

Kinematics of Muscles and Joints

Biomechanics of Joints

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This introduction to biomechanics aims to show the reader how bioengineers approach the analysis of human joints. It shows particularly that the forces acting on our joints and other internal structures are usually very much larger than the external forces imposed when we interact with the outside world. A clear example of this is that the forces in the joints of the lower limbs when walking are several times larger than our body weight. It is important for the orthopedic surgeon to have an understanding of the mechanical principles that govern the working of the musculoskeletal system, because only that will allow an informed basis for many aspects of orthopedic practice. Although one may “muddle through” on the basis of common sense, a more scientific basis leads to a deeper understanding. This is needed for evaluating the design or fixation of novel joint prostheses, or the design of fracture fixation devices—What loads must they withstand? How best to maintain reduction of a bone fragment? Is the material strong enough?—for example, so that the surgeon has a solid basis on which to choose the best way to treat the patient.

13.1 Basic Concepts

13.1.1 Joint Classification and General Structure

Jargon Simplified: Joint Range of Motion

Both active and passive ranges of motion (ROM) of joints are used: The active ROM is caused by muscle contractions, whereas the passive range is found by an examiner moving the limb. The passive ROM is usually larger, because the muscles remain flaccid and so they do not impinge between the bones as early as actively contracting muscles when the limit of motion is approached. A person’s flexibility is joint specific and so high flexibility in one joint does not guarantee the same amount of flexibility in all other joints.

ROM is measured in degrees, and there are several techniques used to measure the ROM of a joint: Optical, electromagnetic, and inertial sensors can be used, but the most common technology in use is goniometers, which work much like a large protractor with extended arms to improve accuracy.

The joints of the body can be classified as: diarthroses, which are freely movable, amphiarthroses, which are semimovable, and synarthroses, which are nonmovable. This chapter will focus on the most common of the human joint classifications: the diarthrodial joints. These joints are often referred to as synovial joints and can be further classified depending on their shape and the types of movement they allow (Fig. 13.1). Regardless of their subclassifications, all synovial joints share common structural features (Fig. 13.2).

