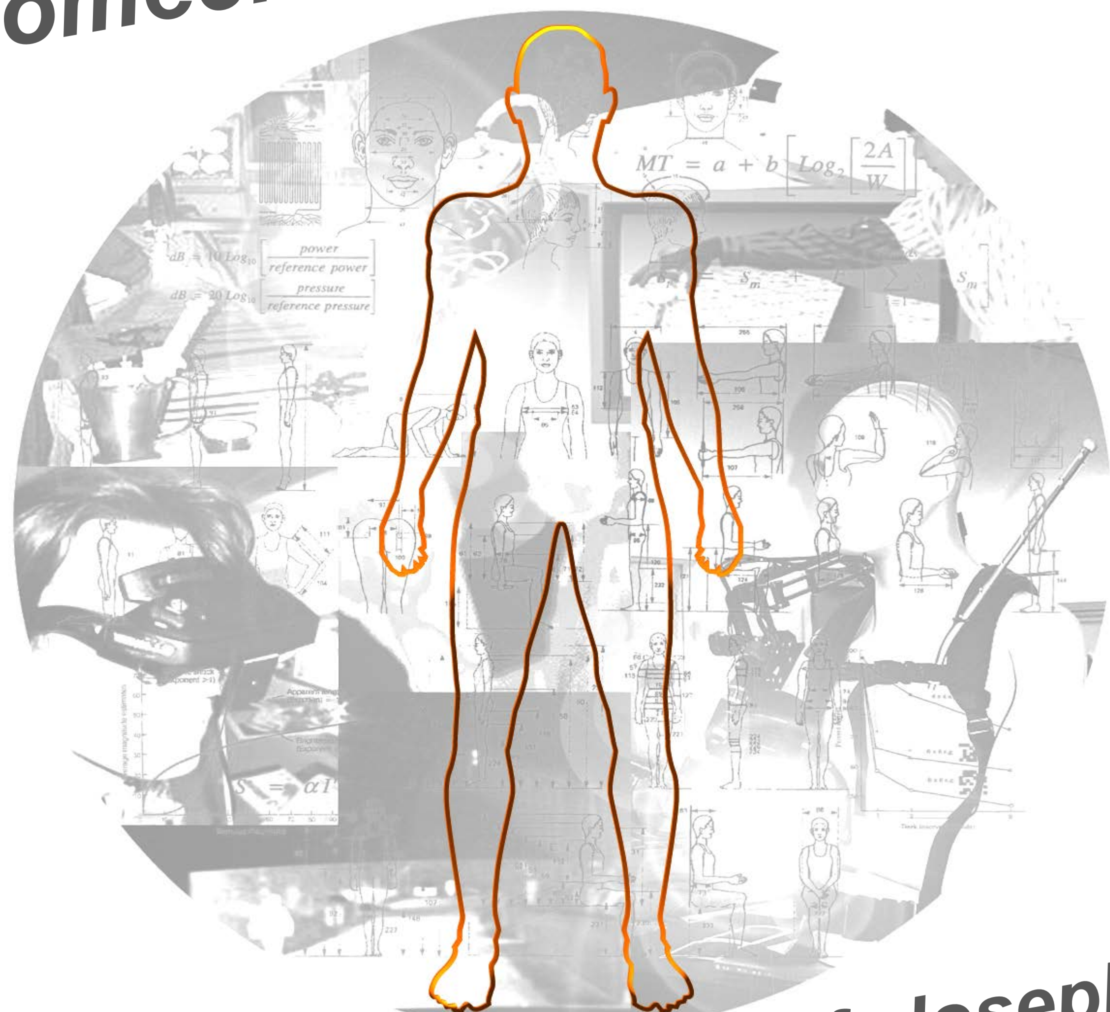
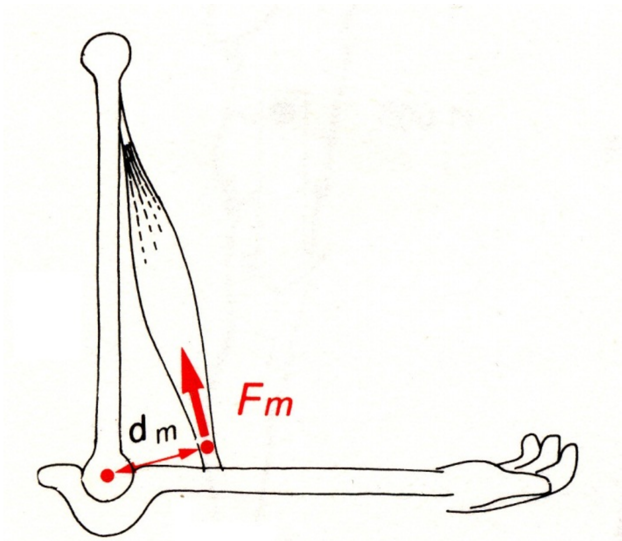
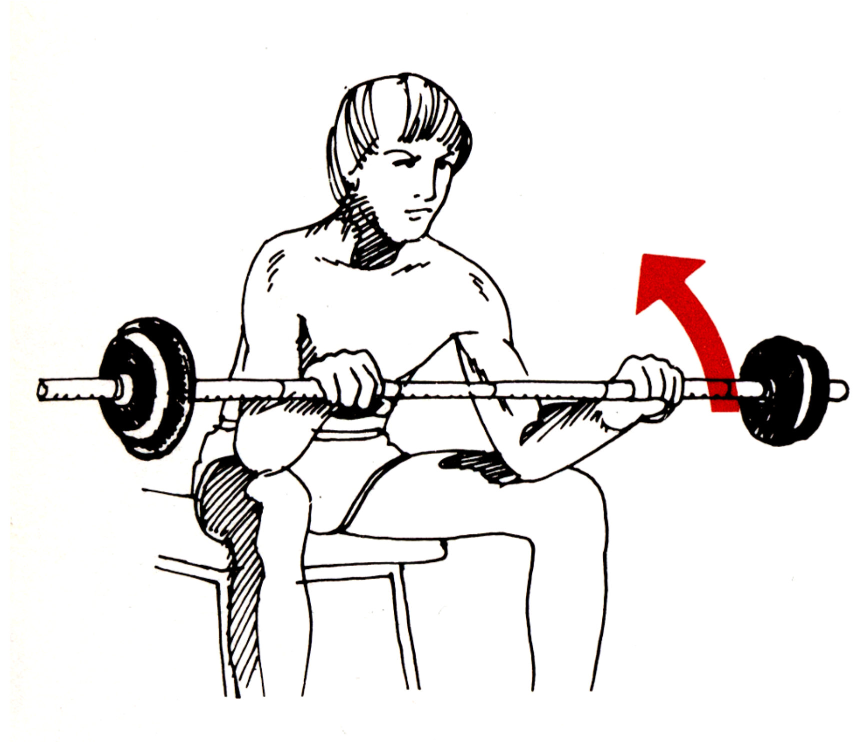
Biomechanics



Prof. Joseph Giacomin

Biomechanics





Biomechanics is an interdisciplinary field that uses information from biology and engineering to analyse the human body.

The mechanical properties of body structures and the loadings acting on them are analysed to determine human tolerance capabilities and the human ability to perform external work.

Biomechanics

From the time of Borelli the human body has been modelled using links that are connected by joints, and powered by muscle forces. Treating the body as a mechanical system leads to the following analogies:

bones: act as structural members and lever arms

articulations: act as the joints and bearing surfaces

tendons: act as cables transmitting muscle forces

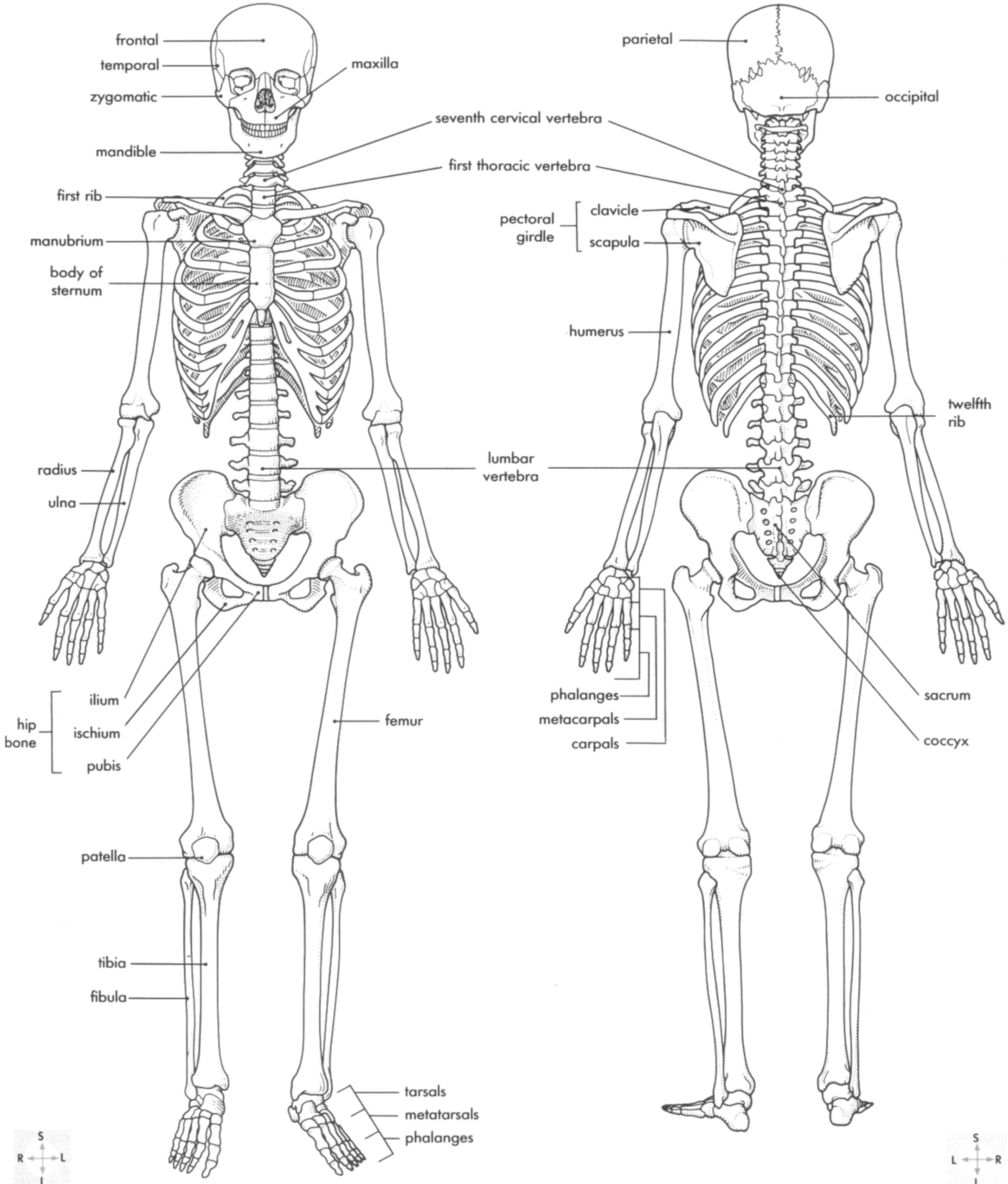
tendon sheaths: act as pulleys and sliding surfaces

muscles: act as motors, dampers or locks

flesh: act as mass or volume elements

nerves: act as control and feedback circuits

organs: act as generators or consumers of energy



Bones

The human skeleton is composed of 206 bones and associated connective tissues and articulations.

