Chapter 2
BIOMECHANICS

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Some understanding of the action of forces on bodies and of the reactions of the human body to the application of forces is essential if the therapist is to comprehend the various factors which affect human motion. Mechanics is the study of forces and their effects upon a body; biomechanics is the study of those forces applied to the human body. A good working knowledge of mechanics will often help to isolate the therapeutic problems and suggest a solution.

This chapter will consider the various aspects of mechanics which the therapist will need in order to study the working of the body.

The main areas considered are:

(1) Force and motion
(2) Newton's Laws and their relationship to force and motion
(3) Force analysis
(4) Moments
(5) Friction
(6) Equilibrium and stability
(7) Work, power and energy
(8) Machines based on the principles of moments
(9) The behaviour of materials under stress
(10) Fluid mechanics.

Force and motion

It is difficult to separate force from motion; motion may be considered to be continuing change in position while force is that which generates or modifies motion.

Force

The study of force may be divided into two areas:

(1) *Statics*: the study of the effect of forces on a body in equilibrium, i.e. at rest or in constant motion. No change in the state of motion is produced.
(2) *Dynamics*: the study of forces not in equilibrium. Unbalanced forces produce some change in the state of motion of a body.

In order to study this subject, mass, force and weight should be defined.

Mass
Mass is the quantity of material a body contains. Units of mass: kg.

Force
Force is a push or pull, measured by its effect on a body. A force can:

(a) change or tend to change the shape or size of a body
(b) cause or tend to cause movement of a stationary body
(c) change or tend to change the movement of a body in motion.

expressed as

ss × acceleration

a

force is the newton (N). A newton
s 'a force which, when applied to a
e kilogram, gives it an acceleration
re per second squared'.
may be described as having:

nitude
of application
of action (Fig. 2.1A).

fore known as a *vector quantity* and
epresented by an arrow of specific
oportional to the magnitude of the
nting in the direction of the force (Fig.

a specific type of force and is the effect
th's gravitational force on a body.

is the weight, *m* is the mass and *g* is
ational constant (9.8 m/s²). The gravi-
constant (or gravity) represents the
on of the body towards the earth in

are:

nvolves a change in the position or
body. Motion depends on the appli-
forces. In order to initiate movement,
or slow it down, unbalanced forces

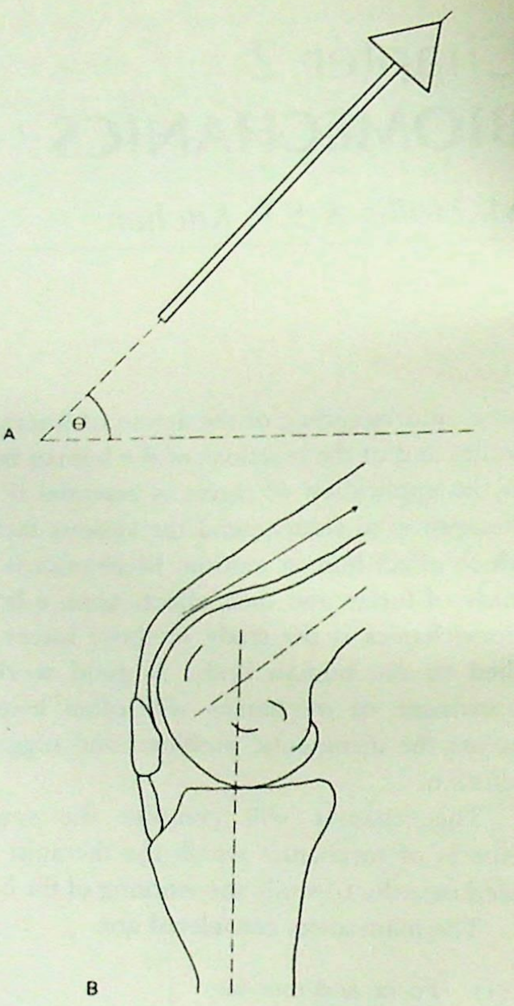


Fig. 2.1 A, A vector: the solid line indicates the magnitude, the arrow tip the direction, angle θ the orientation and the base of the arrow the point of application of the force; B, The force vector applied by the quadriceps muscle to the patella with the knee joint at 50° of flexion.

