

Anthony M.J. Bull
Jon Clasper · Peter F. Mahoney
Editors

Blast Injury Science and Engineering

A Guide for Clinicians
and Researchers

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Part I

Basic Science and Engineering

William G. Proud

1.1 Overview

The basis of blast injury lies in the effects of an explosion and, by extension, in the use of explosives. There are many books on explosives that start with a historical summary of the discoveries and personalities involved before developing the theories and quantitative measure of explosive chemistry, physics and engineering. This is useful information, however, in this chapter the aim is to present the reader with a timeline of events working from the point of activation of the initiator to the arrival of the blast wave at the human body or target. On this timeline the steps will be presented in a simple, non-technical way introducing the basic concepts and placing the information within the wider context. The amount of mathematical derivation is kept to a minimum; for those who wish greater depth, a selection of references is provided to allow for further study.

2. Provide an outline of how mines, blast and fragmentation work
3. Describe the energy release process and the efficiency of the process
4. Describe and distinguish between waves transmitting in solids, liquids and gases
5. Describe the range of fragment sizes and velocities
6. Provide an overview of shock and blast wave propagation
7. Outline how waves expand and interact with the surrounding environment

1.3 Explosives and Blast: A Kinetic Effect

Explosives form part of a range of materials classified as ‘**energetic materials**’, other members of this class include propellants and pyrotechnics. The distinguishing feature of energetic materials compared to other materials is in the very fast rate of energy release. The energy release rate determines the application of the energetic material.

The basic chemical components involved are a fuel, an oxidiser and a material that allows a rapid ignition of reaction. In terms of total energy released energetic materials are not particularly distinguished from other chemical reactions, petrol and butter release more energy per molecule when oxidised than tri-nitro toluene (TNT) for

1.2 The Aims of this Chapter

1. Introduce some fundamental aspects of explosives and timescales

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example. This difference is that while petrol needs to be mixed with air and then set alight, the explosive comes with the fuel and oxidiser intimately mixed, sometimes with both fuel and oxidiser present in the same molecule. Within energetic materials the use of the chemical or composition gives information on the reaction rate.

Sound is a low magnitude stress wave, it propagates through air causing a very minor change in the density of the air and moves at a fixed velocity. An **explosion** is a term used to describe the rapid expansion of gas, it may be from the rupture of a pressure vessel, for example, a gas cylinder, the sudden vaporisation of a liquid, for example, water exposed to hot metal, or by a rapid chemical reaction as seen in an explosive. The energy associated with a blast wave causes significant compression of the air through which it passes and the blast wave travels at a velocity faster than the sound speed in air.

High Explosives, correctly called **High Order Explosives** involve materials like TNT, HMX, RDX and PETN often mixed with other chemicals which make the explosive composition more stable, easier to industrially process or fit into cavities within a munition. As these materials detonate, they release their energy due to a shock wave being produced within them. A shock wave is a high-pressure pulse which moves through the material at supersonic speed. In the case of a detonation the shock wave consists of a thin, often sub-millimetre, region where the explosive turns from a solid or liquid into a hot high-pressure gas (Fig. 1.1). The velocity of a detonation wave is of the order 8 km s^{-1} and the energy release rate is of the order of Gigawatts i.e. the same output as a large electrical plant, over the time of a few microseconds. The pressure associated with detonation waves are of many hundreds of thousands of atmospheres. The produced gases expand quickly, a rule of thumb gives the rate of product gas expansion to be $\sim 1/4$ of the detonation velocity. It is not

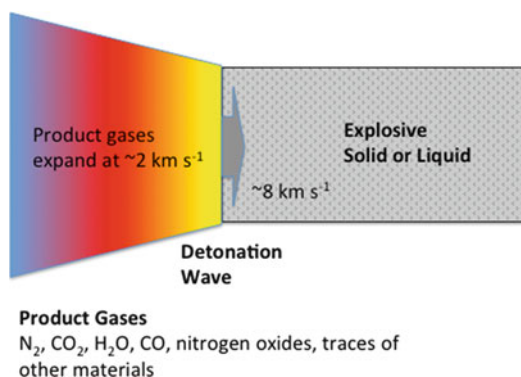


Fig. 1.1 Schematic of detonation process

surprising that such aggressive energy release is used to shatter and push materials at high velocities.

Within the class of high explosives there is a sub-division between so-called '**ideal**' and '**non-ideal**' explosives. Ideal explosives have very thin detonation-reaction zones where the reaction takes place on a sub-microsecond basis. Ideal explosives have a more pronounced shattering effect or brisance, on materials placed in contact with them, this class of materials includes TNT. Non-ideal explosives have much thicker reaction zones and give out their energy over slightly longer timescales, up to several microseconds. The most widely used explosive in the world, Ammonium Nitrate: Fuel Oil (ANFO) falls into this class. The chemical make-up of ANFO results in much lower pressures of detonation, about a quarter of the pressure seen in high explosives, producing less shattering effect. However, ANFO does generate a lot of gas, this gives the mixture a lot of 'heave'. The low detonation pressure means this mix produces cracks in rocks which are then pushed open, heaved, by the detonation gas. These materials tend to be used in the mining and quarrying industry.

Low Order Explosives are materials that give out their energy as a result of rapid burning, called deflagration. This class of materials includes much of the materials often called

gun-powders. Here the energy reaction rate is much lower, of the order of a thousandth of that seen in high explosives. The total energy output is similar to that of high explosives but the lower rate means that the pressures developed are much lower.