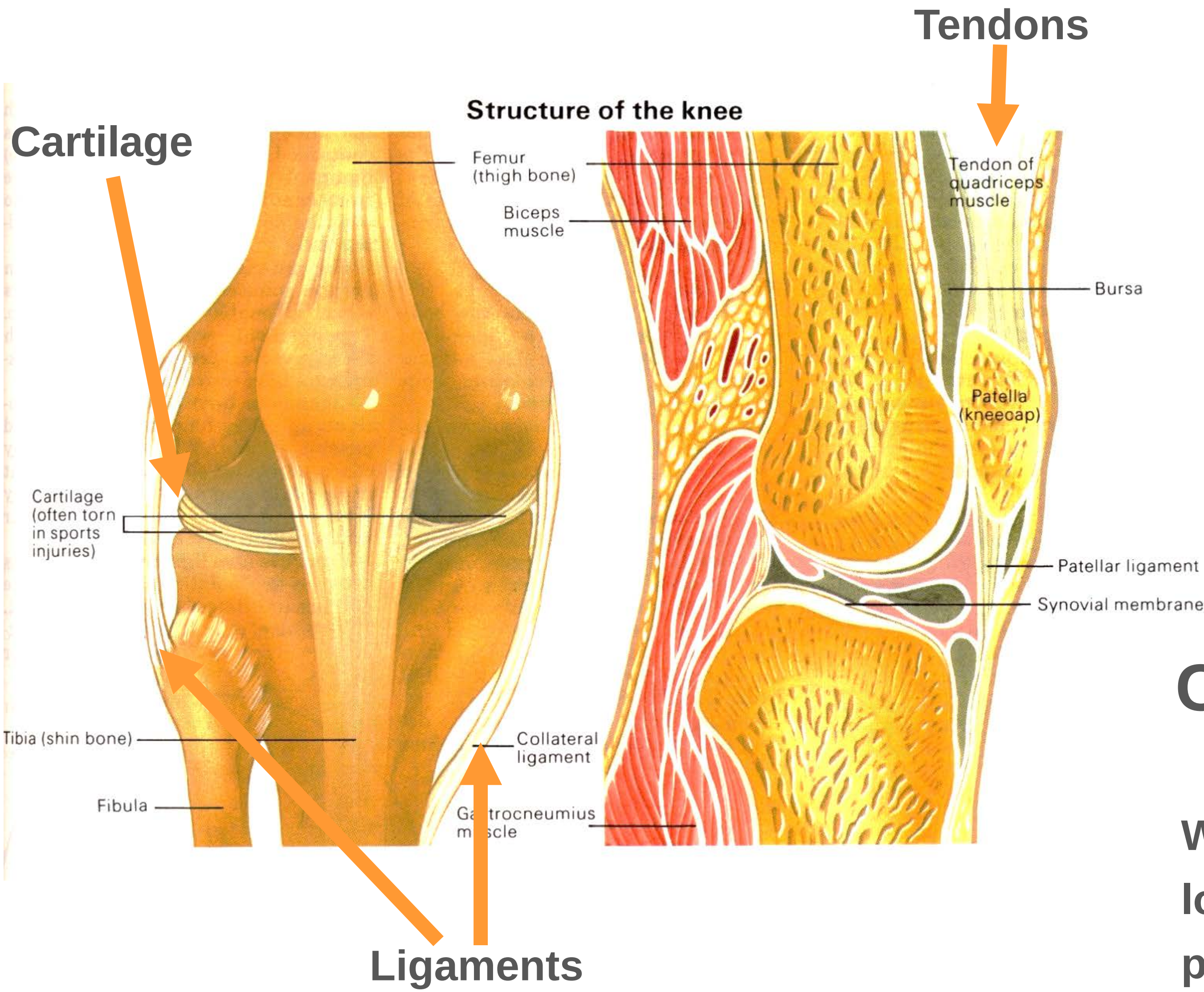
The main function of skeletal bones is to provide a structural framework for the body.

Bones

	Diaphyseal cortical shell	Metaphyseal cortical shell
$E_{longitudinal}$(MPa)	17 000	9650
$E_{transverse}$(MPa)	11 500	5470
ρ density (g cm^{-3})	1.95	1.62
Reference	Reilly et al.	Lotz et al.

The stress-strain relationship for bone is linear but anisotropic. Long bones in particular are optimised to resist loads acting along the natural direction associated with activities such as walking and jumping.

The Young's Modulus therefore depends on the direction of the test as shown by the results for two samples of cortical bone shown above.



Connective Tissue

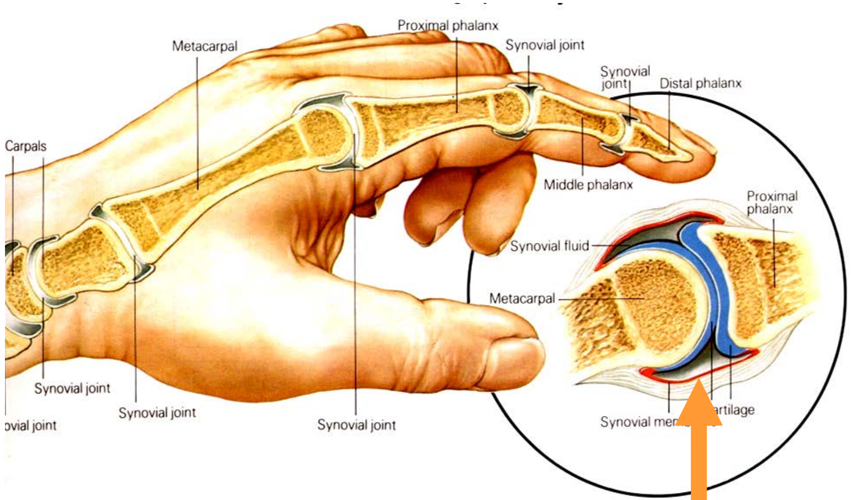
While bones support the loadings, connective tissues provide the flexibility and elasticity for movement. There are three types of connective tissue.

Cartilage

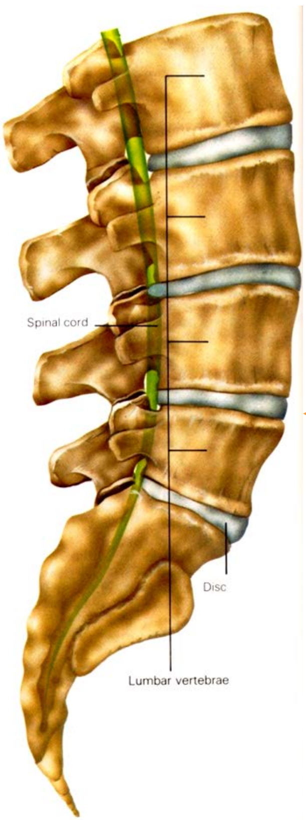
Cartilage is a smooth, tough and flexible part of the body's skeletal system. In adults it is found mainly in the joints and at points where toughness and flexibility are needed.

Its collagen structure gives it smoothness and resiliency, making it ideal for sliding and shock absorption.

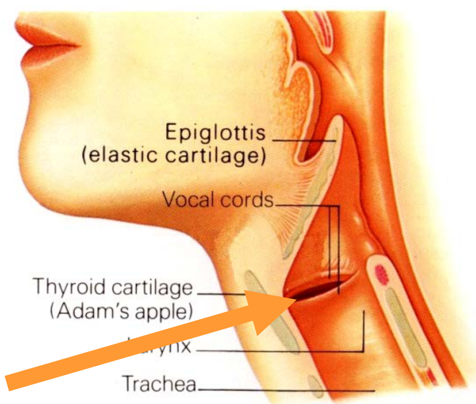
Three types of cartilage are found in the human body, each specialised to the role being performed.