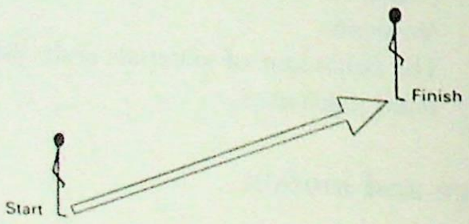
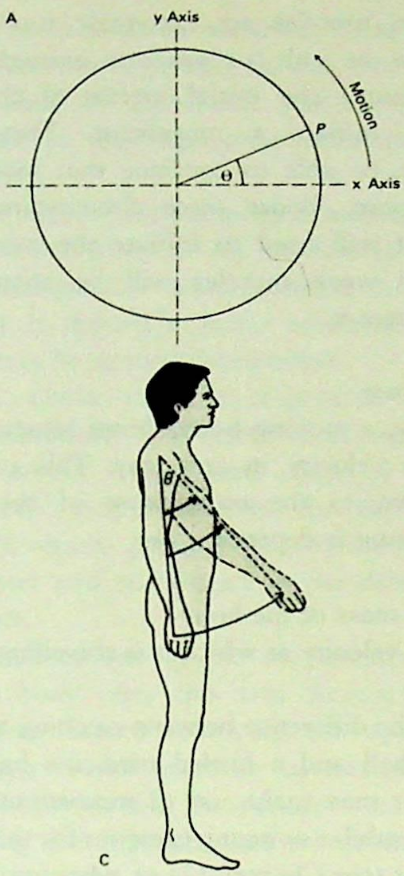


Fig. 2.2 Linear motion.



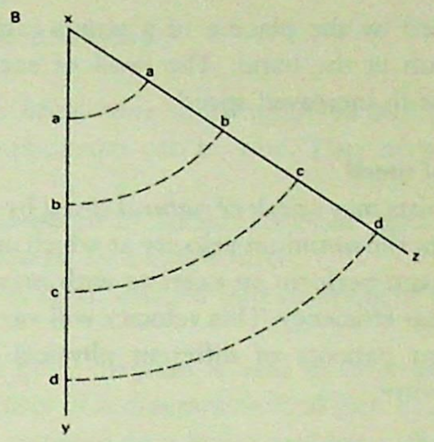


Fig. 2.3 A, Angular motion: angle θ represents the angular displacement between the 'x' axis and position *P*; B, The distance between lines XY and XZ lengthens with an increase in the radius of the arc; C, Angular motion occurring at the shoulder joint.

must be applied. If a body is to remain at rest or in constant motion balanced forces must prevail.

Types of motion

(1) *Linear motion*: linear motion occurs when an object or part moves in one direction only (Fig. 2.2).

(2) *Angular motion*: angular motion occurs when an object describes a circle or arc of motion about a fixed point (Fig. 2.3A–C).

(3) *Curvilinear motion*: a combination of the two is possible and is termed curvilinear motion. This is most often seen in the flight path of a projectile (Fig. 2.4).

Motion is described in the following terms:

(1) *Displacement* (s): how far the object moves: the amount of movement. Units: metres.

(2) *Velocity* (v): how fast the object moves: the rate of change of displacement in time. Units: metres/second.

(3) *Acceleration* (a): any alteration in speed: the rate of change of velocity in time. Units: metres/second^2.

Angular motion and velocity

It should be noted that at a given rate of displacement the velocity of motion of any point along the course of a part moving through an arc will be constant for that point only. The velocity of movement of the point depends on the radius of the arc and corresponding distance to be covered (Fig. 2.3B). Thus (Fig. 2.3C) during flexion of the arm, the hand will be seen to move at a greater velocity than the elbow. Both parts take the same length of time to reach their destination; the hand, however, has to describe a greater distance. This effect would be increased by the placing of a tennis racket or golf club in the hand. The head of each will move with increased speed.

Natural speed

Therapists may speak of *natural speed* by which is meant the optimum velocity at which an individual can perform an exercise with maximum muscular efficiency. This velocity will vary with different patients of different physical builds and ability.

Newton's Laws of Motion

The study of the behaviour of forces in the production of motion is based on Newton's three laws:

Newton's First Law of Motion

Every object will remain at rest or continue to move with uniform velocity unless acted upon by an unbalanced force.

No alteration in condition can occur without the action of a further force.

