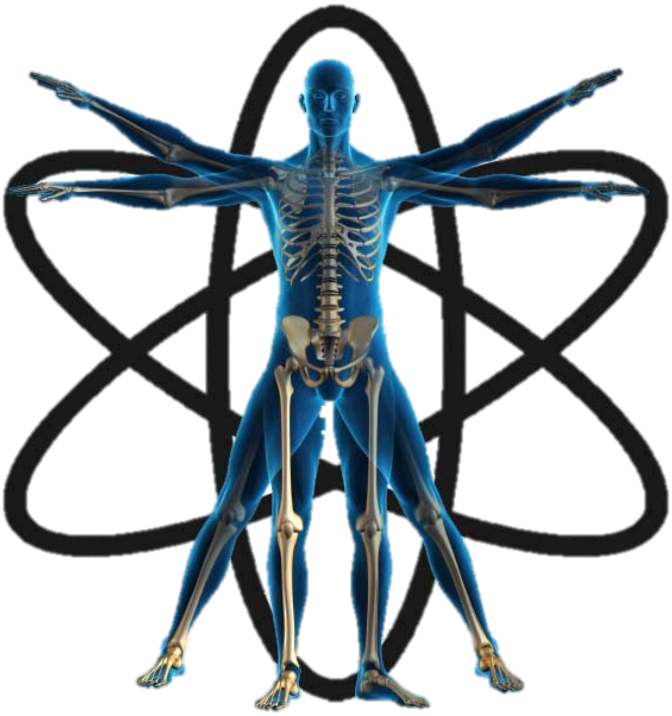
Medical Physics(I)

PHY-311

Department of Physics
College of Science-University of Basrah



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Medical Physics Syllabus (I)
PHY-311

Introduction

Chapter One

1-1 Physics of the body
1-2 Equilibrium and Stability
1-3 Forces on and in the body.
1-4 Medical effects of gravitation forces
1-5 Equilibrium considerations for the human Body
1-6 Stability of the human body
1-7 Skeletal Muscles
1-8 Levers
1-9 Frictional forces
1-10 The Object under dynamical force

Chapter Two

2-1 Physics of the skeleton
2-2 Introduction
2-3 Bone composition
2-4 Skeleton design and bone strength
2-5 Lubrication of bone joints
2-6 Measurement of bone mineral in the body

Chapter Three

3-1 **Energy, work, and power of the body**
3-2 Energy Conversion in Humans
3-3 Power Consumed at Rest
3-4 Energy from Food
3-5 Regulation of Body Temperature
3-6 Control of Skin Temperature
3-7 Work and power
3-8 Efficiency of the human Body

Chapter Four

4-1 Pressure inside the body

4-2 Measurement of pressure in the body

4-3 Pressure inside spinal column and skull

4-4 Eye pressure

4-5 Pressure in the lung

4-6 Pressure in the skeleton

4-7 Pressure in the urinary bladder

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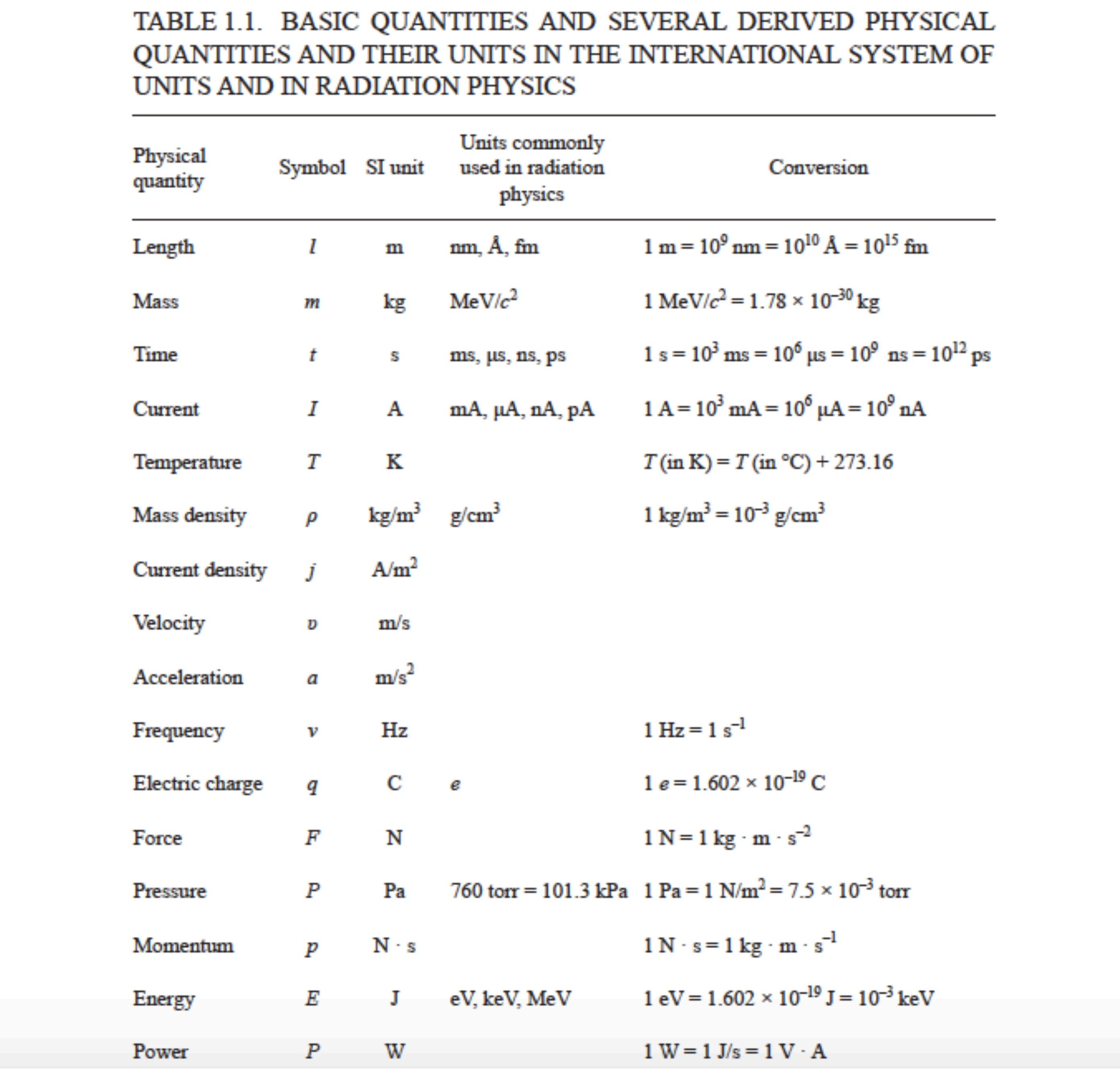


TABLE 1.1. BASIC QUANTITIES AND SEVERAL DERIVED PHYSICAL QUANTITIES AND THEIR UNITS IN THE INTERNATIONAL SYSTEM OF UNITS AND IN RADIATION PHYSICS

Physical quantity	Symbol	SI unit	Units commonly used in radiation physics	Conversion
Length	l	m	nm, Å, fm	1 m = 10^9 nm = 10^{10} Å = 10^{15} fm
Mass	m	kg	MeV/c^2	1 MeV/c^2 = 1.78 × 10^{-30} kg
Time	t	s	ms, μs, ns, ps	1 s = 10^3 ms = 10^6 μs = 10^9 ns = 10^{12} ps
Current	I	A	mA, μA, nA, pA	1 A = 10^3 mA = 10^6 μA = 10^9 nA
Temperature	T	K		T (in K) = T (in °C) + 273.16
Mass density	ρ	kg/m^3	g/cm^3	1 kg/m^3 = 10^{-3} g/cm^3
Current density	j	A/m^2		
Velocity	v	m/s		
Acceleration	a	m/s^2		
Frequency	ν	Hz		1 Hz = 1 s^{-1}
Electric charge	q	C	e	1 e = 1.602 × 10^{-19} C
Force	F	N		1 N = 1 kg · m · s^{-2}
Pressure	P	Pa	760 torr = 101.3 kPa	1 Pa = 1 N/m^2 = 7.5 × 10^{-3} torr
Momentum	p	N · s		1 N · s = 1 kg · m · s^{-1}
Energy	E	J	eV, keV, MeV	1 eV = 1.602 × 10^{-19} J = 10^{-3} keV
Power	P	W		1 W = 1 J/s = 1 V · A

Introduction

Physics, along with biology, chemistry and psychology, is one of the basic sciences that are the foundation of medicine. Physics is especially significant because the human body is a physical environment and system. It is within the physical body that all of the other scientifically based functions take place producing and supporting life.

Medicine is the comprehensive science and practice of diagnosing, treating or preventing disease and other damage to the human body and mental system. This is usually achieved by interacting with the different scientifically based functions within the body. For example, infections are biological events and poison is a chemical condition. These would generally be diagnosed and treated based on those sciences.

Because the structure, composition and many functions of the human body are physical, physics is the basic science for the diagnosis and treatment of many conditions and is the foundation of the profession of medical physics.

I) Terminology

A) Medical Physicists

Medical physicists are professionals with a strong academic background in general physics, medical physics topics and other medically related subjects including anatomy, physiology and pathology. They work in research and development, education and clinical medical physics. Clinical medical physicists generally have academic degrees in medical physics, supervised work experience (for example a residency programme in the US or the UK Scientist Training Programme (STP)), and are certified by regulatory bodies or professional organizations.

In addition to physicists, there are many other medical professionals, especially radiologists, radiographers and technologists, who apply physics in their clinical activities.

B) Physics and Medicine

An overview of the relation of physics to medicine is shown in Figure 1.1. The two types of medical procedures that are based on physics are diagnosis and therapy (treatment).

C) The Diagnostic Process

Diagnosis of diseases or injuries is usually a two-step process. The first step is obtaining information from the human body in the form of images that are produced by physical interactions within the body. The second step is the ‘reading of the image’ and interpreting or translating that information into a medical diagnosis. This last step is usually performed by qualified medical doctors, generally radiologists.

Physicists play a major role in the first step, designing and optimizing imaging methods and procedures to capture the medically significant information from within the body while managing any potential risks to patients. This can be a complex process because images are physical objects with a number of important characteristics that can affect the visibility of objects and conditions within the body. It is the physicist who has the knowledge and experience required to analyze and adjust or optimize these factors for specific clinical procedures.

Clinical medical physicists are high-level professionals on the staff of hospitals and clinics. Their role is in assuring the diagnostic quality of imaging procedures and optimizing procedures with respect to image quality and potential risks to patients. This is through several activities. One activity that is often required by government and accrediting regulations is the periodic evaluation of imaging equipment performance and image quality with specific testing procedures. Physicists use their knowledge and experience to consult and collaborate with the other medical imaging professionals, especially radiologists and technologists, in developing and optimizing clinical procedures.

Many medical physicists are educators, teaching medical physics students and physics residents, and also trainee radiologists who require knowledge of physics to qualify as radiologists.

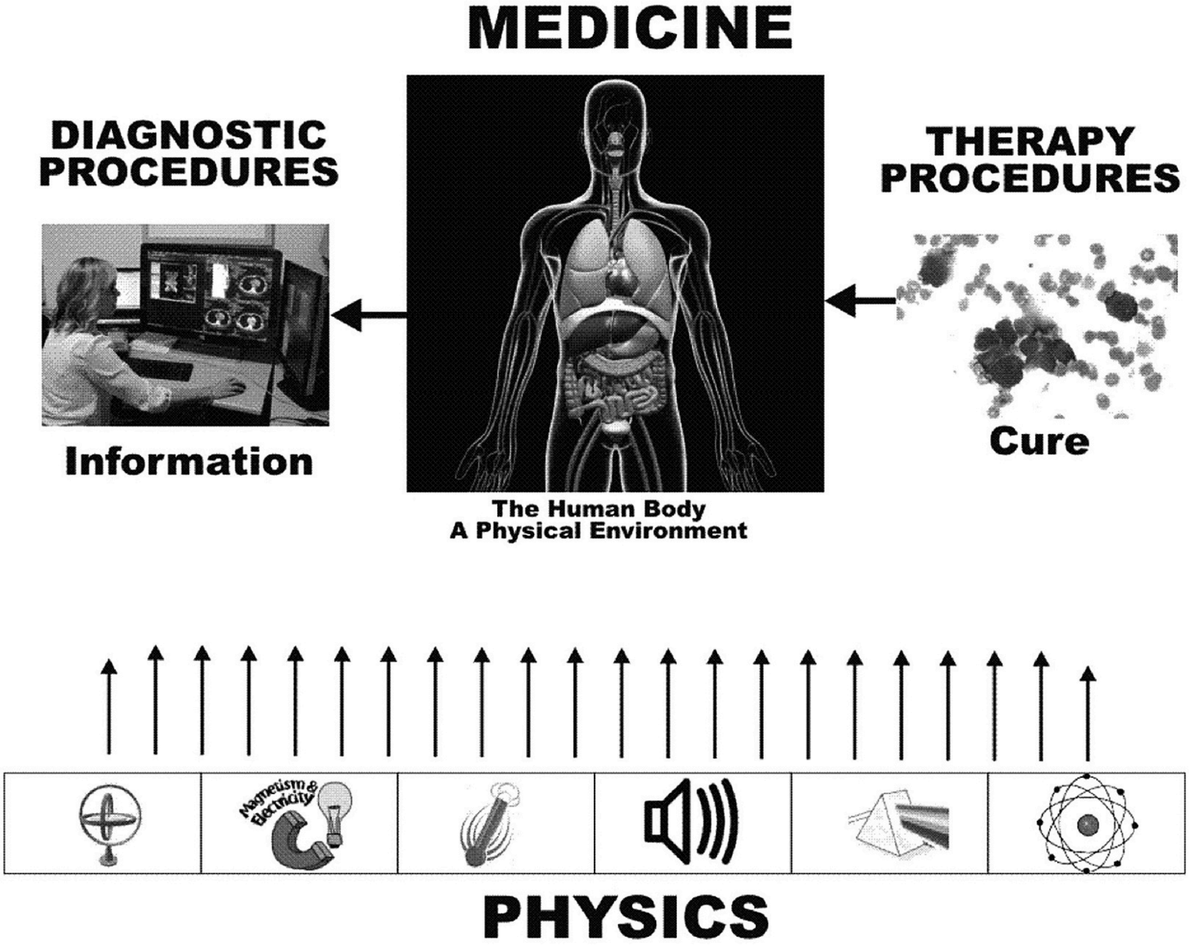
D) The Therapeutic Process

There are several forms of therapy based on the application of various forms of physical energy to the body to treat and hopefully cure various diseases, injuries or other abnormal conditions. The use of ionizing radiation is the medical specialty of radiation oncology or radiotherapy and is done by or under the direction of qualified medical professionals, generally physicians certified in that field. Medical physicists play a significant role in therapeutic procedures using ionizing radiation to treat cancer. The challenge and goal for each procedure is to maximize the radiation dose to the cancer tissues while minimizing the radiation to the surrounding healthy tissues. This is achieved by the often-complex process of treatment planning conducted by medical physics staff.

E) Areas of Physics

All areas of physics, ranging from mechanical to atomic and nuclear, have applications in both diagnostic and therapeutic procedures. Some are much more significant in modern medicine as will be described.

Atomic and nuclear physics is by far the foundation of most physics applications in medicine because this is both the source of several types of radiation and the basis of the interactions of radiation within the human body.



Overall relationship of physics to medicine.

II) Measurement

Measurements are values which made meaningful into specific units, its act as labels which make those value more useful in term of details, for example instead of saying that someone tall, we can say that the individual length is (6 feet).

Practice medical measurements can be divided into: quantitative and qualitative measurements.

A) Quantitative measurement includes:

1. Thermometer: which measure the temperature.

2. A weighing machine to measure the weight.

3. Sphygmomanometer to measure blood pressure.

4. Syringes of different sizes for injection and aspiration of blood and the body.

fluid from.

Qualitative measurement gives information about the inside of the body, such as X- ray image, computed tomography (CT scan), ultrasound (US) image, magnetic resonance image (MRI) ...

B) Units

There are several systems of units:
1- International system SI unit: it measures quantity such as length (meter) , Mass (kilogram), time (second), current (ampere).

2- Nonstandard unit: which is used in medicine such as blood pressure which is measured in millimeter of mercury (mmHg).

3- Static characteristics that include accuracy and precision it is used in science and has different meanings.

- **Accuracy**: refers to the degree of correctness of measurement when compared to true or absolute value.

- **Precision**: refers to the degree of refinement of measurement.

After taking a lot of measurements, you notice that they are all close to each other this is precision, if they are degree with the true value this is accuracy.

C) Sources of error in medical measurements

1. Psychological effects

2. Human factors such as environmental, individual characteristic which influence behavior.

3. Laboratory misleading test values, this error can be reduced by Development of new clinical tests and better instrumentation.

D) Errors or uncertainties from measurements can be reduced by: -

1. Being Careful in taking the measurement.

2. Repeating measurements.
3. Using reliable instruments.
4. Properly calibrating the instruments.

Chapter One

Physics of the body

1-1 Physics of the body

Physics of the body is to understanding physical aspect of the body such as; forces on and in the body, work, energy, power of the body, heat, blood flow, respiration, electricity, circulation and hearing.

1-2 Equilibrium and Stability

- A body is in static equilibrium if the vectorial sum of both the forces and the torques acting on the body is zero.
- A body is in stable equilibrium under the action of gravity if its center of mass/gravity (c.g) is directly over its base of support (Fig. 1.1 a,b).
- If the center of mass is outside the base, the torque produced by the weight tends to topple the body (Fig. 1.1c).

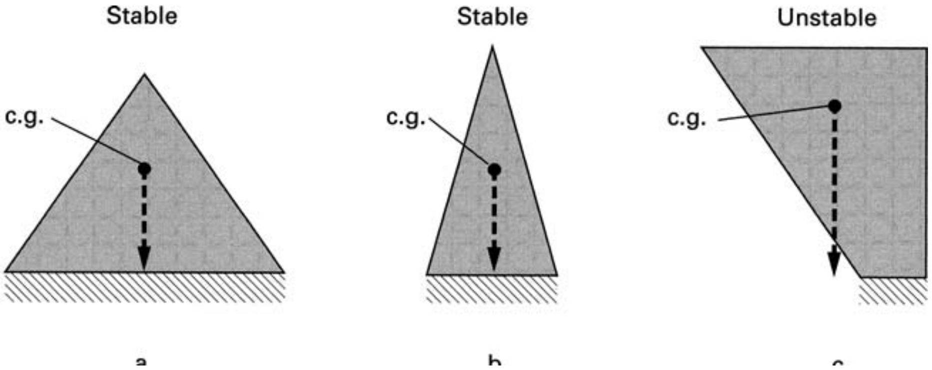


Figure 1.1 Stability of bodies.

1-3 Forces in and on the body

Physicists recognize four fundamental forces.

1-Muscular forces that cause the blood to circulate and the lungs to take in air.

2-Molecular forces (in bone, calcium atom).

3-Electric forces.

4-Gravitational forces.

1-4 Medical effects of gravitation forces

Medical effects of gravitation forces are the formation of **varicose veins** in the legs as the venous blood travels against the force of gravity on its way to the heart, and the second effects is on the bone.

If a person becomes weightless such as in orbiting satellite, he may lose bone mineral. Long term bed rest removes much of the force of the body weight from bones.

1-5 Equilibrium considerations for the human Body

- The center of gravity (c.g.) of an erect person with arms at the side is at approximately 56% of the person's height measured from the soles of the feet (Fig 1.2)
- The center of gravity shifts as the person moves and bends. The act of balancing requires maintenance of the center of gravity above the feet.
- A person falls when his center of gravity is displaced beyond the position of the feet.

For example, when a person carries a weight in one arm, the other arm. swings away from the body and the torso bends away from the load (Fig 1.2b). This tendency of the body to compensate for uneven weight distribution often causes problems for people who have lost an arm, as the continuous compensatory bending of the torso can result in a permanent distortion of the spine. It is often recommended that amputees wear an artificial arm, even if they cannot use it, to restore balanced weight distribution.

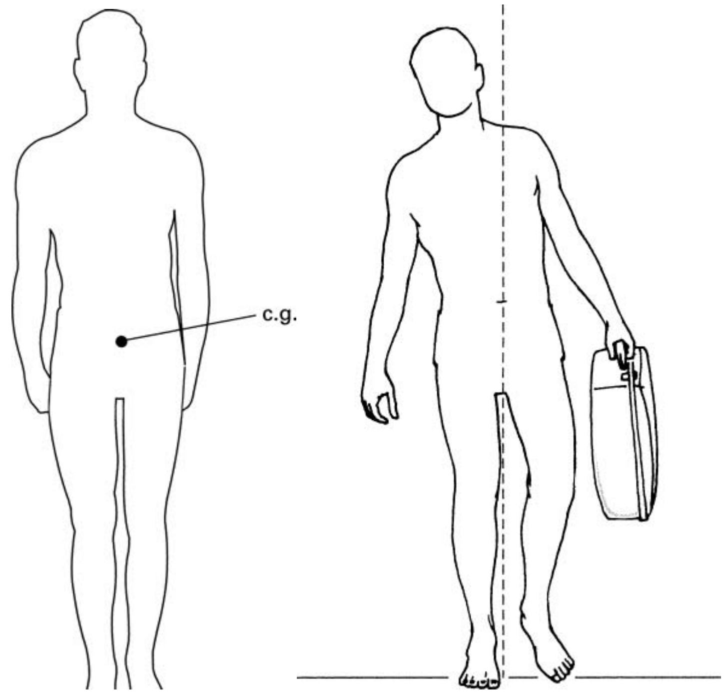


Figure 1.2 a) Center of gravity for a person. b) A person carrying a weight.

1-6 Stability of the human body under the action of an external force

The body may of course be subject to forces other than the downward force of weight. Let us calculate the magnitude of the force applied to the shoulder that will topple a person standing at rigid attention. The assumed dimensions of the person are as shown in Fig. 1.3.