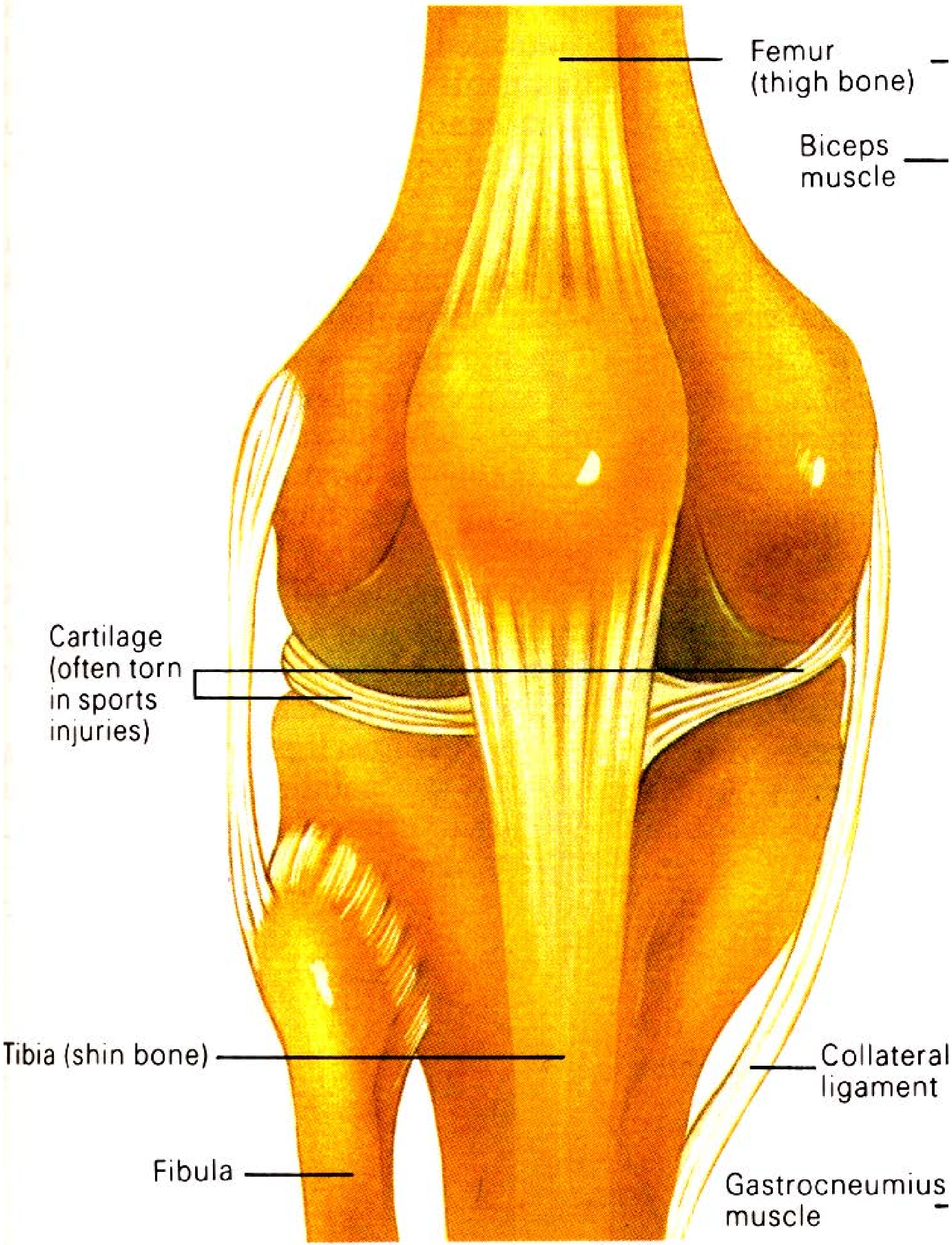
Hyaline



Fibrocartilage



Elastic

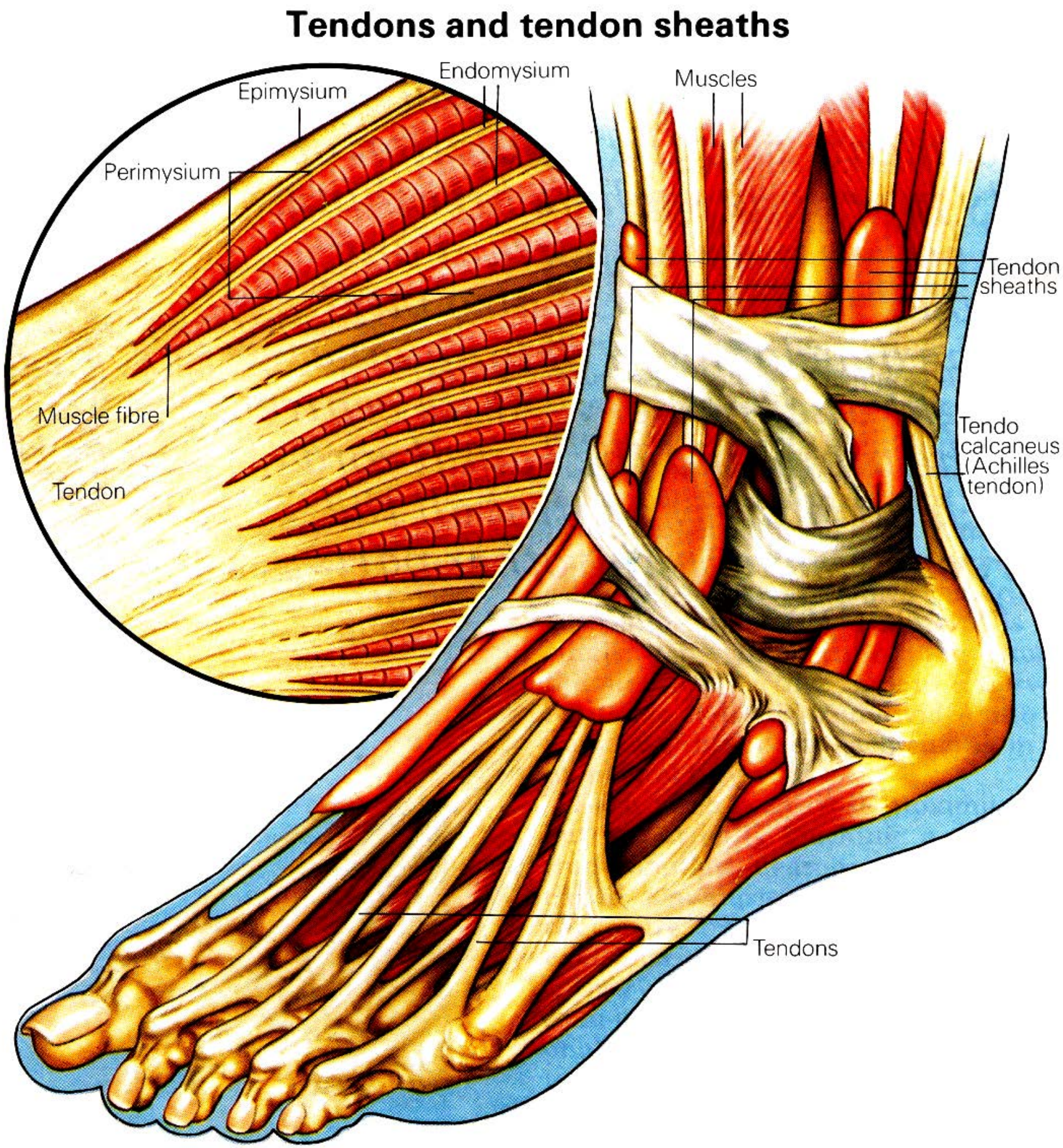


Ligaments

Ligaments are a connective tissue formed of bundles of collagen fibres. The bundles are arranged longitudinally so as to resist in tension.

Ligaments connect bones at joints, holding them in place. Without ligaments bones would be easily dislocated.

Ligaments are attached to the bones by fibres which penetrate the outer cover of the bones.



Tendons

Tendons join muscles to bones, the force of the contracting muscle being transmitted through the tendon.

One end of a tendon extends from a muscle group and the other consists of collagen fibres which are embedded in the bone.

Tendons at the ankle and wrist are enclosed in sheaths at the points where they cross other structures. This helps them to move smoothly with low friction and also helps to protect them from abrasion.

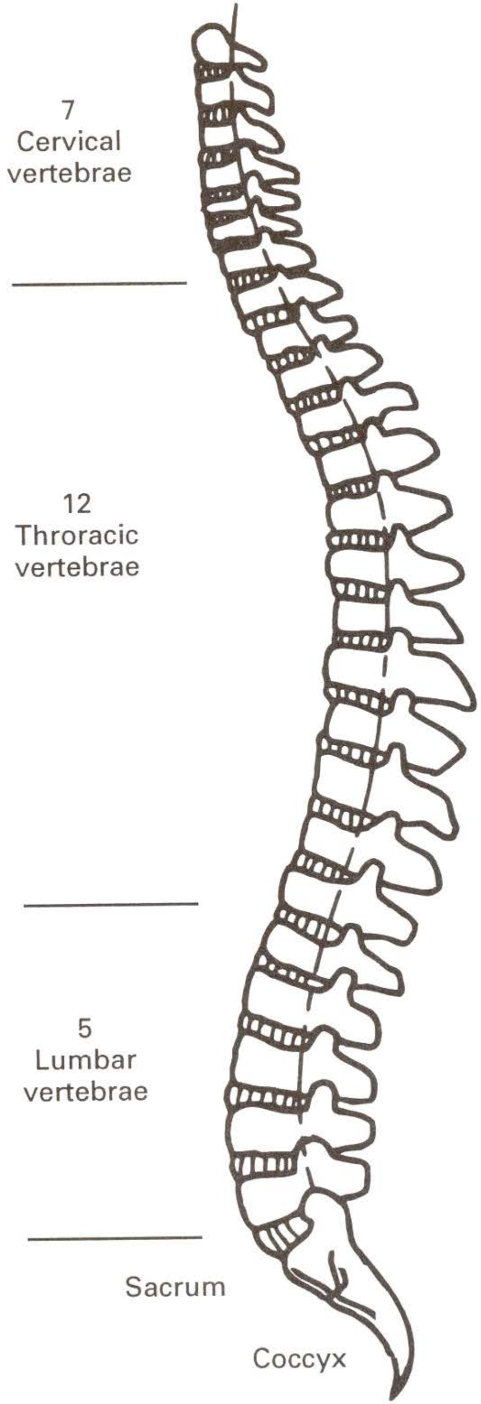
Ligaments and Tendons

Structure	Estimated Ultimate Stress (σ_u) (MPa)
Muscle	32–60
Ligament	20
Tendon	60–100
Bone Longitudinal Loading	
Tension	133
Compression	193
Shear	68
Bone Transverse Loading	
Tension	51
Compression	133

Source: Adapted from Ozkaya and Nordin, 1991.

The ultimate stress of ligaments and tendons is roughly 20 MPa and 80 MPa respectively.

The values are similar to those of muscle tissue, but less than bone in compression.



Spinal Column

The spinal column is a complex structure consisting of 24 small bones called vertebrae, the sacrum bone, cartilaginous disks, tendons and ligaments.

The spine transfers forces between the upper and lower body. Since it is formed of small sections it is very flexible.

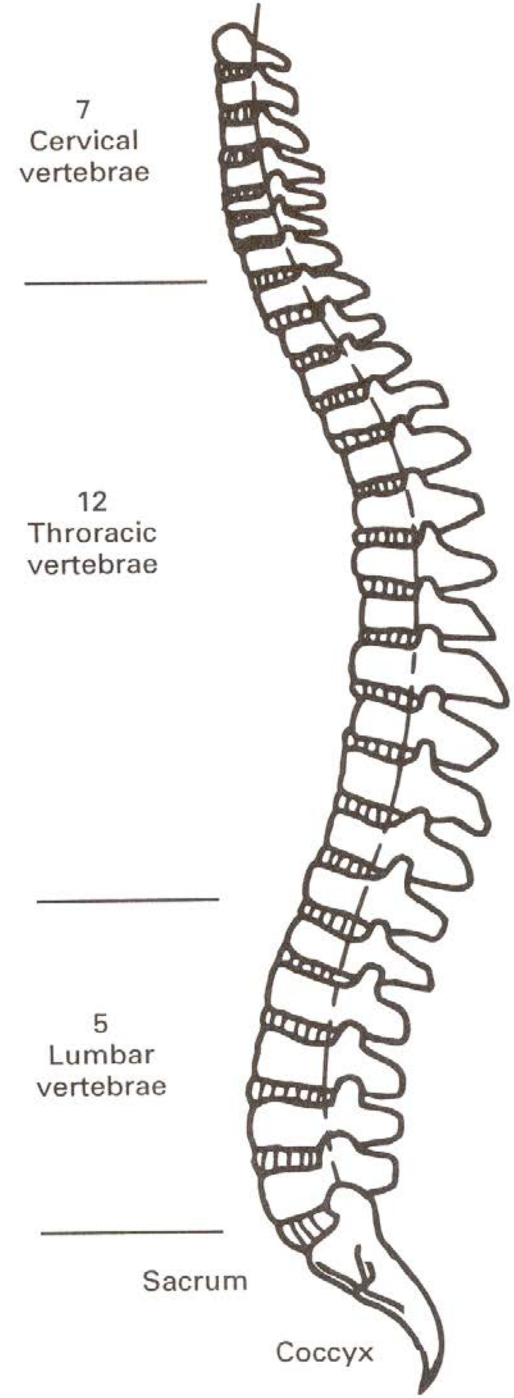
The spinal column acts as a protective casing for the motor neurons of the spinal cord which transmit information to and from the brain.

Spinal Column

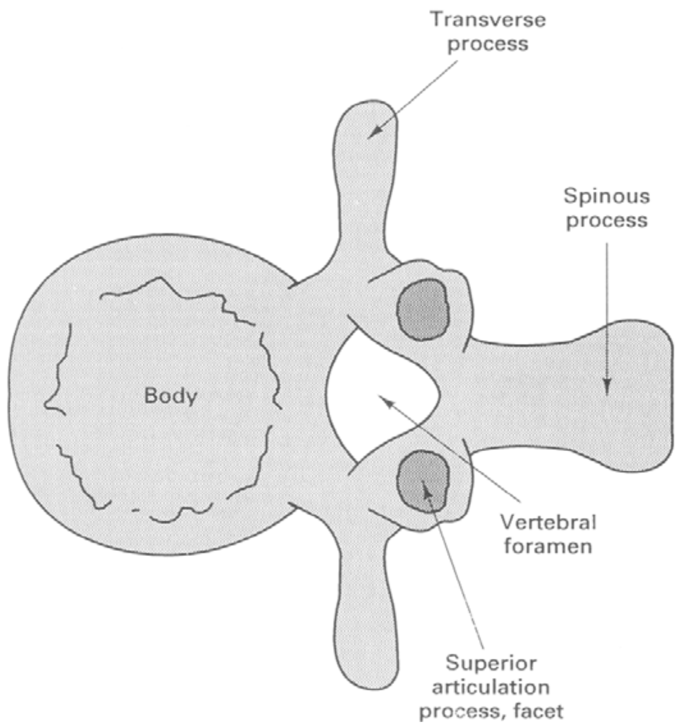
An important point to note is that the spinal column is not straight. There are two forward curvatures (called lordosis) in the cervical and lumbar sections and one backward curvature (called a kyphosis) in the thoracic section.