Inertia

Newton's first law is often referred to as the *Law of Inertia*. Inertia may be defined as the reluctance of a body of mass 'x' to start moving. The greater the mass of a body the greater the inertia.

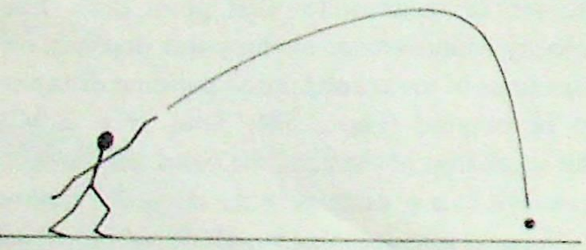


Fig. 2.4 Curvilinear motion.

When muscles are extremely weak, they may not be able to generate enough force to overcome the initial inertia of the part and so initiate a movement. They may, however, be able to continue that movement once begun. Under these circumstances the therapist will need to initiate the movement and the weak muscles will be encouraged to continue it.

Momentum

Similarly, a moving body shows reluctance to alter its velocity in any way. This property is known as the *momentum* of the body. Momentum is dependent on:

- The mass of the body
- The velocity at which it is travelling.

Hence the difference between catching a tossed games ball and a hurled medicine ball! The therapist may make use of momentum when using pendular swinging exercises for the shoulder joint (see Chapter 12) or when mobilizing the limbs in suspension.

Newton's Second Law of Motion

When a force acts on an object the change in motion experienced by the object takes place in the direction of the force and is proportional to the size of the force and the duration for which the force acts.

Any change in motion is due to the application of an unbalanced force. The application of such a force may:

(1) Initiate movement
(2) Increase the velocity of movement
(3) Decrease the velocity of movement
(4) Change the direction of movement.

All forces capable of achieving these changes are contact forces; that is, the object must be touched by the force. The exception to the rule is the one great attraction force of gravity.

Any change in the velocity of a moving body is called *acceleration*. An increase in velocity represents positive acceleration; a decrease in velocity is termed negative acceleration. The latter may be termed deceleration.

The above may be re-phrased as *Law of Acceleration*. 'The acceleration experienced by an object when acted upon by a force is directly proportional to the size of the force, inversely proportional to the mass of the object and takes place in the direction of the force.'

All alterations in the movements of the human body obey this law. Acceleration of movement occurs following the application of greater muscle force in the existing direction of movement. Deceleration may occur following the application of a breaking force, provided by an opposing group of muscles. Deceleration may also occur as the result of a loss of force in the primary muscle group as a result of fatigue or reduced neurological stimulation.

Newton's Third Law of Motion

To every action there is an equal and opposite re-action.

Whenever a force is applied to an object, as when the weight of the body is applied to the floor in standing, an equal reaction force is returned by the floor to the foot. This is demonstrated in Fig. 2.12, showing the phases of gait.

Force analysis

Forces often have to be analysed before their full implications can be seen. They may be:

(1) *summated*: added together and represented by a single force
(2) *resolved*: divided into component parts.

A free body diagram is used in force analysis; it consists of a diagrammatic sketch having all forces imposed on it in vectoral form (Fig. 2.5A and B).

Summation of forces

Forces rarely present singly. Often, more than one force will affect a part and it will be necessary to summate them in order to appreciate