- In the absence of the force, the person is in stable equilibrium because his center of mass is above his feet, which are the base of support.
- The applied force F_a tends to topple the body. When the person topples, he will do so by pivoting around point A—assuming that he does not slide. The **counterclockwise torque** T_a about this point produced by the applied force is;

$$T_a = F_a \times 1.5\text{ m} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .1-1$$

The opposite restoring **torque** T_w due to the person's weight is;

$$T_w = W \times 0.1\text{ m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.1-2$$

Assuming that the mass ***m*** of the person is 70 kg, his **weight *W*** is

$$W = mg = 70 \times 9.8 = 686\ N \ldots\ldots\ldots\ldots..1-3$$

The restoring torque produced by the weight is therefore 68.6 N-m

The person is on the verge of toppling when the magnitudes of these two torques are just equal; that is $T_a = T_w$

$$F_a \times\ 1.5 = 68.6\ N.m \ldots\ldots\ldots\ldots\ldots\ldots..1-4$$

Therefore, the force required to topple an erect person is

$$F_a = \frac{68.6}{1.5} = 45.7\ N$$

- Actually, a person can withstand a much greater sideways force without losing balance by bending the torso in the direction opposite to the applied force as shown in Fig. 1.3 b.
- Stability against a toppling force is also increased by spreading the legs, as shown in Fig. 1.3 c

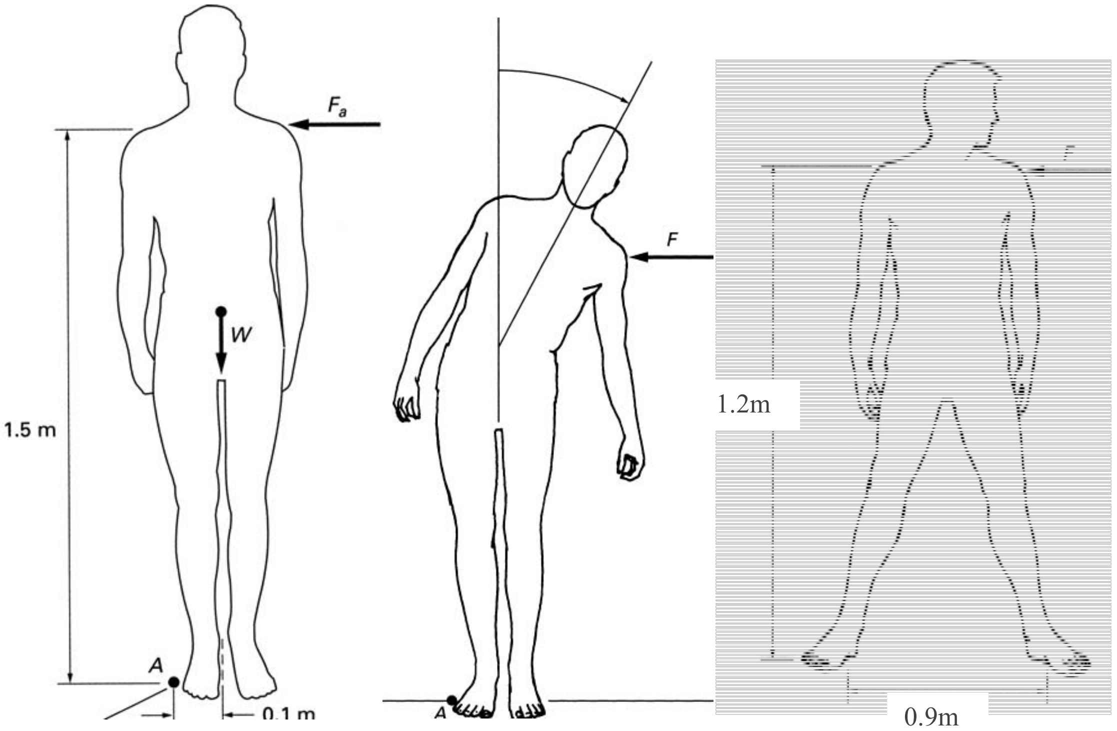


Figure 1.3 a) Force applied to an erect person. b) Compensating for a side-pushing force c) Increased stability resulting from spreading the legs.

1-7 Skeletal Muscles

- The skeletal muscles producing skeletal movements consist of many thousands of parallel fibers wrapped in a flexible sheath that narrows at both ends into tendons (Fig. 1.4).
- The tendons, which are made of strong tissue, grow into the bone and attach the muscle to the bone.
- Most muscles taper to a single tendon. But some muscles end in two or three tendons; these muscles are called, respectively, **biceps** and **triceps.**
- This arrangement of muscle and bone was noted by **Leonardo da Vinci,** who wrote, “The muscles always begin and end in the bones that touch one another, and they never begin and end on the same bone.

Experiments have shown that the maximum force a muscle is capable of exerting is proportional to its **cross section**. From measurements, it has been estimated that a muscle can exert a force of about 7×10^6 dyn/cm^2 of its area which mean (7×10^6 dyn/cm^2 = 7×105 Pa).

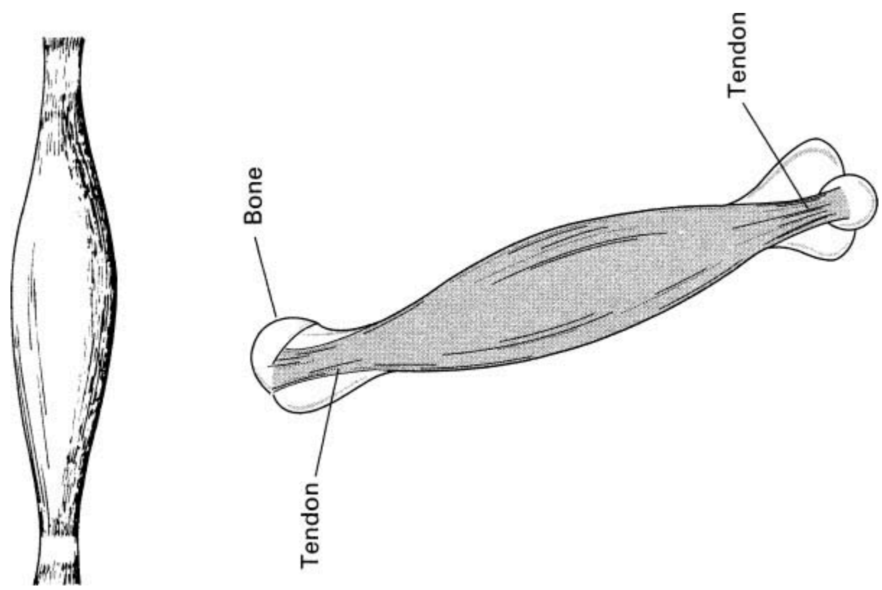


Figure 1.4 Drawing of a muscle.

- To compute the forces exerted by muscles, the various joints in the body can be conveniently analyzed in terms of **levers**. Such a representation implies some simplifying assumptions.
- We will assume that the tendons are connected to the bones at well-defined points and that the joints are **frictionless**.

1-8 Levers

A **lever** is a rigid bar free to rotate about a fixed point called the **fulcrum**. Levers are used to lift loads in an advantageous way and to transfer movement from one point to another.

There are three classes of levers, as shown in Fig. 1.5

- **A Class 1 lever**, the fulcrum is located between the applied force and the load.

- **A Class 2 lever**, the fulcrum is at one end of the bar; the force is applied to the other end; and the load is situated in between.
- **A Class 3 lever**, has the fulcrum at one end and the load at the other. The force is applied between the two ends.

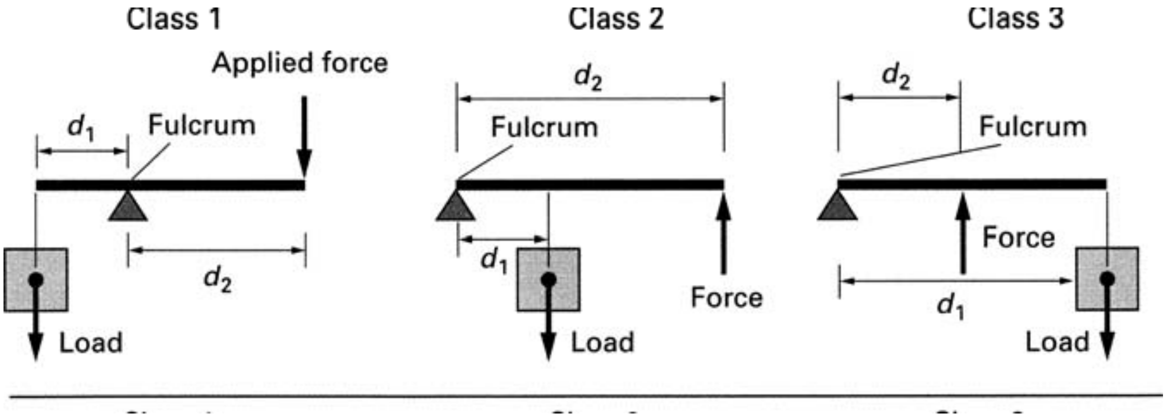


Figure 1.5 The three classes of lever.

From the conditions for equilibrium, for all three types of levers, the force *F* required to balance a load of weight *W* is given by;

$$Fd_2 = Wd_1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..1-5$$

where d_1 and d_2 are the lengths of the lever arms, as shown in Fig. 5

The **Mechanical advantage *M*** of the lever is defined as;

$$M = \frac{W}{F} = \frac{d_2}{d_1} \dots\dots\dots\dots\dots\dots\dots\dots..1-6$$

A force slightly greater than what is required to balance the load will lift it. As the point at which the force is applied moves through a distance L_2, the load moves a distance L_1 (Fig. 1.6). The relationship between L_1 and L_2, is given by

$$\frac{L_1}{L_2} = \frac{d_1}{d_2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.1-7$$

The ratio of velocities of these two points on a moving lever is likewise givenby;

$$\frac{v_1}{v_2} = \frac{d_1}{d_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .1-8$$

Here v_2 is the velocity of the point where the force is applied, and v_1 is the velocity of the load.

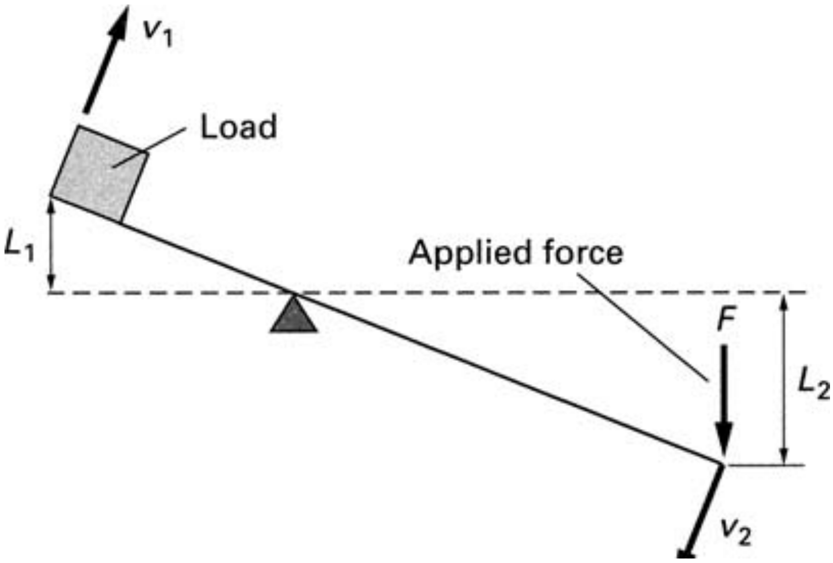


Figure 1.6 Motion of the lever arms in a Class 1 lever

1-8-1 The Elbow

The two most important muscles producing elbow movement are the **biceps** and the **triceps** (Fig. 1.7)

- The contraction of the **triceps** causes an extension, or opening, of the elbow,
- While contraction of the **biceps** closes the elbow.
- For simplification, we will consider the action of only these two muscles.

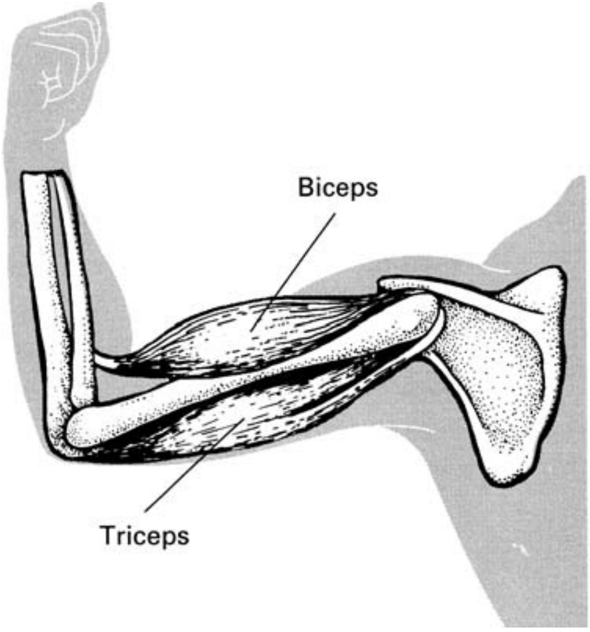


Figure 1.7 The elbow.

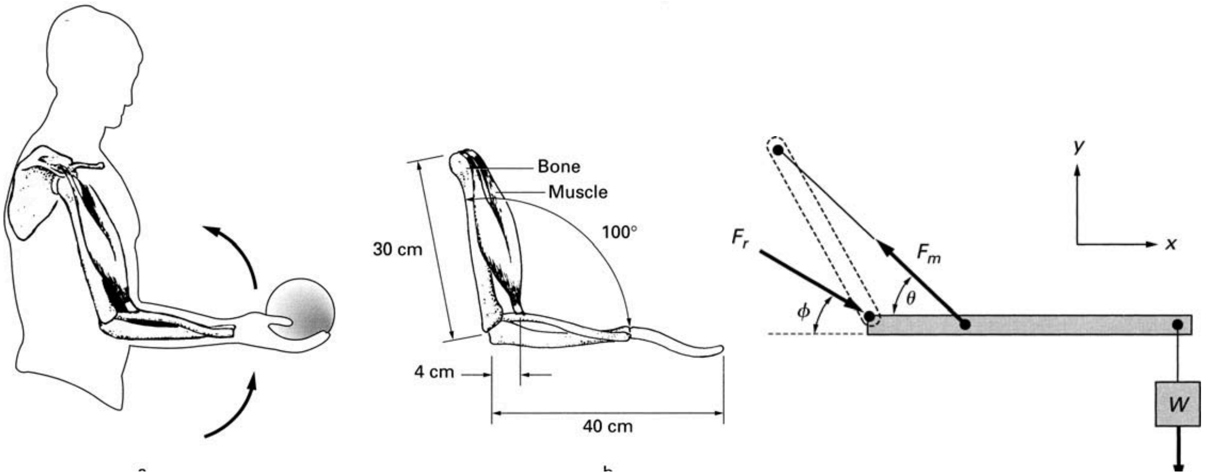


Figure 1.8 a) Weight held in hand. b) A simplified drawing of (a). c) Lever representation

- The weight pulls the arm downward.
- Therefore, the muscle force acting on the lower arm must be in the up direction.
- Accordingly, the prime active muscle is the **biceps**.
- The position of the upper arm is fixed at the shoulder by the action of the shoulder muscles.

We will calculate, under the conditions of equilibrium, the pulling force F_m exerted by the biceps muscle and the direction and magnitude of the reaction force F_r at the fulcrum (the joint). Considering the arm position as a Class 3 lever, as shown in Fig. 1.8c.

In this problem we have three unknown quantities: the **muscle force F_m**, the **reaction force at the fulcrum F_r**, and the **angle**, or direction, of this force ϕ

The angle θ of the muscle force can be calculated from **trigonometric** considerations. As is shown in Exercise 1-3, the angle θ *is 72.6°*.

For equilibrium, the sum of the x and y components of the forces must each be zero. From these conditions we obtain,

$$F_m \, cos\theta = F_r \, cos\emptyset \ldots\ldots\ldots 1-9 \qquad x \quad comps. of \; force$$

$$F_m \, sin\theta = W + F_r \, sin\emptyset \ldots 1-10 \qquad y \quad comps \; of \; force$$

In equilibrium, the torque about any point in Fig. 1.8c must be zero. The torque about the fulcrum must be zero.

Two torques about this point: a **clockwise** torque due to the weight and a **counterclockwise** torque due to the vertical y component of the muscle force. Since the reaction force F_r acts at the fulcrum, it does not produce a torque about this point.

$$4\,cm \; \times F_m \, sin\theta = 40\,cm \; \times \; W \ldots\ldots\ldots .1-11$$

Or

$$F_m \, sin\theta = 10W \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .1-12$$

With $\theta = 72.6°$, from (1-12) the muscle force F_m is

$$F_m = \frac{10\,W}{0.954} = 10.5\,W \ldots\ldots\ldots\ldots\ldots .\ldots\ldots .1-13$$

If the 14-kg weight in hand, the force excreted by the muscle is

$$F_m = 10.5 \times 14 \times 9.8 = 1440N \dots\dots\dots..1-14$$

If we assume that the diameter of the biceps is **8 cm** and that the muscle can produce a 7×10^6 dyn force for each square centimeter of area, the arm is capable of supporting a maximum of 334N in the position shown in Fig. 1.8c. (Exercise 1-4).

The solutions of Eqs. 1.9 and 1.10 provide the magnitude and direction of the **reaction force *F_R***

$$1440 \times \cos 72.6 = F_R\, cos\emptyset \dots\dots\dots\dots..\dots\dots\dots 1-15$$

$$1440 \times \sin 72.6 = 14 \times\ 9.8 +\ F_R\, sin\emptyset \dots\dots..1-16$$

Or

$$F_R\, cos\emptyset = 430\ N \dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots.1-17$$

$$F_R\, sin\emptyset = 1240\ N \dots\dots\dots\dots\dots\dots\dots\dots\dots..\dots..1-18$$

Using $cos^2\emptyset +\ sin^2\emptyset = 1$, and adding them,

$$F_R^2 = 1.74 \times 10^6\ N^2$$

Or

$$F_R = 1320\ N$$

The angle can be calculated from;

$$cot\emptyset = \frac{430}{1240}\ 0.347 \dots\dots\dots 1-19$$

$$\Rightarrow\ \emptyset = 70.9^o$$

It is clear, the force exerted by the muscle is much greater than the weight it holds up. This is the case with all the skeletal muscles in the body. It seems that nature prefers speed to strength. In fact, the speeds attainable at limb extremities are remarkable.

1-8-2 The Hip

Figure 1.9 shows the hip joint and its simplified lever representation, giving dimensions that are typical for a male body.

The hip is stabilized in its socket by a group of muscles, which is represented in Fig. 1.9b as a single resultant force F_m. When a person stands erect, the angle of this force is about 71° with respect to the horizon.

W_L represents the combined weight of the leg, foot, and thigh. Typically, this weight is a fraction (0.185) of the total body weight W (i.e., $W_L = 0.185W$). The weight W_L is assumed to act vertically downward at the midpoint of the limb.

We will now calculate the magnitude of the muscle force F_m and the force F_R at the hip joint when the person is standing erect on one foot as in a slow walk, as shown in Fig. 1.9.

The force W acting on the bottom of the lever is the reaction force of the ground on the foot of the person. This is the force that supports the weight of the body.

From equilibrium conditions

$$F_m \cos 71^o - F_R\, cos\theta = 0 \ldots\ldots\ldots\ldots\ldots\ldots 1-20 \quad x\ comp\ of\ force = 0$$

$$F_m \sin 71^o + W - W_L - F_R\, sin\theta = 0 \ldots\ldots\ldots 1-21 \quad y\ comp\ of\ force = 0$$

$$(F_R \sin\theta) \times 7cm + W_L \times 10cm - W \times 18cm = 0 \ \ldots 1-22\ (torq\ about\ A)$$

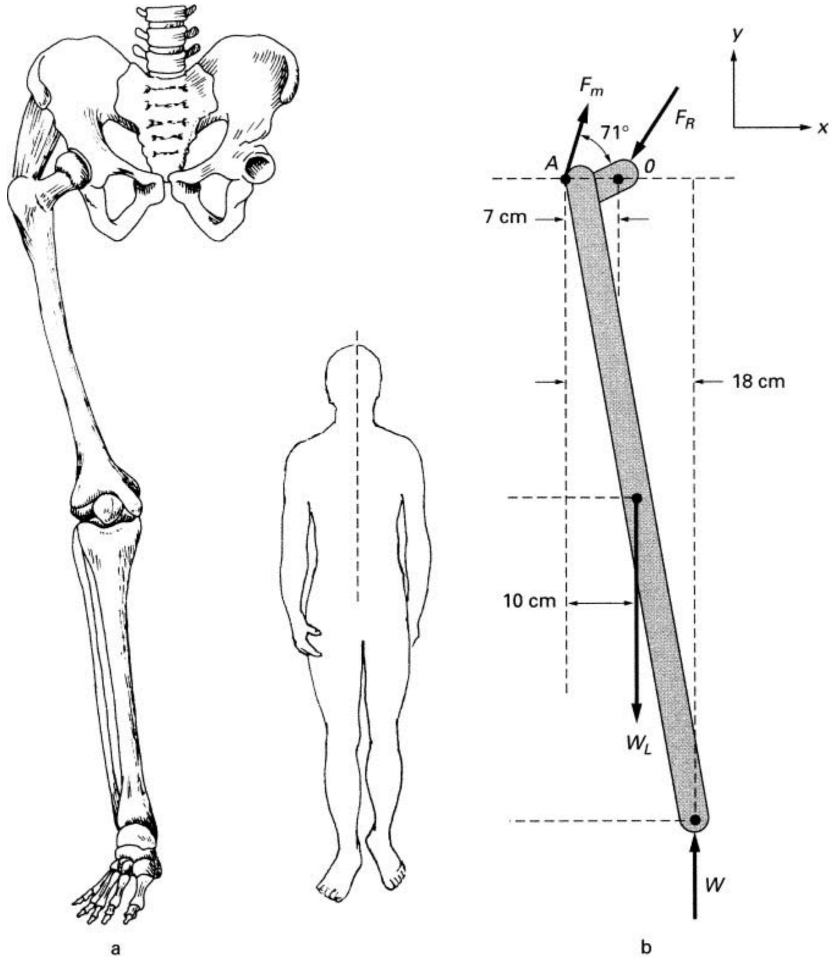


Figure 1.9 (a) The hip. (b) Its lever representation.

Since $W_L = 0.185W$, from eq. (1-22) we have;

$$F_R \sin\theta = 2.31\, W$$

Using the result in Eq. 1.21, we obtain

$$F_m = \frac{1.50\, W}{\sin 71^o}$$

From Eq. 1.20, we obtain

$$F_R \cos\theta = 1.59W \cos 71^o = 0.52\, W$$

therefore,

$$\theta = \tan^{-1} 4.44 = 77.3^o$$

$$F_R = 2.37\, W \ldots\ldots\ldots\ldots.\ldots\ldots 1-23$$

This calculation shows that the force on the hip joint is nearly two- and one-half times the weight of the person. Consider, for example, a person whose mass is 70 kg and weight are 9.8×70 = 686 N. The force on the hip joint is 1625N (366Ib).

1-8-3 Limping

Persons who have an injured hip limp by leaning toward the injured side as they step on that foot (Fig. 1.10). As a result, the center of gravity of the body shifts into a position more directly above the hip joint, decreasing the force on the injured area.

Calculations for the case in Fig. 1.10 show that the muscle force $F_m = 0.47W$ and that the force on the hip joint is $1.28W$. This is a significant reduction from the forces applied during a normal one-legged stance.

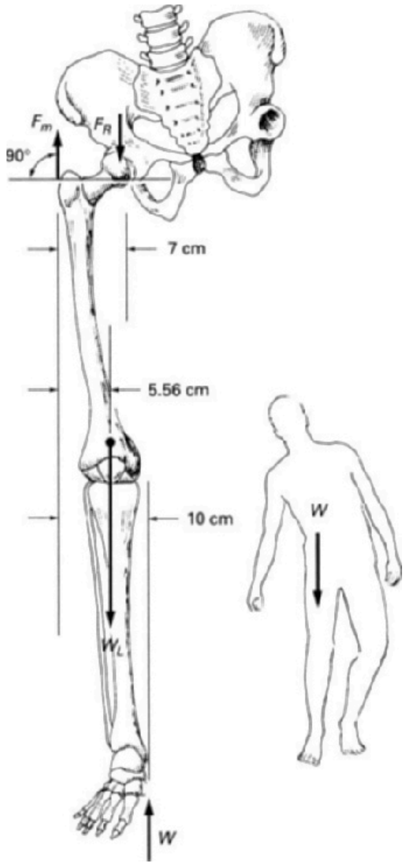


Figure 1.10 Walking on an injured hip

1-8-4 The Back

When the trunk is bent forward, the spine pivots mainly on the fifth lumbar vertebra (Fig. 1.11 left).

We will analyze the forces involved when the trunk is bent at 60° from the vertical with the arms hanging freely. The lever model representing the situation is given in Fig. 1.11 right.