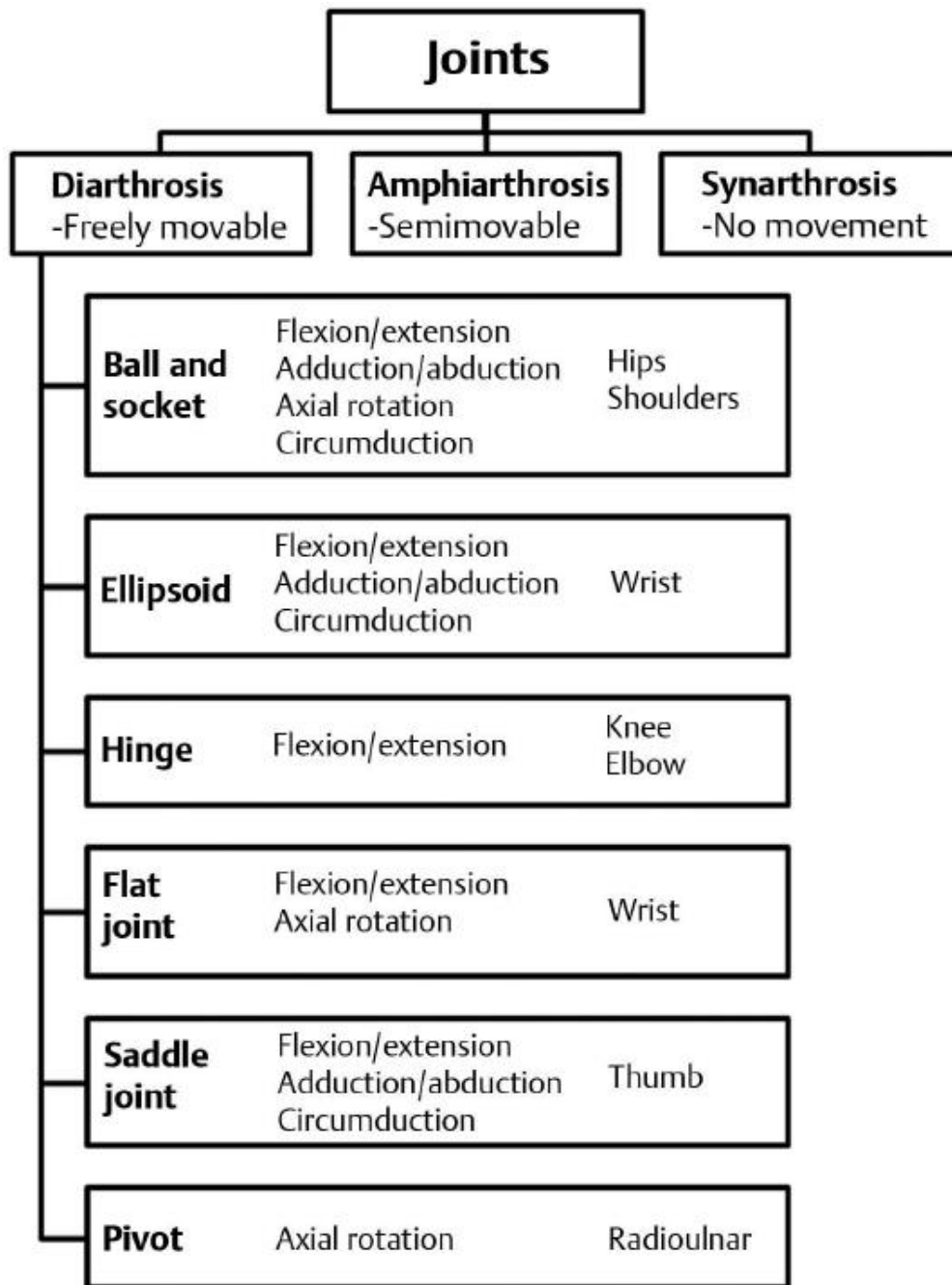


Fig. 13.1 Classification of joints with the most common subcategories for diarthrotic or synovial joints. Subcategories include the most common modes of joint movement and an example.

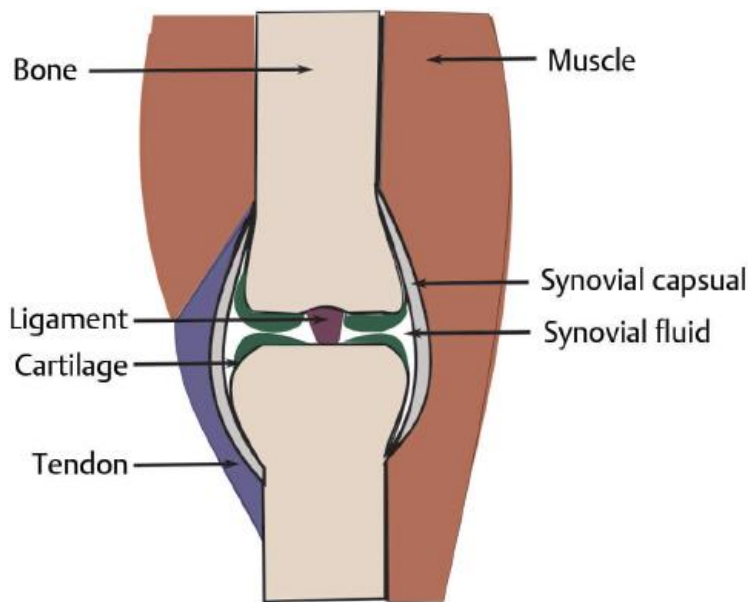


Fig. 13.2 Common structures of a synovial joint.

13.1.2 Static Analysis of Joints

The musculoskeletal system can be thought of as a set of connected links, with the bones acting as beams and the joints as the links between them. Considering this analogy, the movement around the joints can be analyzed much like any other mechanical system. With static analysis, the forces and moments acting around a joint are balanced (that is, they are in both rotational and translational equilibrium) and there is assumed to be no acceleration component to the forces. The concept of static analysis of joints is best explained using an example.

