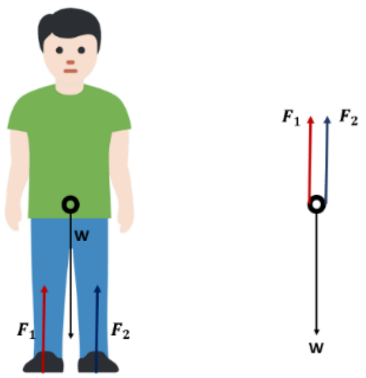
CHAPTER 4

HUMAN BODY ANTHROPOMETRY

The primary area of anthropology called anthropometry (Easterby, 2012) examines how to measure body parts and other physical traits to identify variations between people and groups. The biomechanical model of the human body is used to determine the moments and forces acting on joints. Recently, the need for technological innovations, particularly man-machine interactions, has supplied a significant impetus: workspace layout, compartments, defences parts, and so on. Human movement analysis, on the other hand, requires kinetic measures such as weights, a moment of inertia, and coordinates. Newton's second equation of motion-based inverse dynamics technique is used in biomechanics to calculate intersegmental forces and moments using the system's known biomechanics. (Huston, 2008)

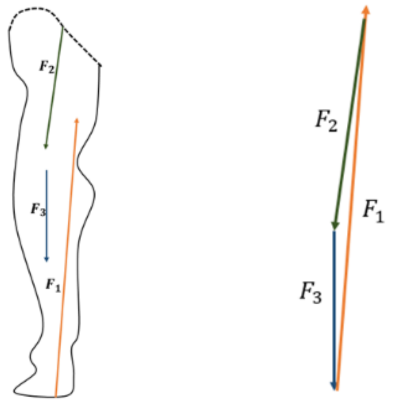
In a link segment model, the forces exerted on a body part can be categorized into three types: external forces, internal forces, and inertia forces. Numerical simulations of biological and physical processes are used to get force data and analysis on the human leg. Interaction with the environment generates external forces. They come in two varieties: those caused by forces that are exerted directly on a bodily part, and those brought on by gravity. For instance, while standing, the body is subject to two external forces: one from gravity and one from each of the feet as shown in the Free Body Diagram (FBD) in Figure 4.1 (b).



(a) Force acting on a person (b) FBD of person

Figure 4.1: External forces acting on the human body during standing

These forces include those generated by muscle contraction and those carried by ligaments as shown in Figure 4.2. Internal forces can also be derived from frictional forces in joints. However, these pressures are frequently so minor that they are inconsequential, and most link segment models assume frictionless couplings.



(a) Force acting on the leg (b) FBD of person's leg

Figure 4.2: Internal forces acting on the human body during standing

The product of a segment's mass and acceleration yields inertial force. In many cases, a body segment's acceleration is so small that the inertial force is negligible.

An element that is in static equilibrium has no resultant force or moment acting on it as shown in Figure 4.3 (a). Therefore, the object is either stationary or moving at a constant linear and/or rotational velocity. In static equilibrium, the total of the forces operating on the human body is stated as follows;

$$\sum F = F_2 - F_1 - mg = 0 \qquad \text{.................. (Eqn. 4.1)}$$

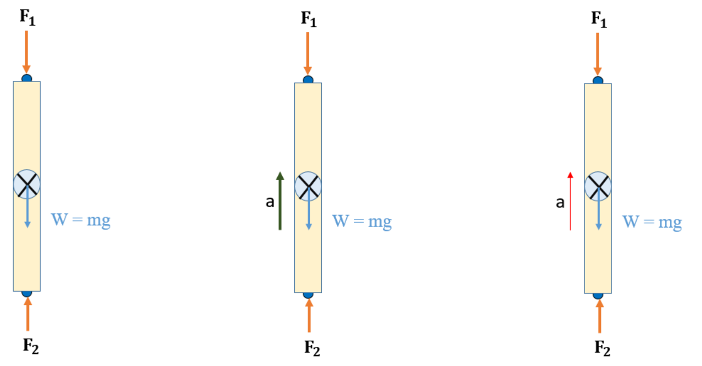
A consequent force or moment acts on an item in dynamic equilibrium. As a result, the object experiences linear and/or angular acceleration as shown in Figure 4.3 (b). The resulting force is equal to the object's mass multiplied by its acceleration. In dynamic equilibrium, the sum of the forces and consequent forces operating on the human body is stated as follows;

$$\sum F = F_2 - F_1 - mg = \text{ma} \qquad \text{.................. (Eqn. 4.2)}$$