The pivot point A is the fifth lumbar vertebra. The lever arm AB represents the back. The weight of the trunk W_1 is uniformly distributed along the back; its effect can be represented by a weight suspended in the middle. The weight of the **head** and **arms** is represented by W_2 suspended at the end of the lever arm.

The erector spinalis muscle, shown as the connection D-C attached at a point two-thirds up the spine, maintains the position of the back. The angle between the spine and this muscle is about 12°. For a 70-kg man, W_1 and W_2 are typically 320N and 160N, respectively.

Solution of the problem is left as an exercise. It shows that just to hold up the body weight, the muscle must exert a force of 2000N and the compressional force of the fifth lumbar vertebra is 2230N. If, in addition, the person holds a 20-kg weight in his hand, the force on the muscle is 3220N, and the compression of the vertebra is 3490N (Exercise 1-12).

This example indicates that large forces are exerted on the fifth lumbar vertebra. It is not surprising that backaches originate most frequently at this point. It is evident too that the position shown in the figure is not the recommended way of lifting a weight.

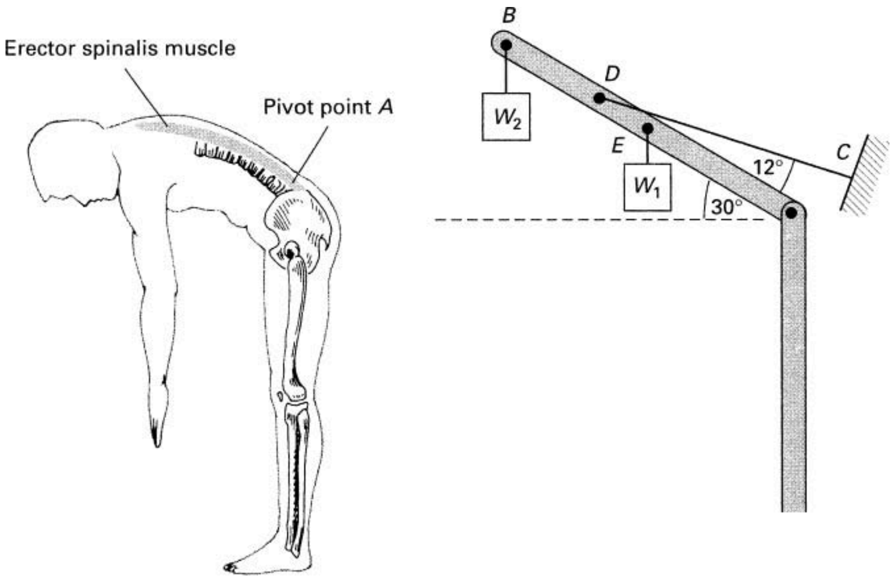


Figure 1.11 (Left) The bent back. (Right) Lever representation

1-8-5 Standing Tip-Toe on One Foot

The position of the foot when standing on tiptoe is shown in Fig. 1.12. The total weight of the person is supported by the reaction force at point A. This is a **Class 1 lever** with the fulcrum at the contact of the tibia. The balancing force is provided by the muscle connected to the heel by the **Achilles tendon**.

The dimensions and angles shown in Fig. 1.12b are reasonable values for this situation. Calculations show that while standing tiptoe on one foot the compressional force on the tibia is $3.5W$ and the tension force on the Achilles tendon is $2.5 \times W$ (see Exercise 1-13). Standing on tiptoe is a fairly strenuous position.

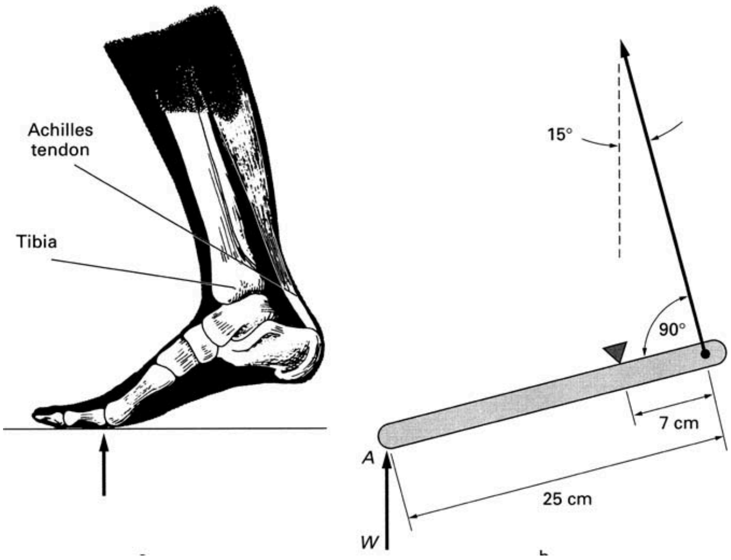


Figure 1.12 (a) Standing on tip-toe. (b) Lever model

1-9 Frictional Force

Friction and energy loss due to friction appear every day in our life. When two surfaces are in contact, their irregularities intermesh, and as a result there is a resistance to the sliding or moving of one surface on the other. This resistance is called **friction**. Consider a block resting on a surface as shown in Fig. 1.13. If we **apply a force *F*** to the block, it will tend to move. But the intermeshing of surfaces produces a **frictional reaction force F_f** that opposes motion. In order to move the object along the surface, the applied force must overcome the frictional force. The maximum force of friction F_f is

$$F_f = \mu \, F_n \ldots\ldots\ldots\ldots\ldots\ldots .1 - 24$$

Where F_n is a normal force. μ is the coefficient between the two surfaces.

The value of μ depends upon the two materials in contact, and it is essentially **independent of the surface area**, as shown in Table 1-1.

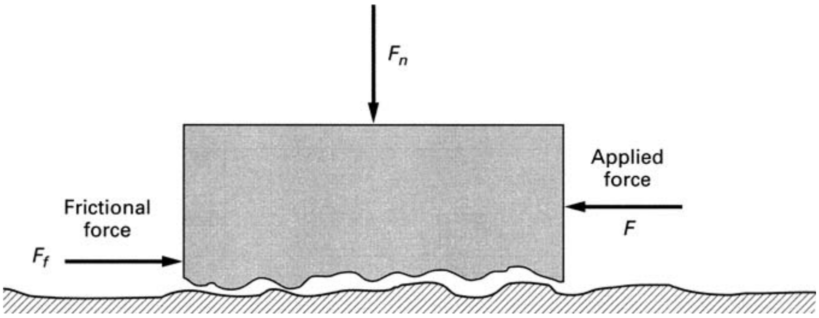


Figure 1.13 Friction.

H.W) Does the magnitude of the frictional force depend on the size of the contact area? Why?

H.W) Is the coefficient of static friction for given surfaces is larger or smaller than the coefficient of kinetic friction?

Table 1-1 Coefficients of Friction, Static (μ_s) and Kinetic (μ_k)

Surfaces	μ_s	μ_k
Leather on oak	0.6	0.5
Rubber on dry concrete	0.9	0.7
Steel on ice	0.02	0.01
Dry bone on bone		0.3
Bone on joint, lubricated	0.01	0.003

- Without friction we could not walk, friction provides the necessary reaction force
- Friction also produces undesirable wear and tear and destructive heating of contact surfaces.
- Friction is greatly reduced by introducing a fluid such as oil at the interface of two surfaces
- A natural example of such lubrication occurs in the joints of animals, which are lubricated by a fluid called the **synovial fluid.**

We can resolve this force into horizontal and vertical components. The **vertical reaction force** is applied by the surface and is labeled F_n (normal force). **The horizontal reaction** component must be applied by frictional forces, as shown in figure 1-14.

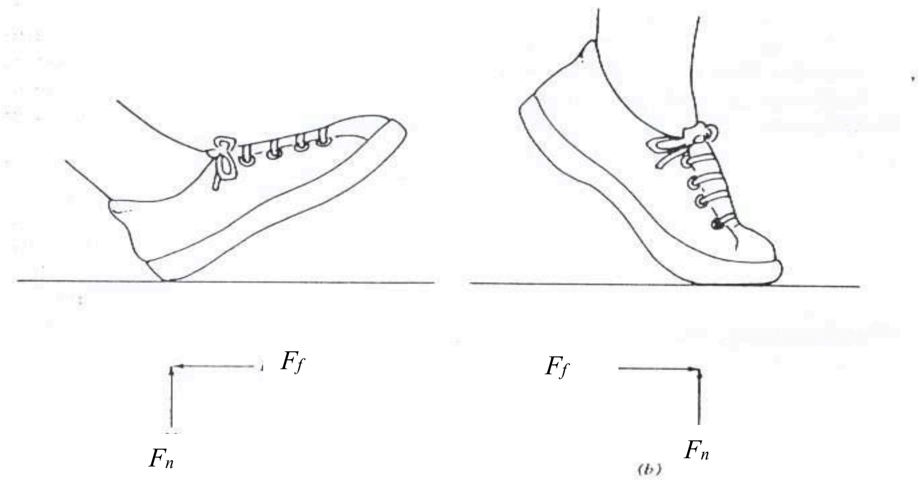


Figure 1.14 Normal walking a) Both horizontal friction component of force F_f and a vertical (normal) component of force F_n exist on the heel as it strikes the ground. Fraction between the heel and surface prevent the foot from slippering forward. B) when the foot leaves the ground the friction component of force F_f prevent the toe from slippering backward.

Measurements have been made of the horizontal force component of the heel as it strikes the ground when a person is walking, and it has been to be = 0.15 *W*.

The frictional force is large enough both when the heel touches down and when the toe leaves the surface to prevent a person from slipping. this how large the frictional force must be in order to prevent the heel from slipping.

The coefficient of friction in bone joints is very small (Table 1-1). If a disease of the joint exists, the friction may become large. The synovial fluid in the joint is involved in the lubrication.

The saliva we add when we chew food acts as a lubricant (to reduce the friction force). For example, if you swallow a piece of dry toast you become painfully aware of this lack of lubricant.

1-9-1 Friction at the Hip Joint

We have shown that the forces acting on the joints are very large. When the joints are in motion, these large forces produce frictional wear. which could be damaging unless the joints are well lubricated.

Frictional wear at the joints is greatly reduced by a smooth cartilage coating at the contact ends of the bone and by synovial fluid which lubricates the contact areas.

We will now examine the effect of lubrication on the hip joint in a person. When a person walks, the full weight of the body rests on one leg through most of each step. Because the center of gravity is not directly above the joint, the force on the joint is greater than the weight.

Depending on the speed of walking, this force is about 2.4 times the weight.

In each step, the joint rotates through about 60^o. Since the radius of the joint is about 3 cm, the joint slides about 3 cm inside the socket during each step. The frictional force on the joint is

$$F_f = 2.4\, W_\mu \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots..1-25$$

The work expended in sliding the joint against this friction is the product of the **frictional force** and the **distance over which the force acts**. Thus, the work expended during each step is;

$$Work = F_f \times distance = 2.4W_\mu\,(3cm) = 7.2W_\mu\, erg \ldots\ldots\ldots..1-26$$

If the joint were not lubricated, the coefficient of friction (μ) would be about (0.3). Under these conditions, the work expended would be;

$$Work = 2.16 \times W\, erg \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.1-27$$

This is a large amount of work to expend on each step. It is equivalent to **lifting the full weight of the person 2.16 cm**. Furthermore, this work would be dissipated into heat energy, which would destroy the joint.

As it is, the joint is well lubricated, and the coefficient of friction is only (0.003). Therefore, the work expended in counteracting friction and the resultant heating of the joint are negligible.

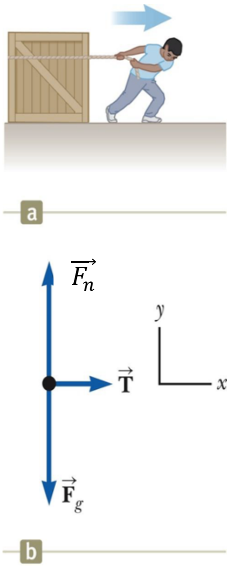
However, as we age, the joint cartilage begins to wear, efficiency of lubrication decreases, and the joints may become seriously damaged. Studies indicate that by the age of **70** about **two-thirds** of people have knee joint problems and about **one-third** have hip problems.

1-10 The Object Under a Net Force, the dynamical force

According to second law of Newton, the force is equal

$$F = ma = \frac{\Delta(mv)}{\Delta t} \dots\dots\dots\dots\dots\dots\dots\dots\dots 1-28$$

mv is the momentum



Example: Forces acting on the crate:

- A tension, acting through the rope, is the magnitude of force $\vec{T}$
- The gravitational force, $\vec{F_g}$
- The normal force, $\vec{F_n}$, exerted by the floor

Apply Newton's Second Law in component form:

$$\sum F_x = T = ma_x \dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots.1-29$$

$$\sum F_y = F_n - F_g = 0 \implies F_n = F_g \dots\dots\dots\dots\dots\dots\dots..\dots.1-30$$

Example 1: A 60-Kg person walking at 1 m/sec bumps into a wall and stops in a distance of 2.5 cm in about 0.05 sec. what is the force developed on impact?

Solution:

$\Delta(mv) = (60\text{ Kg})\,(1\text{m/sec}) - (60\text{ Kg})\,(0\text{ m/sec}) = 60\text{ Kg m/sec}$

The force developed on impact is,

$F = \Delta\,(mv)/\Delta t = 60\text{Kg m/sec} / 0.05 = 1200\text{ Kg m/sec.}$

$F = 1200\text{ N}$

Example 2: A 50kg person jumping from a height of 1 m is travelling at 4.5 m/sec just prior to landing. Suppose she lands on a pad and stops in 0.2 sec. What maximum force will she experience?

Solution:

$F = \Delta\,(mv)/\Delta t = 50\text{x } 4.5/0.2 = 1125\text{ N}$

Example 3: Estimate the force on the forehead if the mass of the head is 4-kg, its velocity is 15 m/sec, and the padded dash stops it in 0.002 sec.

Solution:

$F = \Delta\,(mv)/\Delta t = 4 \text{ x } 15 / 0.002 = 3 \text{ x } 10^4\text{ N}$

Problems

1-1. (a) Explain why the stability of a person against a toppling force is increased by spreading the legs as shown in Fig. 1.3c. (b) Calculate the force required to topple a person of mass = 70 kg, standing with his feet spread 0.9 m apart as shown in Fig. 1.3c. Assume the person does not slide and the weight of the person is equally distributed on both feet.

1-2. Derive the relationships stated in equations. 1.5, 1.6, and 1.7.

1-3. Using trigonometry, calculate the angle θ in Fig. 1.8c. The dimensions are specified in Fig. 1.8b.

1-4. Using the data provided in the text, calculate the maximum weight that the arm can support in the position shown in Fig. 1.8.

1-5. Calculate the force applied by the biceps and the reaction force (F_r) at the joint as a result of a 14-kg weight held in hand when the elbow is at (a) 160° and (b) 60°. Dimensions are as in Fig. 1.8. Assume that the upper part of the arm remains fixed as in Fig. 1.8 and use calculations from Exercise 1-3. Note that under these conditions the lower part of the arm is no longer horizontal.

1-6. Consider again Fig. 1.8. Now let the 14-kg weight hang from the middle of the lower arm (20 cm from the fulcrum). Calculate the biceps force and the reaction force at the joint.

1-7. Consider the situation when the arm in Fig. 1.8c supports two 14-kg weights, one held by the hand as in Fig. 1.8c and the other supported in the middle of the arm as in Exercise 1-6. (a) Calculate the force of the biceps muscle and the reaction force. (b) Are the forces calculated in part (a) the same as the sum of the forces produced when the weights are suspended individually?

1-8. Calculate the additional forces due to the weight of the arm itself in Fig. 1.8c. Assume that the lower part of the arm has a mass of 2-kg and that its total weight can be considered to act at the middle of the lower arm, as Exercise 1-6.

1-9. Estimate the dimensions of your own arm, and draw a lever model for the extension of the elbow by the triceps. Calculate the force of the triceps in a one arm push-up in a hold position at an elbow angle of 100°.

1-10. Suppose that the biceps in Fig. 1.8c contracts 2 cm. What is the upward displacement of the weight? Suppose that the muscle contraction is uniform in time and occurs in an interval of 0.5 sec. Compute the velocity of the point of attachment of the tendon to the bone and the velocity of the weight. Compare the ratio of the velocities to the mechanical advantage.

1-11. Calculate the forces in the limping situation shown in Fig. 1.10. At what angle does the force F_R act?

1-12. (a) Calculate the force exerted by the muscle and the compression force on the fifth lumbar vertebra in Fig. 1.11. Use information provided in the text. (b) Repeat the calculations in (a) for the case when the person shown in Fig. 1.11 holds a 20-kg weight in his hand.

1-13. Calculate the force on the tibia and on the Achilles tendon in Fig. 1.12.

1-14. (a) Assume that a 50-kg skater, on level ice, has built up her speed to 30 km/h. How far will she coast before the sliding friction dissipates her energy? (Kinetic energy $=1/2\ mv^2$) (b) How does the distance of coasting depend on the mass of the skater?

1-15. Referring to Fig. 1.3a, compute the coefficient of friction at which the tendency of the body to slide and the tendency to topple due to the applied force are equal.

Chapter Two

Physics of the skeleton

2-1 Introduction

Bone is of interest to medical physics and engineers. Perhaps this organ system of the body appeals most to physical scientists because engineering type problems dealing with static and dynamic leading forces that occur during standing, walking, running, lifting, and forth.

In the body, we have some 270 bones when born. After fusing, some 206 distinct bones are left in adulthood. Those 206 bones are of very different sizes and shapes. We distinguish long and hollow bones for the extremities; short bones for hands and feet; irregularly shaped bones for the spine and knee; flat bones for the skull, shoulder blade (scapula), ribs, and breastbone (sternum). All bones share a hard shell (compact or **cortical** shell) and a spongy bone interior (**trabecular** bone).

The hardness of bones makes them good fossils that last for millions of years. Figure 2-1 shows an example of a long bone (femur) featuring the characteristic bone structure of a hard-cortical shell and a spongy trabecular interior. But the femur has, in addition, a medullary cavity, which is characteristic only for long bones.

Bones have many tasks. 1)Bones protect vital organs like the heart and the lung. 2)They lend stability and mobility to the body via joints between bones and attachment points for tendons of muscles and ligaments. 3) And they act as production and storage centers. They produce blood cells in the bone marrow and store minerals and lipids released on demand. Table 1 shows the physical properties of bone.

Note: Bones have a heterogeneous structure: a hard-cortical shell envelops a spongy trabecular interior.

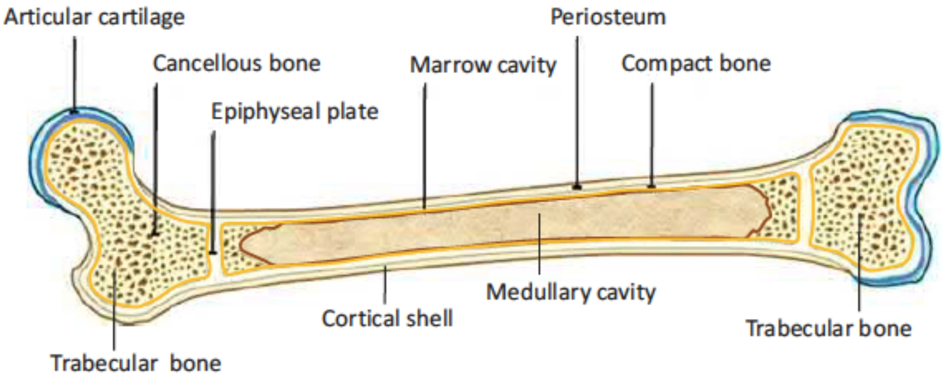
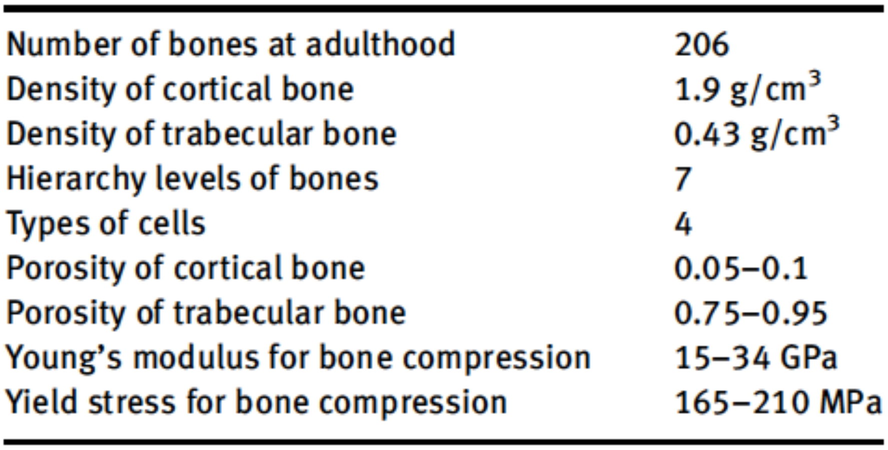


Figure 2-1 Structure of a long bone (femur).

Table 2-1 Physical properties of the bone



Number of bones at adulthood	206
Density of cortical bone	1.9 g/cm^3
Density of trabecular bone	0.43 g/cm^3
Hierarchy levels of bones	7
Types of cells	4
Porosity of cortical bone	0.05–0.1
Porosity of trabecular bone	0.75–0.95
Young's modulus for bone compression	15–34 GPa
Yield stress for bone compression	165–210 MPa

Muscle and bone are two examples of biomaterials with very different mechanical properties. In a way, muscles and bones work together like the ropes and boom arms of a crane.

In this chapter, we aim to answer some of the most obvious questions: why are bones hard? Can bones be bent? When do bones break? How and why do bones age?

2-2 Function of the bones in the body

1) Support: - It's obvious in the leg, muscles are attached to the bone by tendons and ligament and the system of bones plus muscle supports the body.

2) Movement (Locomotion): -Bone joints permit movement of one bone with respect to another. These hinges or articulation, are very important for walking as well as for many of the other motions of the body.

3) Protection: - The skull protects the brain and several of the most important sensory organs (eyes, and ears), ribs protect heart and lungs, spinal column protect spinal cord.

4) Storage of chemicals: - Bones acts as a chemical bank for storing elements for future use by the body. For example, a minimum level of calcium is needed in the blood, if the level falls too low, the calcium sensor causes parathyroid gland to release more Parathormone into the blood; this causes the bone to release the needed calcium.

5) Nourishment: - Teeth are specialized bones that can cut food by incisors, tear it by canines and grind it by molars and thus serve in providing nourishment for the body.

6) Cell blood production: - Red blood cells, white blood cells, and platelets are all produced in the red bone marrow.

Note:

- ***Red bone marrow is where the production of blood cells.***
- ***Yellow bone marrow contains adipose tissue, and the triglycerides stored in the adipocytes of this tissue can be released to serve as a source of energy for other tissues.***

2-3 Bone composition

The Bone is a living tissue which has blood supply as well as nerves with a special kind of cells distributed through the bone tissue; these cells are called ***"Osteocytes"***

The Osteocytes cells maintain the bone in a healthy condition. These cells make up about 2% of the volume of the bone, if these cells die (e.g. due to poor blood supply), the bone dies and it loses some of its strength. A series hip problem is caused by a condition called ***aseptic necrosis*** in which the bone cells in the hip die due to the lack of blood. Up to seven levels are distinguishable from the molecular level up to the macroscopic scale.

In general, Bones consist of two quit different materials plus water:

Collagen is the major organic fraction of the solid bone. It is quite flexible, it has a fair amount of tensile strength so that it can bend easily if it's compressed. It forms about 40% of the weight of the solid bone and 60% of its volume.

