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# PART I ORTHOPAEDIC BIOMATERIALS AND THEIR PROPERTIES



Just as there are three states of matter: solid, liquid and gas, there are three basic forms of solid materials: metals, ceramics and polymers. A composite is formed when any of the types of materials combine in an insoluble state. This radiograph shows all four types of solid material in function in a total hip replacement. The internal structure of the materials produces their unique physical properties, which are utilised in designing orthopaedic implants.

# INTRODUCTION TO ORTHOPAEDIC BIOMECHANICS

# Introduction to orthopaedic biomechanics

Orthopaedic surgery is the branch of medicine that deals with congenital and developmental, degenerative and traumatic conditions of the musculoskeletal system. Mechanics is the science concerned with loads acting on physical bodies and the effects produced by these loads. Biomechanics is the application of mechanics to biological systems. Therefore, orthopaedic biomechanics is about the effects of loads acting on the musculoskeletal system only or with the associated orthopaedic interventions.

Mechanics, and therefore biomechanics, is divided into two main domains:

- Statics is concerned with the effects of loads without reference to time. Static analysis is applied when the body is stationary or at one instant in time during dynamic activity.
- Dynamics addresses the effects of loads over time. It is further divided into two main subjects:
  - Kinematics describes motion of a body over time and includes analyses such as displacement, velocity and acceleration.
  - *Kinetics* is the study of forces associated with the motion of a body.

The main functions of the musculoskeletal system are to support loads and to provide motion of body segments. These two functions come together to achieve the musculoskeletal system's third main purpose: to provide locomotion, i.e. movement from one place to another. These are all mechanical tasks and therefore mechanics can be applied to the musculoskeletal system in the same way as to ordinary mechanical systems. Biomechanics is, in fact, a fundamental basis of orthopaedic practice: the mechanics of the body guide the principles of orthopaedic interventions. Biomechanics is also central to the design and function of modern orthopaedic devices. The orthopaedic surgeon therefore has the responsibility to understand musculoskeletal biomechanics and materials and structural limitations of orthopaedic devices and the principles of their application in order to minimise failure.

This chapter introduces fundamental biomechanical concepts. It defines different types of loads and material properties, and the relationships between them. All the physical interactions between loads and materials can be considered in terms of the two domains of biomechanics mentioned above: statics and dynamics. This book, in fact, focuses on these basic interactions; the different sections simply consider the fundamental statics, kinematic or kinetic aspects of the musculoskeletal system and/or orthopaedic interventions. The basic principles are introduced and explained in the initial sections, and then integrated together in the latter sections. Therefore, even if the biomechanical concepts become complex, they can always be considered in terms of statics, kinematics and kinetics.

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Fig. 1.1 Orthopaedic surgery is the branch of medicine that deals with congenital and developmental, degenerative and traumatic conditions of the musculoskeletal system. Although it is a surgical discipline, over two-thirds of patients with orthopaedic issues are managed with non-surgical treatments.



# Fig. 1.2 Biomechanics merges together three sciences: anatomy, physiology and mechanics



**Fig. 1.3** The loads acting on the musculoskeletal system can be considered in the same way as averages in mathematics. The average of a data set can be represented by (a) mean, (b) median or (c) mode – the average that is considered depends on the conditions of the data set. In the same way, loads acting on the musculoskeletal system can be represented by force, stress or strain – the load that is considered depends on the conditions of the loading situation.



Fig. 1.4 Orthopaedic biomechanics is a fundamental basis of orthopaedic practice. The understanding of biomechanics is as essential in orthopaedics as the understanding of properties of the different types of sutures and needles in surgical practice.

# INTRODUCTION TO ORTHOPAEDIC BIOMECHANICS

# FORCE

## Force

Force is a simple way of representing load in biomechanics. Force is defined as the action of one object on another. Therefore, there must be interaction between two objects to produce a force. Force can have two effects on the object it is acting upon: it can change the shape and/or the state of motion of the object.

Force is a vector quantity, which means that it has a magnitude and a direction. Force, in fact, has three characteristics: magnitude, direction and point of application; and direction is further divided into 'line of action' and 'sense' of the force. All these factors determine the effect of a force on an object. In diagrams, force is drawn as a vector arrow that represents these four characteristics.

When there are multiple forces acting on an object, they can be resolved into a single 'resultant' force that has the same effect as all the other forces acting together. However, forces cannot just be added together, as their direction must also be taken into consideration. A single force can also be broken down into two component forces, which are usually taken perpendicular to each other as 'rectangular' components.

### Newton's laws of motion

A force can change the motion of an object. Newton's laws of motion explain the relationship between force and motion:

- Newton's first law states that a resultant force must act on an object to change its state of motion. Therefore, a stationary object remains stationary and a moving object maintains its velocity, i.e. speed and direction, unless a resultant force acts on it. This law shows that objects have an inherent reluctance to change in their motion. This built-in resistance to change in motion is known as inertia. Inertia is directly proportional to the mass of an object.
- Newton's second law states that a resultant force leads to a change in momentum of an object. Therefore, a resultant force causes an object to accelerate (or decelerate).
  - This law shows that force is directly proportional to acceleration.
- Newton's third law states that, for every force, there is an equal and opposite force. As force is basically an 'action', therefore every action has an equal and opposite reaction.