Resultant force: F = ma

When a body segment experiences only minor accelerations, the resulting force, which is comparable to the inertial force, is frequently insignificant in comparison to other forces operating on the segment as shown in Figure 4.3 (c). As a result, the segment's acceleration may be ignored. In these instances, the link segment model is considered to be quasi-static, which means that the segment seems to be static. The total of the forces operating on the human body in quasi-static conditions is shown below;

$$\sum F = F_2 - F_1 - mg = 0 \qquad \text{.................. (Eqn. 4.3)}$$



(a) static equilibrium (b) dynamic equilibrium (c) quasi-static
Figure 4.3: An object equilibrium conditions

A quasi-static model, for example, is sufficient for estimating joint moments and forces at the ankle joint during a single regular motion of walking (when only one foot is on the ground). However, the inertial effects are not insignificant when examining moment and force at the hip socket during the single gait cycle of walking. This is due to the larger magnitudes of the accelerations and the involvement of the entire mass of the lower limb.

In biomechanics, the body segment parameters are of particular importance. To solve biomechanical problems, four essential body segment data are required: mass, length, center of mass, and radius of gyration. These mechanical properties are frequently linked to the appropriate whole-body property. The length of the thigh, for example, is proportional to height. The mechanical properties of the body are discussed in depth in the section on anthropometry that follows. As seen in Figure 4.4, the pertinent body segments are typically arranged in a structure known as a link segment model. This is a model of the entire body or just the part of interest, with individual segments linked together. The linkages usually correspond to anatomical joints.

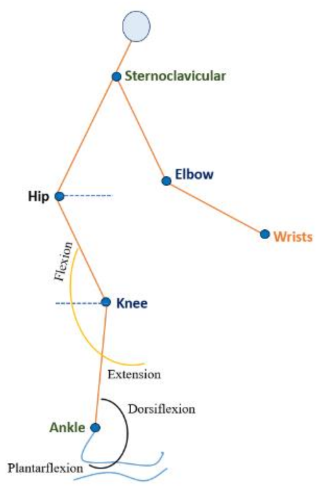


Figure 4.4: Link segment model

Despite the source of the anthropometric measurements (Norton, et al., 1996), the model utilizes the following assumptions:

- At the COM of each section, a constant mass is situated as a single parameter.
- Throughout the move, the COM location of each part remains constant.
- The joints are regarded as ball-and-socket or hinge joints.
- Throughout the movement, each section's mass moment of inertia around its mass center remains constant.
- The duration of each part remains consistent throughout the movement.

4.1 SEGMENT LENGTH

The length of the segments between each join is the most important body dimension. A set of typical segment lengths is expressed in terms of body height, which is illustrated in Figure 4.5 (Drillis & Contini, 1966). When there are no more accurate measurements available, these section proportions are an acceptable estimate, ideally commonly measured from the person. Due to the industry's expanding usage of additive manufacturing for the creation of highly customized limb prosthetics, the investigation into body segmentation is currently growing rapidly. (Winter, 2009)