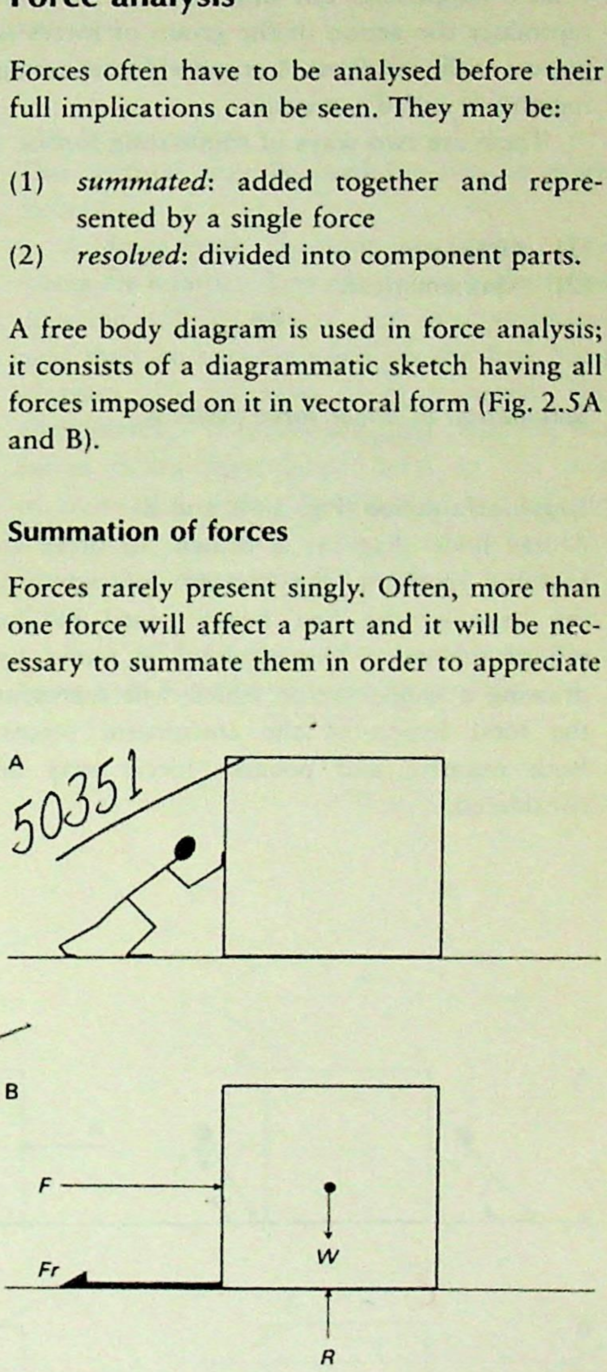


Fig. 2.5 A, Man pushing object; B, Free body diagram to show forces present in (A) in vectoral form. *F* – force applied by man. *W* – weight of box. *R* – reaction force. F_r – frictional resistance.

hat is happening. The single force which can eproduce the action of the group of forces is nown as the *resultant*. A group of forces acting ogether is called a system.

There are two ways of summating forces:

1) Graphical
2) Mathematical.

Summation of linear force systems

Graphical solution (Fig. 2.6A and B)
A free body diagram is drawn. In order to find the resultant, the vectors are redrawn, the head of the first being joined to the tail of the next. The resultant is found by drawing a single vector which will represent the total length of the constituent forces. Both negative and positive forces may be considered.

Mathematical solution

$R = F1 + F2 + F3 + [-F4] \ldots$

$R = \sum F$

where R is the resultant, F is the vectoral force, and $\sum$ is the sum of.

Forces directed towards the right – positive;
Forces directed towares the left – negative.

Complex systems are often regarded as linear in order to simplify the mathematics.

Summation of co-incident, co-planar force systems

Co-incident forces originate or terminate at a single point. Co-planar forces act within a single plane.

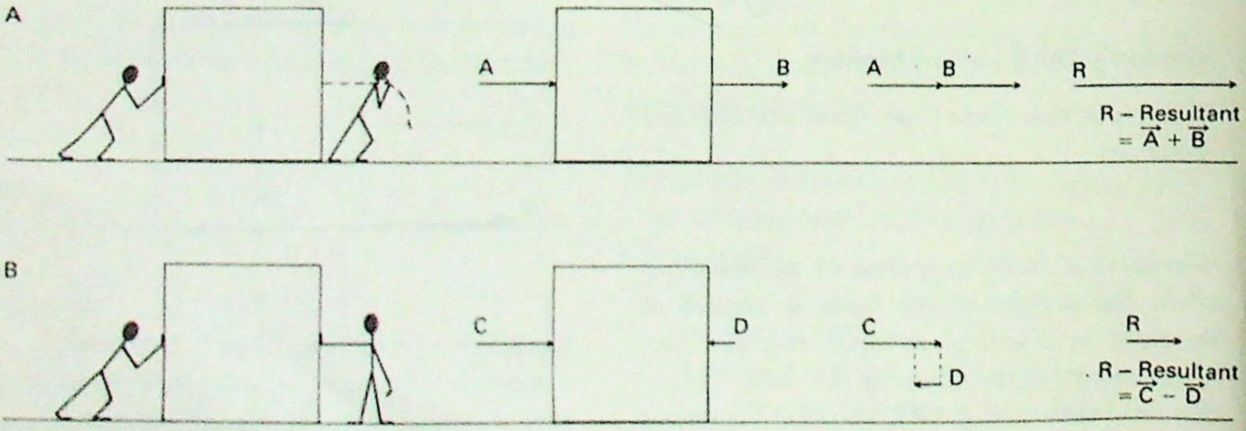


Fig. 2.6 Graphical summation of forces. A, Summation of two forces acting in the same direction; B, Summation of two forces acting in opposite directions.