The fundamental structural unit is a right-handed triple helix consisting of three coiled and intertwined polymer chains. The chains are held together by hydrogen bonds. The collagen triple helix is 300 nm long and only 1.5 nm wide. Collagen fibers are shown schematically in figure 2-2.

Thousands of collagen fibers are packed laterally and one on top the other to form cylindrical fibrils. Fibrils have a 25–500 nm diameter, depending on the collagen type and the number of fibers figure (2-4). The ends of adjacent collagen fibers are shifted by a distance of 67 nm, producing a stair like appearance visible in electron micrographs.

In bones, the gaps between the fibers are filled by nanocrystalline minerals of **calcium hydroxyapatite** ($Ca_5(PO_4)_3OH$)) (short notation: **HA**). The crystal structure is shown in figure 2-2. The HA is also known as bone mineral. Bones contain HA up to 50% by volume and 70% by weight. Note that HA only contains atoms that are abundant in the body.

Collagen fibers and HA minerals together form organic–inorganic composite biomaterials that constitute the building blocks of fibrils in the cortical bone structure. The collagen fibers provide bending resistance to bones, whereas the minerals give the bones hardness10 as well as a high elastic modulus for the compressional load. The organic collagen material lends bones its flexibility, while the inorganic HA material is responsible for its resilience.

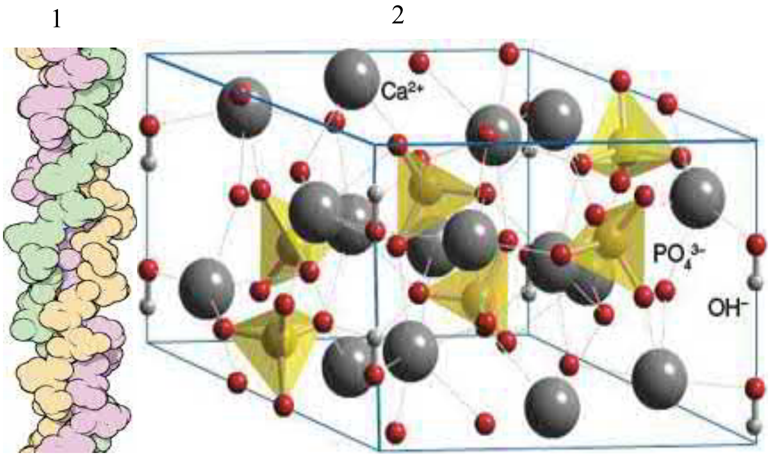


Figure 2-2 (1) Right-handed triple helix structure of collagen. The individual strands are differently colored. (2) Crystal structure of naturally occurring calcium hydroxyapatite ($Ca_5(PO_4)_3OH$), short HA)

In other words, collagen prevents HA from brittle cracking, while HA prevents collagen from yielding. The right mix is essential. Figure 2-3 shows strikingly what happens when one or the other component is not optimized. Without HA minerals, bones bend; without collagen, bones shatter. Nanocrystals of HA are also present in dental enamel.

Note: Bones are composite materials combining soft collagen fibers and hard nanocrystals. This combination provides a material that is strong as granite in compression and 25 times stronger than granite under tension.

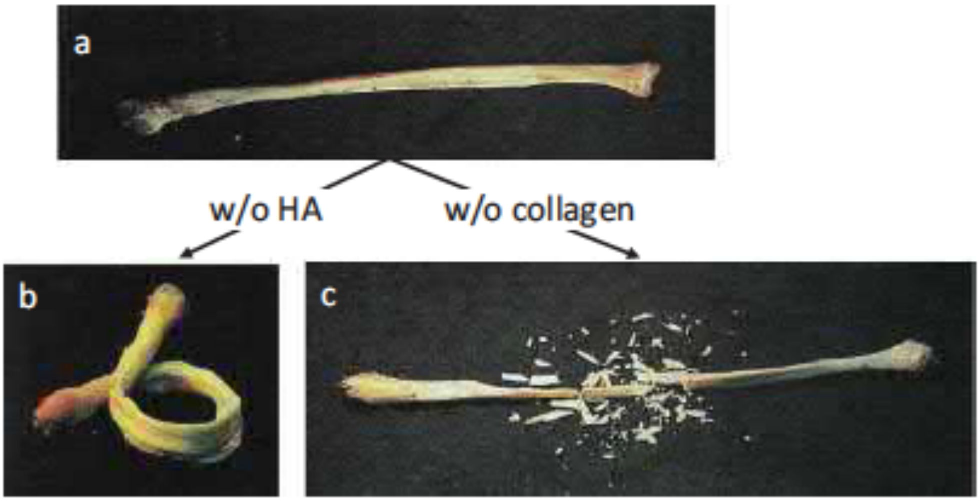


Figure 2-3 A long bone (a) is treated such that either the HA minerals are dissolved, leaving a flexible bone in panel (b), or the collagen fiber density is reduced, resulting in a cracked and shattered material after impact in panel (c).

Figure 2-4 gives an overview of the hierarchical architecture of bones. Collagen fibers intertwine and form a triple helix structure. As already mentioned, the helical structure leaves gaps that are filled with HA nanocrystals. Many fibers combine to collagen fibrils.

In turn, the collagen fibrils are the building blocks for the next level in the hierarchical structure that constitutes cylindrical lamellas forming osteons in the compact part of bones. Osteons have a diameter of about 100µm. The osteons are cemented together and form highly regular structures in the cortical part of bones. Each cylindrical osteon has in its center a Haversian canal that contains blood vessels and nerve fibers. The longitudinal Haversian11 canals are interconnected by transverse Volkmann canals, which link different osteons. The blood vessels carry away and distribute newly generated blood cells from the bone marrow and minerals from the osteons.

Note: Bones contain four types of cells: three for building bone structure (osteogenic, osteoblast, and osteocyte), and one for eliminating the old bone material (osteoclast).

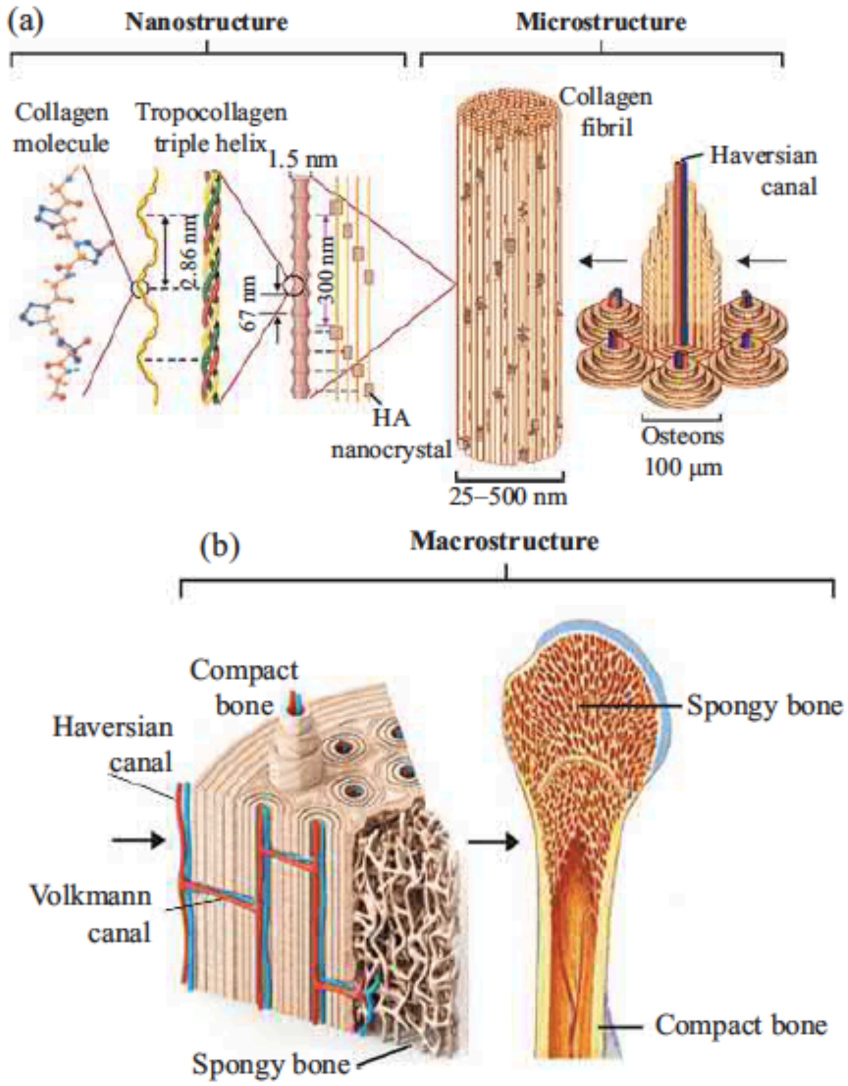


Figure 2-4 Hierarchical structure of compact bones from nanostructure level (panel a) to the macroscopic level (panel b)

Table 2-2The detailed chemical composition of the bone

Element	**% of the element in the bone**
H	3.4
C	15.5
N	4
O	44
Mg	0.2
P	10.2
S	0.3
Ca	**22.2**
Miscellaneous	0.2

2-4 Skeleton design and bone strength

2-4-1 Elastic deformation

1) Strain and stress

Any solid body can be deformed by a pair of forces $(\overrightarrow{F_1})$ and $(\overrightarrow{F_2})$ acting on opposite surfaces and in opposite directions. In such a situation, the body cannot move since the resulting force cancels: $(\overrightarrow{F_1} + \overrightarrow{F_2} = 0)$. For the following it is sufficient to consider the magnitude of the force component $(\overrightarrow{F_1} = \overrightarrow{F_2} = F)$ acting perpendicular to a surface area ***A***. The ratio of the force ***F*** per surface area ***A*** yields a pressure ***P* = *F/A***, also called **stress** or **tension**:

- If the stress is exerted in only one direction, whereas all other body surfaces are free, the stress is called uniaxial. Depending on the direction of forces, the uniaxial stress can be either tensile or compressive figure (2-5-a, b)
- If all body surfaces experience the same pressure (stress), the acting pressure is called hydrostatic figure (2-5-c) Hydrostatic pressure plays a decisive role in many body parts, such as the cardiovascular system, respiration, kidneys, and eyeballs.

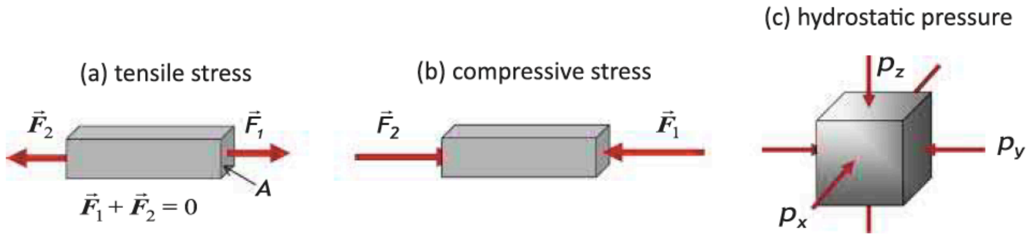


Figure 2-5 (a) and (b) Tensile stress and compressive stress are due to pairs of forces acting on opposite surfaces of area A in one spatial direction; and (c) hydrostatic pressure is due to pairs of forces acting on surfaces in all three spatial directions.

If an extended solid body is under uniaxial external pressure (stress), it will react by changing its length *L*. The resulting deformation is called **strain**. Strain ε is measured in terms of a relative length change:

$$\varepsilon = \frac{\Delta L}{L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .2-1$$

L is the original length of the body. ε is usually expressed in percent.

2) Hooke's law

Tensile stress results in elongation, compressive stress causes contraction. For small deformations, the relation between stress σ and strain ε is linear, which is known as **Hooke's 2 law** as shown in figure (2-6):

$$\sigma = Y\,\varepsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots ..2-2$$

The proportionality constant *Y* is the elastic modulus, also known as Young's modulus. The elastic modulus *Y* characterizes a material as elastically soft or hard, easy to deform like rubber, or hard to deform like steel. The stress $\sigma = F/A$ has the unit N/m^2=*Pascal.*

$$1\frac{N}{m^2} = 1\,pascal\ (Pa) = 1kg/ms^2$$

$$1\ bar = 10^5\ Pa = 100\ kPa$$

The strain ε is dimensionless. Therefore, the unit of σ and the unit of *Y* are identical. Typical values of *Y* range from 0.5 GPa for rubber to 200 GPa for steel. Some elastic moduli are listed in Table. 2.2.

****Ultimate compressive stress (UCS) which is 170MPa for compact bone represents the stress when reaches its maximum just before fracture occurs.***

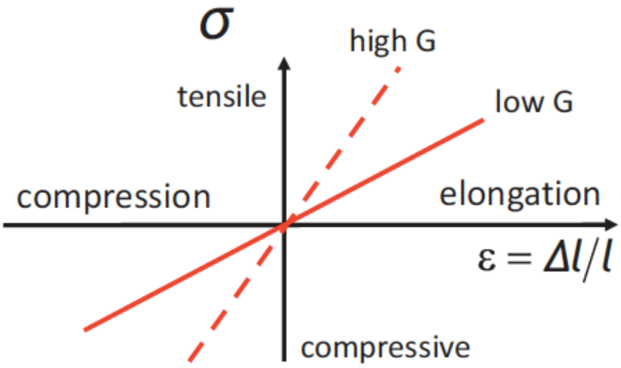


Figure 2-6 Solid red line: Hooke's law for materials with low elastic modulus like wood or bones; dashed red line: for materials with a large elastic modulus like steel.

Table 2-2 Elastic moduli of some selected materials.

Material	Y (GPa)
Aluminum	70
Steel	200
Wood	13
Bones	15
Rubber	0.5

Hooke's law is explicitly limited to the elastic deformation of materials. This limitation implies three fundamental properties: first, the relationship is linear without offset, i.e., for $\sigma = 0$ follows $\varepsilon = 0$. Second, the deformation is completely reversible, i.e., any release of stress results in a fully reversible strain without memory effect. Third, the strain relaxation is instantaneous, i.e., there is no time lapse between a stress release and strain relaxation. Elastic deformation is clearly distinguished from plastic deformation, the latter features irreversible deformations

Note: The elastic deformation of solids implies that the strain is linearly proportional to the applied stress. After stress relief, the strain is fully restored.

In addition to the length change parallel to the applied stress, solid bodies react by changing their thickness (t) in two perpendicular directions. For instance, tensile stress causes an elongation $\Delta L/L$ in the stress direction and a contraction $\Delta t/t$ in the two directions perpendicular to the stress line. The ratio:

$$\mu = \frac{\Delta t/t}{\Delta L/L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2-3$$

is called the Poisson ratio? The total volume change upon uniaxial stress is then

$$\frac{\Delta V}{V} = \frac{\sigma}{Y}(1-2\mu) \ldots\ldots\ldots\ldots 2-4$$

The factor of 2 is due to the two perpendicular directions to the applied stress. The volume change is zero for $\mu = 0.5$. Typical μ-values range from 0.2 to 0.4. As the Poisson contraction does not play a role for the human body, we will neglect this effect further on.

3) Shear deformation

Other forms of elastic deformation occur by applying tangential forces at opposite sides of a body that change the angles of the body but not its volume. The tangential force is the force component projected into the surface area A. Pairs of forces act such that the body does not gain angular momentum. We differentiate between shear deformation, torsional deformation, and bending deformation. These three types are sketched in figure (*) below.

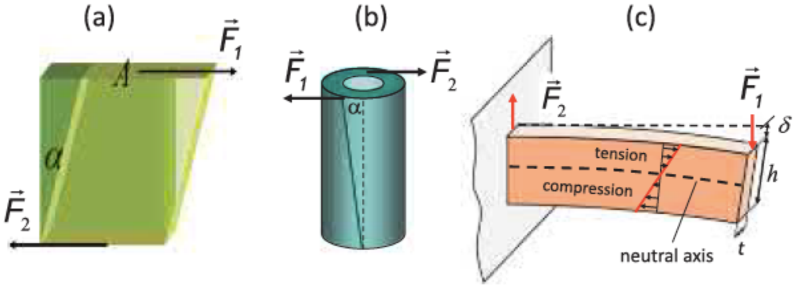


Figure (*) Elastic deformations by tangential forces: (a) shear; (b) torsion; and (c) bending. Note that pairs of shear forces are applied parallel to a surface in all three cases. By bending of a beam, the counterforce *F2* is exerted by a fixture.

Through bending, the elastic stiffness k of a material can be tested. The stiffness is defined as the ratio of force *F* applied to the end of the beam, and the deflection *δ*:

$$k = \frac{F}{\delta}$$

A high k-value indicates a stiff material. Note the difference between stiffness k and elastic modulus *Y*: *Y* is an intrinsic material property, while *k* depends on the geometry of the beam and the boundary condition imposed.

Q) A 0.5 m long bone is clamped on one end, and the other free end is exposed to a bending force of 100 N. What is the relative deflection δ/L and the absolute deflection δ if the stiffness of the bone is $k=2\times10^3$ N/m?

2-4-2 Mechanical properties of bone

As we mention before, bone is composed of small hard bone mineral crystals attached to a soft flexible collagen matrix. These components have vastly different mechanical properties that also differ from those of bone. The mineral-reinforced fibrils constitute the elementary building blocks for a large variety of bone structures. They may be parallelly aligned and closely packed as in the bone's cortical part or randomly arranged to form a trabecular meshwork.

Therefore, bones are heterogeneous materials with different densities and different elastic properties. The main elements "collagen, fibrils, and osteons" are schematically displayed in figure (2-7). The bone's elastic properties and fracture formation have been studied on the macroscopic and microscopic scales. We will review the main results for both scales.

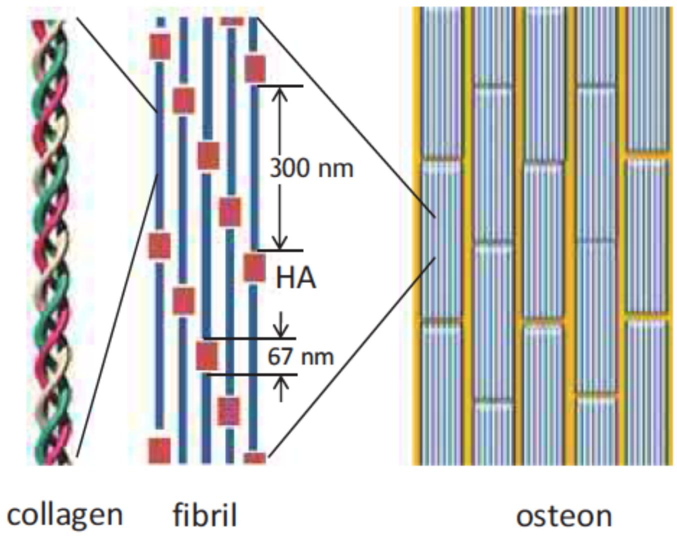


Figure 2-7 Schematic overview of the bones' main building blocks. We find triple helix **collagen** fibers on the molecular level, which line up in a stacked fashion on the fibrillary level, leaving gaps that are filled by mineral nanocrystals. **Fibrils**, in turn, bundled together in lamellar structures, form **osteons**.

1) Macroscopic level

For a general characterization of the bones' elastomechanical properties, macroscopic strain–stress tests are justified because of their similarity to in vivo behavior. However, they do not provide any insight into the mechanism of strain resistance or reasons for failure. Long bones have an intrinsic shape anisotropy. The tensile and compressive load can be determined when applying a force parallel to the long axis. The bending load is probed by applying forces perpendicular to the long axis. The strain resistance is lower for bending load than for compressional load. Therefore, we expect that fractures are more likely to occur due to bending than due to compressional or tensile load. The torsional load is particularly likely to cause fracture with the lowest yield stress and elastic modulus. Different types of macroscopic fractures associated with the loads discussed are highlighted in figure 2-8.

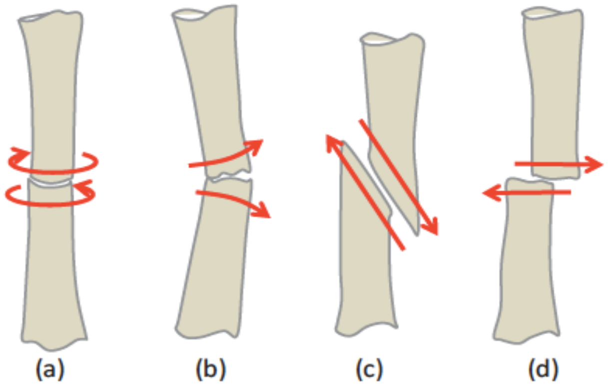


Figure 2-8 Fracture of long bones due to different types of loads: (a) torsional load; (b) bending load; (c) compressional load; and (d) shear load.

Bones also show fatigue. Fatigue is a general material property, meaning that the strength decreases with the number of load cycles applied. Fatigue depends on many different parameters such as the **magnitude of load, type of load, the rate applied, temperature, and humidity**. In contrast to most other materials, fatigue in bones occurs already after a few cycles, not after thousands or millions of cycles as normally observed. This indicates that microfractures arise at an early stage that dramatically reduces the strength of bones. If no time is provided for self-repair, these microfractures accumulate, resulting finally in failure.

Elastic properties have also been tested for cortical and trabecular bones independently by taking samples from both parts. First, there is quite a dramatic difference in structure (compare figs.2-1 and 2-4) and density. The cortical bone has a much higher density (1.9 g/cm^3) than the trabecular bone (0.43 g/cm^3). This correlates well with differences in porosity P defined as the ratio of void volume to the total volume. It is more convenient to determine the bone volume than the void volume. Therefore, we redefine the porosity by the following expression:

$$P = 1 - \frac{BV}{TV} \dots\dots\dots\dots\dots\dots 2-5$$

where BV is the bone volume and TV is the total volume.

For cortical bone, the porosity $P = 0.05–0.1$, whereas for trabecular bone it is 0.75–0.95. Accordingly, the elastic properties are quite distinct. **Cortical** bones are **strong but not tough**. In contrast, **trabecular** bones are **less strong but much tougher**. The difference can easily be recognized in figure (2-9), which compares the stress–strain relationships of both bone structures. In both cases, the **bone mineral density** (***BMD***) is important. If the *BMD* is higher than average, bones become brittle. If the *BMD* is lower than average, bones lose strength and become soft, as shown in figure 2-9. The correlation between bone strength and mineralization of fibrils has again recently been confirmed.

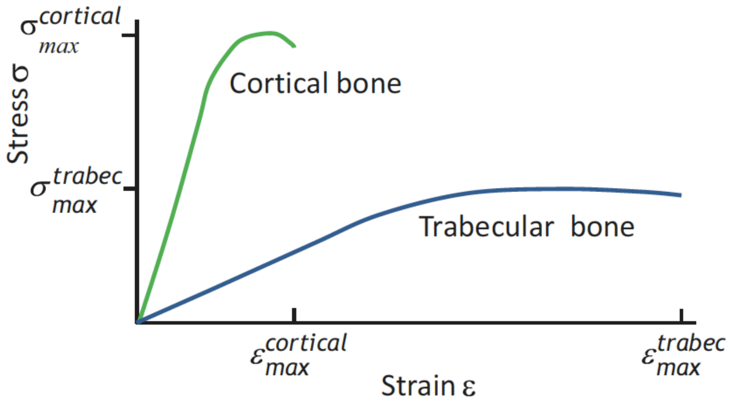


Figure 2-9 Stress–strain relationship for cortical bone and trabecular bone. Note the different slopes and different toughness of both bone structures

Although the meshwork of trabecular fibers appears random, it is actually not. A good example is the complex stress distribution of the femur shown in figure (2-10). Using samples from different parts of the trabecular meshwork, it could be shown that the elastic properties are anisotropic. Most of the fibrils align along the lines of greatest stress, while the remaining fibrils are used for cross-linking.

