Structures have relevance to biomedical research

Dr Chris Burgoyne, Reader at Cambridge University, discusses the 'quiet revolution' in physics and engineering which is influencing the biological sciences

What is the most common structural material you work with? What is the most efficient structure you have ever built? Where are the openings for innovation in structural engineering? The answers are not steel or concrete, new bridges or buildings, new techniques for analysis or design. Instead we should look inside our own bodies. There is a quiet revolution going on in which physics and engineering are having a major impact on the biological sciences.

Consider an apparently simple bone, such as a rib. Anatomy text books show it as elliptical in cross-section, with variations in size from the breast bone to the back bone. But if you take a human rib and take sections through it every few centimetres, you will find that the section shape varies significantly along the length (Fig 1). Why? Your breathing is performed not only by the diaphragm but also by the intercostal muscles that criss-cross between your ribs. Studies of the control of breathing have shown significant bending and torsion in the ribs; the peak stresses in the ribs, during normal day-to-day exertion, are virtually constant[1]. The action of the muscles relieves bending moments on the ribs and this principle is seen in other parts of the body. The shape of the ribs precisely matches the loads to which they are subjected.

Studies on other bones have shown that they respond to changed circumstances. Tennis players have more bone mass in their serving arm than in their non-serving arm, and the skeletons of medieval pike-men and archers can be distinguished by the development of their shoulders.

It is also known that bone mass can be increased by exercise, and decreases during periods of inactivity (or weightlessness in the case of astronauts). People with broken legs are encouraged to put weight on them as soon as possible to prevent reabsorption of the bone, and there is very important study going on to find better materials or a better design for replacement hips[2].

The prosthetic hip is a metal ball and socket joint, with the connection to the femur via a spike that is placed in the medullary space. The metal insert, being stiffer, attracts more of the stress, which leaves the surrounding bone to carry less load. So the body reabsorbs the surrounding bone, which leads to a loosening of the bone in the femur. The pain returns, and in some cases, a second operation is needed, this time with a longer spike sticking further into the femur (with greater mortality and complications).

It is known that the 'factor of safety' in bone is quite low; typically applying about 1.2 times the normal loads on a bone will cause the elastic limit to be exceeded. The bone does not break but it then evokes repair mechanisms to strengthen itself. This is why one is not encouraged suddenly to take up exercise, but to build up the effort gradually.

So what is the mechanism by which the body regulates our bones? How did we get the way we are? Is it in the genes or in the way we use (or misuse) our bodies? The bones we die with almost certainly contain none of the material we were born with. Bone has cells called osteoclasts which remove old or unused bone matrix, while osteoblasts lay down new bone matrix which respond to osteocytes which act as signalling transducers in response to high bone stress.

There is considerable discussion about the processes by which these cells work – the biologists look at hormone concentrations and molecular processes, while the structural engineer looks at what the processes must be for stability and healthy operation. One of the commonest diseases, osteoporosis (when bone matrix is reduced partially by actions of osteoclasts) is almost certainly due to imbalance between control of the two processes. Finding a solution to this imbalance would save a lot of people from pain in their later years.

> *'An A-level in biology is a useful qualification for a structural engineer as well as an open mind.'*

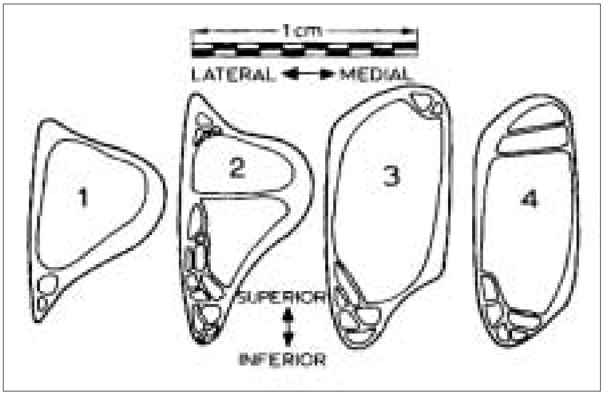

Fig 1. Cross sections at various positions of the same human rib. The variations of the section, including the internal subdivisions, are structurally significant[1].