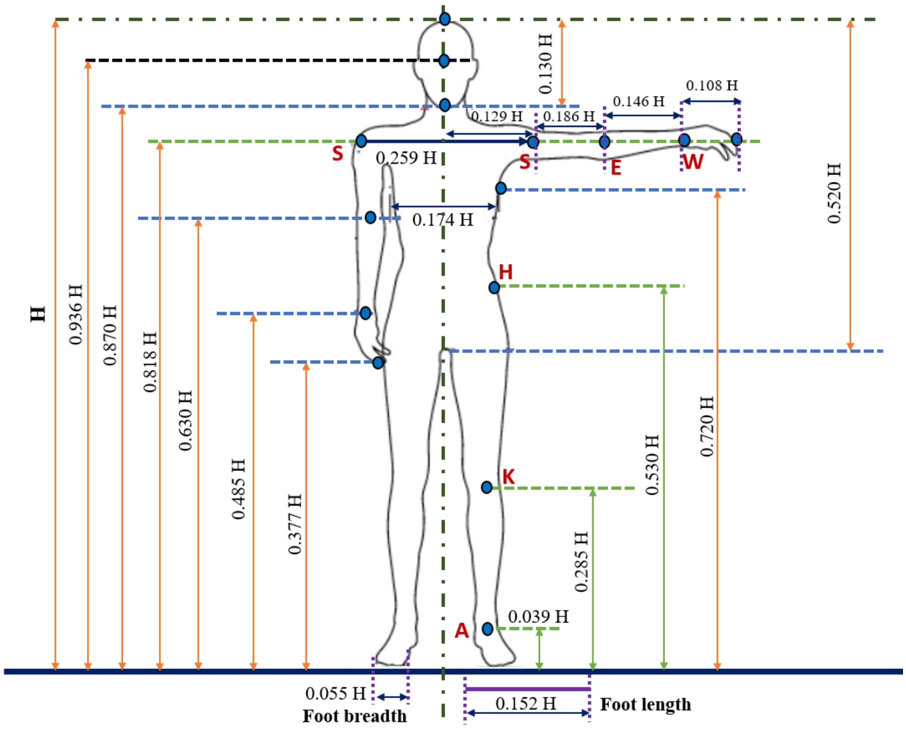


Figure 4.5: Anatomical structure's length as a proportion of total body height H

Figure 4.5 depicts a standardized data collection that is relevant to the whole adult population. However, body measurements differ depending on age, body type, gender, and racial origin. Standardized sets for body segment lengths should thus be used only when direct measurements are not feasible.

4.2 SEGMENT MASS AND CENTER OF MASS

Additionally, uniform data sets for the mass and position of the mass's center of everybody segment are being established. Each of these characteristics is required for even the most basic biomechanical studies. Table 4.1 displays an average set of anthropometric measures for each human segment's mass and the position of the mass center. The coefficients are given as ratios of the center mass to segment length and segment mass to total body mass. (Adolphe, Clerval, Kirchof, Lacombe-Delpech, & Zagrodny, 2017)

Table 4.1: Anthropometric data of the human body (Winter, 2009)

Segment	**Segment weight/Total body weight**	**Center of Mass/ segment length**		**Radius of gyration / Segment length**			
		Proximal	***Distal***	***C of G***	***Proximal***	***Distal***	***Density***
Hand	0.006 M	0.506	0.494 P	0.297	0.587	0.577 M	1.16
Forearm	0.016 M	0.430	0.570 P	0.303	0.526	0.647 M	1.13
Forearm and hand	0.022 M	0.682	0.318 P	0.468	0.827	0.565 P	1.14
Upper arm	0.028 M	0.436	0.564 P	0.322	0.542	0.645 M	1.07
Total arm	0.050 M	0.530	0.470 P	0.368	0.645	0.596 P	1.11
Foot	0.0145 M	0.50	0.50 P	0.475	0.69	0.690 P	1.1
Leg	0.0465 M	0.433	0.567 P	0.302	0.528	0.643 M	1.09
Foot and leg	0.061 M	0.606	0.394 P	0.416	0.735	0.572 P	1.09
Thigh	0.100 M	0.433	0.567 P	0.323	0.54	0.653 M	1.05
Total leg	0.161 M	0.447	0.553 P	0.326	0.56	0.650 P	1.06

Each segment's mass increases as the body's overall mass rises. As a result, the mass of each section may be stated as a percentage of the body's overall mass. Table 4.1 reviews the findings of different researchers (Nikolova & Toshev, 2007). The kinetic and energy analyses that follow in this article use these statistics.