Forces acting both in a single plane and through one point may be summated either graphically or mathematically.

Graphical solution

There are two types of summating graphically.

Parallelogram of forces

This method may be used for two forces.

A free body diagram is drawn (Fig. 2.7A). A parallelogram of forces is then constructed as in Fig. 2.7B. The resultant may then be imposed as in the diagram. This method is satisfactory for use with many muscular examples. Figures 2.7C and 2.7D show its application to the sternal and clavicular fibres of pectoralis major. Other examples would be the anterior and posterior fibres of deltoid, the two heads of gastrocnemius and both sets of oblique abdominal muscles.

Use of coordinates

This method may be used for two or more forces.

A free body diagram is drawn. The forces are numbered progressing in a clockwise direction (Fig. 2.8A). A set of coordinates may then be superimposed on the free body diagram. The position of F_1 is noted. The coordinates and forces are then redrawn, the forces being reproduced head to tail and in numerical order. Finally, the tail of the first vector is linked to the head of the last. This vector represents the resultant force (Fig. 2.8B).

Fig. 2.9A–C shows the same procedure being used for a more complex problem.

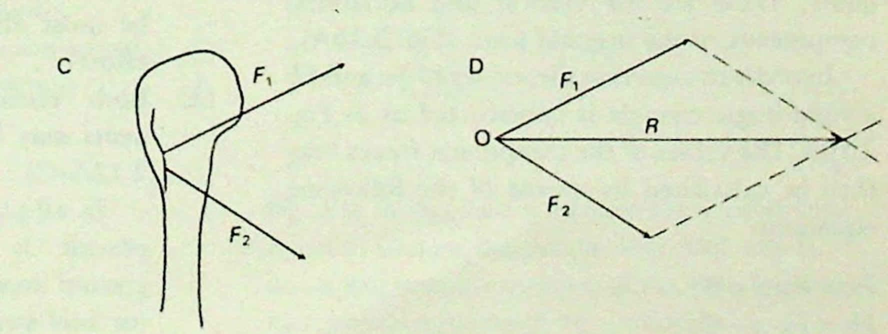
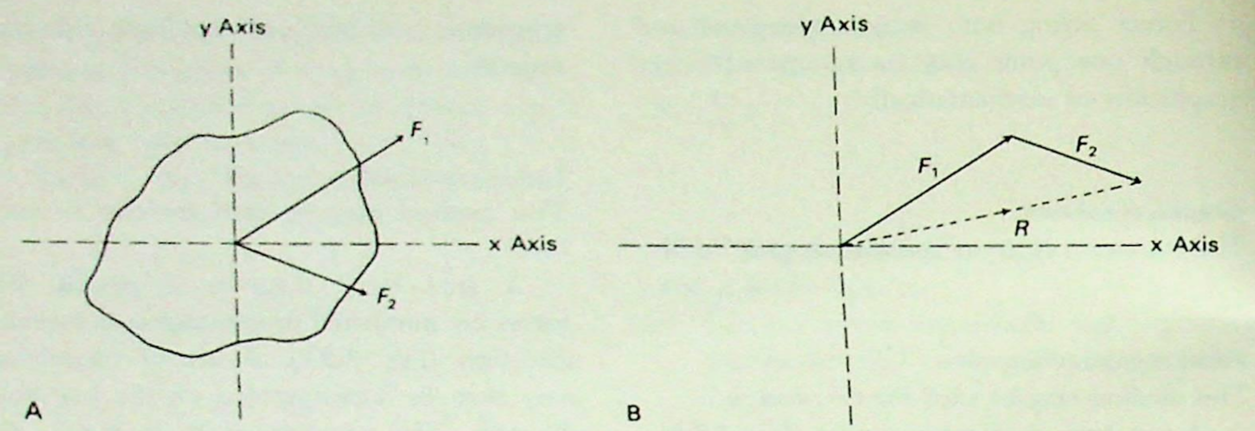