This law shows that forces *always* act in pairs and that the two forces are *always* equal in magnitude but opposite in direction. These forces do not simply cancel each other out because they are acting on different objects.

Newton's laws of motion are principles of interaction between different forces and between forces and the material world. These are fundamental to understanding the biomechanics of the musculoskeletal system (Table 1.1).

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# Table 1.1. Forces acting on the musculoskeletal system

Two types of forces act on an object: internal and external forces. Internal forces are the molecular forces found within the object. These are expressed in all directions. Internal forces do not have a specific action on the object, but instead hold it together. Internal forces are considered to be unlimited, but with the overall effect of producing no resultant action on the object. Different components of the musculoskeletal systems, e.g. bones and muscles, all have internal forces acting within them.

External forces are the usual forces that represent the action of one object on another. External forces acting on the musculoskeletal system arise due to *the action of another object on the musculoskeletal system*. External forces are produced in only three ways in the musculoskeletal system:

- · action of a part of the body, e.g. muscle contraction
- action of gravity of Earth, i.e. weight
- reaction\* from other objects, e.g. the ground.

Joint reaction\* force, or joint force, is an unusual internal force. It acts within a joint and holds it together, but its point of application is at the contact point between two bones. Therefore, it acts within a structure, i.e. a joint, as well as between two structures, i.e. bones. As a result, although joint reaction force is an internal force, it can also be considered as an external force. Therefore, the fourth external force considered in the musculoskeletal system analyses is:

• joint reaction force.

\* The term 'reaction' in this context simply means 'contact', so a reaction force is due to contact between two objects.

FORCE

# MOMENT OF A FORCE

# Moment of a force

A force acting on an object can cause it to rotate. This turning effect of a force is called the moment or torque. The moment of a force depends on the magnitude of force and perpendicular distance from the force to the axis (also known as the lever arm):

Moment  $[Nm] = Force [N] \times Distance [m]^*$ 

Moments are conventionally described as clockwise or anticlockwise.

### Couple

A couple is formed when two forces acting on an object are equal in magnitude and opposite in direction, but have different (but parallel) lines of action. A couple produces no resultant force; it only produces a moment on the object.

## Conditions of equilibrium

In equilibrium, an object maintains its state of motion, i.e. a stationary object remains stationary and a moving object maintains its velocity. An object is in equilibrium only when:

• there is no resultant force acting on it, i.e. the sum of all forces is zero

• there is no resultant moment acting on it, i.e. the sum of all moments is zero.

This is the application of Newton's first law of motion.

#### Levers

A lever is a simple machine that operates on moments. It consists of a rigid bar that rotates about an axis, and has two forces acting on it: an applied force that works against a resistance force. The lever amplifies either the magnitude of applied force or the range and speed of motion it produces. There are three types of levers:

• First-class lever: Axis is between applied force and resistance.

Force amplification. When the axis is closer to resistance, the applied force has a longer lever arm; therefore, less force is required to overcome resistance.

Motion amplification. When the axis is closer to applied force, resistance has a longer lever arm; therefore, greater force is required to overcome resistance, but the resistance moves through a larger range of motion or at greater speed than the applied force.

- Second-class lever: Resistance is between axis and applied force.
- Force amplification. Applied force has a longer lever arm; therefore, less force is required to overcome resistance. • *Third-class lever*: Applied force is between axis and resistance.

Motion amplification. Resistance has a longer lever arm; therefore, greater force is required to overcome resistance, but the resistance moves through a larger range of motion or at greater speed than the applied force.

#### Levers in the musculoskeletal system

Levers are commonly found in the musculoskeletal system: bones represent rigid bars, joints represent axes, and the external loads represent applied force, e.g. muscle contraction, and resistance, e.g. body weight and external contact forces. Most of the anatomical levers are third-class; this arrangement promotes the musculoskeletal system to be designed for speed and range of motion at the expense of force.

\* Square brackets show SI (International System) units of physical measurements or chemical symbols of elements and compounds.

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# **MOMENT OF A FORCE**





Fig. 1.7 A couple produces only a moment, but no resultant force, on an object.

Fig. 1.6 Moment = Force  $\times$  Distance



R

Second-class lever











Fig. 1.8 A lever is a simple machine that operates on moments. The illustrations show the arrangement of axis (A), applied force (F) and resistance (R) in first-, second-, and third-class levers. Most of the levers in the musculoskeletal system are third-class.

# STATIC ANALYSIS

# Static analysis

Static analysis is an engineering method of analysing forces and moments produced when objects interact. There are a number of steps to applying static analysis.

Step one. A dynamic system is simplified to a static system at one instant in time. Therefore, all interacting objects are taken to maintain their relative positions.