Fig. 13.3 shows an outstretched arm of mass 3 kg (≈ 30 N weight) supporting a dumbbell of mass 5 kg (≈ 50 N weight). The center of mass of the arm will be approximately 40% between the point of rotation and the end of the arm (x_1). The corresponding free body diagram is also shown, where R_X and R_Y represent the reaction forces acting onto the head of the humerus in the horizontal and vertical directions, respectively, and JRF is the compound joint reaction force. FM is a muscle force, WL is the weight of the limb (30 N), and WD is the weight of the dumbbell (50 N). The distances of each force away from the center of rotation of the shoulder are shown by x_1 and x_2 are 0.24 m and 0.6 m, respectively, and MA is the muscle moment arm. Note that the muscle moment arm is perpendicular to the muscle force, FM , which is at an angle of θ from the horizontal limb. While in this static example, θ is constant at 20 degrees, if the arm was moving this angle would continually be changing as would the muscle moment arm.

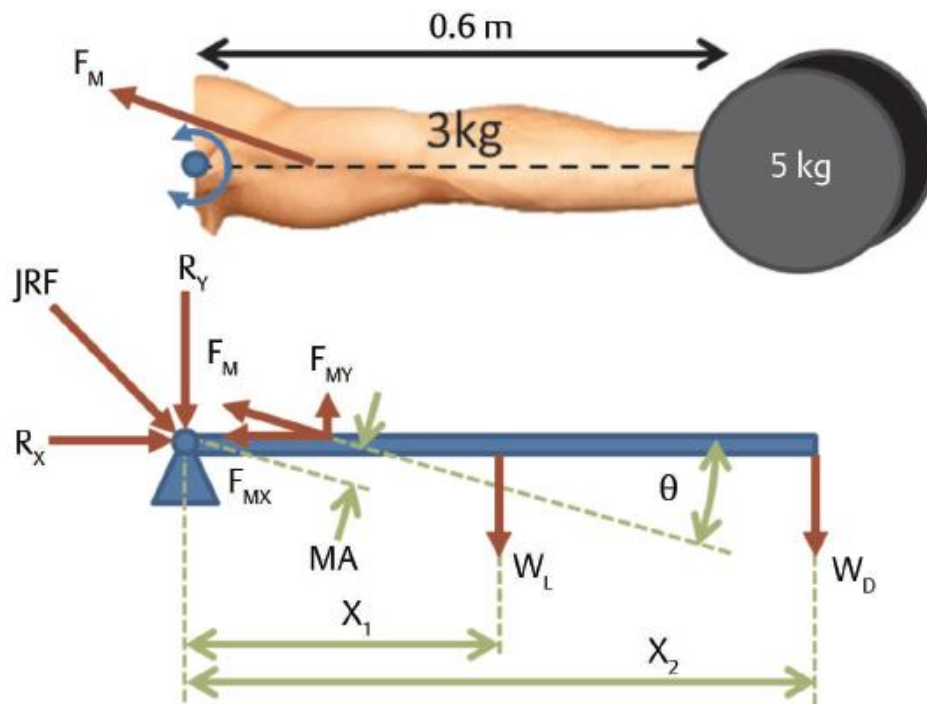


Fig. 13.3 An arm outstretched holding a dumbbell weight and the corresponding free body diagram. Static analysis of the forces and moments required to stabilize the shoulder joint. For details, see text.

Jargon Simplified: Moment

A moment is when a force creates a rotating or pivoting action, and is defined as the product of a force and moment arm (perpendicular distance of the line of action of the force from the pivot point). A moment balance is the sum of all the moments acting about a point; for equilibrium, all anticlockwise and clockwise moments must be equal and opposite.