Both high and low explosives generally need a degree of mechanical **confinement** in order to detonate. A gramme of gun-powder on a bench will react quickly with a flash of light, a small fireball, some heat but little other effect. The same quantity placed inside a sealed metal can, where the confinement allows the hot gases to stay close to the powder, allows pressure and temperature to build-up thus accelerating the reaction until the confinement shatters and an explosion is produced.

Propellants are a wide group of materials where the reaction pressures are of the order of thousands of atmospheres and the reaction timescales are measured in milliseconds. These materials are used in rocket motors, and to drive bullets or shells. In some cases propellants, if confined or impacted at high velocity may detonate; gun-powder is an example, driving bullets if burnt inside a gun but producing explosives if confined within a metal shell. Missile motors may detonate if they overheat or if the product gas cannot vent quickly enough. As a group of materials they can present a significant fire hazard and can be used in improvised explosive systems.

Pyrotechnics are a wide range of materials including flares and obscurants. They do not produce high pressures but can generate significant heat and can be used to ignite explosives. They can be very sensitive to electrostatic discharge, but badly affected by moisture. Magnesium-Teflon-Viton (MTV) flares have been used to protect aircraft from heat-seeking missiles as they emit very strongly in the infra-red region, this can produce severe burns and cause other materials to combust due to the large energy deposited with no visible flame.

1.4 Explosive Systems: The Explosive Train

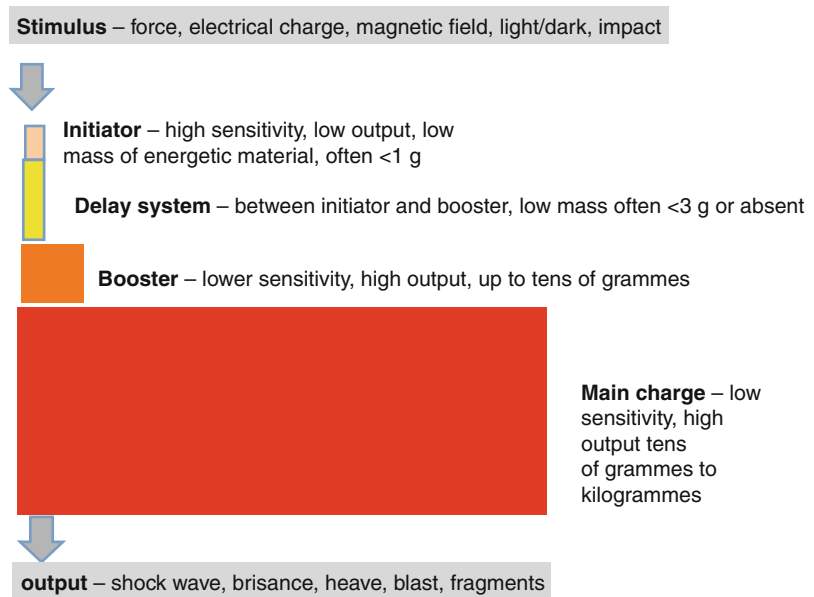
Energetic materials are extensively used in munitions, both the type of energetic material and its function cover a wide range of masses and outputs. This can be seen clearly if we consider the amount of these materials contained in a number of munitions; a small arms round often has less than 1 g of propellant to drive the bullet, while a hand grenade would contain something of the order of a few tens of grammes to shatter and throw the casing; a large anti-tank mine would contain up to 25 kg of high explosive. Given this confusing array of systems it is easiest to think of the munition in terms of the explosive train (Fig. 1.2), which indicates the pre-requisites of munition system.

A variety of stimuli can be used to put the explosive train in motion such as standing on a mine, closing an electrical switch or activating a magnetic action. These actions input energy into an initiator. The initiator contains a material that is highly sensitive, combusting with ease. The main function of the initiatory system is to produce heat or a shock wave. In anti-personnel mines a common design is based on a simple crush switch where the pressure stabs a metal pin into a small metal thimble filled with a sensitive explosive.

From the point of view of weapon system design it is useful to keep the amount of initiatory compound as low as practical, otherwise the weapon could become very sensitive to being dropped, shaken or transported. For many systems a physical space or barrier exists between the initiator and the rest of the explosive system for the purposes of safety. This barrier is removed when the system is armed either manually or using an electrical/mechanical arming system. In the case of bombs and missiles the arming sequence occurs after the weapon has been launched to provide security to the user and launch platform.

The heat is transmitted either along a delay system or directly into a booster charge.

Fig. 1.2 The explosive train



The function of the delay is to burn for a known period of time allowing time for other processes to occur. These processes could be throwing a grenade or allowing a small propellant charge to ‘bounce’ a mine into the air. In many simple systems delays are not present.

The booster system consists of an explosive compound that is less sensitive than the initiatory compound but which will detonate due to the heat of shock wave from the initiator. The energy output of the booster is much higher than that of the detonator. The shock wave then transmits to the main charge.

The main explosive charge consists of a relatively low-sensitivity explosive composition that will detonate from the energy delivered by the booster. The mass of such main charges is extremely variable, however, the output from the main charge can be defined in terms of the outputs.

These outputs take the form of (a) shock waves transmitted into the immediate environment around the explosive, (b) the shattering of surrounding material, such as a metal case or rocks and soil, (c) the expansion of hot product gases, (d) the coupling of some of the explosive energy into the air, producing a blast wave, and (e) the aggressive acceleration of fragments, shrapnel or target vehicles and people.