Fig. 2.7 Graphical summation of forces. A, Free body diagram; B, Parallelogram of forces: *R* – resultant force; C, Anatomical example: pectoralis major; D, Parallelogram of forces – pectoralis major. F_1 – clavicular fibres. F_2 – sternal fibres. The resultant gives rise to adduction of the upper limb.



ig. 2.8 Use of coordinates in the summation of forces. A, Free body diagram, having coordinates imposed; , Summation of forces, showing resultant.

Mathematical solution

Equation: $R = (Fv_1 + Fh_1) + (Fv_2 + Fh_2) + \ldots$

or

$$R = \sqrt{(\sum Fv)^2 + (\sum Fh)^2}$$

where R is the resultant, $\sqrt{}$ is the square root and $\sum$ is the sum of.

Fv – force: vertical component (see resolution of forces).
Fh – force: horizontal component (see resolution of forces).

Resolution of forces

It is possible to divide any single force into a number of components; two are normally adequate. These are the vertical and horizontal components of the original force (Fig. 2.10A).

In order to ascertain the values of Fv and Fh a right angle triangle is constructed as in Fig. 2.10B. The values of the component forces may then be calculated by means of the following equations:

$Fv = F\sin - \theta$
$Fh = F\cos - \theta$

The following examples will show the importance of component forces.

(1) A force of 10 newtons (10 N) is applied by the therapist to the leg of the patient at an angle of 60° (Fig. 2.11A). The component forces are calculated (Fig. 2.11B and C):

$Fv = F\sin\theta$	$Fh = \cos\theta$
$= 10 \times \sin 60$	$= F\cos 60$
$= 10 \times 0.87$	$= 10 \times 0.50$
$= 8.7\,\text{N}$	$= 5.0\,\text{N}$

Fv is the effective force for resisting the upward movement of the thigh; Fh is wasted effort on the part of the therapist. Therefore, all resistance should be applied at an angle of 90° to the part in order to be most effective and eliminate wasted effort.

(2) Both vertical and horizontal components may be important, as in gait (Fig. 2.12A–C).

In all phases of gait the vertical component is responsible for providing ground support. In the phase of restraint (or heel strike), it is the horizontal force