4.3 PROPERTIES OF DENSITY, MASS, INERTIA AND RADIUS OF GYRATION

Kinematic and kinetic studies necessitate information on mass distributions, mass centers, M.I., and other factors. A significant number of the measurements were obtained from cadavers, while certain used calculated segment volumes in combination with density data; and more modern procedures used scanning technology to offer a cross-sectional image across the segment at numerous intervals. The human body is composed of several sorts of tissue, with each having distinctive densities. Muscle cells have a relative density that is slightly higher than 1.0, fat has a relative density that is lower than 1.0, and the lung includes light respiratory gases. Compact bone has a relative density that is more than 1.8. Drillis and Contini (1966) suggested the following formula for ponderal index c as a function of the body's density d (Winter, 2009).

$$d = 0.69 + 0.9c \text{ kg/liter} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(Eqn. 4.4)}$$

Where $c = h / (w^{1/3})$, h = height in meter, and w = weight in kg.

Compared to a tall slender person, a short obese person has a lower ponderal index, which results in a lower body density.

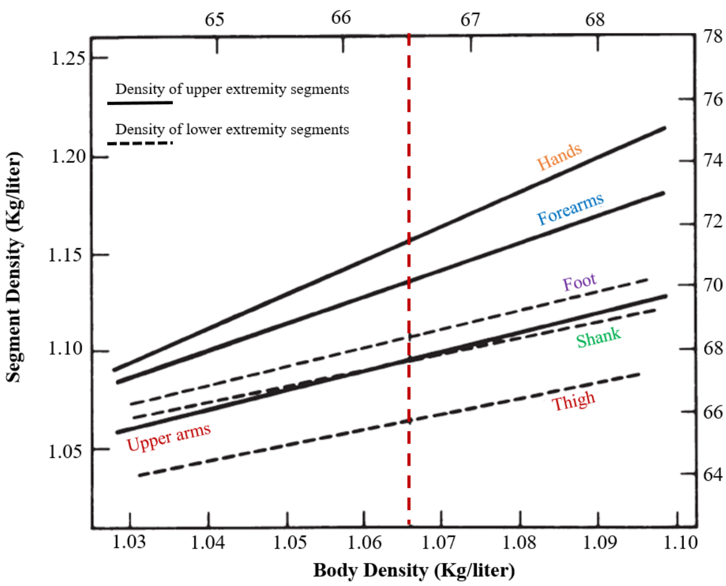


Figure 4.6: Leg segment density concerning average body density (Winter, 2009)

The RH column of Table 4.1 shows typical segment densities for an "average" individual. These segments' densities roughly scale with body densities. Each line in Figure 4.6 reflects segment density (y) as a fraction of total body density (x). Several of these lines are investigated and measured, resulting in non-dimensional slopes of 1.75 for the hands, 0.95 for the foot, and 0.80 for the thigh.

The inertia moment is defined as the product of each particle's mass and the square of the angle at which it is perpendicular to the axis of rotation. When studying linear motion, the assumption is that all of a body's mass is centered at the center of mass. When examining rotational motion, it is helpful to imagine all of a body's mass as being centered at a certain radius from the axis of revolution. This radius is defined as the body's radius of gyration. The M.I. may thus be determined using the predicted radius of gyration and the mass of the segment, which can be approximated using data from

Table 4.1. There are three possible axes of rotation described because the radius of gyration is determined by the distribution of mass about the axis of rotation.

4.4 FORCES AND MOMENTS IN SHOULDER JOINTS

The inter-segment force is the sum of all forces that pass the joint between two body segments. It's also referred to as the net joint force or the resulting joint force. The inter-segment force is very simple to compute since it does not involve knowledge of the forces produced by muscles and ligaments across a joint.