1.5 Energy Levels and Energy Distribution

A rule of thumb in terms of thinking about the amount of energy output is to consider the order of magnitude of the energy and the materials involved. One gramme of propellant will produce 1 kJ of energy. Gases are about a thousand times less dense than solids and liquids. The temperature of the product gases can be easily 3000 K.

The result of this is that the 1 g of solid turns into 1 litre of gas if that gas were at room temperature, however, the gas is ten times hotter than normal atmosphere. This means that the 1 g of material turns into a gas that, if allowed to expand freely, would occupy 10 l. Alternatively it would take 10,000 atm to keep the gas from expanding. This order of magnitude calculation is for the less aggressive propellant materials.

Of the energy that is released by the energetic material the proportion that goes into different parts of processes is revealing. Again, a simple order of magnitude indicates that 20–30 % will go into the kinetic energy of the fragments, 60 % into the kinetic energy and temperature of the product gases while the remaining 10 % will be spread over a number of other effects, such as

the blast wave, fracturing of shell casings, or the motion of the ground.

1.6 Formation and Velocity of Fragments

Many munition systems have a casing, usually of metal or plastic, often with shapers to form specific fragments. Some systems have very thin casings, this is generally done to reduce the metal content of the munition, make it harder to detect. This also has the effect of increasing the blast effect as less energy is used in fragmentation and acceleration of fragments.

The initial effect of the detonation wave is to send a shock wave into the casing and produce a violent acceleration of the casing. Figure 1.3 shows the velocity profile from the outer surface of a copper cylinder subject to loading from the explosive filling. On the right hand side of this figure a schematic of the process of acceleration is shown. This diagram considers the motion of the wall of a cylinder filled with explosive, as the explosive detonates: the horizontal axis represents distance and the vertical axis time. The detonation products send a shock wave into the cylinder from the inner surface to the outer surface, this is represented by the black line with an arrow on it. A wave reflection takes place at the outer surface, sending a release wave back into the casing, towards the inner surface. This in turn is reflected from the inner surface as a shock. As this back-and-forth wave reflection process takes place each reflection represents the acceleration of the casing as it expands in a series of steps. As the casing is accelerated outwards it expands and becomes thinner. The diagram on the left also indicates the violence of this acceleration, the outer surface moves from rest to reach a velocity of $0.8 \text{ mm } \mu\text{s}^{-1}$ (corresponding to 800 m s^{-1}) within $5 \text{ } \mu\text{s}$. More detailed discussion of how this can be calculated can be found in the specialised texts of the explosives engineering community, detonation symposia and shock physics literature. The total distance moved by the casing within this very narrow time window

is only 0.6 mm. Thus the metal casing is subject to very violent acceleration, this causes fracture and fragmentation within the casing producing metal splinters moving at high velocity.

The study of fragments and fragmentation took a major step forward during the Second World War (1939–1945) with the scientific efforts placed in the service of militaries of industrialised nations. The two major steps are named after their main originators; Neville Mott and Ronald Gurney.

The number and size of metal fragments from a casing was addressed by the Mott fragmentation criteria. This is a statistical model based on the idea of a rapidly expanding ring of metal which contains imperfections which form the basis of fractures which eventually break the ring. As the ring breaks the stress inside the resulting fragment reduces and further fragmentation does not occur. This model was developed and populated in a semi-empirical fashion and the results of theory and experiment were then compared.

This model has been the subject of much development since the 1940s with much recent effort being given by Kipp and Grady in the USA. However, the original theory and Mott criteria are still regarded as valid and useful tools. Mathematically the fragmentation can be represented as;

$$N(m) = \frac{M_0}{2M_k^2} e^{-\left(\frac{m^{1/2}}{M_k}\right)} \quad (1.1)$$

$N(m)$ is the number of fragments that are larger than mass (m), m the mass of a fragment, M_0 the mass of the metal cylinder, and M_k is called the distribution factor which can be calculated from the following equation;

$$M_k = B t^{\frac{5}{16}} d^{\frac{1}{3}} \left(1 + \frac{t}{d}\right) \quad (1.2)$$

where B is a constant for the particular explosive-metal pair that is used, t is the cylinder thickness and d is the inside diameter of the cylinder.

The result of this was to produce a series of curves giving fragment size distribution. An example is shown below, in Fig. 1.4.

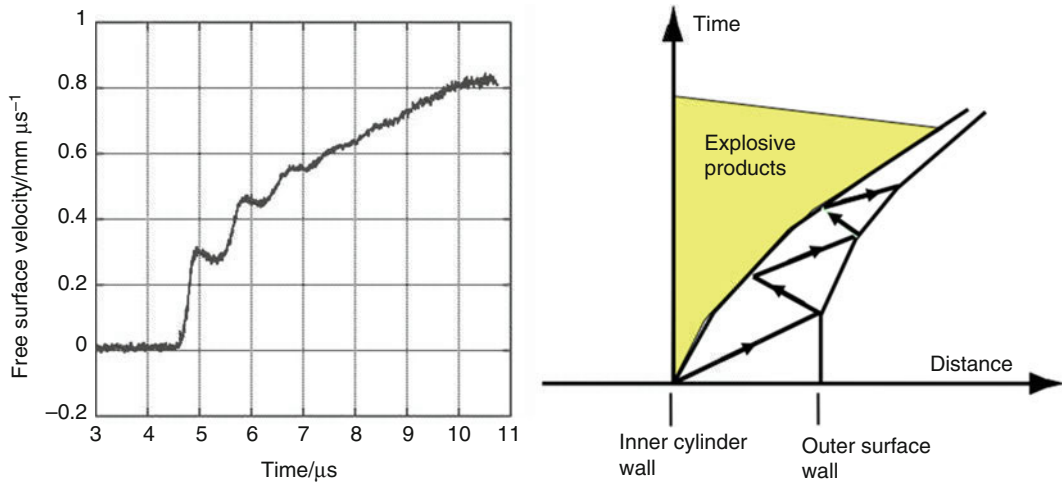


Fig. 1.3 *Left:* the velocity history of the outer surface of an explosively loaded metal cylinder. *Right:* a distance-time diagram of the wave processes taking place within the casing