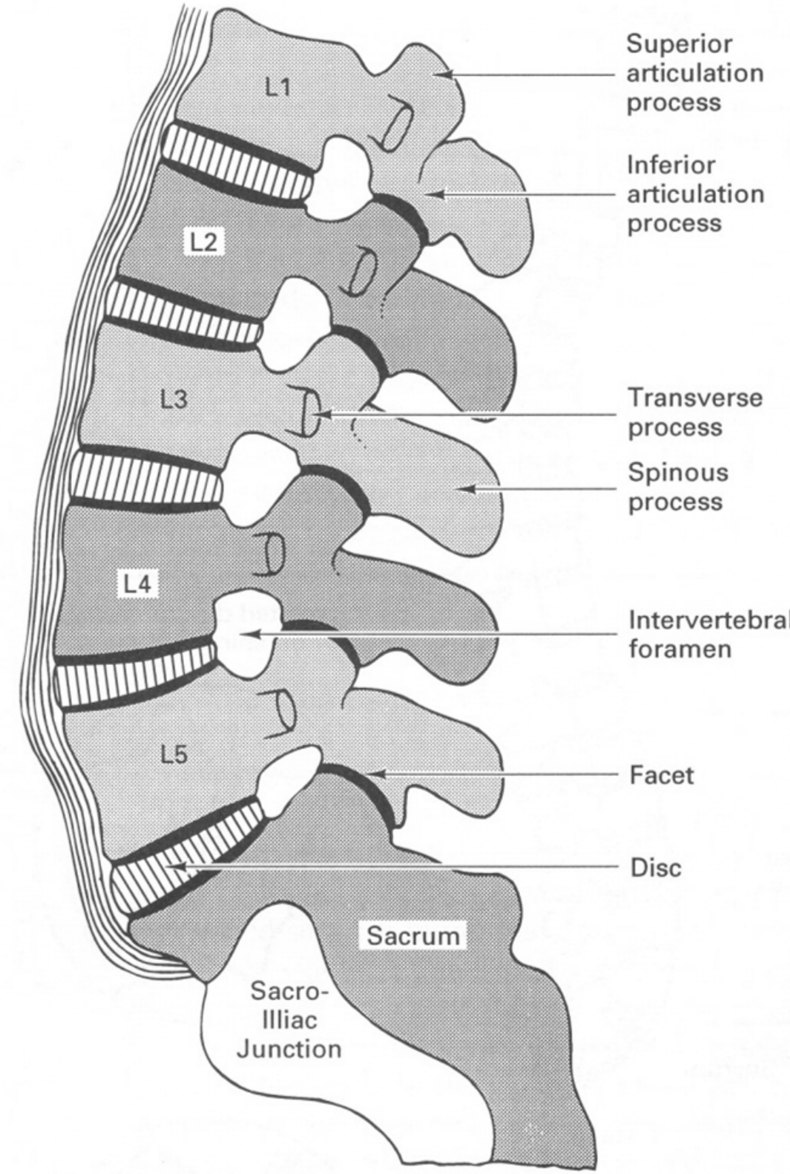
Postures which modify these curvatures, particularly lumbar lordosis, with respect to a standing posture are a potential source of stress on the spine.

In the long term this can cause back pain.



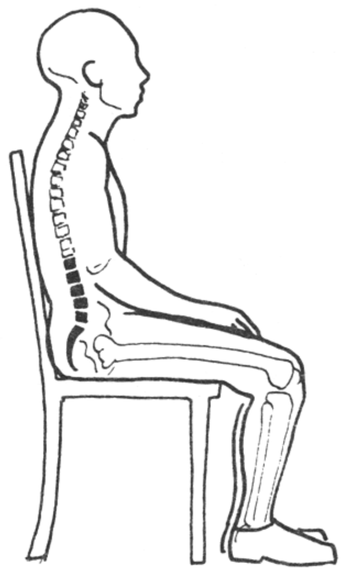
Spinal Column



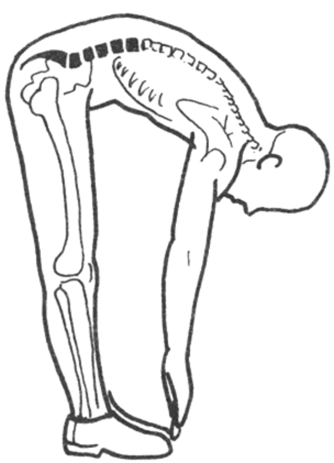


Each vertebrae is connected to the successive by two cartilage structures. The first is the intervertebral disk which carries most of the load while the second is the facet which adds stability to the column.

(a)



(b)

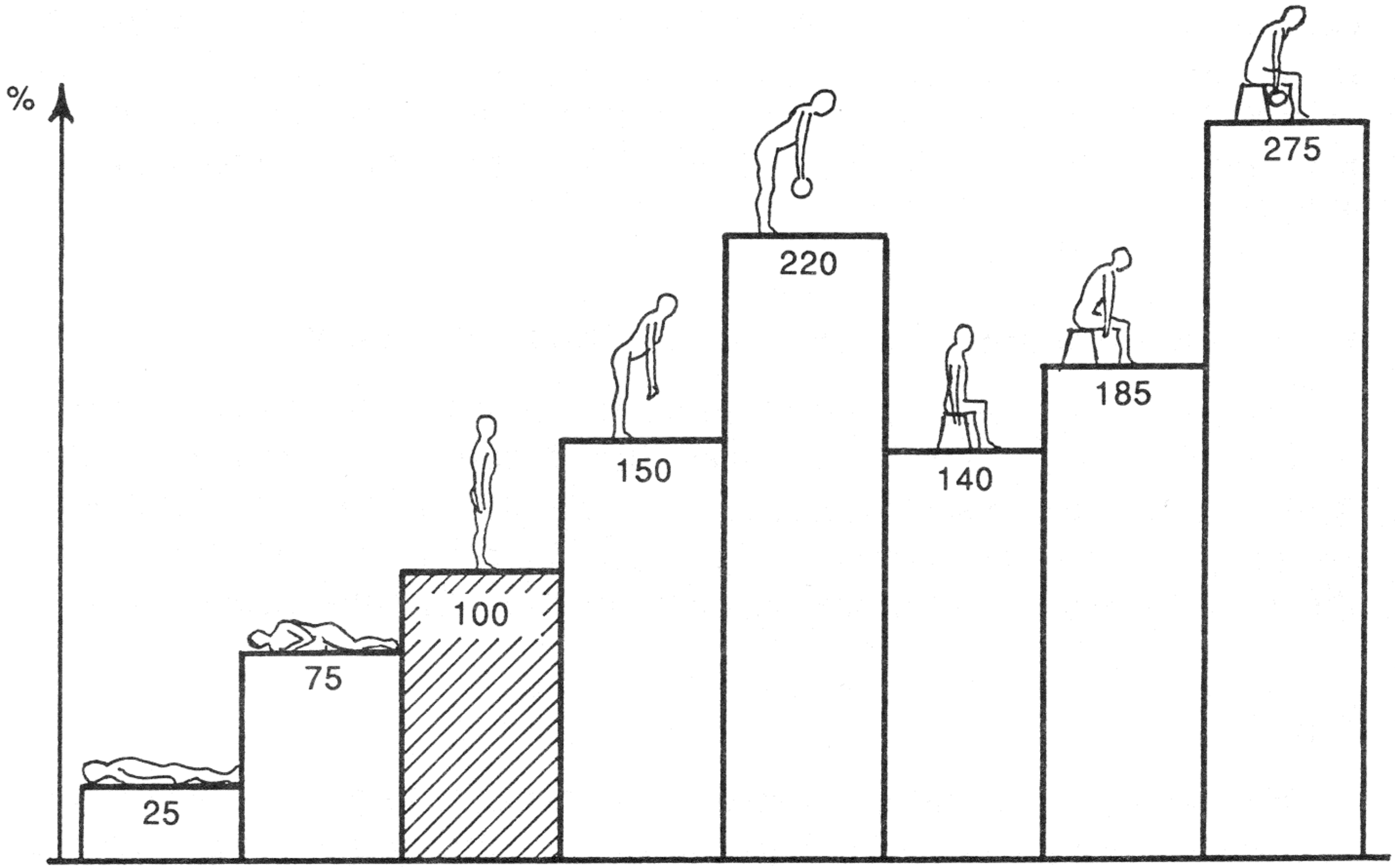


(c)

Spinal Column

A series of in-vivo experiments by Nachemson and Morris in 1964 measured the loadings in lumbar disks L2 through L4 with subjects in various positions and performing various exercises.

Sitting positions were found to cause the highest disk loads with values from 100 to 180 kg.



Spinal Column

Nachemson measured the load in the third lumbar disk (L3) for various postures.

