

Editor's Introduction

Orthotics (musculoskeletal supports) and prosthetics (musculoskeletal replacements) have in common their affect on the skeletal system. To understand better the laws of biomechanics as related to orthotics and prosthetics, a look at the structure and function of the components of the skeletal system is warranted. This article will explore components of the skeletal system affected by our field. Perhaps by a better understanding of the human body, enhanced patient care is possible.

With this article, I would like to extend an invitation to potential authors to submit similar "Tutorial" articles for publication in *Orthotics and Prosthetics*, thereby providing a solid base of continuing education for our readers.

Lawrence R. Lange, C.P.O.

Bone and Cartilage: Structure and Biomechanics

H.R. Lehneis, Ph.D., C.P.O.

BONE

Histology

Unlike other connective tissue, the extracellular components of bone are calcified to produce a relatively unyielding substance constituting the major characteristic in the evolution of vertebrate animals. The function of bone is to support, provide protection for vital organs, and to serve as a lever system in the locomotor and manipulative apparatus. Furthermore, it plays a metabolic role in enclosing the blood-forming elements of the bone marrow and to serve as a store for calcium for homeostatic regulation of the calcium concentration in the blood and other fluids.

Macroscopic Structure

Spongy bone consists of trabeculae which delimit inter-communicating spaces, which are occupied by bone marrow.

Compact bone appears as a solid mass and blends into the spongy bone without any sharp boundary. Long bones such as the femur and humerus consist of a diaphysis (shaft) which encloses the medullary cavity, and epiphyses at the ends of the shaft, which consist mainly of spongy bone. The trabecular spaces in the epiphyses are directly continuous with the medullary cavity. In the growing individual, the epiphyses and diaphysis are separated by the epiphyseal plate containing cartilaginous material, which constitutes the growth zone. Nearly all bone is covered by periosteum, which is a layer of specialized connective tissue possessing osteogenic properties (i.e., the property to form bone).

Microscopic Structure

Under microscopic examination, it is found that the cellular elements of the

bone contribute to the total mass of the bone to only a small extent.

Compact bone is composed of bone matrix or lamellae. These are arranged concentrically around a longitudinal channel, or Haversian canals. Haversian canals contain blood vessels, and are interconnected with the marrow cavity by transverse, Volkmann's canals. The interstitial substance contains lacunae, which contain osteocytes.

Spongy bone is also composed of lamellae with lacunae in the interstitial substance. The whole makes up the trabeculae of the spongy bone.

Periosteum contains the inner layer of bone-forming osteoblasts in the embryonic and post-natal stage. In the adult, they assume their bone-forming function only when bone is injured, but otherwise remain in their resting form. The outer layer is mostly acellular and contains blood vessels.

Interstitial substance consists of an organic matrix and inorganic salts. Organic matrix consists of collagenous fibers of protein polypeptides. The inorganic matter is composed of submicroscopic crystals of an apatite of calcium and phosphate resembling hydroxy apatite.

Bone cells are three kinds (osteoblast, osteocyte, and osteoclast) in actively growing bones. Osteoblasts are associated with the formation of bony tissue found in growing bones and are located at the inner layers of the periosteum and in direct contact with the bone.

Osteocytes are the main cells of the fully formed bone located in the lacunae of the calcified interstitial substance. They are believed to be transformed osteoblasts which in the adult bone are surrounded by a bony matrix.

Osteoclasts are transformed osteocytes. They are believed to play an active role in the reformation of the trabeculae of spongy bone in response to stresses applied to the bone and consequent remodeling.

STRUCTURE AND BIOMECHANICS

The structure and biomechanical requirements placed on bone are remarkably interrelated. The architecture of bone, both internal and external, reflects to a great degree an adaptation to stresses applied by external mechanical forces, which may be gravitational, locomotive, or due to functional activities.

The biological response to the stresses placed on bone is explained by Wolff's law, which states that the spongiosa of bone is able to reorient itself through modification of the trabecular system in response to mechanical stresses. This is true both under normal and pathological conditions, while in the development of bone other factors play an important role, such as heredity. It is still believed that the normal geometric configuration of bone is primarily a biological response to the stresses due to forces transmitted through the bone. In recent years, evidence has been accumulating to indicate that the biological structures, including bone, exhibit piezoelectric effects when stressed. For example, a beam which is vertically loaded, and as a result of the load begins to bow, will exhibit an accumulation of positive charges on the convex side and negative charges on the concave side. It has been experimentally shown that bone stressed in the manner described above will remodel itself by resorption of bone on the convex side and accretion on the concave side. More recently, the healing of fractures has been promoted by passing an electric current in the order of two to five microamperes, simulating piezoelectric magnitudes, to promote and accelerate healing of the fracture site. Although the total mechanism by which piezoelectricity affects bone remodeling is not yet known, it is believed that a possible mechanism may be that the osteocytes, with their many long dendrites acting as stress sensors, mobilize the cell and may transform it into an osteoblast or osteoclast, but the mechanism at the cellular level is not known or understood. Nevertheless, piezoelectric phenomena seem to play a crucial role in the modeling of bone.