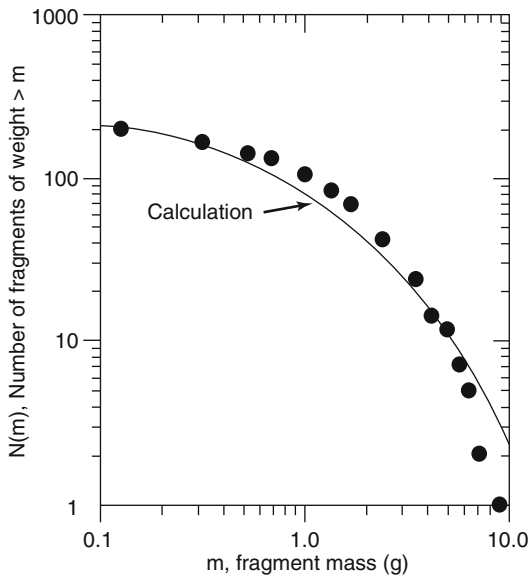


Fig. 1.4 Fragment distribution from an iron bomb (From Cooper, 1996)

The research of Gurney considered the balance of energy in the system, how much of the released energy would be captured by the metal casing and so predict the expected fragment velocity. In the derivation of the velocity the casing was assumed to remain intact. The shape of the explosive charge and the casing has a

major effect; this work resulted in the production of a whole series of Gurney equations. In the equation below the expression is for the velocities achieved by explosive loading of a cylinder;

$$\frac{V}{\sqrt{2E}} = \left(\frac{M}{C} + \frac{1}{2} \right)^{-1/2} \quad (1.3)$$

C – is the mass of the explosive charge, M – The mass of the accelerated casing, and V – Velocity of accelerated flyer after explosive detonation. The term $(2E)^{1/2}$ – is the Gurney Constant for the explosive, it has the same units as velocity and is sometimes called the Gurney velocity. Each explosive has a particular value of Gurney constant and accounts for the coupling between the energy of the detonation products and the energy deposited into the metal casing.

While the two approaches may seem contradictory, one assuming fragmentation and the other an accelerated but intact material, using both approaches is useful due to the timescales of the initial acceleration and fragmentation. The energy delivery by the detonating material occurs very quickly giving the initial impulse, while fractures take time to develop and open sufficiently to allow the product gases to escape.

Overall the two approaches provide a reasonable and predictive approach to fragmentation and fragment velocity.

From this section it can be seen that explosives produce a violent acceleration producing a large number of small fragments and much fewer large fragments moving at velocities in the range from several hundred to a few thousand metres per second. These fragments can produce significant, life-threatening injury in themselves, irrespective of the blast wave associated with the explosive charge.

1.7 Shock and Stress Transmission

At this point the munition has detonated and a shock wave has passed through the casing, which is starting to move and fragment. In total time, a few tens of microseconds has passed since the main charge has started to detonate.

One effect that needs to be considered in some depth is *the transmission of the stress waves between materials*. How does the detonation pressure transmit into the casing and then into the environment around the casing; what are the properties involved? What is the resulting velocity of material when it is subject to a stress wave?

In all cases of wave transmission it is important to consider what the type of the wave is, what the magnitude of the wave is, what are the properties of the material through which it is travelling and what is the change in materials properties across the interface.

1.7.1 Wave Type

Wave motion can be broadly defined into three classes, compression, tension and shear. Compressive waves are associated with positive stresses and pressures, tensile waves with negative stresses and pressures, while shear waves produce motion lateral to their direction of propagation. To think of the action of a lateral wave consider a pack of cards placed on a table, if you press down on the top card and move it sideways then the cards underneath will move sideways as

well, each one not quite so much as the one above it, the resulting shape of the deck of cards is the result of shear. Shear waves produce the same kind of motion in materials.

The velocity at which the stress wave moves changes with stress level. For solids with strength at stress levels below that of the elastic strength, the velocity of the wave is the same as the sound speed in the material. For stress pulses that are above the strength of the material, the compression of the material results in the wave speed being higher than that in the uncompressed material, this is the definition of a shock wave.

Waves that take the stress down are called tensile waves, if the material is behaving elastically while if the material is dropping from a shock state, this is called a release fan.

There are differences between elastic waves and shock waves, the main difference being the significantly higher degree of compression and associated temperature rise associated with a shock wave. Similarly, tensile waves and release fans are different, however, for the purposes of space and clarity we will consider them to be approximately equal. There are a series of excellent texts dealing in more depth with shocks and wave propagation.

1.7.2 Magnitude of the Wave

The magnitude of the stress wave is defined in terms of its stress level. One factor that often leads to confusion in the field of stress propagation is the relationship between stress and velocity. The important thing here is to remember one of Newton's laws of motion – *a body will continue in a state of rest or motion until acted upon by an external force* (further description is found in Chap. 2). It is, therefore, perfectly possible to have a material or fragment moving at a high velocity under no external force and also easy to have a material under high pressure but not moving.