Muscle Tissue

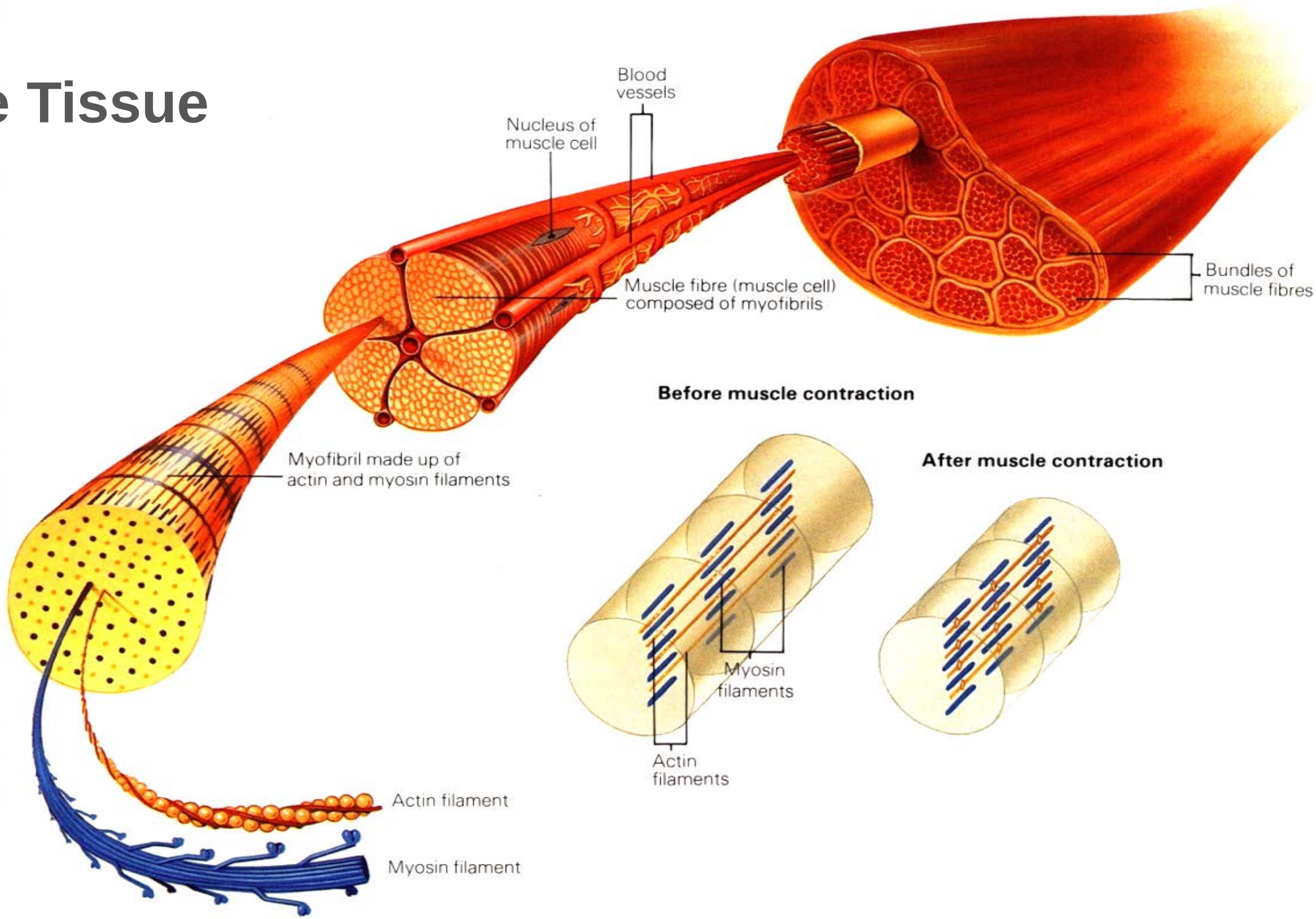
Muscle tissue accounts for 40% of overall body weight and is of three types:

Skeletal Muscle **is under the voluntary control of the nervous system. It maintains balance and generates motion of the body segments. It is also called striated (striped) muscle because the arrangement of the fibres gives it a striped appearance.**

Smooth Muscle **is not under the voluntary control of the brain. It produces the contractions required for processes such as digestion and pressure regulation of the blood vessels.**

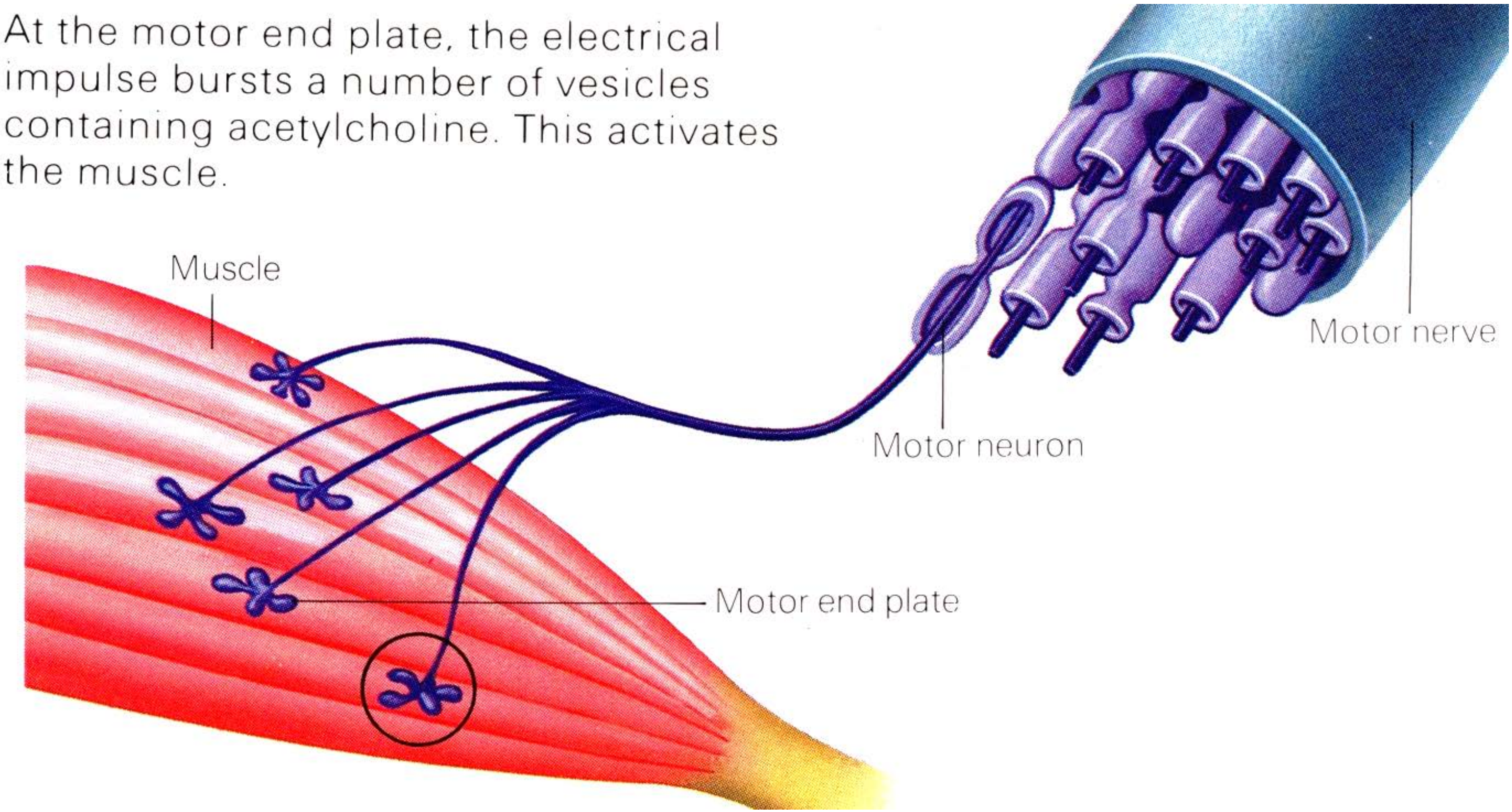
Cardiac Muscle **has a structure similar to skeletal muscle, but the fibres are short and thick and form a dense mesh. Cardiac muscle generates heart contractions.**

Muscle Tissue

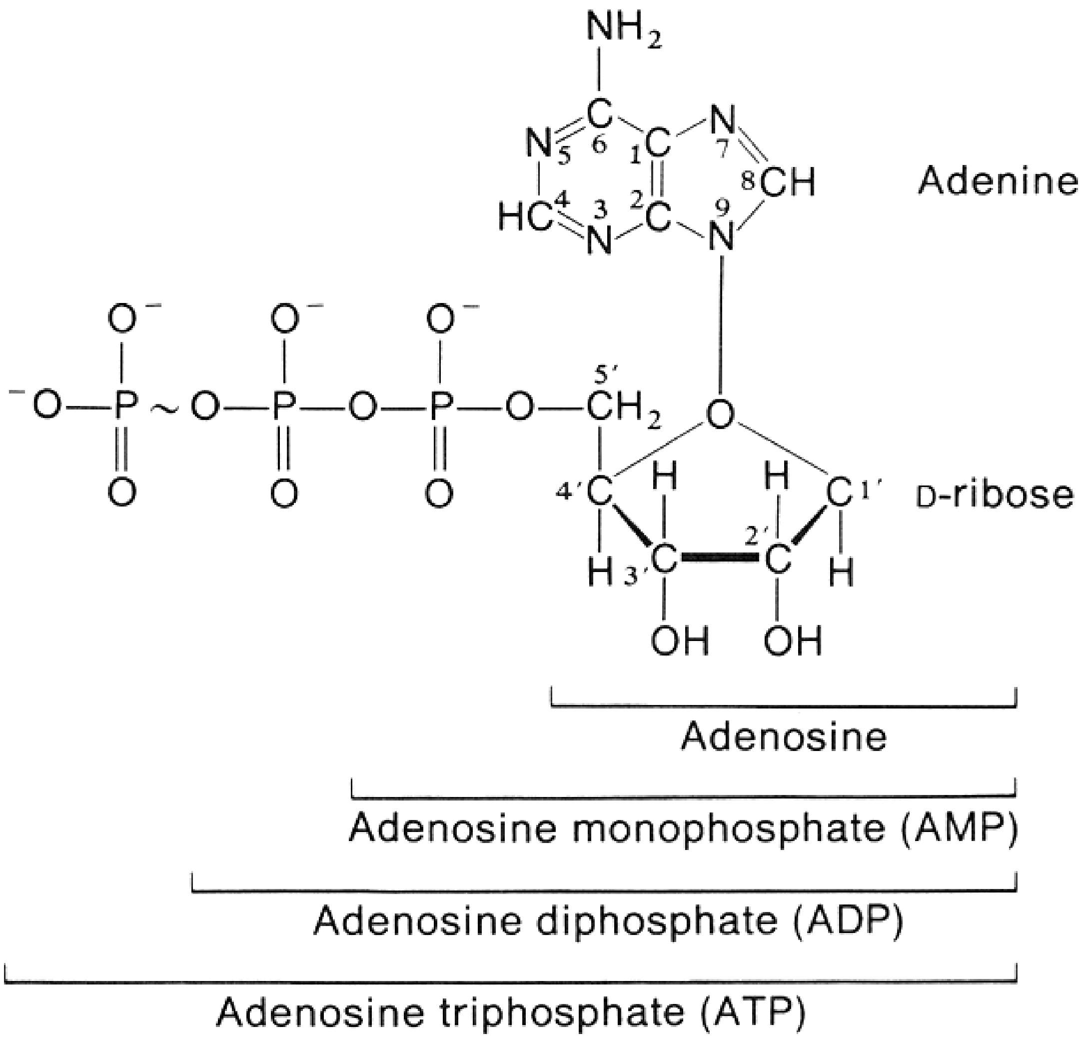


The contractile elements of skeletal muscle are pairs of actin and myosin proteins. When activated, the filaments connect together and shorten the fibre bundle. Each muscle cell contains many parallel filaments aligned along the axis of contraction.

Muscle Tissue



Alpha motor neurons from the central nervous system connect to muscle sarcolemma at junctions called motor endplates. At a motor endplates hundreds of fibrils below the sarcolemma are brought under the control of a common electrochemical signal.



Muscle Contraction

The energy for muscular contraction comers from the molecular compound called adenosine triphosphate (ATP).

Its phosphate bonds can be broken quickly by hydrolosis, releasing adenosine diphosphate (ADP) and mechanical work.

