1 INTRODUCTION TO MEDICAL PHYSICS

Medical physics is the application of physics concepts, theories and methods to medicine and healthcare.

In **hospital work**, the medical physicist represents a healthcare profession with a specific mission statement such as medical imaging, nuclear medicine, and radiotherapy.

In **university work**, medical physicist performs research in any applications of physics to medicine from the study of biomolecular structure to microscopy and nanomedicine.

1.1 THE MECHANICS OF BODY

1.1.1 Equilibrium Considerations for the Human Body

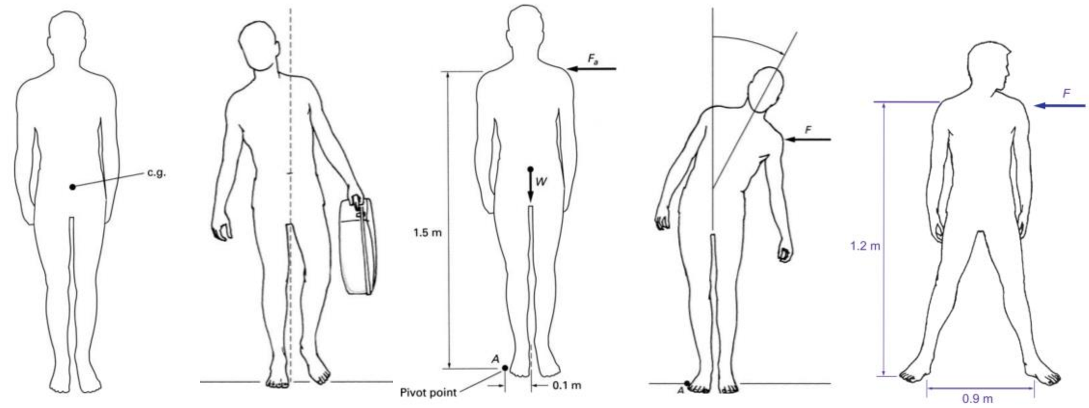
The center of gravity (c.g.) of an erect person with arms at the side is at approximately 56% of the person's height measured from the soles of the feet (Fig. 1a). The center of gravity shifts as the person moves and bends.

When carrying an uneven load, the body tends to compensate by bending and extending the limbs so as to shift the center of gravity back over 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. 1b).

1.1.2 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.



(a) **(b)** **(c)** **(d)** **(e)**

Fig. 1: (a) Center of gravity of a person, (b) A person carrying a weight, (c) A force to an erect person, (d) Compensating for a side-pushing force and (e) Increased stability resulting from spreading the legs.

The applied force F_a tends to topple the body. When the person with height h 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

$$\boldsymbol{T_a = F_a \times h}$$

$$h = 1.5\,m \qquad \Rightarrow \qquad T_a = F_a \times 1.5 \text{ m}$$

The **opposite restoring torque** T_w due to the person's weight W around his foot base length L is

$$\boldsymbol{T_w = W \times L}$$

$$L = 0.1\,m \qquad \Rightarrow \qquad T_w = W \times 0.1 \text{ m}$$

If the mass m of the person is 70 kg, his weight W is

$$\boldsymbol{W = m \times g}$$

$$W = 70 \times 9.8 = 686 \text{ N}$$

Here g is the gravitational acceleration.

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, $\boldsymbol{T_a} = \boldsymbol{T_w}$, or

$$F_a \times 1.5\ m = 68.6\ \text{N.m}$$

Therefore, the **force required to topple** an erect person is

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

1.2 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. 2). When an individual fiber receives an electrical stimulus, it tends to contract to its full ability. If a stronger pulling force is required, a larger number of fibers are stimulated to contract.

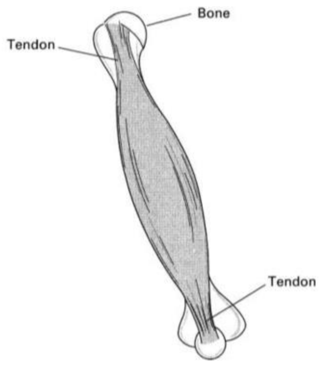


Fig. 2: Drawing of a muscle.

1.3 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. 3 and their existence in the human body, as shown in Fig. 4.

The force F required to balance a load of weight W is given by

$$\boldsymbol{F = \frac{W d_1}{d_2}}$$

where d_1 and d_2 are the lengths of the lever arms.