The basic equation to be defined is the relationship between stress, the volume through which it moves and the acceleration it produces in the material. The law to be considered here is

conservation of momentum; the product of mass multiplied by velocity.

The definition of stress (σ) is force (F) divided by the area (A) it acts over

$$\sigma = F/A \quad (1.4)$$

The mass (m) of the material that is affected by the passage of the wave is going to be the volume the stress wave has moved through multiplied by its density.

The volume (V) that the stress has swept through will be the area (A) multiplied by the velocity at which the wave moves (U_s) over the time window we are interested in (δt). The density of the material is represented by ρ .

So the mass that has been accelerated will be

$$m = V\rho \quad (1.5)$$

and from the argument above

$$V = A U_s \delta t \quad (1.6)$$

So the mass is

$$m = \rho A U_s \delta t \quad (1.7)$$

The final step is to consider the acceleration and the final velocity obtained. Here we use one of the fundamental equations representing the acceleration (a) produced by a force (F).

$$F = ma \quad (1.8)$$

Where the acceleration (a) is the change in velocity of the material (δu_p), sometimes this is called the particle velocity, over the time window we are considering (δt).

$$a = \delta u_p / \delta t \quad (1.9)$$

Combining these terms to relates stress to change in velocity we arrive at the equation

$$\sigma A = \rho A U_s \delta t (\delta u_p / \delta t) \quad (1.10)$$

Which simplifies to

$$\sigma = \rho U_s \delta u_p \quad (1.11)$$

This is one of the fundamental equations in shock physics, one of the so-called ‘Rankine-Hugoniot’ relations, where σ is stress, ρ is material density, U_s is the wave velocity, and δu_p is the change in material velocity.

The full set of these Rankine-Hugoniot relations can be found in the introductory texts by Meyers or Forbes (see Further Reading).

The fundamental property shown here is that the change in velocity produced by a stress wave is dependent on the density and the velocity of stress transmission through the material. At low stress levels the velocity at which a stress wave travels through a material is the same as the material’s sound speed. At higher stresses, when a lot of force is applied as in an explosion, the velocity of the stress wave can be higher than the sound speed - a shock wave. From what we have stated earlier, a detonation wave moves through an explosive at a very high velocity, in fact a detonation wave is a shock wave that is driven and supported by the energy release of the chemical reaction.

The value of the density of the material multiplied by the wave speed is called the impedance (Z) of the material.

1.7.3 Impedance: The Property of the Material

In principle the value of impedance for low stress levels is easy to calculate, it is the product of the density multiplied by the sound speed in the material. Table 1.1 contains the density, sound speeds and impedances of some common materials, air at 1 atm, water, iron and Perspex. All of these materials have been studied extensively and their properties are quite well known. The impedance of air changes strongly with pressure and is discussed in Sect. 1.8.1.

However, as the stress level in the wave increases then other properties such as strength and compressibility, become important. As the stress level increases so the amount of energy

Table 1.1 The density, sound speeds and impedances of common materials

Material	Density/ kg m^{-3}	Sound speed at 1 atm pressure/ m s^{-1}	Impedance/ $\text{kg m}^{-2} \text{s}^{-1}$
Tungsten	19,220	4030	77.4×10^6
Iron	7850	3570	28.0×10^6
Perspex	1190	2600	3.09×10^6
Water	1000	1500	1.50×10^6
Air	1.292	343	4.43×10^2

that is being deposited in the material will increase, some of this will result in increasing the kinetic energy of the material while another part of the energy will result in the material being compressed and becoming hot. The exact mathematics of this situation is complex and beyond the space available in this brief chapter, however, we can outline some simple conceptual guidelines.

The strength of a material is its ability to resist distortion; this strength will be different in compression, shear or tension (further details are included in Chap. 3). Materials with high strength tend to have high sound speeds as a result. Metals, in general have similar strengths in tension and compression, while rocks and ceramics are strong in compression but weak in tension. Granular materials have no tensile strength, but can have significant compressive strength. Given the three-dimensional jig-saw like nature of sand, the more you press down on the sand the harder it is to move it sideways (shear it).

Compressibility is the ability of a material to deform and is the inverse of strength. Highly compressible materials, foams, are often used to protect objects from impact, they do this because the energy of the impact is absorbed in locally distorting and compressing the material in the region of impact and not into globally increasing the kinetic energy of the foam. Sands, soils and granular materials absorb energy in a number of ways by grains deforming, grains fracturing and the particles moving together to fill the pores; these energy absorption mechanisms act to mitigate the shock or blast wave.

As the material compresses its density will change and its sound speed will tend to increase.

At some point the amount of compression in the foam will result in the removal of the majority of the voids at which point the material will behave like a stronger, solid mass; there is a limit to energy absorption. Similarly all materials will have a yield point, where their strength is exceeded and they begin to deform and compress so there will be a change in how the energy in the stress pulse is deposited, more will go into temperature and into internal compression processes and less into velocity. In addition, time-dependent processes will also be occurring - the time for pores to collapse in foams and for particles to fracture in sands - so there will be a time dependence to the stress transmission.

The same issue of time dependence in the change of impedance, degradation of strength and interplay between kinetic energy and compressibility occur in biological materials. The impedance of the material will change through the stress pulse and so the simple equations given should always be used with caution and to produce estimates.