Muscle Contraction

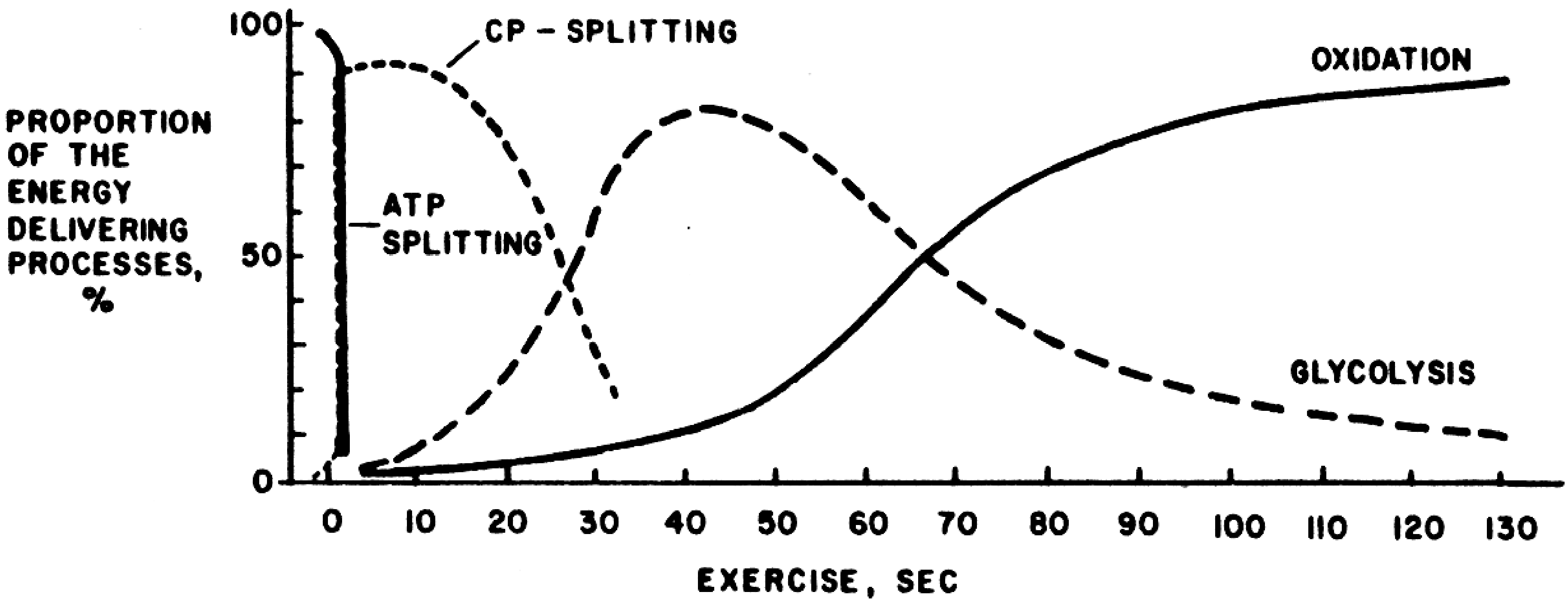
During muscular contraction ATP splits into ADP, releasing energy.

$$ATP + H_2O \longrightarrow ADP + \text{energy (output)}$$

Within less than a millisecond of splitting, however, ADP is converted back to ATP by reaction with another high-energy phosphate called creatine phosphate.

$$ADP + CP + \text{energy (input)} \longrightarrow ATP + H_2O$$

Muscle Contraction



During muscular contraction the creatine phosphate which is used to produce the ATP is depleted within 30 seconds.

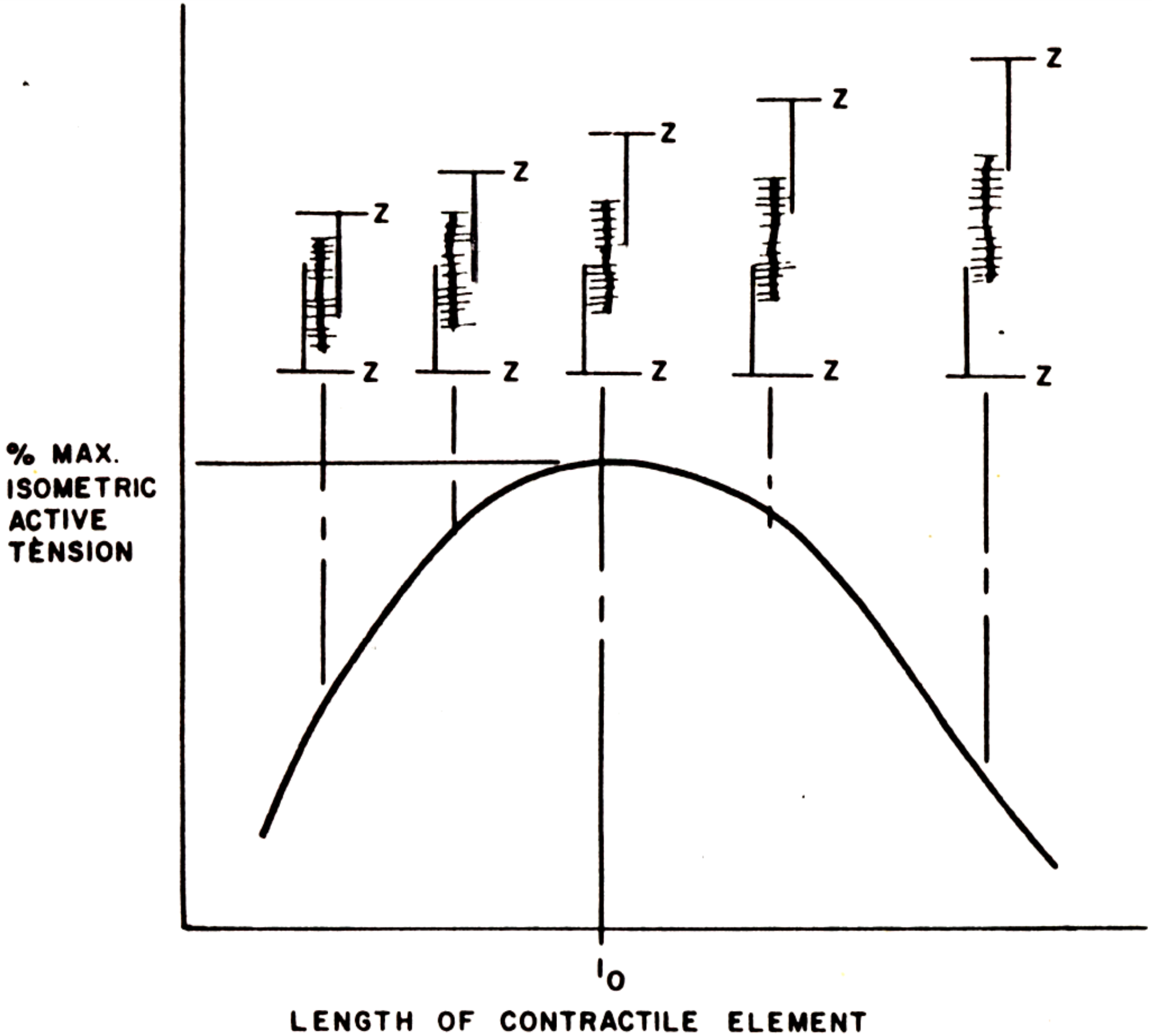
The primary source of ATP from 30 to 90 seconds is the anaerobic glycolysis of sugar, which produces lactic acid as a by-product.

For muscular contractions lasting more than 90 seconds the primary source of ATP is aerobic oxidation which produces CO_2 and H_2O as by-products.

Muscle Contraction

Energy System Contribution in Percent for Different Sports Activities

Activity	Anaerobic: ATP + CP	Anaerobic: Glycogen	Aerobic (Oxidative)
Marathon	0	5	95
1500 m Run	20	60	20
100 m Run	95	5	0
Long distance cycling	5	5	90
Baseball	80	20	0 Walking
Tennis	70	20	10
Golf (with golf cart)	95	5	0 Walking
Weight lifting	98	2	0 Walking



Muscle Contraction

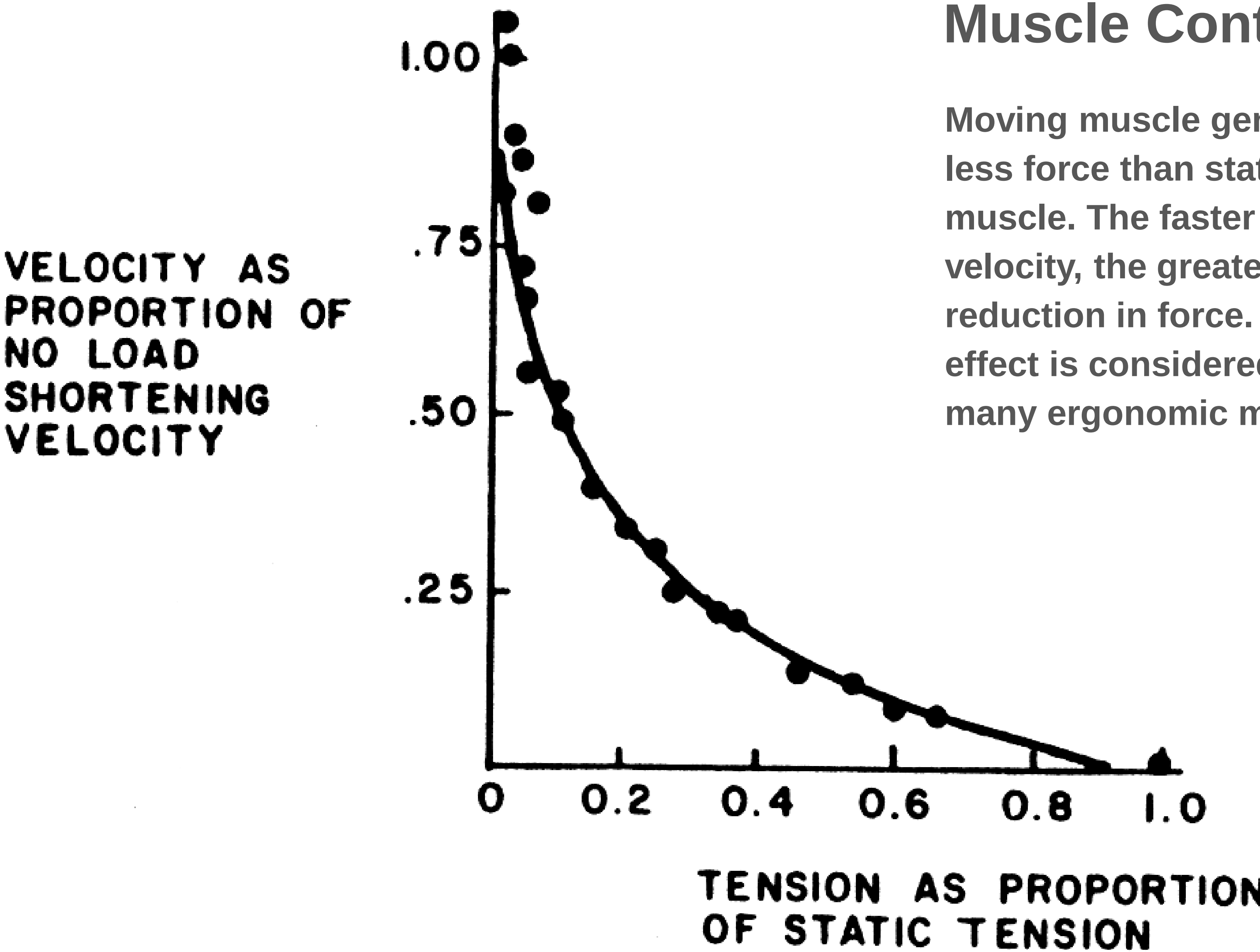
Maximum muscle force is only possible when it is at its resting length.

With increasing length there is a decreasing overlap between the actin and myosin filaments, which reduces the number of cross-bridges and thus the force.