The joint force is the force that operates between two segments at a joint. The joint force varies from the inter-segment force in that the forces generated from the activity of the muscles across the joint must be included in the calculation.

Inter-segment force = Joint force + Muscle forces

When no muscles are active, the joint force equals the inter-segment force. To demonstrate the distinction between joint force and inter-segment force, examine the forces at the shoulder joint when the arm is stretched out straight to the side, as illustrated in Figure 4.7. The arm has a total mass of 4.0 kg, with the center of mass placed at the shoulder joint.

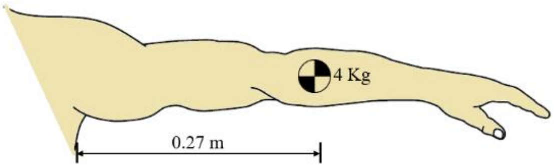


Figure 4.7: Arm held out straight to the side

The inter-segment force at the shoulder joint will be computed. The entire arm is considered as one part for the sake of simplicity. The principal forces acting on the arm segment are the inter-segment force and the force due to the mass of the arm segment. Figure 4.8 depicts both of them on the free-body diagram.

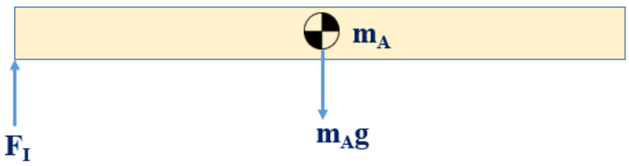


Figure 4.8: Free body diagram of arm

Because the arm segment is in static equilibrium, the total of all forces should be zero. Vertical components are added together, with upwards regarded as positive.

$$\sum Fv = F_I - m_A g = 0 \qquad \text{(Eqn. 4.5)}$$

Where; F_I is the inter-segment force at the shoulder joint; m_A is the mass of the whole arm (4.0 kg), and g is the acceleration due to gravity (10 m/s).

Thus the inter-segment force at the shoulder joint can be calculated by;

$$F_I = m_A g \quad \text{……………………. (Eqn. 4.6)}$$

$$F_I = 4 * 10 = 40 \text{ N}$$

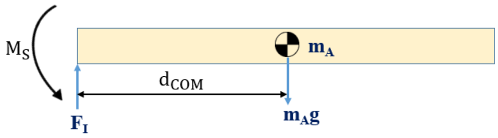


Figure 4.9: Free body diagram of the arm including moments

Thus, the times of the shoulder joint are added together (Figure 4.9).

$$\sum M = M_S - m_A g * d_{COM} = 0 \quad \text{……..………….. (Eqn. 4.7)}$$

$$M_S = m_A g * d_{COM}$$

$$M_S = 4 * 10 * 0.27 = 10.8 \text{ N.m}$$

Where: M_S is the moment around the shoulder joint, and d is the distance from the shoulder joint.

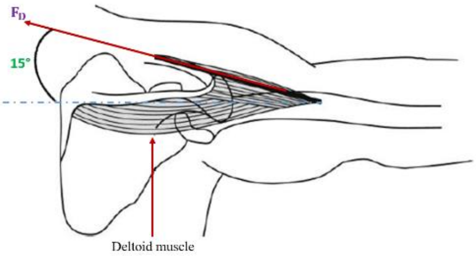


Figure 4.10: Deltoid muscle force

As a result, to maintain the arm segment in place, a moment of magnitude 10.8 Nm is required. This moment is caused by internal forces created by muscle action and ligaments. The deltoid muscle produces the moment exclusively, which is inserted 7 cm distal and 1 cm superior to the shoulder joint center and applies a force at 15 degrees to the arm segment as shown in Figure 4.10 & Figure 4.11.