1.7.4 Wave Transmission Across Interfaces

When a stress wave reaches an interface it is the difference in the mechanical impedance of the materials which determines how much of the stress wave is transmitted and how much is reflected. By using conservation of momentum and the impedances of the materials the amount of the stress transmitted and that reflected can be calculated and the **change in stress** in the materials calculated. The result of this is given in the Eqs. (1.12) and (1.13)

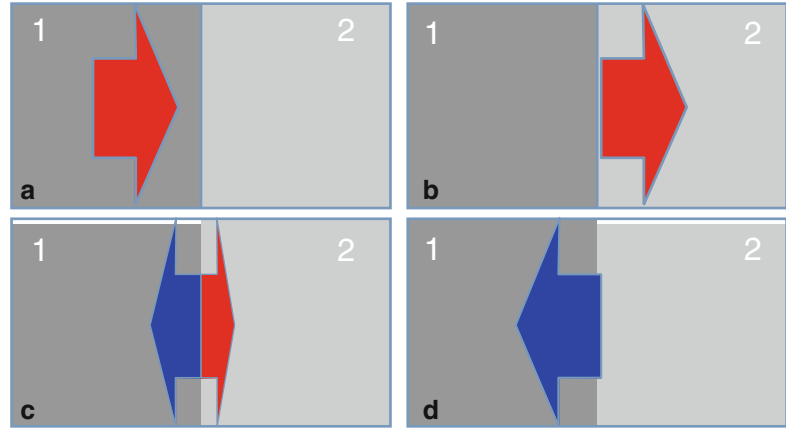
$$T = 2Z_2/(Z_1 + Z_2) \quad (1.12)$$

$$R = (Z_1 - Z_2)/(Z_1 + Z_2) \quad (1.13)$$

Where T is the fraction of the stress transmitted, R is the fraction of the stress reflected, Z_1 is the impedance of the material through which the stress is originally transmitting, and Z_2 is the material on the other side of the interface. Three situations are shown in Fig. 1.5.

Fig. 1.5 Stress

Transmission across the interface between two materials (a) a stress pulse approaches a boundary (b) If materials 1 and 2 have the same impedance the stress pulse is fully transmitted (c) if the materials 1 and 2 have comparable, but different, impedances the stress and energy of the pulse is partially transmitted and partially reflected (d) if material 2 has a very low impedance compared to material 1, virtually all of the stress pulse will be reflected back from the interface



Here it is important to remember that **stress, force and velocity are all vectors**, they have a magnitude and a direction. By convention we make an increase in velocity from left to right to be positive and right to left as negative. A wave which acts to compress a material will be regarded a positive stress and a wave which puts the material into tension or releases will be regarded as a negative change in stress.

In Fig. 1.5a a stress wave travels through material 1 of impedance Z_1 towards an interface with material 2, impedance Z_2 .

Figure 1.5b shows what happens when the wave reaches the interface if the impedance of material 1 and 2 are the same: all the stress wave transmits through the interface. The value of the transmission coefficient is 1 and so the stress in material 2 is exactly the same as the stress level in material 1 i.e. both end up at the same stress. The amount reflected is 0 and so the stress in material 1 remains unchanged.

In Fig 1.5c the materials have impedances that are of a similar magnitude but different values: Z_1 being half the value of Z_2 . Calculating the stress transmission and reflection coefficients gives $T = 4/3$ and $R = -1/3$. This means that that stress produced in material 2 is higher than that produced by the initial wave. This may seem odd, until it is remembered that impedance is related to density and sound speed, so material 2 in this case

is denser and/or stronger than material 1; effectively material 2 slows down the motion of material 1 and the result is higher stress and less particle velocity.

While the transmitted force is still going in the positive direction it is higher by $4/3$ over the initial stress in material 1. For the reflected portion there is a negative reflection coefficient and the wave is propagating in a negative direction, having a negative sign. Mathematically two negative numbers multiplied together equals a positive, so what this implies is that the amount of reflection means we have a stress change of $+1/3$ of the initial pressure **adding** to the initial pressure. The stress in material 1 increases as the denser, stronger material 2 prevents it from moving forward, effectively swapping a change in velocity for higher stress.

This reveals an important point: if surfaces remain in contact, the stress is the same in both sides of the interface. This is the basis of a technique called impedance matching used in shock physics to determine the stress and velocity of materials under the action of shock waves.

Materials with a high density and high sound speed will have a higher impedance and as a result will exert a higher pressure at a given impact velocity than a low density or low speed material. This explains why a much higher stress is produced by tungsten, a preferred material for

anti-tank weapons compared to the lower impedance iron, while Perspex will produce a much lower velocity.

In the case of Fig. 1.5(d), the impedance of material 2 is very low compared to material 1. In this case the change in the reflected stress is of value 1 and it is going in the negative direction. Following the argument above, this means it changes the stress by -1 . This implies that stress change of the reflected wave cancels the stress of the original wave. In this case the stress falls to zero and the energy of the stress pulse accelerates material 1 to a higher velocity, approximately doubling the particle velocity.

1.7.5 The Solid: Air Interface

After the stress wave from the detonation has transmitted through the casing, accelerating it and ultimately shattering it, it is then transmitted through the surrounding soil and sand compressing and fracturing it. When the stress pulse arrives at the solid/air interface, from the transmission-reflection coefficient it is clear that the vast amount of the stress is reflected from the solid/air interface. This reflection is like the case in Fig. 1.5(d) discussed above, the velocity of the sand/soil particles double as the stress drops to zero. Sand/soil has a very limited tensile strength so the result of this is to throw the sand and soil from the surface as a cloud of fast-moving debris.

While the stress wave compresses the material, and ultimately results in a cloud of fast-moving debris, the product gases from the explosive devices are also pushing the soil and fragmenting the compacts formed by the stress wave. It is the expansion of the hot, product gases which results in the formation of the blast wave.