The **mechanical advantage** M of the lever is defined as

$$\boldsymbol{M = \frac{F}{W} = \frac{d_1}{d_2}}$$

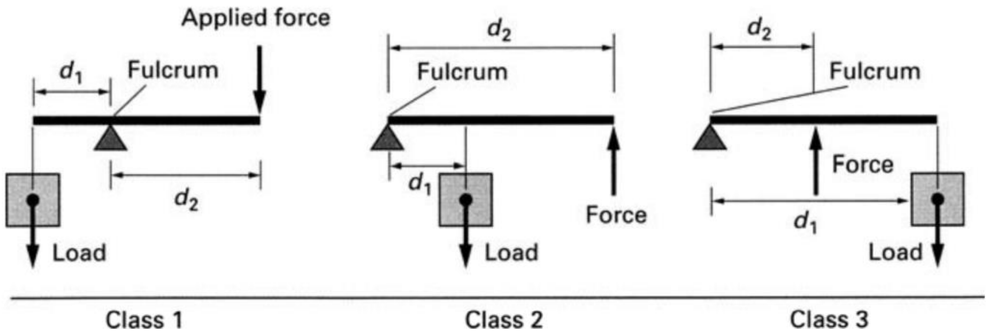


Fig. 3: Types of levers.

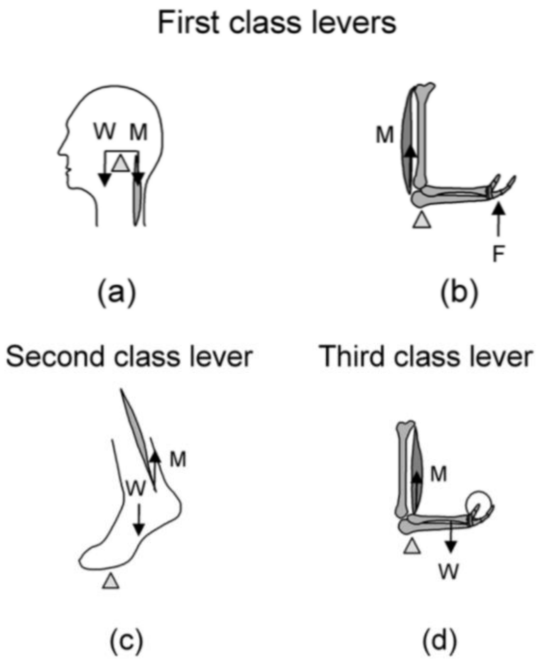


Fig. 4: Examples of levers types in the human body.

1.4 THE ELBOW

The two most important muscles producing elbow movement are the biceps and the triceps (Fig. 5). The **contraction of the triceps** causes an extension, or opening, of the elbow, while **contraction of the biceps** closes the elbow.

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). The calculations will be performed by considering the arm position as a Class 3 lever, as shown in Fig. 3 and Fig. 4.

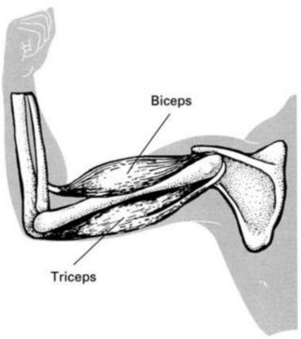


Fig. 5: The elbow.

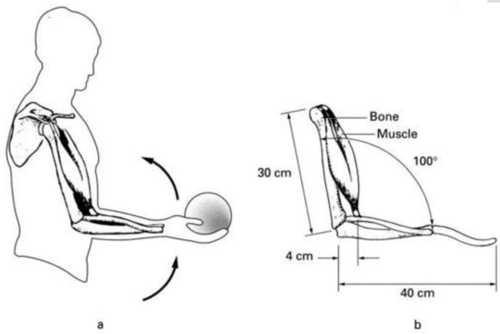


Fig. 6: (a) Weight held in hand and (b) A simplified drawing of (a).

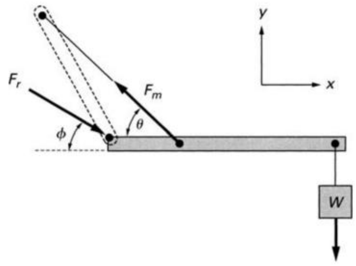


Fig. 7: Lever representation of Fig. 6.

***x* components of the forces:** $\boldsymbol{F_m \cos\theta = F_r \cos\phi}$

***y* components of the forces:** $\boldsymbol{F_m \sin\theta = W + F_r \sin\phi}$

There are 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.