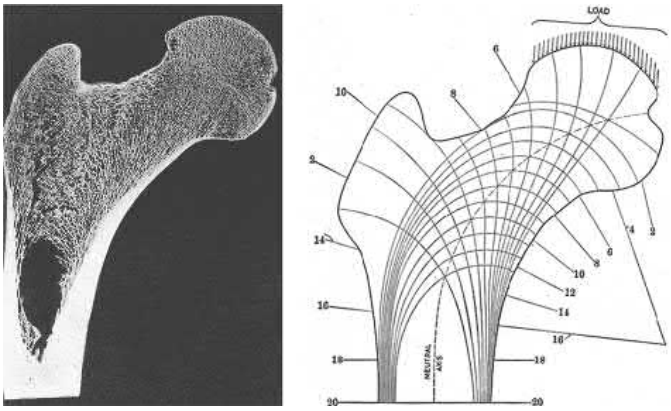


Figure 2-10 Left panel: Cross section of the upper femur. Right panel: Diagram of the lines of stress according to the femur’s mathematical stress analysis.

2) Microscopic level

It has been suggested that bone toughness is due to a molecular slip mechanism, explaining the observed differences in biomechanical and electromechanically properties. Slipping can break weak bonds and stretch the composite without destroying it. Alternatively, bone minerals have been made responsible for the toughness of the bones. The mineral crystallites are considered too small to fracture and thus contribute to the overall strength of the bones. More recently, the mechanical behavior of bones at the molecular level has been elucidated using various imaging modalities, x-ray scattering, and nanoscale stress–strain test methods.

Strain in response to stress on bone tissue varies dramatically from the microscale to the nanoscale. This has been revealed by measuring strain via x-ray scattering independently in the filaments and in the apatite Nano crystallites. The measurements yield a surprising result: for the same macroscopic strain, tissues, fibrils, and mineral.

Particles are exposed to successively lower levels of local strain in a ratio of 12:5:2. Therefore only about 42% of the strain at the tissue level are transmitted to the fibrils, and only 12% of the original strain arrives at mineral particles. This implies that fibrils and minerals are **much less strained in comparison to the actually applied strain**. The authors explain this apparent discrepancy by the hierarchy of the bone structure, displayed schematically in figure (2-11). Much of the strain is taken up by shear forces of cross-linked fibrils in the interfibrillar matrix. On the next lower level, the minerals in the fibrils are again cross-linked, dissipating the tensile strain into shear strain. The brittle apatite minerals remain shielded from overload by this shear transfer mechanism. Nevertheless, the strain at the mineral level is still excessively high by a factor of 2–3 with respect to the yield strain. Here size is indeed important; crack formation is prevented by lack of nucleation points within these nanocrystals. Therefore, the mineral particles can withstand stress and strain beyond the yield point.

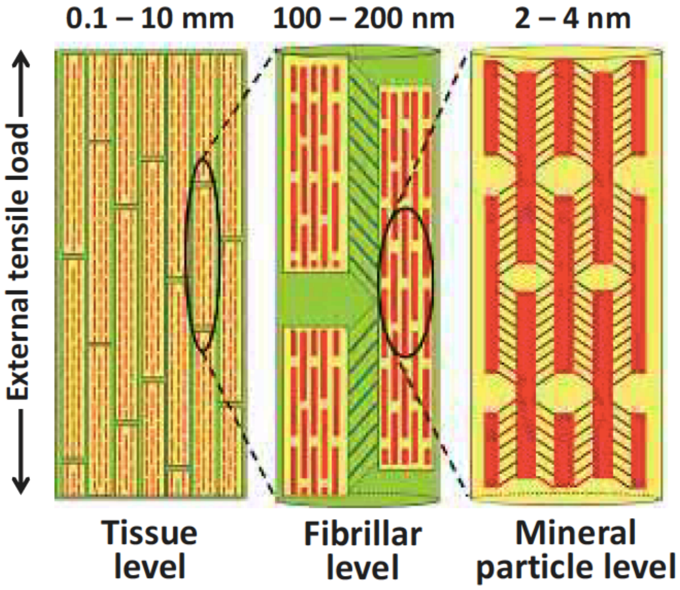


Figure 2-11 The hierarchical structure of bones imposes a hierarchical deformation transfer from tissue level to mineral particle level. Yellow cylinders denote the mineralized collagen fibrils in longitudinal sections of bone tissue such as in osteons. Red tablets denote the mineral apatite crystallites embedded within the collagenous matrix of the fibrils. Green background denotes interfibrillar matrix and slanted lines indicate cross-links between fibrils as well as between mineral plates. The strain decreases from tissue level to mineral particle level in a ratio of approximately 12:5:2

Note: Bones are two-component (soft and hard), heterogeneous (cortical and trabecular), anisotropic (long and narrow), viscoelastic, and self-renewable biomaterials.

2-4-3 Bone Fracture: energy consideration

Knowledge of the maximum energy that parts of the body can safely absorb allows us to estimate the possibility of injury under various circumstances. We shall first calculate the amount of energy required to break a bone of area *A* and length *L*.

Assume that the bone remains elastic until fracture. Let us designate the breaking stress of the bone as σ_B (Fig. 2.12). The corresponding force F_B that will fracture the bone is,

$$F_B = \sigma_B A = Y\frac{\Delta L}{L}\, A \ldots\ldots\ldots\ldots\ldots 2-6$$

The compression ΔL at the breaking point is, therefore,

$$\Delta L = \frac{\sigma_B\, L}{Y} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2-7$$

The energy stored in the compressed bone at the point of fracture is,

$$E = \frac{1}{2}\frac{Y\,A}{L}\,(\Delta L)^2 \ldots\ldots\ldots\ldots\ldots 2-8$$

Or

$$E = \frac{1}{2}\,\frac{A\,L\,\sigma_B^2}{Y} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2-9$$

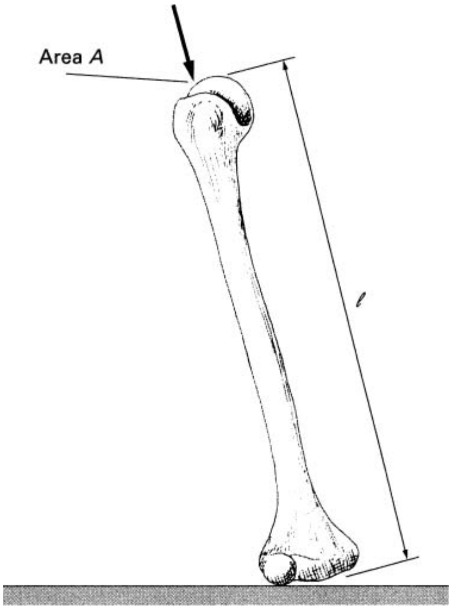


Figure 2-12 Compression of a bone.

As an example, consider the fracture of two leg bones that have a combined length of about 90 cm and an average area of about 6 cm^2. What is the total energy absorbed by the bones of one leg at the point of compressive fracture? Consider the breaking stress σ_B is 10^9 dyn/cm^2, and Young's modulus for the bone is 14×10^{10} dyn/cm^2.

Solution)

$$E = \frac{1}{2}\,\frac{A\,L\,\sigma_B^2}{Y}$$

$$E = \frac{1}{2}\,\frac{6\times 90\times 10^{18}}{14\times 10^{10}} = 19.25\times 10^{8}\,erg = 192.5J$$

The combined energy in the two legs is twice this value, or 385 J.

It is certainly possible to jump safely from a height considerably greater than 56 cm if, on landing, the joints of the body bend and the energy of the fall is redistributed to reduce the chance of fracture.

2-4-4 Impulsive Forces

In a sudden collision, a large force is exerted for a short period of time on the colliding object. The general characteristic of such a collision force as a function of time is shown in figure 2-13. The force starts at zero, increases to some maximum value, and then decreases to zero again. The time interval $t_2 - t_1 = \Delta t$ during which the force acts on the body is the duration of the collision. Such a short-duration force is called an impulsive force.

Because the collision takes place in a short period of time, it is usually difficult to determine the exact magnitude of the force during the collision. However, it is relatively easy to calculate the average value of the impulsive force F_{av}. It can be obtained simply from the relationship between force and momentum; that is,

$$F_{av} = \frac{m\,v_f - m\,v_i}{\Delta t} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2-10$$

Here ***mv**ᵢ* is the initial momentum of the object before the collision and ***mv**_f_* is the final momentum after the collision.

For example, if the duration of a collision is 6×10^{-3} sec, and the change in momentum is 2 kg m/sec, the average force that acted during the collision is

$$F_{av} = \frac{2}{6\times10^{-3}} = 3.3\times10^{2}N$$

Note that, for a given momentum change, the magnitude of the impulsive force is inversely proportional to the collision time; that is, the collision force is larger in a fast collision than in a slower collision.

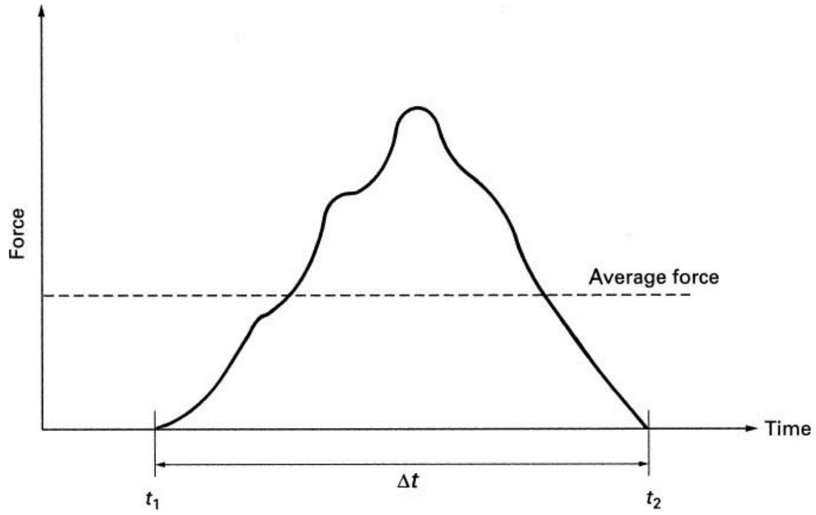


Figure 2-13 Impulsive force.

2-4-5 Fracture Due to a Fall

In the preceding section, we calculated the injurious effects of collisions from energy considerations. Similar calculations can be performed using the concept of impulsive force. The magnitude of the force that causes the damage is computed from Eq. 2-10. The change in momentum due to the collision is usually easy to calculate, but the duration of the collision *Δt* is difficult to determine precisely. It depends on the type of collision,

If the colliding objects are hard, the collision time is very short, a few milliseconds. If one of the objects is soft and yields during the collision, the duration of the collision is lengthened, and as a result the impulsive force is reduced. Thus, falling into soft sand is less damaging than falling on a hard-concrete surface.

When a person falls from a height h, his/her velocity on impact with the ground, neglecting air friction is,

$$v = \sqrt{2\,g\,h} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots 2-11$$

The momentum on impact is,

$$mv = m\sqrt{2\,g\,h} = W\sqrt{\frac{2h}{g}} \ldots\ldots\ldots\ldots\ldots .2-12$$

After the impact the body is at rest, and its momentum is therefore zero (mv_f= 0). The change in momentum is,

$$mv_i - mv_f = W\sqrt{\frac{2h}{g}} \ldots\ldots\ldots\ldots\ldots..\ldots 2-13$$

The average impact force, from Eq. 2-10, is

$$F = \frac{W}{\Delta t}\sqrt{\frac{2h}{g}} = \frac{m}{\Delta t}\sqrt{2gh} \ldots\ldots\ldots\ldots\ldots .2-14$$

Now comes the difficult part of the problem: Estimate of the collision duration. If the impact surface is hard, such as concrete, and if the person falls with his/her joints rigidly locked, the collision time is estimated to be about 10^{-2} sec. The collision time is considerably longer if the person bends his/her knees or falls on a soft surface.

If the force per unit area that may cause a bone fracture is 10^9 dyn/cm^2. If the person falls flat on his/her heels, the area of impact may be about 2 cm^2. Therefore, the force F_B that will cause fracture is,

$$F_B = 2 \times 10^9 = \ 2 \times 10^9\ dyn\ (4300\ Ib)$$

From Eq. 2-14, the height h of fall that will produce such an impulsive force is given by,

$$h = \frac{1}{2g}\left(\frac{F\,\Delta t}{m}\right)^2 \ldots\ldots\ldots\ldots .2-15$$

For a man with a mass of 70-kg, the height of the jump that will generate a fracturing average impact force (assuming $\Delta t = 10^{-2}$ sec) is given by,

$$h = \frac{1}{2g}\left(\frac{F\,\Delta t}{m}\right)^2 = \frac{1}{2 \times 980}\left(\frac{2 \times 10^9 \times 10^{-2}}{70 \times 10^3}\right)^2 = 41.6cm$$

This is close to the result that we obtained from energy considerations. Note, however, that the assumption of a 2 cm^2 impact area is reasonable but somewhat arbitrary. The area may be smaller or larger depending on the nature of the landing; furthermore, we have assumed that the person lands with legs rigidly straight.

2-4-6 Airbags: Inflating Collision Protection Devices

The impact force may also be calculated from the distance the center of mass of the body travels during the collision under the action of the impulsive force. This is illustrated by examining the inflatable safety device used in automobiles (Fig. 2.14). An inflatable bag is located in the dashboard of the car. In a collision, the bag expands suddenly and cushions the impact of the passenger.

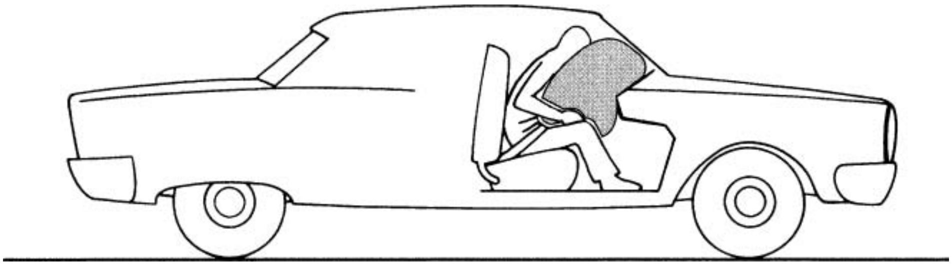


Figure 2-14 Inflating collision protective device

The forward motion of the passenger must be stopped in about 30 cm of motion if contact with the hard surfaces of the car is to be avoided. The average deceleration is given by,

$$a = \frac{v^2}{2s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..2-16$$

where v is the initial velocity of the automobile (and the passenger) and s is the distance over which the deceleration occurs. The average force that produces the deceleration is

$$F = ma = \frac{mv^2}{2s} \ldots\ldots\ldots\ldots..2-17$$

where m is the mass of the passenger, s stopping distance.

For a 70-kg person with a 30-cm allowed stopping distance, the average force is

$$F = \frac{70 \times 10^3\ v^2}{2 \times 30} = 1.17 \times 10^3\ v^2\ dyn$$

At an impact velocity of 70 km/h (43.5 mph), the average stopping force applied to the person is 4.45×10^6 dyn. If this force is uniformly distributed over a 1000-cm^2 area of the passenger's body, the applied force per cm^2 is 4.45×10^3 dyn. This is just below the estimated strength of body tissue.

The necessary stopping force increases as the square of the velocity. At a 105-km impact speed, the average stopping force is 10^{10} dyn and the force per cm^2 is 10^7 dyn. Such a force would probably injure the passenger.

In the design of this safety system, the possibility has been considered that the bag may be triggered during normal driving. If the bag were to remain expanded, it would impede the ability of the driver to control the vehicle; therefore, the bag is designed to remain expanded for only the short time necessary to cushion the collision. (To estimate of this period, see Exercise 2-4.)

2-4-7 Whiplash Injury

Neck bones are rather delicate and can be fractured by even a moderate force. Fortunately, the neck muscles are relatively strong and are capable of absorbing a considerable amount of energy. If, however, the impact is sudden, as in a rear-end collision, the body is accelerated in the forward direction by the back of the seat, and the unsupported neck is then suddenly yanked back at full speed. Here the muscles do not respond fast enough and all the energy is absorbed by the neck bones, causing the well-known whiplash injury (see Fig. 2.15). The whiplash injury is described quantitatively in Exercise 2-5.

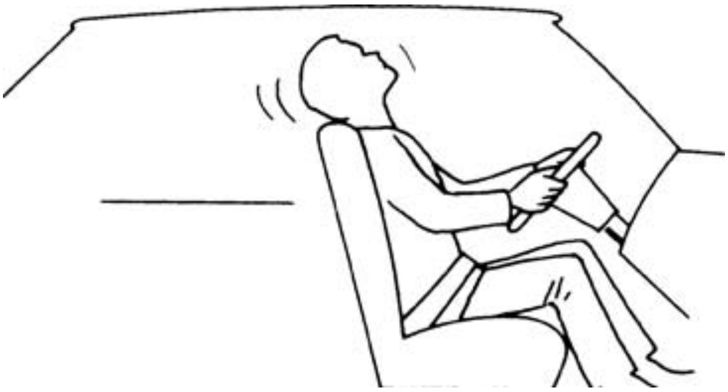


Figure 2-15 Whiplash.

2-4-8 Falling from Great Height

There have been reports of people who jumped out of airplanes with parachutes that failed to open and yet survived because they landed on soft snow. It was found in these cases that the body made about a 1-m-deep depression in the surface of the snow on impact. The credibility of these reports can be verified by calculating the impact force that acts on the body during the landing. It is shown in Exercise 2-6 that if the decelerating impact force acts over a distance of about 1 m, the average value of this force remains below the magnitude for serious injury even at the terminal falling velocity of 62.5 m/sec (140 mph).

2-5 Lubrication of bone joints

There are two major diseases that affect the joints:

1- Rheumatoid arthritis (over production of synovial fluid).

2- Osteoarthrosis (a disease of the joint itself).

The lubricating properties of a fluid depend on its viscosity; thin oil is less viscous and a better lubricant than thick oil. The good lubricating properties of synovial fluid are thought to be due to the presence of hyaluronic acid and mucopolysaccharides (molecular weight, ~500,000) that deform under load.

The components of a joint are:

1-The synovial membrane (encases the joint and retains the lubricating synovial fluid).

2-Articular cartilage (it is a tissue that forms the lining of the bone ends).

3-Synovial fluid (it ensures perfect sliding between the bone ends).

4- Subchondral bone (the part of the bone located just above the cartilage which consider the foundation of cartilage.

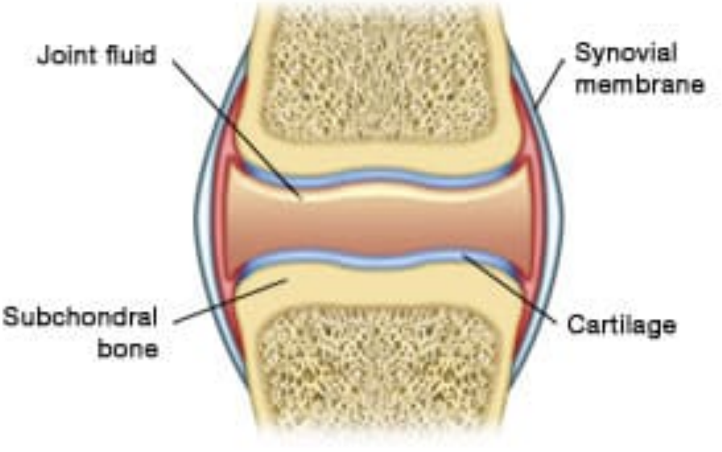


Figure 2-16 The main components of a joint

2-6 Measurement of bone mineral in the body

The strength of bones depends on the mass of bone mineral present. Bone mineral mass decreases slowly 1-2% per year, so physical techniques needed to show changes:

1) X-ray image: - The ideal of using an X-ray image to measure the amount of bone mineral is an old one. the major problems of using an ordinary X-ray are:

a- The usual X-ray beam has different energies and the absorption of the X-ray by Ca^{+2} varies rapidly with energy in this range of energies.

b- Large beam contains much scattered radiation when it reaches the film

c- The film is poor detector for making quantitative measurements since it is nonlinear with respect to both the amount and the energy of X-ray. developing the film introduces additional variations.

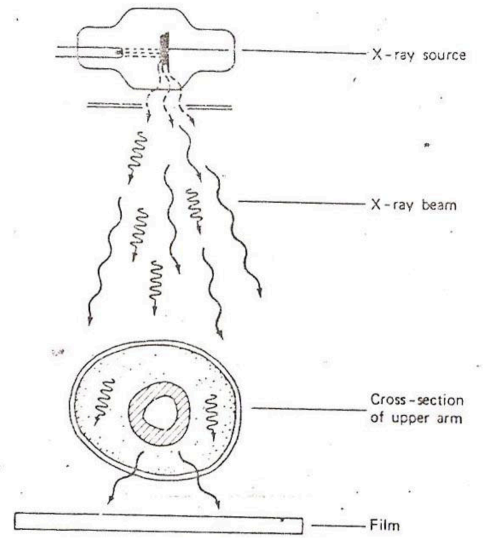


Figure 2-17 Conventional X-ray imaging

2) Photon absorptiometry

The problems with the X-ray technique were largely eliminated by using

- Monoenergetic X-ray or gamma rays' source.
- A narrow beam to minimize scatter.
- Scintillation detector that detects all photons and permits them to be sorted and counted individually.

Bone is immersed in a soft media (like water) to determine of bone mineral mass.

Bone mineral mass (BM gm/cm^2) =*K log I$_o$/I.*

Where *K* is a constant,

I (intensity of X-ray that transmit the bone).

I$_o$ (intensity before beam enter the bone)

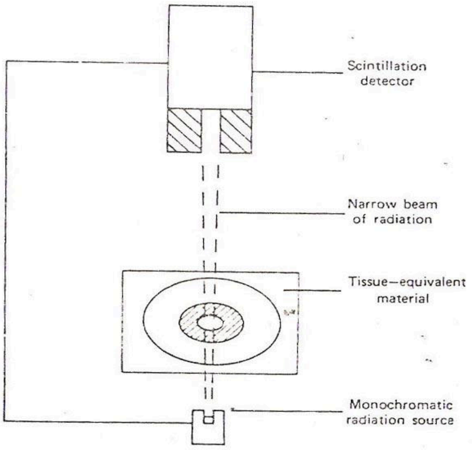


Figure 2-18 The basic components used in photon absorptiometry

3) In vivo activation:

Whole body is irradiated with energetic neutrons that convert a small amount of the Ca^{+2} and some other elements into radioactive form that give off energetic gamma rays then detected and counted. The gamma rays from radioactive calcium can be identified by their unique energy as in figure (2-19), and the number of them indicates the amount of calcium in the body. The amount of bone mineral is then obtained by multiplying by constant. This detected to give the amount of Ca^{+2}. Disadvantages of this technique are: 1- Expensive technique. 2- Hazard of large radiation exposure.