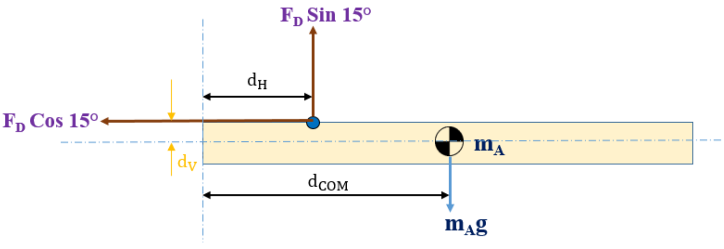


Figure 4.11: FBD represents forces generating moments near the center of the shoulder joint

Using rotational equilibrium at the shoulder joint's axis;

$$\sum M = F_H\, d_V + F_V\, d_H - m_A g\, d_{COM} \qquad \text{(Eqn. 4.8)}$$

Where: F_H is the deltoid muscle's horizontal component of force; d_V is the deltoid muscle's insertion's vertical displacement concerning the shoulder joint; F_V is the deltoid muscle's vertical component of force; and D_H is the deltoid muscle's horizontal displacement concerning the shoulder joint.

$$F_D \text{ Cos } 15° \, d_V + F_D \text{ Sin } 15° \, d_H - m_A g\, d_{COM} = 0$$

$$F_D (\text{Cos } 15° \, d_V + \text{Sin } 15° \, d_H) - m_A g\, d_{COM} = 0$$

$$F_D = m_A g\, d_{COM} / (\text{Cos } 15° \, d_V + \text{Sin } 15° \, d_H)$$

$$= (4*10*0.27) / (\text{Cos } 15° * 0.01 + \text{Sin } 15° * 0.07)$$

$$= 10.8 / (0.0096593 + 0.018117)$$

$$= 389 \text{ N}$$

The magnitude of the components is calculated as follows:

$$F_H = F_D \cos 15° = 389 * \cos 15° = 376 \text{ N}$$

$$F_V = F_D \sin 15° = 389 * \sin 15° = 101 \text{ N}$$

To maintain the arm segment in rotational equilibrium, the force exerted by the deltoid muscle must be around 390 N.

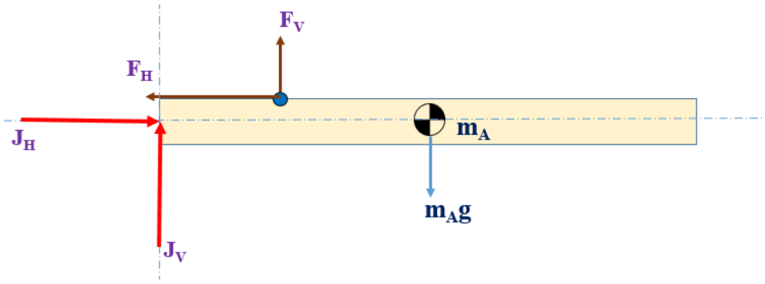


Figure 4.12: FBD includes components of deltoid muscle force and joint force

Figure 4.12 shows an FBD of an arm segment with vertical and horizontal deltoid muscle force components. To counterbalance the stresses exerted on the arm segment and keep it in static equilibrium, the joint force must have both a horizontal and a vertical component.

Adding up the horizontal forces:

$$\Sigma F_H = J_H - F_H = 0 \qquad \text{(Eqn. 4.9)}$$

Where: J_H is the combined force's horizontal component.

$$J_H = F_H = 376 \text{ N}$$

Adding up the vertical forces:

$$\Sigma F_V = J_V + F_V - m_A g = 0 \qquad \text{(Eqn. 4.10)}$$

$$J_V = -F_V + m_A g = -101 + 4.0 \times 10 = -61 \text{ N}$$

Now Pythagoras' theorem may be used to determine the size of the joint force:

$$J = \sqrt{J_H^2 + J_V^2} \qquad \text{……………. (Eqn. 4.11)}$$

$$J = \sqrt{376^2 + 61^2} = 380 \text{ N}$$

Calculating the joint force's angle θ with respect to the horizontal,

$$\tan\theta = J_V / J_H \qquad \text{…..……………… (Eqn. 4.12)}$$

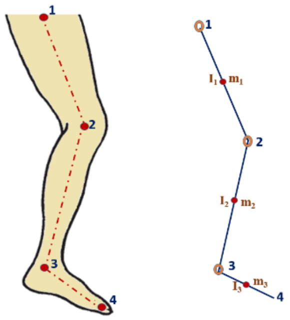
$$\theta = 9.2°$$

As a result, the shoulder joint force operating on the arm segment is 380 N in a 9.2° relative to the horizontal plane. When the joint force is evaluated to the inter-segment force of 40 N acting vertically, it is evident that there is a significant difference.