In order to calculate the reaction forces and moments at the joint, force and moment equilibrium balances are performed.

$$\text{Moment Balance} = F_M \text{MA} = W_L x_1 + W_D x_2$$

$$F_M = \frac{W_L x_1 + W_D x_2}{\text{MA}} = \frac{30 \times 0.24 + 50 \times 0.6}{\text{MA}} = \frac{37.2}{\text{MA}}$$

If

$$\text{MA} = 0.2\text{m}$$

then

$$F_M = 186\text{N}$$

If,

$$\text{MA} = 0.02\text{m}$$

then

$$F_M = 1860\text{N}$$

It can be seen that the muscle force required to support the arm depends greatly on the size of the muscle moment arm. In general, most muscles are attached close to the joint and so they have a small moment arm, which requires a large muscle force in

comparison to the external force at the hand. The example will continue assuming a typical human muscle moment arm of 50 mm giving a muscle force $F_M = 744$ N.

Resolving Forces: The muscular force acts at an angle to the horizontal and thus has both a vertical, F_{MY} , and horizontal F_{MX} , component. These components can be found using simple trigonometry:

$$\begin{aligned}\text{Muscle Force Vertical Component : } F_{MY} &= F_M \times \sin\theta \\ &= 744 \times \sin 20 = 254\text{N}\end{aligned}$$

$$\begin{aligned}\text{Muscle Force Horizontal Component : } F_{MX} &= F_M \times \cos\theta \\ &= 744 \times \cos 20 = 699\text{N}\end{aligned}$$

Force balance: The vertical forces and horizontal forces are independent of each other and so are summed separately.

$$\begin{aligned}\text{Vertical Balance : } R_y &= F_{MY} - W_L - W_D = 254 - 30 - 50 \\ &= 174\text{N}\end{aligned}$$

$$\text{Horizontal Balance : } R_x = F_{MX} = 699\text{N}$$

The joint reaction force is the resultant reaction force at the joint and can be found using the Pythagorean theorem:

$$\text{JRF} = \sqrt{R_x^2 + R_y^2} = \sqrt{699^2 + 174^2} = 721\text{N}$$

The joint reaction force is the equal and opposite reaction to the sum of all the other forces and hence the glenohumeral joint in this example is under 721 N of compression.

The majority of muscles in the body have small moment arms, and thus joint reaction forces are very high in vivo, often up to 15 times the external load (in the example, the 50 N weight gave a joint reaction force of 721 N!). This effect is magnified when additional muscle actions are needed to maintain joint stability, which is accomplished by using opposing agonist and antagonist muscles. An example might be the addition of a triceps tension during elbow joint flexion, which is an antagonist to the biceps and brachialis, adding to the force onto the humeral trochlea.

13.1.3 Dynamic Analysis of Joints

Joint motion occurs when the clockwise and anticlockwise moments about the joint are not equal. The difference between these moments results in an accelerating torque that acts in the direction of the greater moment. The analysis methods are similar to that for a static analysis, with an additional torque variable in the moment balance that is directly proportional to the joint acceleration. This type of dynamic analysis requires use of data such as the inertial properties of the limb segments, and is necessary if accuracy is needed when analyzing movements such as walking (see Chapter 15, “Musculoskeletal Dynamics”).

13.1.4 Joints and Moment Arms

The geometric structure of the bones that surround and make up a joint provide an increased distance between where the muscle force acts and the joint's point of rotation. This creates mechanical advantage and reduces the amount of muscle force required for movement. An example of this is the patella in the knee (Fig. 13.4). The reduced moment arm of the extensor mechanism about the center of rotation after a patellectomy means that a larger muscle tension would be needed to obtain the same knee extension moment. This is one of the reasons why patellectomy is discredited: It makes it very difficult to rise from a chair, for example.