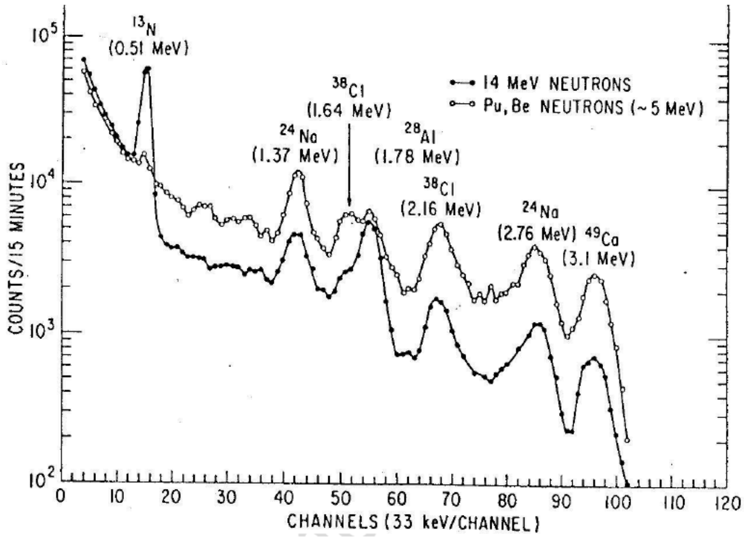


Figure 2-19 A graph of gamma ray intensities from the body as a function of energy after whole body irradiation. The radioactive elements causing the main gamma ray peaks and their energies are given. The area under the peak indicates the amount of calcium in the body.

Problems

2-1. Assume that a 50-kg runner trips and falls on his extended hand. If the bones of one arm absorb all the kinetic energy (neglecting the energy of the fall), what is the minimum speed of the runner that will cause a fracture of the arm bone? let the length of arm is 1m and that the area of the bone is 4 cm^2.

2-2. Repeat the calculations in Exercise 2-1 using impulsive force considerations. Assume that the duration of impact is 10^{-2} sec and the area of impact is 4 cm^2. Repeat the calculation with area of impact =1 cm^2.

2-3. From what height can a 1-kg falling object cause fracture of the skull? Assume that the object is hard, that the area of contact with the skull is 1 cm^2, and that the duration of impact is 10^{-3} sec.

2-4. Calculate the duration of the collision between the passenger and the inflated bag of the collision protection device discussed in this chapter.

2-5. In a rear-end collision the automobile that is hit is accelerated to a velocity v in 10^{-2}/sec. What is the minimum velocity at which there is danger of neck fracture from whiplash? Use the data provided in the text, and assume that the area of the cervical vertebra is 1 cm^2 and the mass of the head is 5-kg.

2-6. Calculate the average decelerating impact force if a person falling with a terminal velocity of 62.5 m/sec is decelerated to zero velocity over a distance of 1 m. Assume that the person's mass is 70 kg and that she lands flat on her back so that the area of impact is 0.3m^2. Is this force below the level for serious injury? (For body tissue, this is about 5×10^6 dyn/cm^2)

Chapter Three

Energy, Work, and Power of the Body

3-1 Energy, work, and power of the body

When he was young, the scientist James Watt (1736-1819) was watching a tea kettle on a fire, he noticed that the steam lifts the lid of the kettle. The lid of the kettle lifted by the steam against the earth's gravity where the steam done a work to lift the lid. This means that the steam has energy.

This observation probably led James Watt for the improvement of the steam energy uses. The energy is defined as the capacity of the body to do a work. The more is the work done the more energy is used to do this work. The energy is a necessity of life.

The study of the relationship between heat, work, and the associated flow of energy is described by thermodynamics branch of physics. After many decades of experience with heat phenomena, scientists formulated two fundamental laws as the foundation of thermodynamics.

The First Law of Thermodynamics states that energy, which includes heat, is conserved; that is, one form of energy can be converted into another, but energy can neither be created nor destroyed. This implies that the total amount of energy in the universe is a constant.

The second law, more complex than the first, can be stated in a number of ways which, although they appear different, can be shown to be equivalent. Perhaps the simplest statement of the Second Law of Thermodynamics is that spontaneous change in nature occurs from a state of order to a state of disorder.

In this chapter, we will examine energy consumption, heat flow, and temperature control in animals. Although most of our examples will be specific to people, the principles are generally applicable to all animals.

Note: Lavoisier noted that less food is burned by the body in a hot environment than in a cold one.

3-2 Energy Conversion in Humans

Our own bodies, like all living organisms, are energy conversion machines. Conservation of energy implies that the chemical energy stored in food is converted into **work**, **thermal energy**, and/or **stored as chemical energy in fatty tissue** as on figure (3-1). The fraction going into each form depends both on how much we eat and on our level of physical activity. If we eat more than is needed to do work and stay warm, the remainder goes into body fat.

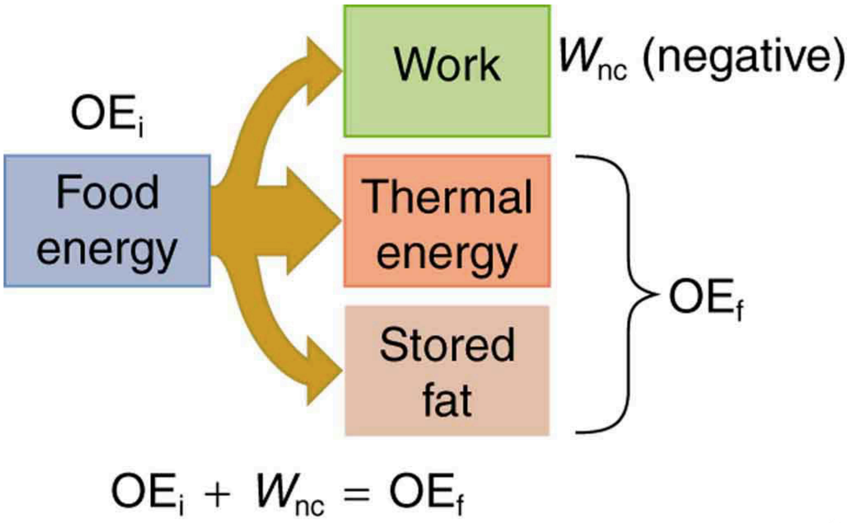


Figure 3-1 Energy consumed by humans is converted to work, thermal energy, and stored fat. By far the largest fraction goes to thermal energy, although the fraction varies depending on the type of physical activity.

***Note**: THE PRINCIPLE OF CONSERVATION OF ENERGY. Energy can neither be created nor destroyed, but can only be converted from one form to another.*

One important concept in the thermal physics of the body is the **heat capacity *C***, which is the energy (or more specifically, the heat) required to raise the temperature ***T*** of an object by ***1°C***.

The heat capacity per unit volume or mass is the **specific heat *c***. The heat capacity is an extensive property of a given object, while the specific heat is an intensive property of a material. The heat capacity C is the specific heat (expressed per unit mass) × the total object mass m, so $\boldsymbol{C = mc}$.

The temperature rises ΔT of an object with a heat flow Q to the body is:

$$\Delta T = \frac{Q}{mc} \ldots\ldots\ldots\ldots..3-1$$

For water, $c_{water} = 1.0$ cal/g-°C = 1.0 kcal/kg-°C. Even though the human body contains much water, the average specific heat of the body is a bit less, $c_b = 0.83$ cal/g-°C = 0.83 kcal/kg-°C. This means that it takes 83 kcal to raise the temperature of a 100 kg person by 1.0°C. This 83 kcal (83 food calories) is approximately the food energy content of a slice of bread.

An obvious question arises: If most of our metabolized energy becomes heat, why does not our body temperature increase by 1.0°C each time we eat and metabolize a slice of bread? We are very fortunate it does not. (The reason is heat loss by the body.)

The heat flux Q that must be supplied or removed to change the phase of a mass m of a substance is

$$Q = m \times L \ldots\ldots\ldots..3\text{-}1^*$$

where $\boldsymbol{L}$ is the **latent heat** of the substance. The latent heat of fusion L_f refers to the change between solid and liquid phases, the latent heat of vaporization L_v applies to the change between liquid and gas phases, and the latent heat of sublimation L_s refers to the change between solid and gas phases.

Q) what is the difference between heat and temperature?

3-3 Power Consumed at Rest

The body gets energy by burning food in a process called **metabolism**. More specifically, metabolism is the combustion of organic compounds with oxygen in living cells to produce energy. Also, the rate at which the body uses food energy to sustain life and to do different activities is called the ***Metabolic***

Rate (MR). Metabolic rate processes can be divided into **catabolic** and **anabolic** reactions.

In ***catabolic reactions*** complex molecules are broken into simple ones, for purposes such as energy usage.

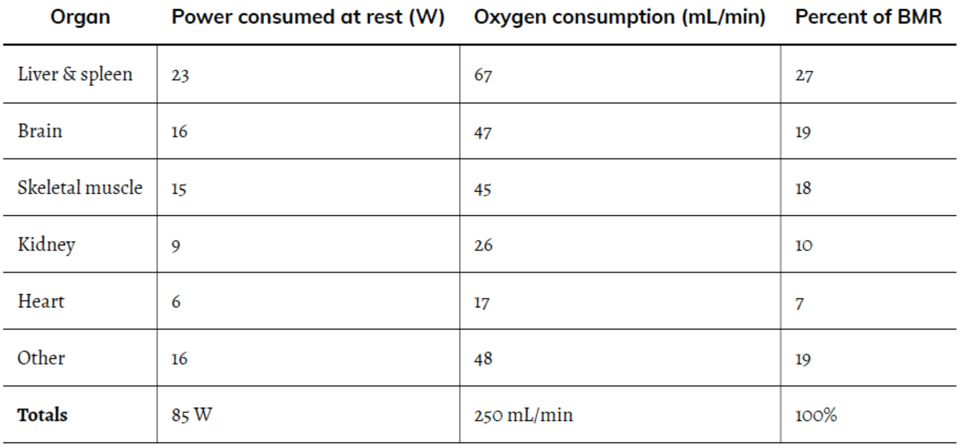
In ***anabolic reactions*** simple molecules are combined to form complex ones, for purposes such as energy storage. The metabolic rates for some human activities are shown in table 3-1. The total energy conversion rate of a person at rest is called **the *Basal Metabolic Rate (BMR)*** and is divided among various systems in the body as shown in table 3-2. For example, a man weighing 70 kg lying quietly awake consumes about 70 Cal/h (1 cal=4.18 J; 1,000 cal =1 Cal; 1 Cal/h=1.16W).

Table 3-1 Metabolic Rates for Selected Activities

Activity	**Metabolic rate (Cal/m^2-hr)**
Sleeping	35
Lying awake	40
Sitting upright	50
Standing	60
Walking (3 mph)	140
Moderate physical work	150
Bicycling	250
Running	600
Shivering	250

The largest fraction of the calories goes to the liver and spleen, with the brain coming next. Of course, during vigorous exercise, the energy consumption of the skeletal muscles and heart increase markedly. About 75% of the calories burned in a day go into these basic functions. The **BMR** is a function of **age**, **gender**, **total body weight**, and **amount of muscle mass** (which burns more calories than body fat). Athletes have a greater BMR due to this last factor.

Table 3-2 Basal Metabolic Rates (BMR)



Organ	Power consumed at rest (W)	Oxygen consumption (mL/min)	Percent of BMR
Liver & spleen	23	67	27
Brain	16	47	19
Skeletal muscle	15	45	18
Kidney	9	26	10
Heart	6	17	7
Other	16	48	19
Totals	85 W	250 mL/min	100%

To obtain the total energy consumption per hour, we multiply the metabolic rate by the surface area of the person. The following empirical formula yields a good estimate for the surface area:

$$Area(m^2) = 0.202 \times W^{0.425} \times H^{0.725} \ldots\ldots..3-2$$

Here W is the weight of the person in kilograms, and H is the height of the person in meters.

For instance, the surface area of a 70-kg man of height 1.55m is about 1.7m^2 His metabolic rate at rest is therefore (40 Cal/m^2-hr)×1.70 m^2 = 68 Cal/hr, or about 70 Cal/hr as stated in our earlier example.

Energy consumption is directly proportional to oxygen consumption because the digestive process is basically one of oxidizing food. We can measure the energy people use during various activities by measuring their oxygen use (see figure 3-2). Approximately 20 kJ of energy are produced for each liter of oxygen consumed, independent of the type of food see table 3-3 shows energy and oxygen consumption rates (power expended) for a variety of activities.

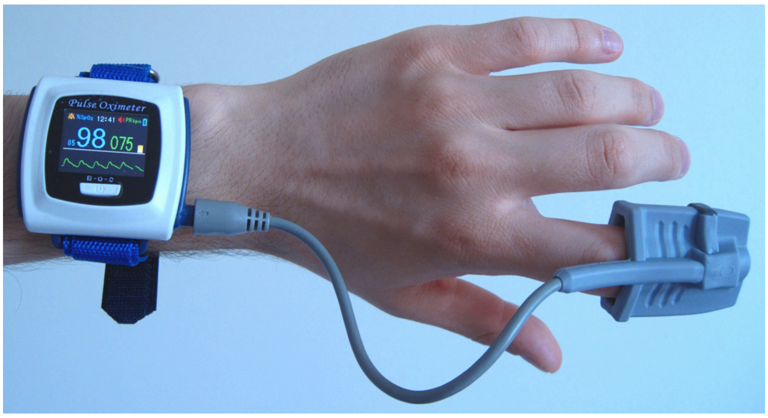
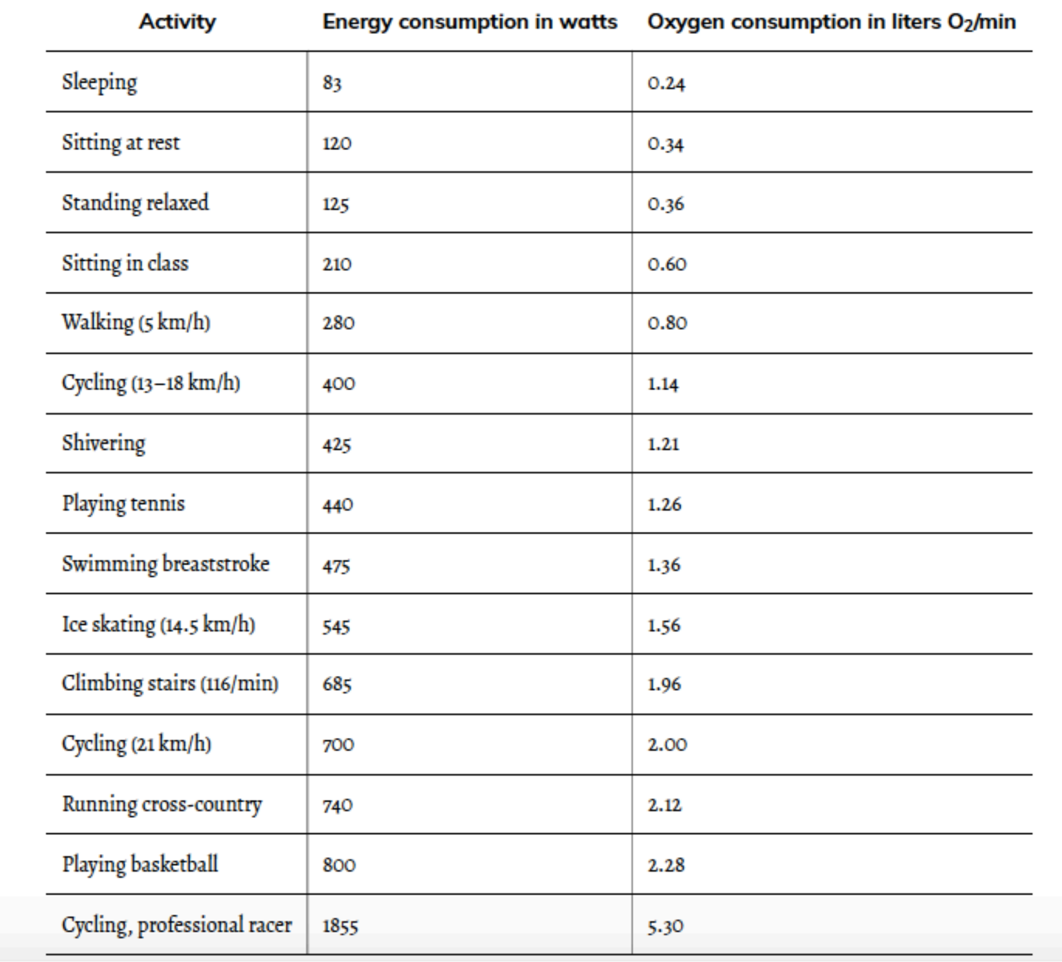


Figure 3-2 A pulse oximeter is an apparatus that measures the amount of oxygen in blood. A knowledge of oxygen and carbon dioxide levels indicates a person's metabolic rate, which is the rate at which food energy is converted to another form. Such measurements can indicate the level of athletic conditioning as well as certain medical problems.

kilo calorie (Kcal) *is defined as the amount of heat required to raise the temperature of one liter of water one degree Celsius where:* 1 Kcal=4184J

Table 3-3 Energy and Oxygen Consumption Rates2 (Power)



Activity	Energy consumption in watts	Oxygen consumption in liters O_2/min
Sleeping	83	0.24
Sitting at rest	120	0.34
Standing relaxed	125	0.36
Sitting in class	210	0.60
Walking (5 km/h)	280	0.80
Cycling (13–18 km/h)	400	1.14
Shivering	425	1.21
Playing tennis	440	1.26
Swimming breaststroke	475	1.36
Ice skating (14.5 km/h)	545	1.56
Climbing stairs (116/min)	685	1.96
Cycling (21 km/h)	700	2.00
Running cross-country	740	2.12
Playing basketball	800	2.28
Cycling, professional racer	1855	5.30

All bodily functions, from thinking to lifting weights, require energy. (See figure 3-3). The many small muscle actions accompanying all quiet activity, from sleeping to head scratching, ultimately become thermal energy, as do less visible muscle actions by the heart, lungs, and digestive tract. Shivering, in fact, is an involuntary response to low body temperature that pits muscles against one another to produce thermal energy in the body (and do no work). The kidneys and liver consume a surprising amount of energy, but the biggest surprise of all is that a full 25% of all energy consumed by the body is used to maintain electrical potentials in all living cells. (Nerve cells use this electrical potential in nerve impulses.) This bioelectrical energy ultimately becomes mostly thermal energy, but some is utilized to power chemical processes such as in the kidneys and liver, and in fat production.

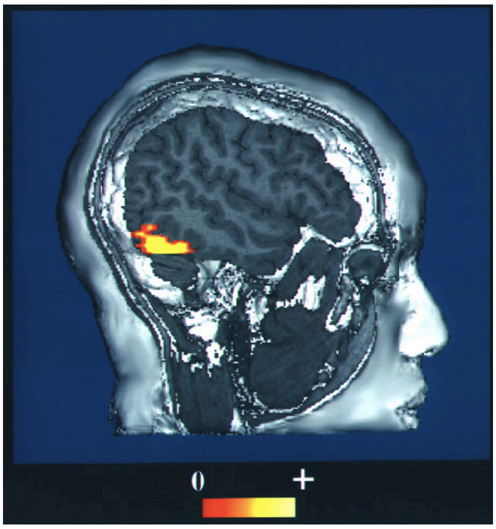


Figure 3-3 This fMRI scan shows an increased level of energy consumption in the vision center of the brain. Here, the patient was being asked to recognize faces.

Note*: If your caloric intake rate exceeds your metabolic rate, you gain weight. If it is less, you lose weight*

3-4 Energy from Food

The body uses food to **(1)** Operate organs, **(2)** Maintain a constant temperature by using some of the heat that is generated by operating the organs (while the rest is rejected), **(3)** Do external work, **(4)** Build a stored energy supply (fat) for later needs, **(5)** Grow to adulthood, and **(6)** Help the fetus grow during pregnancy and then nurse infants. The chemical energy used by animals is obtained from the oxidation of food molecules. The glucose sugar molecule, for example, is oxidized as follows:

$C_6H_{12}O_6 + 6O_2 \rightarrow\ 6CO_2 + 6H_2O + Energy$ (The reaction is reversible)

For every gram of glucose ingested by the body, 3.81 Cal of energy is released for metabolic use. The caloric value per unit weight is different for various foods.

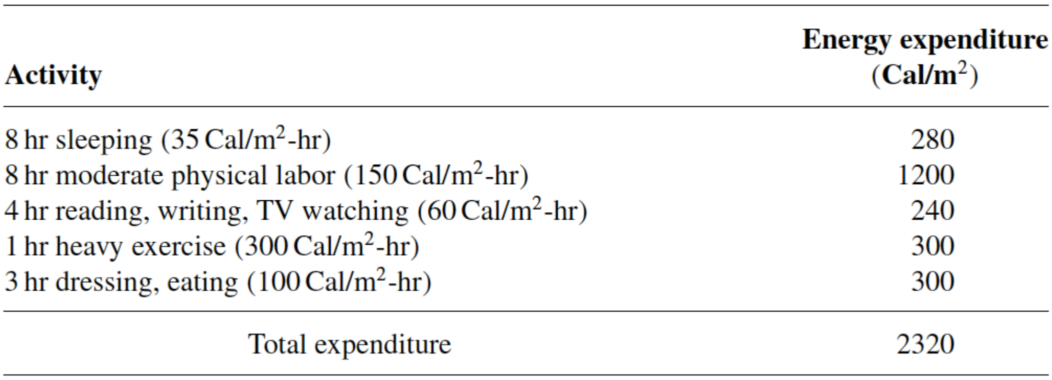
Measurements show that, on the average, carbohydrates (sugars and starches) and proteins provide about 4 Cal/g; lipids (fats) produce 9 Cal/g, and the oxidation of alcohol produces 7 Cal/g.

The oxidation of food, which releases energy, does not occur spontaneously at normal environmental temperatures. For oxidation to proceed at body temperature, a catalyst must promote the reaction. In living systems, complex molecules, called **enzymes**, provide this function.

In the process of obtaining energy from food, oxygen is always consumed. It has been found that, independent of the type of food being utilized, 4.83 Cal of energy are produced for every liter of oxygen consumed. Knowing this relationship, one can measure with relatively simple techniques the metabolic rate for various activities.

The daily food requirements of a person depend on his or her activities. A sample schedule and the associated metabolic energy expenditure per square meter are shown in table 3-4.

Table 3-4 One Day's Metabolic Energy Expenditure



Activity	Energy expenditure (Cal/m^2)
8 hr sleeping (35 Cal/m^2-hr)	280
8 hr moderate physical labor (150 Cal/m^2-hr)	1200
4 hr reading, writing, TV watching (60 Cal/m^2-hr)	240
1 hr heavy exercise (300 Cal/m^2-hr)	300
3 hr dressing, eating (100 Cal/m^2-hr)	300
Total expenditure	2320

Assuming, as before, that the surface area of the person whose activities are shown in table 3-4 is 1.7m^2, his total energy expenditure is 3944 Cal/day.

If the person spent half the day sleeping and half the day resting in bed, the daily energy expenditure would be only 1530 Cal.

For most people the energy expenditure is balanced by the food intake. For example, the daily energy needs of the person whose activities are shown in above table (surface area 1.7m^2) are met by the consumption of 400 g of carbohydrates, 200 g of protein, and 171 g of fat.

The composition and energy content of some common foods are shown in table 3-5. **Note that** the sum of the weights of the protein, carbohydrates, and fat is smaller than the total weight of the food. The difference is due mostly to the water content of the food. The energy values quoted in the table reflect the fact that the caloric content of different proteins, carbohydrates, and fats deviate somewhat from the average values stated in the text.

3-4-1 How to "Burn" Off Food

Let us say you have just eaten a "standard" donut. You feel guilty and you want to burn off those extra calories. What can you do?

If you are sitting at rest you are naturally burning off ∼103 kcal/h (70 kg man). If you decide to play basketball your metabolic rate increases to around ∼688 kcal/h, so you will be increasing your metabolic rate by∼585 kcal/h. You will burn off that standard 280 kcal donut in

$$\frac{280\ kcal}{585\ kcal/h} = 0.48\ h = 29\ min$$

That donut will cost you a half an hour of real up-tempo basketball.