4.5 FORCES AND TORQUE IN LEG JOINTS

Mathematical models of physical and biological systems are used to get force data and analysis on the human leg. In a link segment model, the forces operating on a body segment may be divided into three categories: inertia forces, internal forces, and external forces (Figure 4.13).

The upward push of the floor on the bottom of the foot is represented by F_1, F_2 is the total of all the pushes and pulls the rest of the body makes on the leg through the hip joint and ancillary muscles, and F_3 is the earth's downward gravitational force on the leg. F_1 strikes the bottom of the leg, F_2 strikes the top, and F_3 strikes somewhere in the center. The sum of these forces is 0 if the leg is in equilibrium.



(a) Anatomical model (b) Link-segment model

Figure 4.13: Relationship between anatomical and link-segment model

When the body is in rotating motion, the forces must be treated differently. The rotating item in rotational equilibrium either stops rotating altogether or rotates continuously. Consider the rigid rod in Figure 4.14, which is pivoted at point X and has the potential to spin in the paper's plane. At r_1 and r_2 distances from the pivot and perpendicular to the rod, F_1 and F_2 forces are applied to the rod within the plane of the paper. The pivot maintains translational equilibrium by applying the necessary force F_3 to the rod. If F_1 and F_2 are both perpendicular to the rod, they are regarded as parallel. They must also be parallel to F_3, as translational equilibrium demands that F_3 equals $F_1 + F_2$, therefore they must be parallel to F_3.

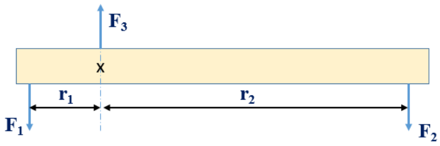
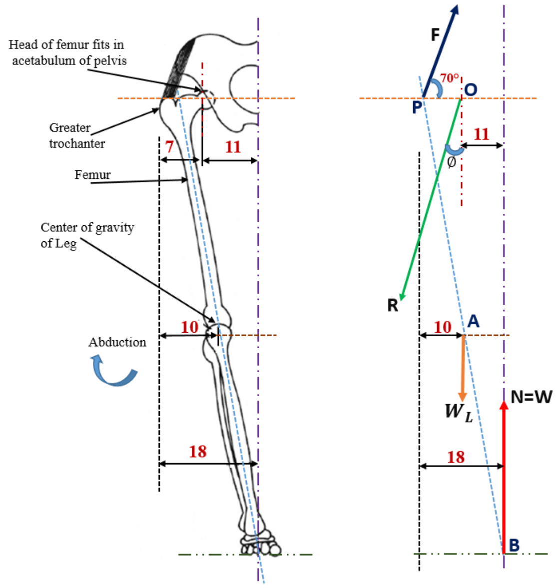


Figure 4.14: A rigid rod that may freely spin around a center at position X

If the algebraic sum of all torques is zero, the rod is in equilibrium:

$$\sum_i \tau_i = \sum_i r_i F_i = 0. \quad \text{…..…………….. (Eqn. 4.13)}$$

The force analysis for a person standing with one leg is mentioned in Figure 4.15. The weight of the person (W) is equal to the normal force (N) of the floor on the foot, which operates under the center of gravity for the entire body of the person. At a 70° appropriate angle, the greater trochanter is subjected to the resultant force (F) of the abductor's muscles. The greater trochanter is roughly 18 cm from the midline, approximately 10 cm horizontally from the leg's center of mass, and approximately 7 cm vertically from the center of the femur's head in an average person. As seen in Figure 4.15 (b), the weight of the leg W_L is typically approximately 1/7 of the person's weight. (Hobbie & Roth, 2007) (Lunn, Lampropoulos, & Stewart, 2016)