In the growing child, for example, it is consistently observed that from a bow-legged position which, of course, represents the embryonic position, the child develops a knock-knee position after he begins to walk, reaching its maximum at the age of about four or five, at which time the leg becomes relatively straight. This clearly indicates a response to the abnormal stresses applied when the leg is not straight. Of course, in the growing child the knock-knee represents an over-compensation which is not found in the adult with a reduced metabolic rate. In the spine, it is observed that the relative size of the vertebrae increases from the first cervical to the fifth lumbar, again in response to the stresses imposed by the superincumbent weight. Another good example of this is seen in the relative size of the medial and lateral condyles of the knee, the medial condyle being considerably larger than the lateral condyle. This is so because the supporting structures (i.e., the limbs) are lateral to the center of gravity. Thus, during weight bearing, a moment is generated on the knee joint, resulting in relative compression of the medial condyle and tension on the lateral collateral ligaments (canted lever). During locomotion, this moment is further exaggerated in single stance due to the lateral thrust produced by the action of the gluteus medius. It can also be seen that bony protuberances, in general, are due to the tension produced by the insertion of tendons from powerful muscles (e.g., the greater trochanter).

The internal structure of bone represents, with almost mathematical precision, a structural arrangement of the trabeculae along the stress trajectories with orthogonal supporting geometry. The orientation of joint axes is also influenced by locomotive patterns, as for example the ankle axis which is externally rotated due to tibial torsion and represents an adaptation to bipedal locomotion.

In the upper limb, the scapula has evolved from a relatively short vertebral border and lateral placement in primitive primates to long proportions of the vertebral border, typical of the hominidae, necessary for and to provide a longer lever

arm for the serratus and rhomboid muscles. Thus, in the hominidae the combination of a very well-developed "S" shaped clavicle and a scapula, which has reached its longest dimension of the vertebral border and is placed dorsally, permit the powerful and great range of arm movement necessary for brachiation. These features, in general, have been retained in man.

It can, therefore, be seen that bone modeling occurs in nearly direct response to the biomechanical demands placed on the skeletal system due to a particular mode of locomotion and functional activity.

CARTILAGE

There are five types of cartilage of which only two are considered here because of their biomechanical relevance. These are white fibro cartilage (fibrous cartilage) and articular cartilage.

Histology

The cells are contained within lacunae in mature cartilage. There may be as many as four cells in each lacuna. The cells have a prominent nucleolus and clear cytoplasm. The matrix is permeated by felt-like structures of fine collagenous fibers. In fibrous cartilage, the cells are widely separated and arranged in rows, while in articular cartilage, one row of cells near the surface is greatly flattened.

Structure and Biomechanics

White fibro cartilage exhibits a great deal of flexibility, but practically no elasticity in tension. This makes it an ideal tissue for attachment of tendons of muscles to the bony lever. Thus, the motor can be most efficiently used in transmitting its force to the lever without the undesirable energy absorbing effects of a material which is highly elastic in tension. The same cartilage is used in ligaments to stabilize the joints, as well as in controlling joint range of motion.

Articular cartilage of all structures in the

locomotor system is more severely exposed to stresses not only due to weight bearing, but also to those produced by muscle tension. In contrast to fibrous cartilage, articular cartilage is highly extensible and compressible. It also exhibits a great degree of functional adaptability in that its modulus of elasticity increases with increasing load. However, the longer the cartilage is loaded, the slower and less complete the rebound. In other words, its elasticity is impaired by excessive and prolonged loading. This is of biomechanical significance in that joint positions should not be maintained fixed over a long period of time, whether this is due to standing position or in functional activities, for this would lead to permanent changes in the elasticity of the cartilage. Even though the load may not need to be decreased, changes in joint position will alleviate this problem, for one of the primary functions of cartilage is to provide joint mobility. The co-efficient of friction of cartilage is three times lower than ice on ice. This is probably due to the fact that water is found between the matrix of cartilage, thus water is compressed out of the matrix, providing joint lubrication, and sucked back into the matrix on removal of weight bearing.

Menisci, which are composed of cartilage, accommodate for the incongruity of mating surfaces in joints. Incongruity of joint surfaces is needed for recoil of collagen fibers on motion and weight bearing. If the mating surfaces of joints were perfectly matched, the joint would lock with the slightest degree of compression.

SUMMARY

Contrary to the static appearance of bone, it is an extremely lively tissue of the body capable of regenerating itself and modeling and adapting itself to stresses imposed either during growth or due to biomechanical demands.

To a somewhat lesser degree, but still remarkably well, articular cartilage is a lively tissue capable of adapting itself to the varying stresses during locomotion and biomechanical activities. Fibrous cartilage serves its function best by being inelastic in tension to provide for stability of joints without muscular exertion.

BIBLIOGRAPHY

- Bassett, C.A.L., *Biochemistry and Physiology of Bone*, Bourne, G., Editor, Vol. 3, Academic Press, 1971, pp. 1-69.
- Lavine, L.S., I. Lustrin, and M.H. Shamos, "Experimental Model for Studying the Effect of Electric Current on Bone in Vivo 'Nature'," Vol. 224, December 13, 1969.
- Lavine, L.S., I. Lustrin, M.H. Shamos, R.A. Rinaldi, and A.R. Liboff, "Electric Enhancement of Bone Healing," *Science*, Vol. 175, March, 1972.
- Lavine, L.S., I. Lustrin, M.H. Shamos, and M.L. Moss, "The Influence of Electric Current on Bone Regeneration in Vivo," *Acta Orthopaedica Scandinavia*, Vol. 42, 1971, pp. 305-314.
- Lehneis, H.R., "Principles of Orthotic Alignment in the Lower Extremity," Instructional Course Lectures, *American Academy of Orthopaedic Surgeons*, Vol. XX, 1971, pp. 131-136.
- Steindler, A., *Kinesiology of the Human Body*, Fifth Printing, 1977, Charles C. Thomas, Publisher.