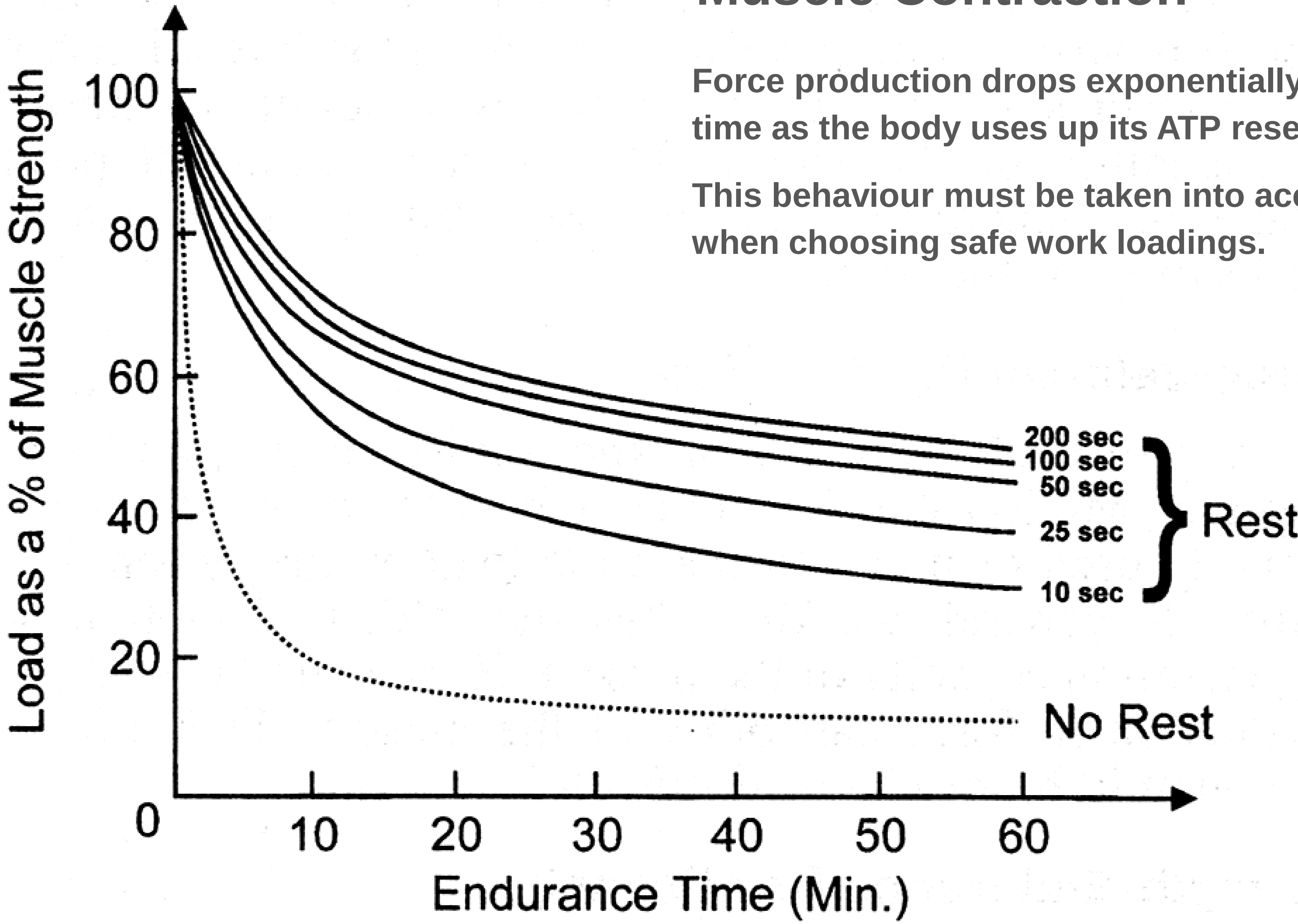
When muscle shortens, an overlap occurs between the actin filaments on opposite sides of the myosin filaments. This leads to cross bridges, which decreases the force.

Muscle Contraction

Moving muscle generates less force than static muscle. The faster the velocity, the greater the reduction in force. This effect is considered in many ergonomic models.



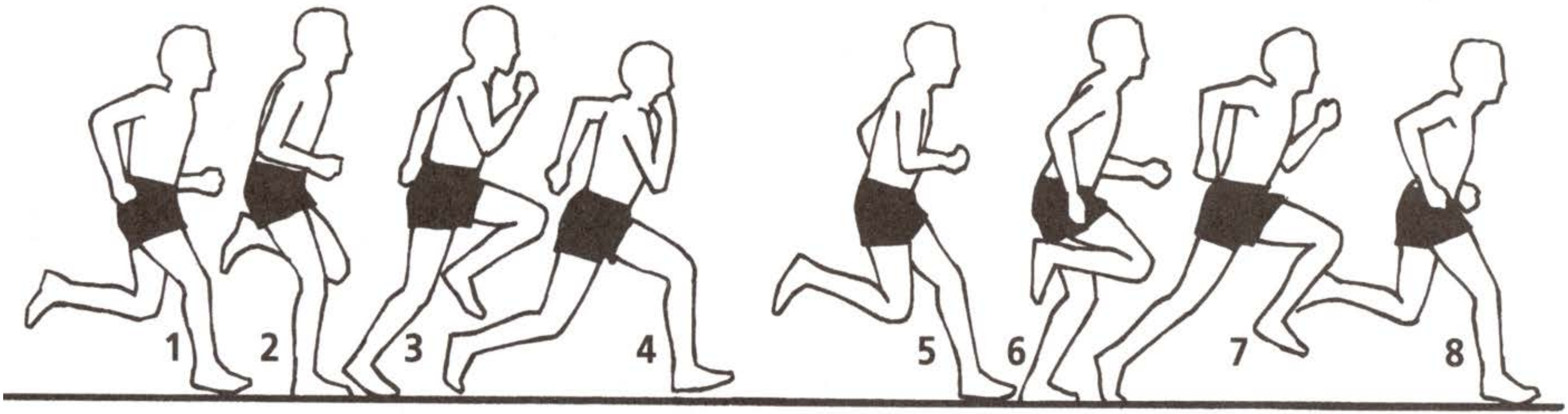
Muscle Contraction



Force production drops exponentially with time as the body uses up its ATP reserves.

This behaviour must be taken into account when choosing safe work loadings.

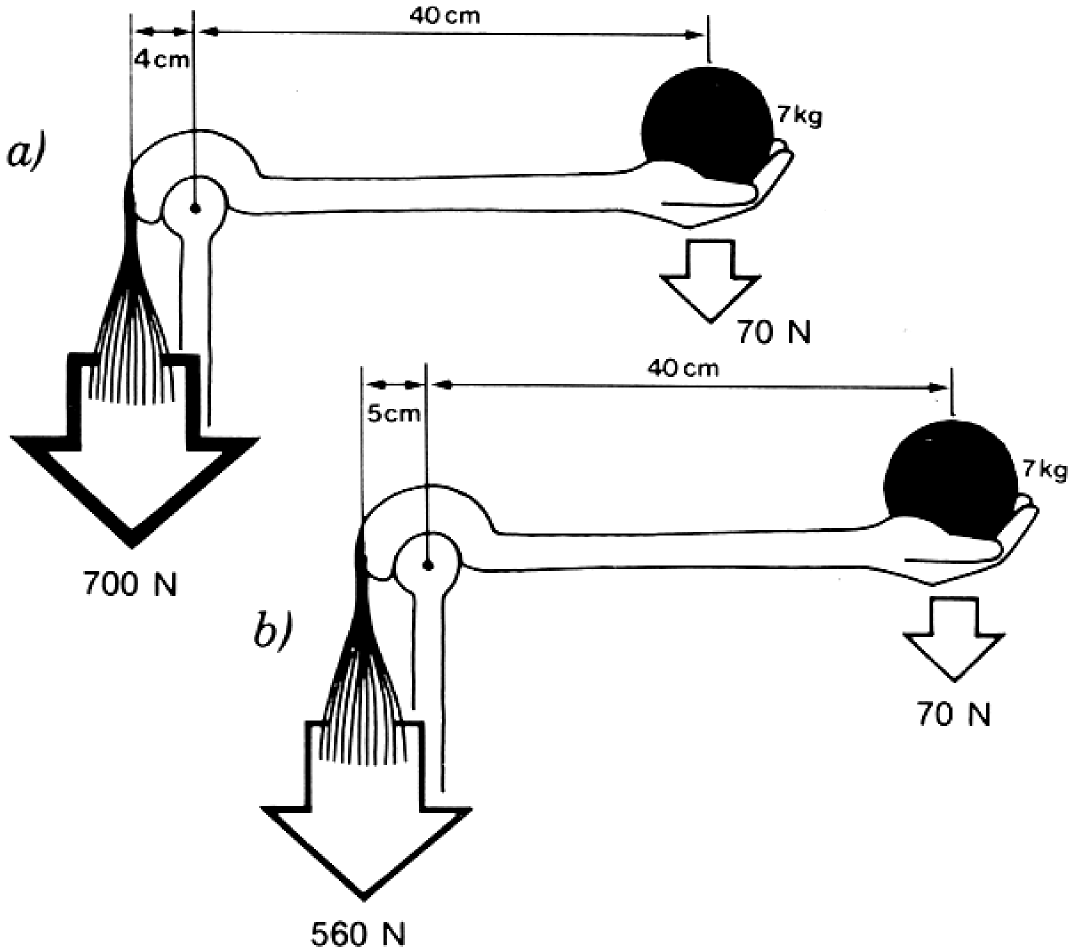
Lever Systems



In the distant past, speed and mobility were essential to the survival of apes and early man.

Evolutionary forces produced a muscular and skeletal system which uses lever arms to create large movements of the long bones by means of short contractions of the muscle fibres.

The lever systems make man highly mobile, but the trade-off is the need to produce large muscle forces and to sustain large resultant loads on the articular surfaces.



Lever Systems

The bone and muscle loadings are not simply the sum of the external forces acting on the body.

The external forces are counteracted by internal forces produced by the muscles.