1.8 Blast Waves

The product gases have a velocity of approximately 2000 m s^{-1} , considerably higher than the sound speed in air, 330 m s^{-1} . The resulting high-pressure pulse of air is pushed outwards by the hot explosive products. In order to allow

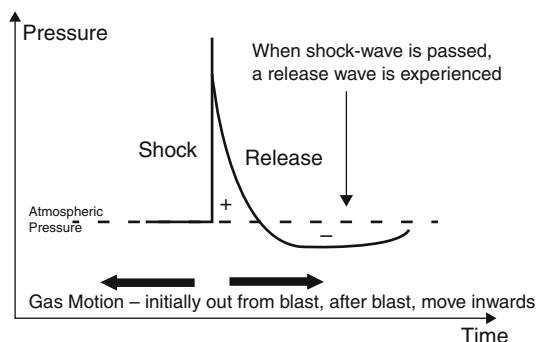


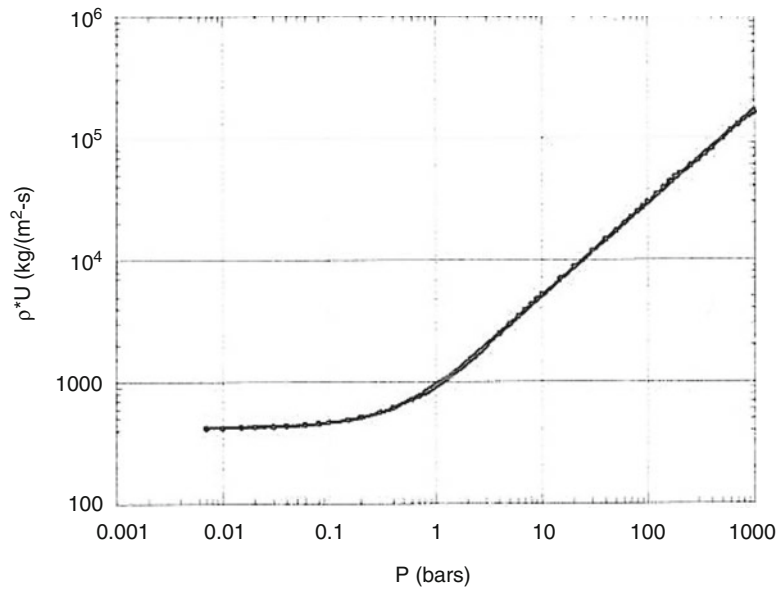
Fig. 1.6 The classic Friedlander form of a blast wave

comparison between charges of different sizes and compositions, explosive engineers conducted experiments using the simplest scenario possible – a bare explosive charge in an empty, flat field. This has resulted in a large body of blast wave literature based around the classic ‘Friedlander’ blast wave form.

Figure 1.6 shows the pressure time profile of this classic blast wave. After the initial rapid rise of the blast wave there is a region of positive pressure, accelerating outwards from the explosion. The speed of the gas moving behind the blast front, in the so-called ‘blast wind’, can be as high as 2000 km h^{-1} . This is followed by a release wave that drops the pressure below atmospheric pressure. The release occurs as both air and product gases have expanded outwards, away from the place where the explosion initiated. As a result, the explosive products have expanded and therefore performed ‘work’ on the surroundings and started to cool. This leaves a partial vacuum in the region of initial explosion and this lower pressure now causes air and gases to flow backwards over a longer period to equalise the pressure. The resulting push-pull movement experienced in the blast wave can be especially damaging to structures and humans.

This simple waveform was often observed in much early research into the effects of blast on humans. These studies used data either from open explosive ranges or with well controlled blast reflections from single walls or barriers. It is important to note that in a cluttered urban or vehicle environment, a casualty will experience a

Fig. 1.7 The change in impedance of air with pressure



number of waves – those directly arising from the charge and those reflected from a wide variety of surfaces and arriving from different directions. In general the amount of reflected pressure waves can be equated to more damage and injury.

1.8.1 Change in Impedance of a Gas in a Blast Wave

In the discussion above the energy deposited in a material can manifest itself in a number of ways, it can give the material kinetic energy, for instance, and it can compress the material increasing its temperature.

In many engineering applications solids and liquid are often assumed to be incompressible. In shock wave studies this is not the case and compressions which halve the volume of the material are relatively common. However, gases are by comparison, very compressible. This means that blast waves are supersonic with respect to sound waves seen at low pressure, they also are associated with a very large change in impedance and often increase in temperature. Figure 1.7 shows the change in impedance of air with pressure. Atmospheric pressure is located at the point where the impedance increases sharply.

A major difference between shocks in solids and liquids and blasts is that blast waves from munitions tend to have durations measured in milliseconds, while shock waves in solids exist on timescales of microseconds. This 1000-fold difference in duration is why the relatively modest pressure seen in blast wave can produce more movement and damage than the much higher pressures in shock waves.

1.8.2 Reflected Waves

While the compression of the air produces a large change in impedance, it is still the case that the impedance of the compressed gas is very much lower than that of any solid or liquid. When the wave hits against a solid barrier, then a compressive pulse is transmitted and the stress in the gas also increases. Calculating the values of the reflected stress change, indicates that the stress level almost doubles.

In the case of an explosion in an enclosed space, or in the partially confined space below a vehicle there is time for multiple wave reflections, leading to complex blast wave-forms of widely differing stress histories. Within a vehicle the reflections add to the injuries seem, over and above the push-pull effect seen in the relatively simple Friedlander waveform (Fig. 1.8).

