue to prove a challenge to artists working in this domain.

In this paper, I have described a process of effecting material transformation, a process of trying and sometimes failing, a process of coming to terms with the huge divergence of scale between that of my perceived world and that of the infinitesimably small response that I had set out to manifest. In the course of this process I have produced not only a piece of bone that can generate sound, that responds dynamically to an electromagnetic stimulus, but also a reflection on the relationship between bodies and technologies – mapping technologies, nano scale technologies, biomedical technologies, old technologies, new technologies, used technologies and useless technologies. Over the past three years, I have dedicated countless hours to this project to make audio speakers out of bone. Like many researchers from engineering and the life sciences I have enacted a process that engages with the body in terms of what it can produce. However, in doing so, I have created a technology that has little or no use and no economic value – I have not been productive with my own body-time. This paradox, lies at the heart of the artifact and its reflection on the manipulation of bodies towards extra-organismic ends. On the one hand, the project seems to reinforce an instrumental approach to bodies, yet this is under-cut by the faintly ridiculous nature of the entire endeavour and the broader economic context in which it is performed. Thus, in a final twist, the exhibition of the completed work will aim to draw out the objective of 'making strange' to encompass, not only the material capacities of bodies and the limitations of human perception, but also the difficult, and often incommensurate, coupling between bodies and economic value.

Thankyou to Professor David Sampson, Dr Julian Armstrong, SymbioticA, the Australia Council for the Arts.

Glossary

Electromagnetic -: Of or relating to electromagnetism.

Electromagnetism -: Refers to the reciprocal relationship that exists between electrical charges and magnetic fields. The movement of electrical charge in a conductor (an electric current) produces a magnetic field and a moving magnetic field in proximity to a conductor produces an electric current.

Interferometer -: "Any instrument in which the interference of waves (e.g. of light) from a common source is employed to make precise measurements of (linear or angular) length or displacement in terms of the wavelength." (Oxford English Dictionary: interferometer)

Nano -: denotes "a factor of 10-9 (one thousand-millionth)". (*ibid:* nano-) So in metric terms movement that occurs at the 'nano scale' is in degrees of one thousand-millionth of a metre. Nano is also used as an abbreviation of nanotechnology.

Piezoelectric -: "A. adj. Of or relating to piezoelectricity; exhibiting or utilizing piezoelectricity.
B. n. A piezoelectric substance, body, or device." (*ibid:* piezoelectric)

Piezoelectricity -: "A phenomenon observed esp. in certain crystals whereby the application of mechanical stress causes a substance to become electrically polarized, and vice versa." (*ibid:* piezoelectricity)
Oscilloscope -: "1. A device for recording oscillations; 2a. Now: spec. (more fully cathode-ray oscilloscope) an

electronic instrument in which a moving spot on the screen of a cathode-ray tube represents by its position the relationship between two variables, usually a steady or varying signal voltage (vertically) and time (horizontally), and which is capable of displaying an oscillating voltage as a stationary trace." (*ibid:* oscilloscope)

Sinusoidal -: "Resembling, pursuing, flowing in, the wave-like course of a sinusoid; having the form of a sinusoid; varying periodically (with time, distance, etc.) as a sine varies with an angle." (*ibid:* sinusoidal)

Sine wave -: "A periodic oscillation of pure and simple form in which the displacement at any point is proportional to the sine of the phase angle at that point; a wave or curve resembling (a segment of) this in form." (*ibid:* sine[2])

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[1] In fact, I later discovered that the operating principle which allows piezo buzzers to translate nano scale movements into clearly audible sound was not actually compatible with the bone.

[2] Fukada and Yasuda

[3] Yadav and Singh. Thankyou to Marta Lyall who originally sent me the information and notes about her attempt to fabricate a bone ultrasonic transducer.

[4] Bassett *et al* 1962

[5] The range of human hearing is traditionally said to be from 20Hz – 20,000Hz. However, these values represent the extreme limits of hearing. The very high and the very low end of the spectrum can only be heard under optimal conditions. The ability to hear the high end of the spectrum decreases with age.

[6] In reference to Alfred Korzybski's famous statement "The map is not the territory"

[7] The parallels drawn between bone and static architectural structure are deeply embedded in our cultural perception of bodies. Andreas Vesalius, one of the key figures in modern anatomy, wrote in 1543: "What walls and beams provide in houses, poles in tents, and keels and ribs in ships, the substance of bones provides in the fabric of man." (*De Fabrica Humanis Corporis*) Bone is described here as a static support. Yet of course anyone who has studied the function of bone *in vivo* will know that this is far from being the case – the bone matrix is constantly being remodelled in response to the mechanical stresses placed upon it.