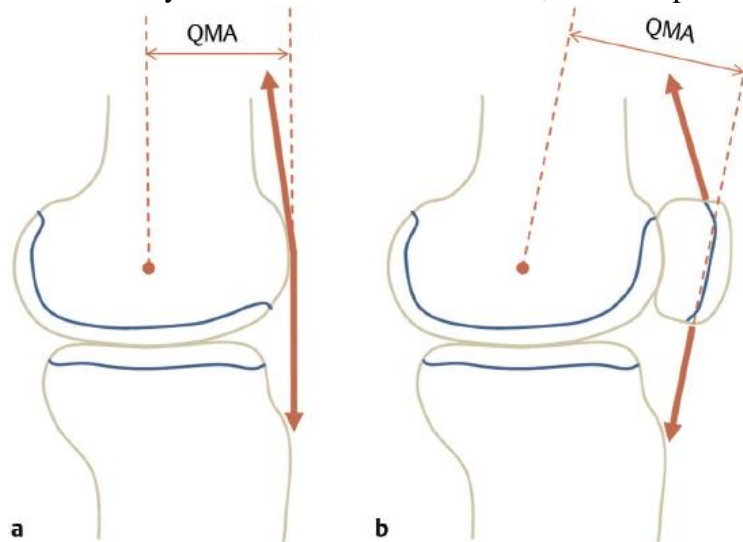


Fig. 13.4 (a) A knee joint without a patella. (b) The human knee (with patella). It can be seen that the extension moment arm of the quadriceps (QMA) is significantly increased by the patella. This means that less muscle force is needed to extend the knee joint. With a smaller muscle force, the knee joint contact force is reduced, which helps protect the cartilage from excessive loading (see section in the text titled “Contact Stress: The Effects of Loads on the Joint”).

13.2 Kinematics

Clinically, the movements of joints are described in relation to the major body planes and axes (Fig. 13.5).

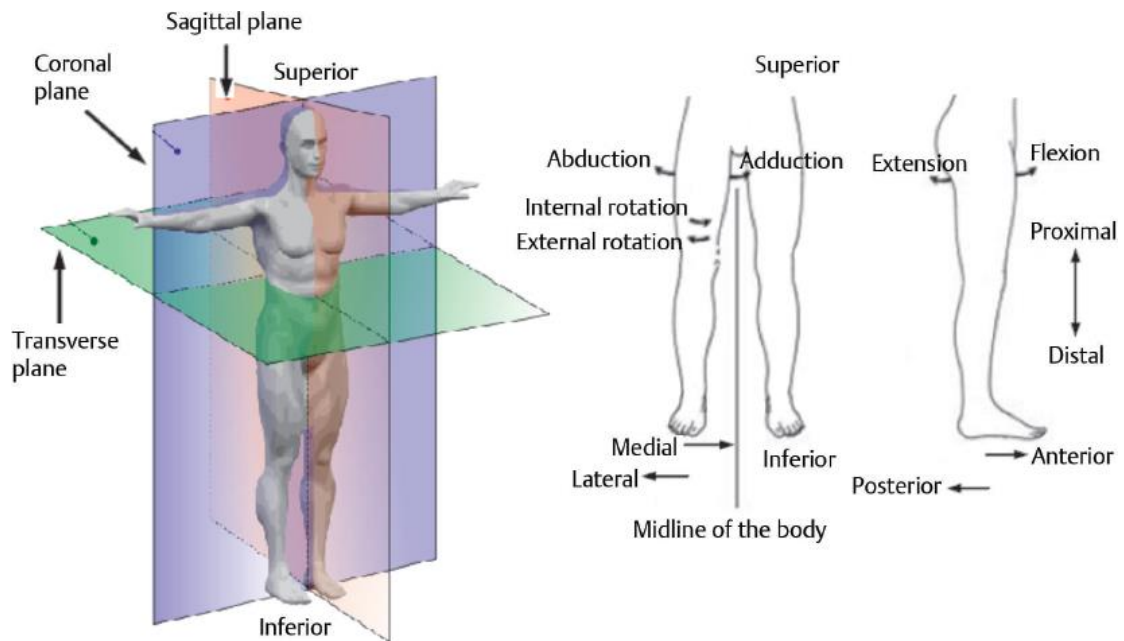


Fig. 13.5 Sketch showing anatomic planes of reference and anatomic directions and movements of the hip joint.

However, movement of the body can be difficult to describe as it does not always take place in single planes and often the center of rotation of a joint can change depending on its orientation. For ease of interpretation of results where the exact degree of rotation is reported, it is recommended that the International Society of Biomechanics definition of joint coordinate systems 1 is used.