(a) Human leg anatomy (b) F.B.D. of force acting on the leg

Figure 4.15: Human leg anatomy with force analysis

F is the total force of the abductor muscles acting on the greater trochanter, R is the force of the acetabulum acting on the head of the femur, and W_L is the weight of the leg acting vertically downward at the center of the leg mass. N is the upward force of the floor acting on the bottom of the foot ($W_L \approx W/7$).

If a person's mass is 80 kg, the weight of the leg is approximately 784.5 N.

$$W_L = W/7 = 112.07 \text{ N}$$

Because the person is stationary, the vertical and horizontal elements of the forces, as well as the total torque, are all equal to zero.

$$\sum F_H = 0\ ;\ \sum F_V = 0; \sum \tau = 0$$

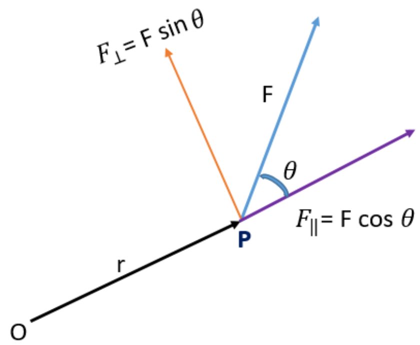


Figure 4.16: An element at point P is subjected to a force F

In Figure 4.16, an element is allowed to spin around point O. Although it applies in any direction at point P, force F, which is positioned in the plane of the paper. The planes of the paper are determined by the vectors r and F if they are not parallel.

The horizontal components of the forces are:

$$\sum F_H = F\cos(70°) - R_H \qquad \text{……………. (Eqn. 4.14)}$$

The forces' vertical components are:

$$\sum F_V = F\sin(70°) - R_V - \frac{W}{7} + W \qquad \text{……………. (Eqn. 4.15)}$$

$$\sum \tau = -F\sin(70°) * 7 - \left(\frac{W}{7}\right) * (10-7) + W * (18-7) \qquad \text{……………. (Eqn. 4.16)}$$

$$6.57 \text{ F} = 10.57\text{W}$$

$$\text{F} = 1.6 \text{ W} \qquad \text{……………. (Eqn. 4.17)}$$

Now, R_H and R_V may be calculated using Equations 4.14 and 4.15.

$$R_H = F\cos(70°) = 1.6 \text{ W } (0.342) = 0.55 \text{ W}$$

$$R_V = F\sin(70°) + \frac{6}{7}W = 1.6 \text{ W } (0.94) + 0.86 \text{ W} = 2.36 \text{ W}$$

$$R = \sqrt{R_H^2 + R_V^2} = 2.4 \text{ W} \qquad \text{……………. (Eqn. 4.18)}$$

The angle $\emptyset$ is calculated from tan ($\emptyset$) = R_H/R_V and is found to be:

$$\emptyset = 13°$$

The solution to all of these equations is:

$$F = 1.6\ W$$

$$R = 2.4\ W$$

If the person with a mass of 80 Kg weighs about 784.5 N then the force acting on the greater trochanter of the femur and the reaction force acting at the head of the femur fits in the acetabulum of the pelvis is calculated from the above equations.

$$F = 1.6\ W = 1.6 * 784.5 = 1255.2\ N$$

$$R = 2.4\ W = 2.4 * 784.5 = 1882.8\ N$$

As a result, there is a gap in the development of foot anthropometry, which may serve as a baseline for the design of prosthetic and orthotic elements. Foot anthropometry has demonstrated that foot proportions vary greatly between individuals, and the significance is that the design of footwear, including prostheses, must take these variations into account to attain the required fitness. This set of calculations concentrates on estimating height and predicting patient weight based on foot dimensions/measurements.