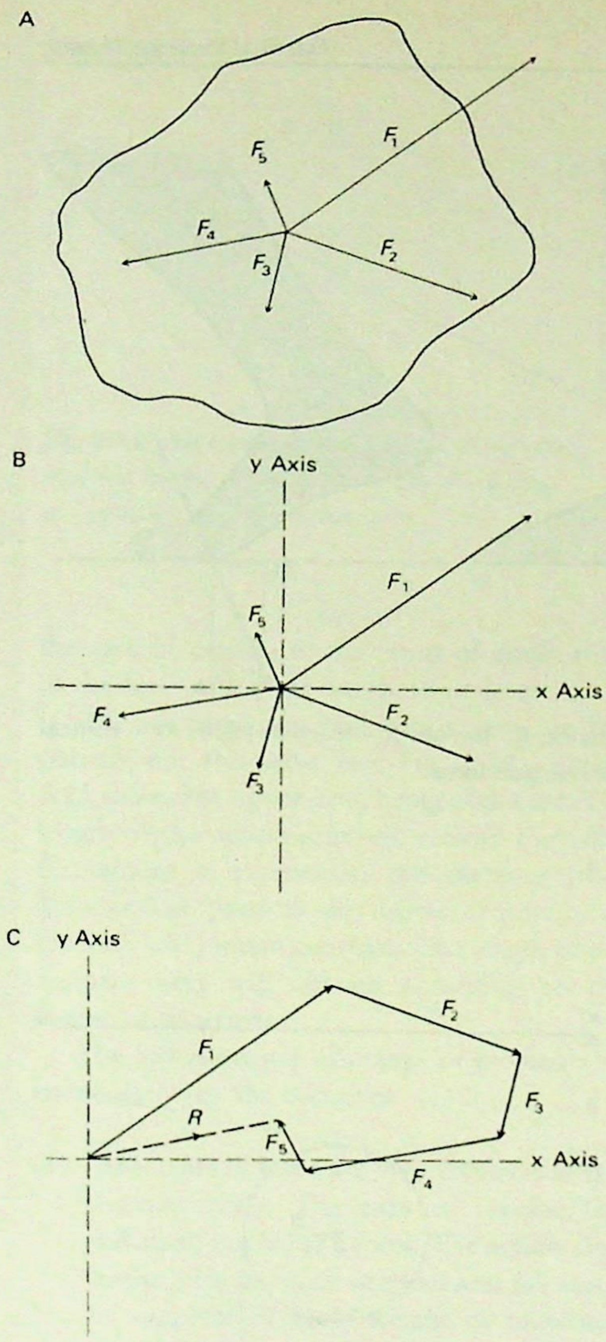


Fig. 2.9 A, Free body diagram; B, Forces superimposed on coordinates; C, Forces joined head to tail to give resultant. F_{1-5} – Forces. *R* – resultant.

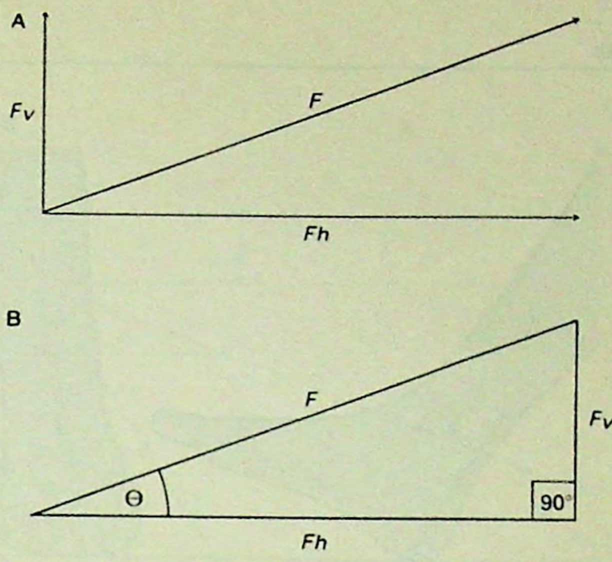


Fig. 2.10 A, Resolution of forces into horizontal and vertical components; B, A right angle triangle incorporating the two component forces. *F* – force. *Fv* – vertical component. *Fh* – horizontal component.

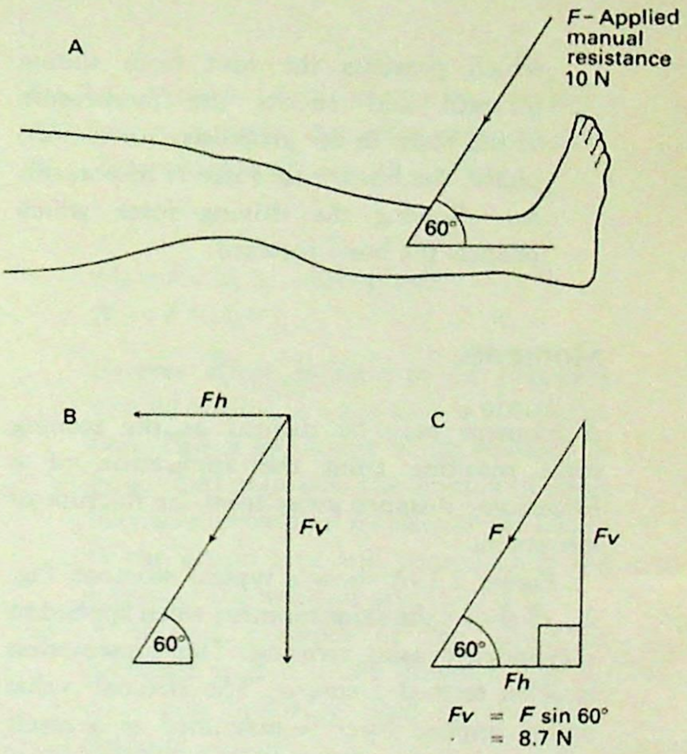


Fig. 2.11 A, Application of force to the lower limb; B and C, Vectoral diagrams to show that only *Fv* resists the upward movement of the limb. *F* – force. *Fv* – vertical component. *Fh* – horizontal components.