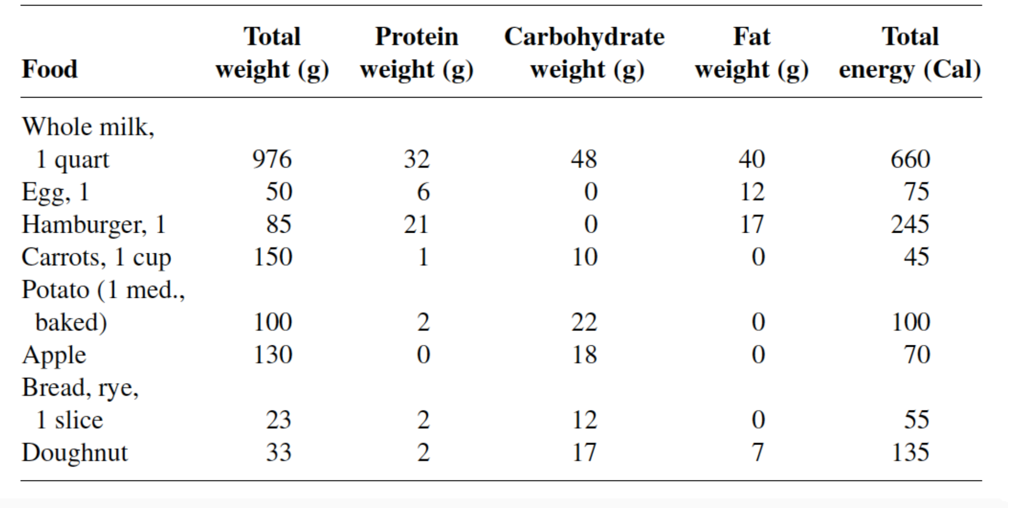
Let us say you want to "walk off" that donut. The metabolic rate during slow walking is ∼228 kcal/h, which exceeds that of sitting at rest by around ∼125 kcal/h. To walk off that donut you would have to walk for

$$\frac{280\ kcal}{125\ kcal/h} = 2.24\ h$$

Which is a little longer than most after-dinner strolls.

Why do people put on weight when they get older? One reason is the decrease in BMR with age. The activity level f_{av} often decreases with age. Also, sometimes people eat more (snacking). We now examine how caloric intake and activity combine to determine body weight.

Table 3-5 Composition and Energy Content of Some Common



Food	Total weight (g)	Protein weight (g)	Carbohydrate weight (g)	Fat weight (g)	Total energy (Cal)
Whole milk, 1 quart	976	32	48	40	660
Egg, 1	50	6	0	12	75
Hamburger, 1	85	21	0	17	245
Carrots, 1 cup	150	1	10	0	45
Potato (1 med., baked)	100	2	22	0	100
Apple	130	0	18	0	70
Bread, rye, 1 slice	23	2	12	0	55
Doughnut	33	2	17	7	135

3-5 Regulation of Body Temperature

People and other warm-blooded animals must maintain their body temperatures at a nearly constant level. For example, the normal core body temperature is in the range of 36.5–37.5°C. A deviation of one or two degrees in either direction may signal some abnormality. If the temperature-regulating mechanisms fail and the body temperature rises to 44°C or 45°C, the protein structures are irreversibly damaged. A fall in body temperature below about 28°C results in heart stoppage.

The body temperature is sensed by specialized nerve centers in the brain and by receptors on the surface of the body. The various cooling or heating mechanisms of the body are then activated in accord with the temperature.

The efficiency of muscles in performing external work is at best 20%. Therefore, at least 80% of the energy consumed in the performance of a physical activity is converted into heat inside the body. In addition, the energy consumed to maintain the basic metabolic processes is ultimately all converted to heat. If this heat were not eliminated, the body temperature would quickly rise to a dangerous level. For example, during moderate physical activity, a 70-kg man may consume 260 Cal/hr. Of this amount, at least 208 Cal is converted to heat.

If this heat remained within the body, the body temperature would rise by 3°C/hr. Two hours of such an activity would cause complete collapse. Fortunately, the body possesses a number of highly efficient methods for controlling the heat flow out of the body, thereby maintaining a stable internal temperature.

Note: Anesthesia lowers core body temperature by ~* 1°C*, probably because the anesthetics interfere with how the body regulates temperature.

3-6 Control of Skin Temperature

As we stated, for heat to flow out of the body, the temperature of the skin must be lower than the internal body temperature. The temperature of the body skin T_{skin} (34˚C) is usually lower than that of the core (rectal) T_{core} (37˚C)—that you measure with a thermometer. Therefore, heat must be removed from the skin at a sufficient rate to ensure that this normal condition is maintained. **Because the heat conductivity of air is very low (2.02 Cal/m^2-hr-^{o}C)**, if the air around the skin is confined—for example, by clothing—the amount of heat removed by conduction is small. Table 3-6 gives the normal temperature of different body organs and blood vessels. The temperature of inner organs can differ by 0.2–1.2 ˚C and by 0.9˚C in a given organ under normal conditions. The temperature throughout the body varies with the temperature in the environment. As shown in Fig. 3-4, these variations can be very large in a cold room.

Table 3-6 Core temperatures within the human body

Body region	Normal temperature (°C)
Skin	32–35
Scrotum	34.0
Liver	36.4–36.8
Oral cavity	36.5–36.6
Superior vena cava	36.65
Esophagus, lungs	36.75
Heart (right ventricle)	36.75
Aorta, inferior vena cava	36.75
Pulmonary artery and vein	36.75
Kidney	36.85
Spinal cord	36.95
Stomach, rectum (mean)	37.0
Rectum (range)	36.2–37.8
Brain, uterus	37.3

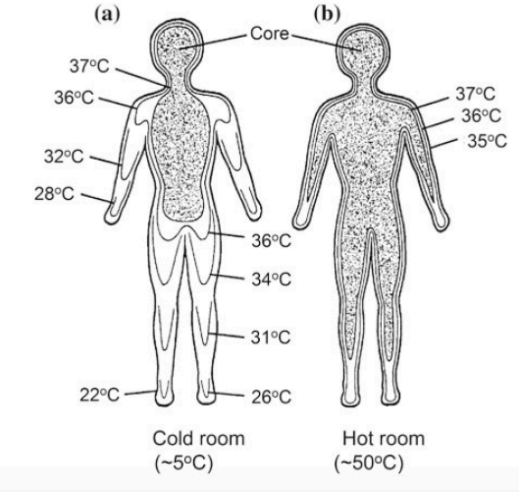


Figure 3-4 Temperature in the body in cold and hot environments

The surface of the skin is cooled primarily by **Convection**, **Radiation**, and **Evaporation**. However, if the skin is in contact with a good thermal conductor such as a metal, a considerable amount of heat can be removed also by **conduction**.

3-6-1 Conduction

Most of the heat generated by the body is produced deep in the body, far from the surfaces. In order to be eliminated, this heat must first be conducted to the skin. For heat to flow from one region to another, there must be a temperature difference between the two regions. Therefore, the temperature of the skin must be lower than the internal body temperature. In a warm environment, the temperature of the human skin is about 35°C. In a cold environment, the temperature of some parts of the skin may drop to 27°C.

The tissue of the body, without blood flowing through it, is a poor conductor. Its thermal conductivity is comparable to that of cork. (K_c for tissue without blood is 18 Cal/m^2-hr-°C.) Simple thermal conductivity through tissue is inadequate for elimination of the excess heat generated by the body.

The following calculation illustrates this point. Assume that the thickness of the tissue between the interior and the exterior of the body is 3 cm and that the average area through which conduction can occur is 1.5m^2. With a temperature difference T between the inner body and the skin of 2°C, the heat flow Q per one hour is,

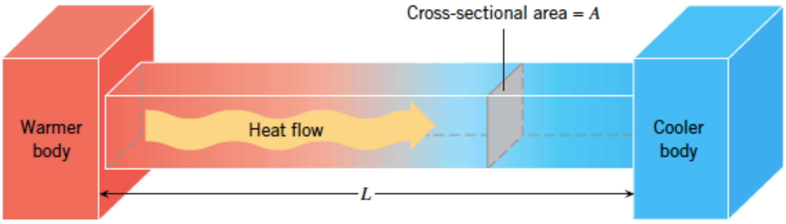
$$\frac{Q}{t}=\frac{(K_c\,A\,\Delta T)}{L}=\frac{18\times 1.5\times 2}{3}=\frac{18Cal}{hr}\dots\dots\dots\dots\dots..3-4$$

In order to increase the conductive heat flow to a moderate level let say 150 Cal/hr, the temperature difference between the interior body and the skin would have to increase to about 17°C.

Fortunately, the body possesses another method for transferring heat. Most of the heat is transported from the inside of the body by blood in the circulatory system. Heat enters the blood from an interior cell by conduction. In this case, heat transfer by conduction is relatively fast because the distances between the capillaries and the heat-producing cells are small. The circulatory system carries the heated blood near to the surface skin. The heat is then transferred to the outside surface by conduction.

In addition to transporting heat from the interior of the body, the circulatory system controls the insulation thickness of the body. When the heat flow out of the body is excessive, the capillaries near the surface become constricted and the blood flow to the surface is greatly reduced. Because tissue without blood is a poor heat conductor, this procedure provides a heat insulating layer around the inner body core.

***Note: Heat conduction** is the transfer of heat between two objects in direct contact with each other as shown below.*



conduction

Q1) When excessive heat is produced within the body, it must be transferred to the skin and dispersed if the temperature at the body interior is to be maintained at the normal value of 37.0°C. One possible mechanism for transfer is conduction through body fat. Suppose that heat travels through 0.030 m of fat in reaching the skin, which has a total surface area of 1.7 m2 and a temperature of 34.0°C. Find the amount of heat that reaches the skin in half an hour. The thermal conductivity of body fat is given as 0.2 J/ (s.m.°C)

Solution)

$$Q = \frac{(K_c\ A\ \Delta T)\ t}{L} = \frac{(0.2)(1.7)(37-34)(1800)}{0.03} = 6.1 \times 10^4 J$$

3-6-2 Convection

When the skin is exposed to open air or some other fluid, heat is removed from it by convection currents. The rate of heat removal is proportional to the exposed surface area and to the temperature difference between the skin and the surrounding air. The rate of heat transfer by convection Q_c' is given by:

$$Q_c' = K_c' A_c (T_s - T_a) \dots\dots\dots\dots..3-5$$

where A_c is the skin area exposed to the open air; T_s and T_a are the skin and air temperatures, respectively; and K_c' is the convection coefficient, which has a value that depends primarily on the prevailing wind velocity.

When the body is resting and there is no apparent wind, the value of K_c is about 2.3 Kcal /m.hr. C°

When the air is moving, the constant K_c increases according to equation $K_c = 10.45 - v + 10\sqrt{v}$, Where the wind speed v is in meter per second. This equation is valid for speeds between 2.23 m/sec and 20 m /sec.

*Note: **Convection** is heat transfer by the macroscopic movement of mass.*
Convection generally transfers thermal energy faster than conduction

3-6-3 Radiation

Radiation loss, also known as black body radiation, is the thermal radiation emitted by an object in thermal equilibrium. At rest, about 54–60% of energy loss is typically through thermal radiation. Bodies in thermal equilibrium emit a specific flow of energy per unit surface area and time depending on their temperature. They also receive a flow of thermal radiation from the outside world over their surface area that depends on the temperature of the surroundings. The net rate of heat transfer by radiation Q_r/t (energy per unit time) is:

$$\frac{Q_r}{t} = \sigma\, e\, A_r (T_s^4 - T_r^4) \ldots\ldots\ldots\ldots 3-6$$

where T_s and T_r are the **skin surface** temperature and the temperature of the nearby **radiating surface** in (K), respectively; A_r is the area of the body participating in the radiation; $\sigma = 5.67 \times 10^{-8}\, J/(s.m^2.K^4)$ is the Stefan-Boltzmann constant.

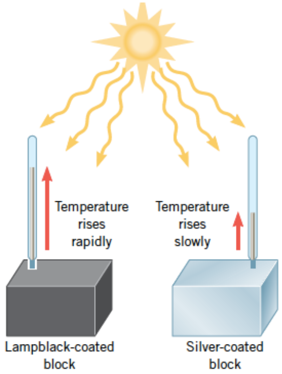
e is the emissivity of the surface which is a measure of how well it radiates. An ideal jet-black (or black body) radiator has e =1, whereas a perfect reflector has e =0. Real objects fall between these two values. For example, tungsten light bulb filaments which have an ***e*** of about 0.5, and carbon black (a material used in printer toner), which has the (greatest known) emissivity of about 0.99.

Skin is a remarkably good absorber and emitter of infrared radiation, having an emissivity of 0.97 in the infrared spectrum. Thus, we are all nearly (jet) black in the infrared, in spite of the obvious variations in skin color. This high infrared emissivity is why we can so easily feel radiation on our skin. It is also the basis for the use of night scopes used by law enforcement and the military to detect human beings. Even small temperature variations can be detected because of the (T^4) dependence. Images, called thermographs, can be used medically to detect regions of abnormally high temperature in the body, perhaps indicative of disease. The environmental radiating surface and skin temperatures are such that the wavelength of the thermal radiation is predominantly in the infrared region of the spectrum. **The emissivity of the skin in this wavelength range** is nearly ***unity***, independent of the skin pigmentation.

If the radiating surface is warmer than the skin surface, the skin is heated by radiation. A person begins to feel discomfort due to radiation if the temperature difference between the exposed skin and the radiating environment exceeds about 6°C.

***Note1**: **Radiation** is the rate of heat transfer through the emission or absorption of electromagnetic waves.*

***Note2**: A material that is a good absorber, lampblack, is also a good emitter, and a material that is a poor absorber, polished silver, is also a poor emitter.*



Q1) What is the rate of heat transfer by radiation, with an unclothed person standing in a dark room whose ambient temperature is 22°C. The person has a normal skin temperature of 33°C and a surface area of 1.5 m^2. The emissivity of skin is 0.97 in the infrared, where the radiation takes place.

Solution)

$$\frac{Q_r}{t} = \sigma\, e\, A_r (T_s^4 - T_r^4)$$

$$= (5.67 \times 10^{-8})(0.97)(1.5)[(295)^4 - (306)^4] = -99\frac{J}{s} = -99\ W$$

This value is a significant rate of heat transfer to the environment (note the minus sign), considering that a person at rest may produce energy at the rate of 125 W and that conduction and convection will also be transferring energy to the environment. Indeed, we would probably expect this person to feel cold. Clothing significantly reduces heat transfer to the environment by many methods, because clothing slows down both conduction and convection, and has a lower emissivity (especially if it is white) than skin.

3-6-4 Evaporation

In a warm climate, convection and radiation cannot adequately cool a person engaged in even moderate physical activity. A large fraction of cooling is provided by the evaporation of sweat from the skin surfaces. At normal skin temperatures, the latent heat of vaporization for water is 0.580 Cal/g. So, about 580 Cal of heat are removed for each liter of sweat that evaporates from the skin.

The body contains two types of sweat glands, the **eccrine** and the **apocrine**. The **eccrine** glands are distributed over the whole surface of the body, and they respond primarily to the nerve impulses generated by the thermoregulatory system of the body. The **apocrine** sweat glands, found mostly in the pubic regions, are not associated with temperature control.

The ability of the human body to secrete sweat is remarkable. For brief periods of time, a person can produce sweat at a rate up to 4 liter/hr. Such a high rate of sweating, however, cannot be maintained. For longer periods, up to 6 hours, a sweating rate of 1 liter/hr is common in the performance of heavy work in a hot environment.

Only sweat that evaporates is useful in cooling the skin. Sweat that rolls off or is wiped off does not provide significant cooling. Nevertheless, excess sweat does ensure full wetting of the skin. The amount of sweat that evaporates from the skin depends on ambient temperature, humidity, and air velocity. Evaporative cooling is most efficient in a hot, dry, windy environment.

We normally breathe in air that is cooler than body temperature. It gets warmed up and is then exhaled: this is also a source of body cooling. Also, we breathe in relatively dry air, and exhale air saturated with water vapor. Because this water vapor is formed by the evaporation of liquid water, this is yet another source of cooling. By evaporative cooling, a person can cope with the heat generated by moderate activity even in a very hot, sunny environment.

Note: The emissivity of the skin in the wavelength region of solar radiation depends on the pigmentation.

Note: Dark skin absorbs about 80% of the radiation, and light skin absorbs about 60%.

Note: Radiative heating is decreased if the person wears light-colored clothing or by changing the orientation of the body.

3-7 Work and power

From the definition of energy (the capacity of doing work), we can conclude that wherever energy exists, there is a capability of doing work. Therefore, because cells of the body store energy, they are capable to do a work. Also, when there is a consumption of energy there should be a work done.

The internal energy liberated (ΔE) during break down of a (fuel) molecule can perform a work (ΔW) and liberate a heat (ΔH) which can be given according to the first law of thermodynamics as follows:

$$\Delta E = \Delta W + \Delta H \ldots\ldots\ldots\ldots..3-7$$

During the body metabolism there is, about 38% of the energy released from the fuel molecules is used as a work and the rest appears immediately as a heat. The heat released in the body cannot be changed to work because our body is not a heat engine, but the heat is used to maintain the temperature of the body and the rest is dissipated outside of the body.

The power (P) is defined as the time rate (Δt) for doing work. Therefore

$$P = \frac{W}{\Delta t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots 3-8$$

Note that you do the same amount of work when you climb the stairs of a building in 2 min or 6 min, but your power output is not the same because it depends on the time interval of doing works.

The units of power are the units of work divided by the unit of time Δt. For example, if the work is measured in Joule and the time is measured in second, therefore the power unit is ***J/sec = Watt***. The power of the cell for breaking glucose molecule at one second can be calculated from equation (3-8) where energy of ATP which converted to work= 262 Kcal, therefore:

$$P = \frac{262Kcal}{1sec} = 262 \times 4184 = 1.1 \times 10^6 \frac{J}{sec} = 1.1\,MW$$

Note: The cell is very big power plant.
Adenosine triphosphate (ATP) is the source of energy for use and storage at the cellular level

3.8 Efficiency of the human Body

We can consider the human body as a machine in doing external work. The efficiency of the body is defined as the rate of the useful work output to the total input work. Therefore:

$$eff = \frac{W_o}{W_i} = \frac{output\ work}{input\ work} \dots\dots\dots\dots\dots\dots 3-9$$

Because the output work is always less than the input work, therefore the efficiency of all machine is less than 100%.

Each cell in the body is a machine which consume energy and it has a power and efficiency. As it is clear from equation (3-6) that the total energy supplied by glucose molecule is 686 Kcal which corresponds to the work input from which only 262 Kcal are used as an output work. Therefore, the efficiency of human cell which can be calculated from equation (3-8) equals to:

$$eff = \frac{W_o}{W_i} = \frac{262}{686} = 38\%$$

The efficiency of human made machine does not exceed 30% until now, which means that the cell of the body is more efficient than any human made machine.

Example) Suppose your mass 60 kg, you climbed a hill of 20 m height during 5min and consumed 3 lit of oxygen, calculate:

1- External work done by your body.

2- Power of your body.

3- Energy consumed in climbing the hill.

4- Efficiency of your body to climb the hill.

Solution)

1) $W=F.\Delta d= m.g\,.\Delta d=$ 60×9.8×20= 11760 J
2) $P=\frac{W}{\Delta t}=\frac{11760}{300\,sec}=39.2W$
3) Since 1 Lit of O_2 consumed liberates energy of 5 Kcal. Therefore: Energy consumed = $3\times 5\ Kcal = 15\ Kcal = 15\ Kcal\times 4184 = 62760\ J$
4)

$$eff=\frac{W_o}{W_i}=\frac{11760}{62760}=\ 18.73\%$$

The work, power and efficiency of the cell for prediabetic or diabetic person are less than that of the healthy persons. This is relative to the number of glucose molecules that can enter from the blood to the cell. The number of glucose molecules enter the cells of the healthy person is more than that of the prediabetic person which is more than that of diabetic person.

From this table we expect that the work and power of the healthy person is not more than 25% than that of the prediabetic person, and 25% or more than that of the diabetic person. Note that the work, power and efficiency of the braking down of the glucose molecule in the cell in the healthy, prediabetic and diabetic person are the same.

Problems

3-1) What is the heat capacity of a typical 20μm diameter human cell? Assume it is a sphere and has a specific heat equal to the body average.

3-2) In a half hour, a 65-kg jogger can generate 8.0×10^5 J of heat. This heat is removed from the jogger's body by a variety of means, including the body's own temperature-regulating mechanisms. If the heat were not removed, how much would the jogger's body temperature increase? Assume the specific heat of human body at 37°C is 3500 J/ kg.°C

3-3) Cold water at a temperature of 15°C enters a heater, and the resulting hot water has a temperature of 61°C. A person uses 120 kg of hot water in taking a shower. Find the energy needed to heat the water. The specific heat of water at 15°C is 4186 J/ kg.°C

3-4) The human brain is a remarkable organ. It only requires approximately 20 W of power to function normally. For comparison, a man-made computer processor with the same computational power as your brain would consume 10–20 MW of power! With that being said, the brain is the most energy hungry organ in the human body. It only accounts for 1/50 of the body's total weight, but it requires 1/5 (20%) of the body's total energy. This power output from the brain produces heat, which raises the temperature of the brain and the surrounding bone and tissues. The brain contains approximately 1.2 kg of water, which accounts for 77% of its total mass. If a human brain was operating at a constant power output of 20 W for one hour, what would be the increase in its temperature? Assume it is composed of only the 1.2 kg of water, and no heat transfer occurs between the brain and its surroundings.

3-5) When resting, a person has a metabolic rate of about 3.0×10^5 joules per hour. The person is submerged neck-deep into a tub containing 1.2×10^3 kg of water at 21°C. If the heat from the person goes only into the water, find the water temperature after half an hour.

3-6) When you drink cold water, your body must expend metabolic energy in order to maintain normal body temperature (37°C) by warming up the water in your stomach. Could drinking ice water, then, substitute for exercise as a way to "burn calories?" Suppose you expend 430 kilocalories during a brisk hour-long walk. How many liters of ice water (0°C) would you have to drink in order to use up 430 kilocalories of metabolic energy? For comparison, the stomach can hold about 1 liter.

3-7) One ounce of a well-known breakfast cereal contains 110 Calories (1 food Calorie = 4186 J). If 2.0% of this energy could be converted by a weight lifter's body into work done in lifting a barbell, what is the heaviest barbell that could be lifted a distance of 2.1 m?

3-8) When excessive heat is produced within the body, it must be transferred to the skin and dispersed if the temperature at the body interior is to be maintained at the normal value of 37°C. One possible mechanism for transfer is conduction through body fat. Suppose that heat travels through 0.030 m of fat in reaching the skin, which has a total surface area of 1.7 m^2 and a temperature of 34°C. Find the amount of heat that reaches the skin in half an hour (1800 s). The thermal conductivity of body fat is 0.2 J/(s.m.C°)

3-9) The amount of heat per second conducted from the blood capillaries beneath the skin to the surface is 240 J/s. The energy is transferred a distance of 2.0×10^{-3} m through a body whose surface area is 1.6 m^2. Assuming that the thermal conductivity is that of body fat, determine the temperature difference between the capillaries and the surface of the skin.