This removes the need to deal with parameters of dynamic motion, such as displacement, velocity and acceleration. Step two. As static analysis of all the forces in three dimensions is too complicated, the analysis is limited to the main (usually up to three) forces and their moments in one plane only.

In this step, the relevant 'co-planar' forces are isolated from the complex three-dimensional systems of forces. Any 'simplifying assumptions' that have a bearing on the analysis are stated and their rationale explained, e.g.

forces acting at an angle could be assumed to act in a vertical direction to make calculations manageable. A static situation can justifiably have different solutions, provided the supporting assumptions are valid.

Step three. A 'free-body force diagram' is drawn of the object under consideration, and all the forces acting on it are identified.

This is a simple but carefully drawn diagram, so that the forces are accurately represented in terms of their magnitude, direction and point of application with reference to the object. Newton's third law of motion is used to determine any 'reaction' forces acting on the object, e.g. ground reaction force.

Normally, more than one free-body diagram can be drawn for the same situation. The selection of free-body diagram for use often depends on the information available.

Step four. The conditions of equilibrium are applied to the free-body diagram, and any unknown forces and moments acting on the object are calculated.

Since the object maintains its relative position, the sum of all the forces and moments acting on it must be zero. This is the application of Newton's first law of motion.

The simplifying steps and assumptions applied mean that static analysis provides an estimation of the minimum magnitude of forces and moments acting on an object.

### Free-body force diagram

A force is produced by interaction between two objects, and it acts upon one of them. It is ineffective to represent all the forces on all the interacting objects in a particular situation. Instead, a free-body force diagram is used to show all the forces acting on just one object. The free-body force diagram therefore isolates an object and the forces acting *on it* – this is an essential requirement before applying the conditions of equilibrium to the object.

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# **STATIC ANALYSIS**



**Fig. 1.9 A free-body force diagram is useful for isolating an object and the forces acting on it**. It helps to simplify interactions between several objects. A simple example of a person standing on Earth involves four forces, which can be represented on separate free-body force diagrams for the (b) person and (c) Earth. It is first assumed that they are static with respect to each other, and that there are no other forces acting on them. Normally, only one of these free-body force diagrams is required, based on the object under consideration and information available.



**Fig. 1.10** This free-body force diagram shows the forces acting on a person whilst running. Here, a dynamic situation is simplified to a static situation at one instant in time. Although the force from air resistance acts over the whole body, in this free-body force diagram it is assumed to act collectively as a point load. In order to take a step forward, the person lifts one foot off the ground and pushes off with the other foot. The supporting foot exerts a contact force on the ground acting backwards. Friction is equal and opposite to this force and prevents the foot slipping backwards. Friction therefore acts forwards and provides motive force, i.e. a force that drives something forwards. The ground reaction force is equal and opposite to body weight. As this is a free-body force diagram of the person, it is not necessary to represent the forces acting on the ground.

# STATIC ANALYSIS APPLIED TO THE MUSCULOSKELETAL SYSTEM

# Static analysis applied to the musculoskeletal system

Static analysis can be applied to the musculoskeletal system to estimate unknown forces, i.e. muscle and joint reaction forces, produced during normal everyday activities.

A number of simplifying assumptions have to be made in order to apply static analysis to a biological system in the same way as in general mechanics. The following general assumptions apply to most static analyses of the musculoskeletal system, and further specific assumptions must also be applied to each situation.

### Static analysis

- The overall assumption in static analysis is that a limited two-dimensional analysis can provide a realistic estimation of the actual forces and moments.
- Average measurements of the human body, e.g. length and weight of limb segments, are usually taken from the reference anthropometric data.

#### Bones

• Bones are rigid bars of a lever. They transmit forces, but are not deformed by them.

#### Joints

• Joints are frictionless hinges. Other joint movements, e.g. rotation and translation, are ignored.

#### Forces

- Static analysis is commonly applied to the musculoskeletal system to estimate joint reaction force. Joint reaction force is an internal force in absolute terms, but is considered as an external force in static analysis. It is considered to be a compressive force that holds a joint together. All other internal forces are considered to cancel each other out (see page 5 for further information).
- The only external forces that can be applied to the musculoskeletal system are weight of the body segments, reaction force from other objects and muscle contraction.
- Muscles are the only soft tissues that actively produce force. Forces produced by other soft tissues, e.g. joint capsule and ligaments, are ignored.
- Muscles produce only tensile force, i.e. there is no compressive component to their action.
- The main group of muscles produces all of the force for a particular movement, e.g. triceps contraction produces elbow extension, and there is no other agonist or antagonist muscle action.
- The line of application of force is taken to be along the centre of the area of muscle cross-section. The point of application of force is where the muscle inserts onto the bone.
- All forces are taken to be as point loads, i.e. act at a specific point; instead of as distributive loads, i.e. act over a large area. The weight of an object or a body segment is taken to act at its centre of gravity. This is the average position of an object's weight distribution. In simple solid objects, e.g. a ball, the centre of gravity is located at the geometric centre; in objects with non-uniform weight distribution, it is closer to where most of the weight is located.