Using the dimensions shown in Fig. 6, we obtain

$$4 \text{ cm} \times F_m \sin\theta = 40 \text{ cm} \times W$$

or

$$F_m \sin\theta = 10\, W$$

Therefore, with $\theta = 72.6°$, the muscle force F_m is

$$F_m = \frac{10\, W}{0.954} = 10.5\, W$$

With a 14 kg weight in hand, the force exerted by the muscle is

$$F_m = 10.5 \times 14 \times 9.8 = 1440 \text{ N}$$

Assuming, as before, that the weight supported is 14 kg, these equations become

$$F_m \, cos\theta = F_r \, cos\phi \Rightarrow 1440 \times cos72.6° = F_r \, cos\phi$$

$$F_m \, sin\theta = W + F_r \, sin\phi \Rightarrow 1440 \times sin72.6° = (14 \times 9.8) + F_r \, sin\phi$$

or

$$F_r \, cos\phi = 430 \text{ N}$$

$$F_r \, sin\phi = 1240 \text{ N}$$

Squaring both equations, using $cos^2\phi + sin^2\phi = 1$ and adding them, we obtain

$$F_r^2 = 1.74 \times 10^6 \text{ N}^2$$

$$F_r = 1320 \text{ N}$$

From Eqs. ($F_r \, cos\phi = 430$ N and $F_r \, sin\phi = 1240$ N) the cotangent of the angle is

$$cot\phi = \frac{430}{1240} = 0.347 \quad \text{and} \quad \phi = 70.9°$$

1.5 THE HIP

The hip is stabilized in its socket by a group of muscles, which is represented in Fig. 8 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., $W_L = 0.185\,W$). 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. 8.

From equilibrium conditions,

$\boldsymbol{F_m cos71^\circ - F_r cos\theta = 0}$ **(x components of the force = 0)**

$\boldsymbol{F_m sin71^\circ + (W - W_L) - F_r sin\theta = 0}$ **(y components of the force = 0)**

$\boldsymbol{(F_r sin\theta \times 7cm) + (W_L \times 10cm - W \times 18cm) = 0}$ **(torque about point A = 0)**

Since $W_L = 0.185\,W$,

$$F_r sin\theta = 2.31W$$

and,

$$\text{Muscle force} \quad \Longrightarrow \quad F_m = \frac{1.50W}{sin71^\circ} = 1.59W$$

Using the Eq. $F_m cos71^\circ - F_r cos\theta = 0 \quad \Rightarrow \quad F_r cos\theta = F_m cos71^\circ$

$$F_r cos\theta = 1.59W cos71^\circ \quad \Rightarrow \quad F_r cos\theta = 0.52W$$

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

$$\text{Reaction force at the hip joint} \quad \Longrightarrow \quad F_r = 2.37W$$

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 is 9.8 × 70 = 686 N. The force on the hip joint is 1625 N.

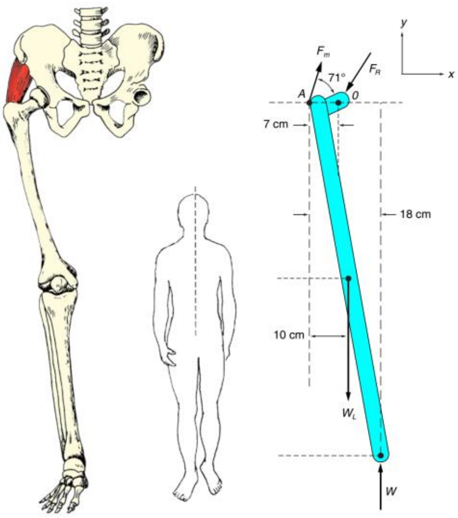


Fig. 8: (a) The hip and (b) Its lever representation.

1.6 DYNAMIC ASPECTS OF POSTURE

The forces exerted by the skeletal muscles are not alaways **static**. The human body (and bodies of all animals) is a **dynamic system continually** responding to **stimuli generated internally** and by **the external environment**.

The **simple act of standing upright** requires the body to be in a continual back and forth, left right, swaying motion to maintain the center of gravity over the base of support.

The **maintaining of balance in the process of walking** requires complex series of compensating movements as the support for the center of gravity shifts from one foot to the other. Keeping the body upright is a highly **complex task of the nervous system**. The performance of this task is most remarkable when accidentally we slip and the center of gravity is momentarily displaced from the base of support.

The nervous system obtains information required to maintain balance principally from three sources: **vision**, the **vestibular system** situated in the inner ear that monitors movement and position of the head, and **somatosensory system** that monitors position and orientation of the various parts of the body. **With age**, the efficiency of the functions required to keep a person upright decreases resulting in an increasing number of injuries due to falls.

Another aspect of the body dynamics is the interconnectedness of the musculoskeletal system. Through one path or another, all muscles and bones are connected to one another, and a change in muscle tension or limb position in one part of the body must be accompanied by a compensating change elsewhere.