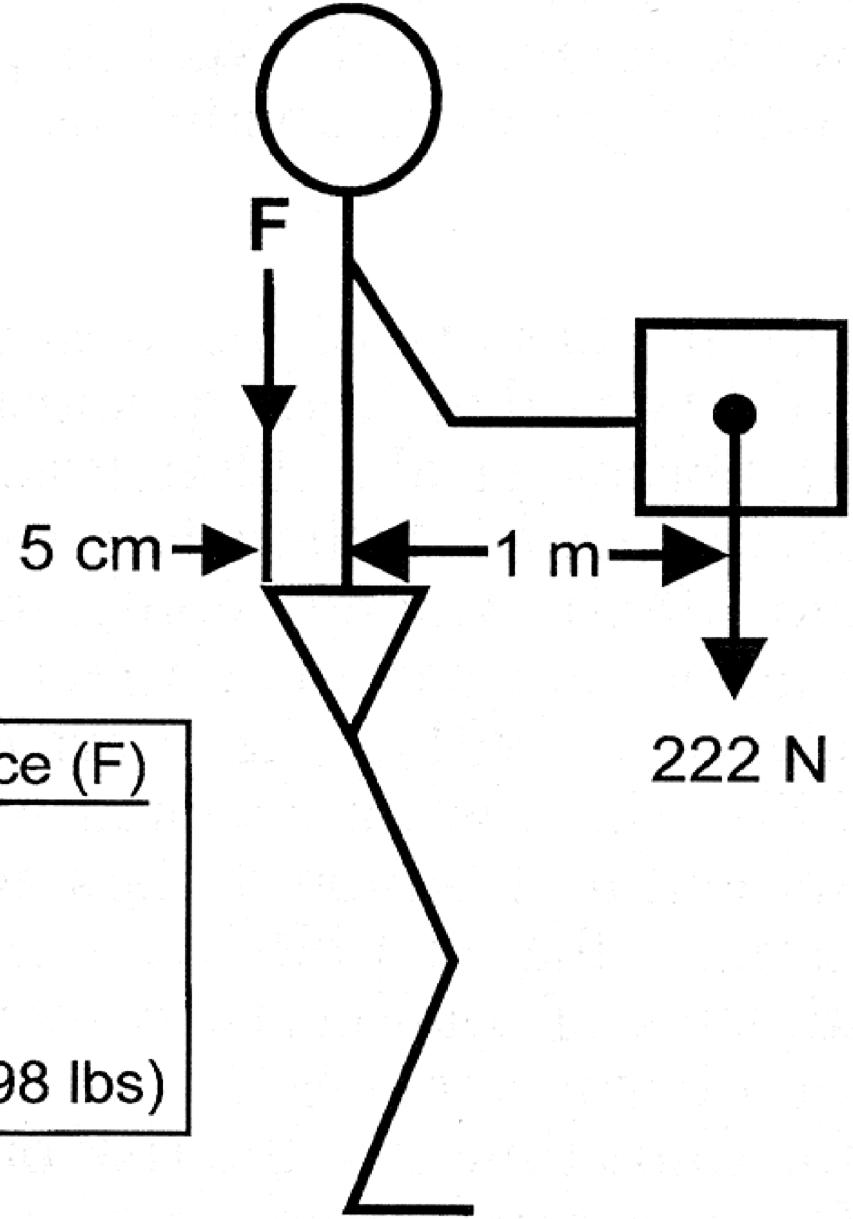
The lever systems are such that the muscles always act at a distance from the centre of the joint which is smaller than that of the external load.

Muscles therefore always suffer a mechanical disadvantage with respect to the external load.

Biomechanical Models

A typical biomechanical application is the estimation of the back muscle loading during materials handling by means of a simple planar model.

Due to the mechanical disadvantage, the muscle and spinal loadings are much greater than the weight of the external object being handled.



Internal Muscle Force (F)

$$F \cdot 5cm = 222N \cdot 1m$$

$$F = \frac{222Nm}{0.05m}$$

$$F = 4{,}440N \text{ (998 lbs)}$$

NIOSH Lifting Equation

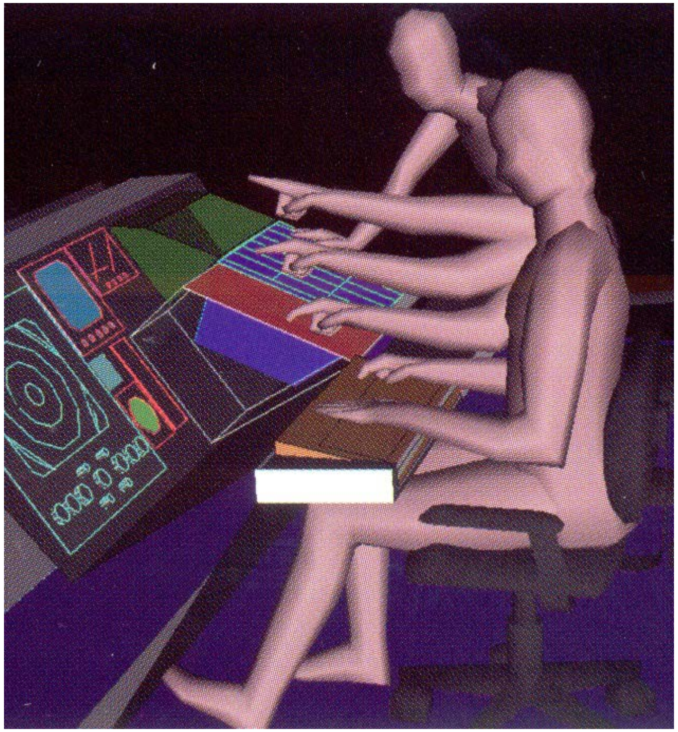
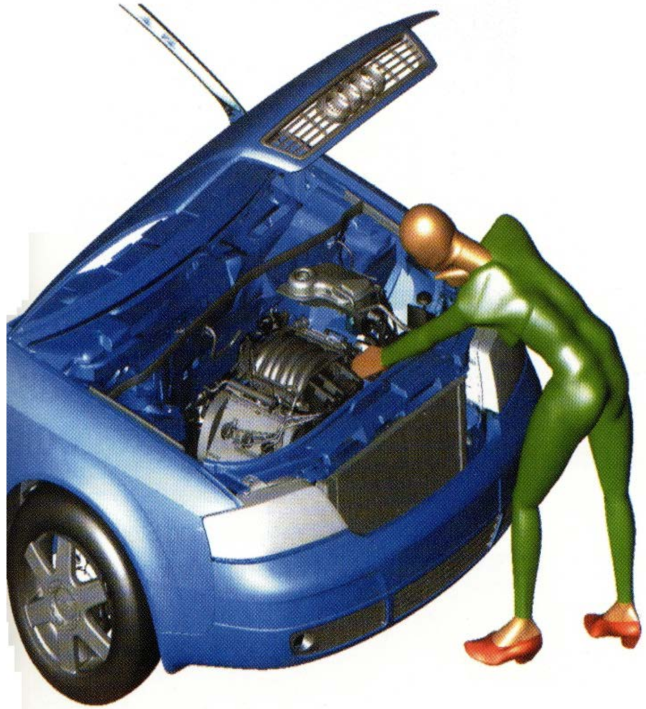
National Institute for Occupational Safety and Health

NIOSH

The *National Institute for Occupational Safety and Health (NIOSH)* is the U.S. federal agency responsible for conducting research and making recommendations for the prevention of work-related injury and illness. The *NIOSH Lifting Equation* is the most widely used methodology for the evaluation of risks associated with manual lifting.

LC x HM x VM x DM x AM x FM x CM = RWL

where : LC is the load constant (23 kg)
HM, the Horizontal Multiplier factor
VM, the Vertical Multiplier factor
DM, the Distance Multiplier factor
FM, the Frequency Multiplier factor
AM, the Asymmetric Multiplier factor
CM, the Coupling Multiplier factor
RWL, the Recommended Weight Limit


Digital Mannequins

Digital biomechanical mannequins are used to evaluate such as reachability, fit, muscle loading, energy expenditure, visual field, postural comfort, motion comfort and risks to human health. The evaluations are usually performed during the concept phase in order to optimise the preliminary design choices and to reduce the development costs.

Design Classic: Nike Tailwind

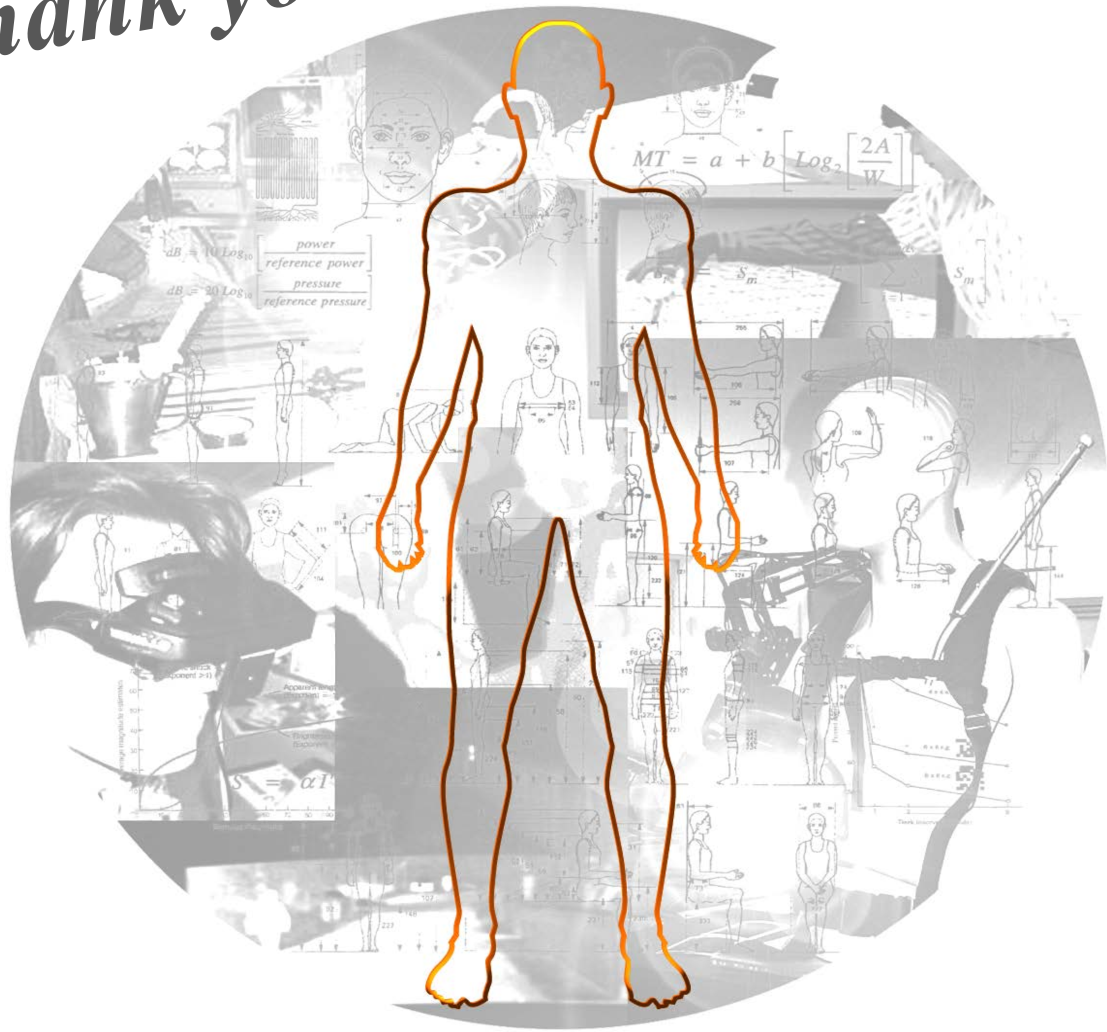
In 1979 Nike's Air technology was patented by inventor M. Frank Rudy and introduced in the Tailwind running shoe. Gas-filled plastic membranes in the sole of running shoes provide cushioning.

Design Classic: X-Brace Wheelchair

In 1933 the mechanical engineers Harry Jennings and Jonny Sharp invented the first lightweight steel collapsible wheelchair.

The "x-brace" was the first mass-produced wheelchair and was so successful that the general design it is still in common use today.

Thank you.



$MT = a + b \left[Log_2 \left[\frac{2A}{W} \right] \right]$
$dB = 10 \, Log_{10} \left[\frac{power}{reference\ power} \right]$
$dB = 20 \, Log_{10} \left[\frac{pressure}{reference\ pressure} \right]$