Chapter Four

Pressure inside the Body

4-1 Pressure inside the body

Pressure is a very common phenomenon in our lives, the service station attendant checks the pressure in our tires and the doctor measures our blood pressure as part of a physical examination. The pressure P under a column of liquid can be calculated from the following:

$$P = \rho\, g\, h \ldots\ldots\ldots\ldots\ldots.\ldots\ldots.4-1$$

ρ is the fluid density, g is the gravitational constant, and h is the height of the column. For mercury ρ is 13.6 g/cm^3. For water $\rho = 1.00$ g/cm^3 at 4°C. The density of whole blood is a bit higher, 1.06 g/cm^3 at 37°C. The units and conversion of pressure are presented in Table 4-1.

So far, we have been discussing absolute pressure, P_{abs}, which is the total force per unit area. In discussions concerning the body it is very common to cite the gauge pressure, P_{gauge}, which is the pressure relative to a standard, which is usually atmospheric pressure, and so

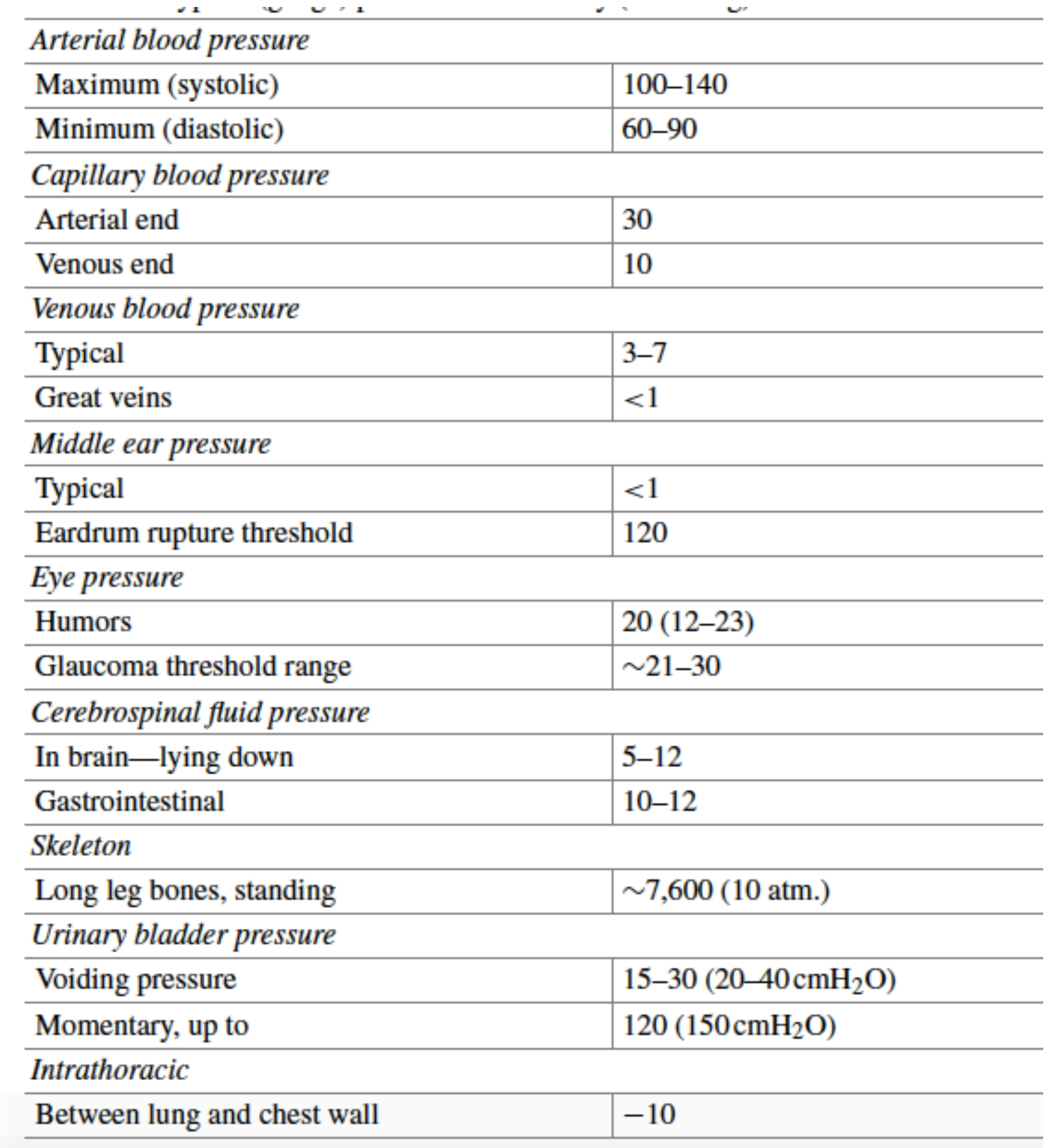
$$P_{gauge} = P_{abs} - 1 \text{ atm}\ldots\ldots\ldots\ldots4\text{-}2$$

This is helpful because it is the difference in pressure that is the net force that acts on a unit area. In discussing blood pressure and the pressure of air in the lungs, it is assumed that the term pressure P refers to the gauge pressure relative to the local atmospheric pressure. During breathing in (which is called inspiration), the pressure in the lungs is lower than that outside the body and so the internal (gauge) pressure is < 0. Table 4-2 gives typical pressures in the body.

Table 4-1 The units of pressure and conversion parameter

1 atm = 760 mmHg
=10332.2 mm water
= 760 torr
= 101325 Pa
= 101.3 KPa
= 14.69 psi

Table 4-2 Typical (gauge) pressures in the body (in mmHg)



Arterial blood pressure	
Maximum (systolic)	100–140
Minimum (diastolic)	60–90
Capillary blood pressure	
Arterial end	30
Venous end	10
Venous blood pressure	
Typical	3–7
Great veins	<1
Middle ear pressure	
Typical	<1
Eardrum rupture threshold	120
Eye pressure	
Humors	20 (12–23)
Glaucoma threshold range	~21–30
Cerebrospinal fluid pressure	
In brain—lying down	5–12
Gastrointestinal	10–12
Skeleton	
Long leg bones, standing	~7,600 (10 atm.)
Urinary bladder pressure	
Voiding pressure	15–30 (20–40 cmH_2O)
Momentary, up to	120 (150 cmH_2O)
Intrathoracic	
Between lung and chest wall	−10

4-2 Measuring of pressure inside the body

One way of directly measuring pressure is with a manometer (Fig.4-1). The measured pressure is that corresponding to the height of the fluid column plus the reference pressure, so

$$P = P_{ref} + \rho\, g\, h \dots\dots\dots\dots 4-3$$

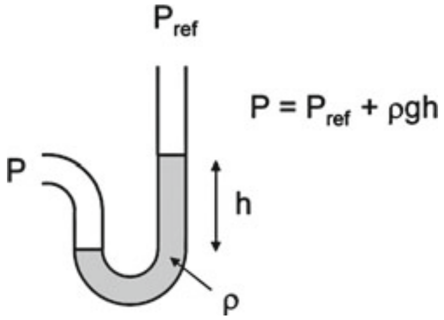


Figure 4-1 Manometer

The most common way to measure blood pressure is with a sphygmomanometer (sfig-muh-ma-nah'-mee-ter), which consists of a cuff, a squeeze bulb, and a meter that measures the pressure in the cuff (Fig.4-2). The cuff is the balloon-like jacket placed about the upper arm above the elbow; this encircles the brachial artery. The cup of a stethoscope is placed on the lower arm, just below the elbow, to listen for the flow of blood. With no pressure in the cuff, there is normal blood flow and sounds are heard through the stethoscope. Gurgling sounds are heard after the cuff is pressurized with the squeeze bulb and then depressurized by releasing this pressure with a release valve in this bulb.

To understand when these sounds occur and their significance, we need to understand how the pressure in the main arteries varies with time. In every heart beat cycle (roughly 1/s), the blood pressure in the major arteries, such as the brachial artery, varies between the systolic pressure (~120mmHg) and the diastolic pressure (~80mmHg), as is depicted in Fig. 4-3. (The units of these cited gauge pressures are in mmHg). When the pressure in the cuff exceeds the systolic pressure, there is no blood flow to the lower arm and consequently there are no sounds. When the pressure in the cuff is lowered with the release bulb to just below the systolic pressure, there is intermittent flow. During the part of the cycle when the arterial blood pressure is lower than the cuff pressure there is no flow; when it is greater, there is flow. This intermittent flow is turbulent and produces gurgling sounds. These sounds, the Korotkoff or K sounds, are transmitted by the stethoscope.

As the cuff pressure is lowered further, the K sounds get louder and then lower, and are heard until the cuff pressure decreases to the diastolic pressure. Blood flow is not interrupted when the cuff pressure is less than the diastolic pressure and the K sounds cease because the blood flow is no longer turbulent. Therefore, the onset and end of the K sounds, respectively, denote the systolic and diastolic blood pressures. (This auscultatory method of Korotkoff was introduced by Russian army physician Korotkoff who discovered a century ago that sound can be heard distally from a partially occluded limb).

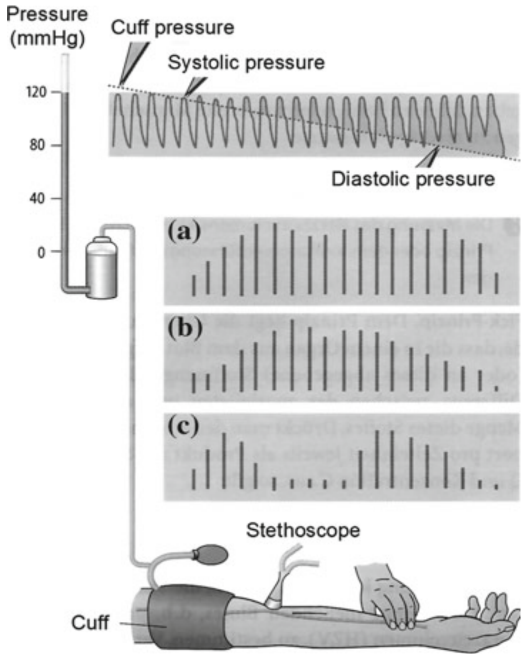


Figure 4-2 Measuring blood pressure with a sphygmomanometer, listening to Korotkoff sounds (of varying levels during the turbulent flow shown in a–c). (Listening to sounds is called auscultation)

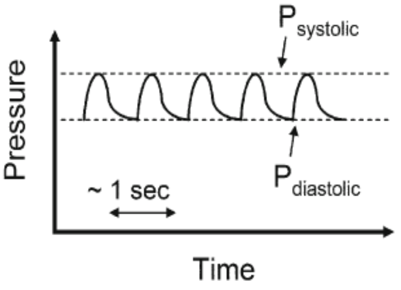


Figure 4-3 Variation of blood pressure with time, for blood leaving the left heart for the systemic system, with the systolic and diastolic pressures.

Note: The pressure inside blood vessel walls, P, exceeds that outside, P_{ext}, by $\Delta P = P - P_{ext}$

Negative pressure: Any pressure lower than atmospheric pressure. For example, when we breathe in (inspire)the pressure in the lungs must be lower than atmospheric pressure or the air would not flow in.

4-3 Pressure inside spinal column and skull

The brain contains approximately 150 cm^3 of cerebrospinal fluid (*CSF*) in a series of interconnected openings called ventricles. Normally, there is a 5-12 mmHg pressure in the fluid surrounding the brain and filling the spinal column as shown in figure (4-4). This cerebrospinal fluid serves many purposes, one of which is to **supply flotation to the brain**. The buoyant force supplied by the fluid nearly equals the weight of the brain, since their densities are nearly equal. If there is a loss of fluid, the brain rests on the inside of the skull, causing severe headaches, constricted blood flow, and serious damage.

CSF (brain)→to ventricles→ to spinal column→ to circulatory system. One of the ventricles, the aqueduct is especially narrow. If at birth this opening is blocked for any reason, the CSF is trapped inside the skull and increased the internal pressure. This serious condition, called hydrocephalus (water head). Spinal fluid pressure is measured by means of a needle inserted between vertebrae that transmits the pressure to a suitable measuring device.

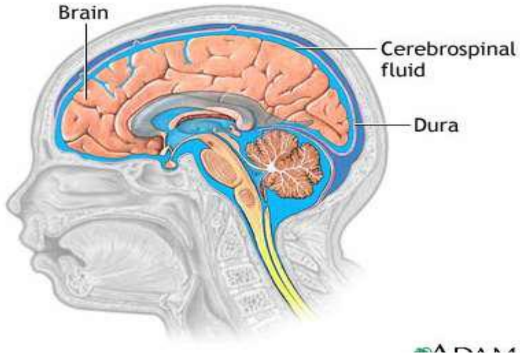


Figure 4-4 cerebrospinal fluid (CSF) in brain

4-4 Eye pressure

The shape of the eye is maintained by fluid pressure, called intraocular pressure, which is normally in the range of 12-24 mmHg. When the circulation of fluid in the eye is blocked, it can lead to a buildup in pressure, a condition called glaucoma as shown in figure (4-5). The net pressure can become as great as 85.0 mmHg, an abnormally large pressure that can permanently damage the optic nerve.

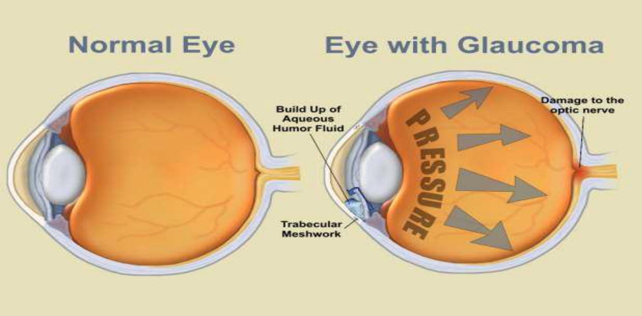


Figure 4-5 glaucoma

To get an idea of the force involved, suppose the back of the eye has an area of 6 cm^2, and the net pressure is 85.0 mmHg. Force is given by $F= P\times A$, then we calculate as follows:

$$F = \rho gh\, A = (85\times 10^{-3})(13\times 10^{3})(9.8)(6\times 10^{-4}) = 6.8N$$

This force is the weight of about a 680-g mass. A mass of 680 g resting on the eye (imagine 1.5 lb resting on your eye) would be sufficient to cause it damage. (A normal force here would be the weight of about 120 g, less than one-quarter of our initial value.)

People over 40 years of age are at greatest risk of developing glaucoma and should have their intraocular pressure tested routinely. Most measurements involve exerting a force on the (anesthetized) eye over some area (a pressure) and observing the eye's response. A noncontact approach uses a puff of air and a measurement is made of the force needed to indent the eye (Figure 4-6). If the intraocular pressure is high, the eye will deform less and rebound more vigorously than normal. Excessive intraocular pressures can be detected reliably and sometimes controlled effectively.

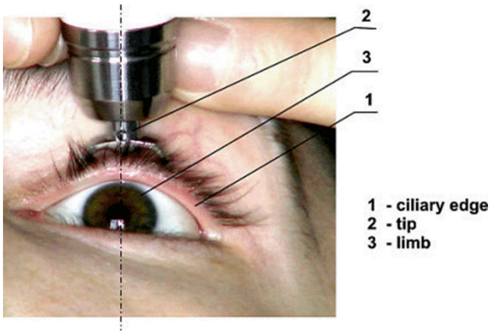


Figure 4-6 The intraocular eye pressure can be read with a tonometer

4-5 **The pressure** in the lung

$\mathbf{P}_{\textbf{in the lung at any depth}} > \mathbf{P}_{\textbf{in the lung at sea level}}$, this means that the air in the lung is denser under water and that the partial pressures of all the air components are proportionately higher. The higher partial pressure of O_2 causes more O_2 molecules to be transformed into the blood, and oxygen poisoning results if the partial pressure of O_2 gets high. Partial pressure of O_2 is (0.8 atm) and absolute air pressure is (4 atm) at depth of (30 m).

Breathing air at a depth of (30m) is also dangerous because it may result in excess N_2 in the blood and tissues, there is a possibility of having:

- Nitrogen narcosis (intoxication effect).
- The bends or decompression sickness (a scant problem).

Note: *O_2 is attached to red blood cells, while N_2 is dissolved in the blood and tissues.*

4-6 Pressure in the skeleton

These pressures are the largest in the body, due both to the high values of initial force, and the small areas to which this force is applied, such as in the joints. For example, when a person lifts an object improperly, a force of 5000 N may be created between vertebrae in the spine, and this may be applied to an area as small as 10 cm^2. The pressure created is

$$P = \frac{F}{A} = \frac{5000}{10^{-3}} = 5 \times 10^{6}\ N/m^{2}$$

This pressure can damage both the spinal discs (the cartilage between vertebrae), as well as the bony vertebrae themselves. Even under normal circumstances, forces between vertebrae in the spine are large enough to create pressures of several atmospheres. Most causes of excessive pressure in the skeletal system can be avoided by lifting properly and avoiding extreme physical activity.

4-7 Pressure in the urinary bladder

This bodily pressure is one of which we are often aware. In fact, there is a relationship between our awareness of this pressure and a subsequent increase in it. Bladder pressure climbs steadily from zero to about 25 mmHg as the bladder fills to its normal capacity of 500 cm^3. This pressure triggers the micturition reflex, which stimulates the feeling of needing to urinate. What is more, it also causes muscles around the bladder to contract, raising the pressure to over 100 mmHg, accentuating the sensation.

Coughing, straining, tensing in cold weather, wearing tight clothes, and experiencing simple nervous tension all can increase bladder pressure and trigger this reflex. So, can the weight of a pregnant woman’s fetus, especially if it is kicking vigorously or pushing down with its head! Bladder pressure can be measured by a catheter or by inserting a needle through the bladder wall and transmitting the pressure to an appropriate measuring device. One hazard of high bladder pressure (sometimes created by an obstruction), is that such pressure can force urine back into the kidneys, causing potentially severe damage.

Problems

4-1) The aqueous humor in a person's eye is exerting a force of 0.300 N on the 1.1cm^2 area of the cornea. (a) What pressure is this in mm Hg? (b) Is this value within the normal range for pressures in the eye?

4-2) The left side of the heart creates a pressure of 120 mm Hg by exerting a force directly on the blood over an effective area of 15 cm^2. What force does it exert to accomplish this?

4-3) Suppose you measure a standing person's blood pressure by placing the cuff on his leg 0.500 m below the heart. Calculate the pressure you would observe (in units of mm Hg) if the pressure at the heart were 120 over 80 mmHg. Assume that there is no loss of pressure due to resistance in the circulatory system (a reasonable assumption, since major arteries are large).

4-4) During forced exhalation, such as when blowing up a balloon, the diaphragm and chest muscles create a pressure of 60.0 mm Hg between the lungs and chest wall. What force in newtons does this pressure create on the 600 cm^2 surface area of the diaphragm?

4-5) Gauge pressure in the fluid surrounding an infant's brain may rise as high as 85.0 mm Hg (5 to 12 mm Hg is normal), creating an outward force large enough to make the skull grow abnormally large. (a) Calculate this outward force in newtons on each side of an infant's skull if the effective area of each side is 70 cm^2 (b) What is the net force acting on the skull?

4-6) A full-term fetus typically has a mass of 3.50 kg. (a) What pressure does the weight of such a fetus create if it rests on the mother's bladder, supported on an area of 90 cm^2? (b) Convert this pressure to millimeters of mercury and determine if it alone is great enough to trigger the micturition reflex (it will add to any pressure already existing in the bladder).

4-7) During heavy lifting, a disk between spinal vertebrae is subjected to a 5000-N compressional force. (a) What pressure is created, assuming that the disk has a uniform circular cross section 2.00 cm in radius? (b) What deformation is produced if the disk is 0.800 cm thick and has a Young's modulus of 1.5×10^9 N/m^2?

4-8) Calculate the maximum force in newtons exerted by the blood on an aneurysm, or ballooning, in a major artery, given the maximum blood pressure for this person is 150 mmHg and the effective area of the aneurysm is 20 cm^2. Note that this force is great enough to cause further enlargement and subsequently greater force on the ever-thinner vessel wall.

4-9) If the pressure in the esophagus is -2 mmHg while that in the stomach is +20 mmHg, to what height could stomach fluid rise in the esophagus, assuming a density of 1.10 g/mL? (This movement will not occur if the muscle closing the lower end of the esophagus is working properly.)

4-10) Pressure in the spinal fluid is measured as shown in Figure below. If the pressure in the spinal fluid is 10.0 mm Hg: (a) What is the reading of the water manometer in cm water? (b) What is the reading if the person sits up, placing the top of the fluid 60 cm above the tap? The fluid density is 1.05 g/cm^3.

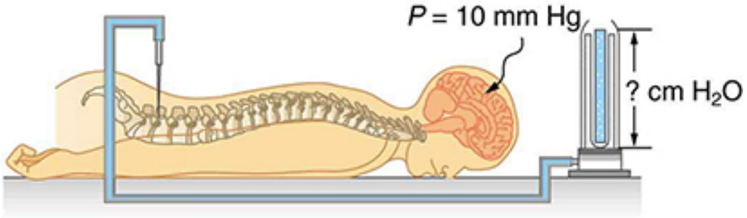
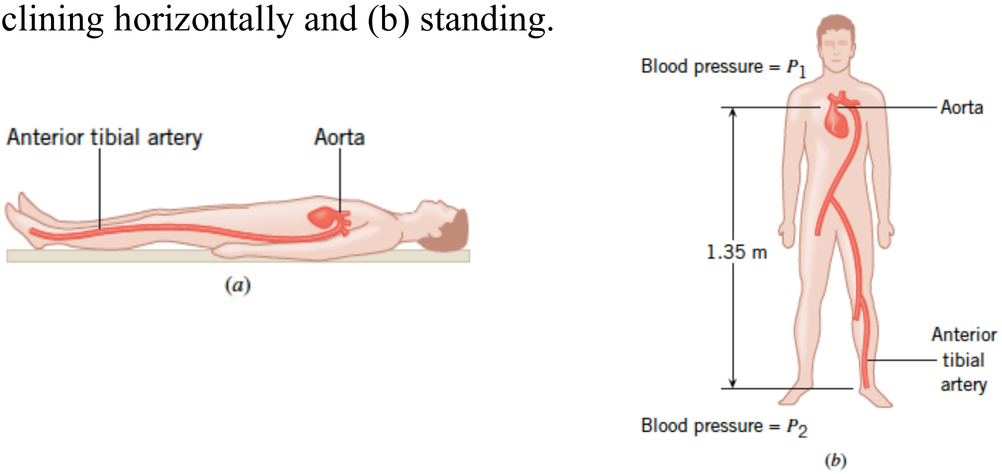


Figure: A water manometer used to measure pressure in the spinal fluid. The height of the fluid in the manometer is measured relative to the spinal column, and the manometer is open to the atmosphere. The measured pressure will be considerably greater if the person sits up.

4-11) Blood in the arteries is flowing, but as a first approximation, the effects of this flow can be ignored and the blood treated as a static fluid. Estimate the amount by which the blood pressure P_2 in the anterior tibial artery at the foot exceeds the blood pressure P_1 in the aorta at the heart when a person is (a) reclining horizontally and (b) standing.



4-12) The drawing shows an intravenous feeding. With the distance shown, nutrient solution (ρ = 1030 kg/m^3) can just barely enter the blood in the vein. What is the gauge pressure of the venous blood? Express your answer in millimeters of mercury.

4-13) The human lungs can function satisfactorily up to a limit where the pressure difference between the outside and inside of the lungs is one-twentieth of an atmosphere. If a diver uses a snorkel for breathing, how far below the water can she swim? Assume the diver is in salt water whose density is 1025 kg/m^3.

4-14) At a given instant, the blood pressure in the heart is 1.6×10^4 Pa. If an artery in the brain is 0.45 m above the heart, what is the pressure in the artery? Ignore any pressure changes due to blood flow. Let density of blood is 1060 kg/m^3