If you want to see how complex your body is as a mechanism, consider the elbow. With your upper arm vertically down and your forearm horizontal, what weight could you support in your hand – perhaps about 20 kg? The muscles in the upper arm give at least a 10:1 lever advantage, so simple mechanics shows that about 200kg must be passing through your elbow. Without the weight, hold your arm out straight and rotate your wrist – you have about 180° of movement, depending on your suppleness. Now flex the elbow so that your forearm is at right angles to the upper arm and repeat the twisting. Do it again with your wrist almost up to your shoulder. You retain almost as much flexibility with the elbow bent. Do you want to make a fortune? Design a replacement elbow joint, or a joint for a robot, that gives the same degrees of freedom.

How much is genetic and how much a product of our environment? We all know that twins look alike and that we resemble our parents, siblings and children. To continue the arm experiment, put your arms together in front of you so that your elbows touch. Are your wrists touching? If so, you are probably male; if not you are probably female. That difference is almost certainly genetic, but it is not obvious what function the difference served when humans were evolving.

There are only about 40 000 genes in human DNA. Imagine having to specify the structure, form and function of something as complex as a human being with only a limited number of pieces of information. Evolution has developed very complex processes by which one set of regulatory genes can control development of a complex tissue such as bone or muscle through gene induction.

It is not just in the field of modern medicine that structural mechanics has a lot to offer. Rhizodonts were shallow-water fishes that flourished from the Late Devonian to the Late Carboniferous period[3]. They were seriously nasty creatures – up to 7m in length, with a jaw about 1m long and two rows of teeth. One row had only a few long teeth; the other had a much more complete set of smaller teeth.

Palaeontologists knew that the jaw

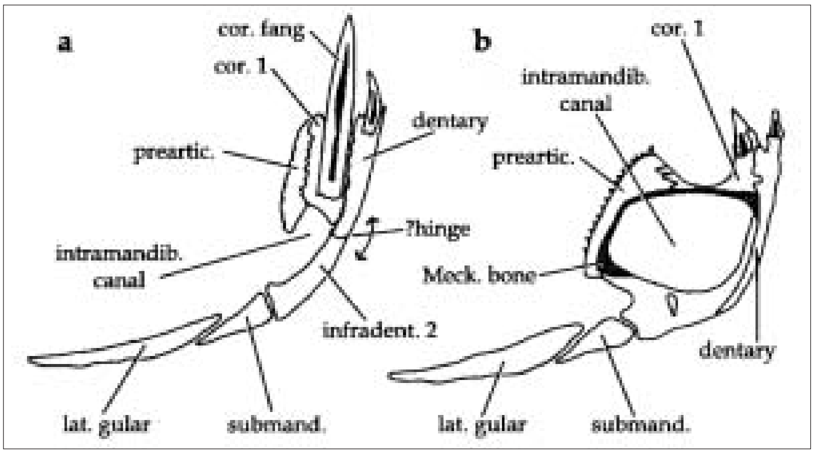

Fig. 2. On the left, the torsionally flexible jaw of a rhizodont. On the right, a much more torsionally stiff jaw bone of a eusthenopteron[3]

bones on either side met at the front of the face with a flexible joint, not one that was fused as is normal. They also knew that the jaw bones were not made up of a closed section with a central canal, but were instead made up of 'C' shaped open sections (Fig. 2).

One probable explanation comes straight from structural mechanics. An open section would have been torsionally less stiff than a normal closed jawbone and the C-section would have had a shear centre that lay outside, and below, the jaw. So when our beast gripped its prey the long teeth would have exerted the first pressure, causing torsion in the jawbone, which twisted inwards, gripping the victim and bringing the second rows of teeth into action. The non-fused joint at the front permitted this motion. This unusual jaw construction allowed rhizodonts to become the top aquatic predators of the time. They were supremely adapted to their environment and flourished for millions of years.

Structural mechanics also plays a part in biology on the micro-scale. The structure of DNA comes from the natural binding angles of the component nucleotides, but some of these bonds are flexible while others are stiff[4]. Many biological processes require a protein to recognise a particular sequence of DNA, which is achieved by fitting together complex complementary shapes. In many cases the DNA is bent around the protein according to sequence-dependent flexibility and twistability. Understanding the structural mechanics will play a large part in the development of new drug strategies to control this interaction.

So structural engineering is not just about reinforced concrete, BS this or Eurocode that. It has direct relevance to many other branches of science. An A-level in biology is a useful qualification for a structural engineer. As well as an open mind. se

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