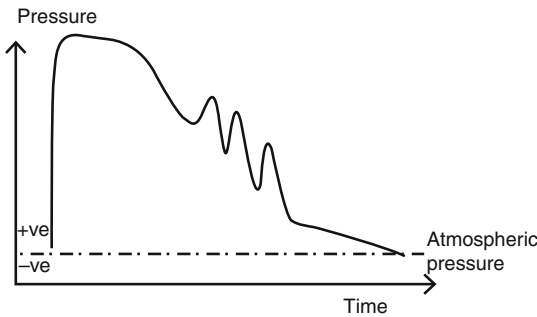


Fig. 1.8 Generic representation of a blast waveform seen inside a vehicle. The wave has many more peaks, plateau and overall variation than the relatively Friedlander waveform shown in Fig. 1.6

1.8.3 Temperature Rise

As well as the motion of the blast wave there is also an associated temperature rise. This can result in burns and combustion. Inside a vehicle the heat deposited into a material can be divided almost evenly between the heat from the intense light flash associated with the detonation or gas compression while physical contact with the hot gas deposits the other half of the energy. The timescale for this energy transfer is of the order of milliseconds.

Shock waves also result in significant heating within metals, even after the metal has been dropped back to normal stresses there may be a residual temperature increase in the fragments of over 100 °C. The timescale for this heating is on the order of microseconds.

1.9 Comparing Explosives Scenarios: Scaled Distance and TNT Equivalence

Munitions and explosive charges come in a range of sizes and vary in terms of materials. In the technical literature the term 'scaled distance' is often used to relate the effects of large explosive charges over tens of metres to those of small charges at close range. This is useful as it allows the effects of small-scale experiments to be extended to larger explosives charges.

The two terms used in virtually all scaling equations are (i) the explosive mass and (ii) the mathematical cube of the distance between the charge and the target, i.e. the increase in volume over which the energy is dispersed.

There are often other terms involved: one of the easiest to conceptualise is the distance of the charge above the ground.

If the charge is in mid-air the energy expands evenly in all directions, effectively spreading the energy through a sphere. However, if the charge is on the ground, the effects of wave reflection occur and the energy is concentrated into an expanding hemi-sphere, above the ground. Within the hemi-sphere so the energy, pressure *etc* is more or less doubled compared to that of the mid-air charge.

Another simple comparative scale between explosive types is that of 'TNT equivalence'. Historically TNT was a widely used material, which could be easily melted and cast into a variety of shapes, unlike many other explosive materials. Given its castable nature many experiments were conducted, resulting in large databases. TNT equivalence is a simple factor that allows a well-defined reference point for the broad comparison of the effects on a non-TNT explosive charge to be estimated.

1.10 The Three-Dimensional World and the Physical Basis of Blast and Fragment Injury

The real world has a complex topography and is made of a wide variety of materials many of which change their properties based on the accelerations produced in them by explosion. This somewhat mundane statement also indicates the difficulty of understanding the precise effects in terms of the materials and the three-dimensional world. However, a well-founded method is to take that complex situation and divide it into smaller, more tractable parts.

This chapter has given an overview of the basis of explosive technology and presented some of the basic processes relevant to the blast process. The importance of the detonation wave,

stress transmission, fragmentation, the ejection of sand/soil, expansion of the product gases, and flash heating have been introduced using simple first-order approximations.

The complexity of the mechanical processes and the resistance of the human body can result in injury patterns that show effects that are distant from the immediate blast or impact. However, it is increasingly possible to adopt an interdisciplinary approach that can bridge the vital mechanical-biological gap in our knowledge. Following chapters will address and expand on these issues.

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2.1 Overview

Biomechanics is the study of biological systems from a mechanical perspective. In this discipline, the tools of mechanics are used in which the actions of force, motion, deformation and failure and their relationship to anatomy and functional aspects of living organisms are analysed. Traditionally biomechanics has been considered in terms of either biofluid mechanics or the biomechanics of connective tissues (“solid biomechanics”), where the former is a key branch of science and engineering that is applied to the cardiovascular and respiratory sciences and the latter is applied to orthopaedics and musculoskeletal rehabilitation. Other branches of biomechanics investigate the interactions between solids and fluids and these are applied in ocular and cellular biomechanics, or the biomechanics of the brain, for example.

These branches of biomechanics are typically associated with specific anatomical regions and physiology; for example, biofluid mechanics might focus on the effect of flow in the arteries and its relationship to cardiovascular disease, whereas connective tissue biomechanics might focus on the mechanical effect of ligaments at a joint and deal with their repair post injury.

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Biomechanics in blast is a key discipline in blast injury science and engineering that addresses the consequences of high forces, large deformations and extreme failure and thus relates closely to knowledge of materials science (Chap. 3) and leads onto the analysis of tissues (see Chap. 5) and, at the smaller scale, cells and molecules (see Chap. 4).

The aim of this chapter is to give the reader a basic understanding of biomechanics and its utility in the analysis of blast injuries. The specific objectives are to:

1. introduce fundamental terminology and concepts in biomechanics; and
2. describe how forces are transmitted through the human body at all loading rates, and hence provide an analytical framework to analyse forces on all relevant tissues and structures associated with blast injury.

2.2 Terminology in Biomechanics

2.2.1 Biomechanics of Motion

Kinematics is the “Biomechanics of Motion”; in other words, it is the branch of biomechanics that deals with the description of motion. It is most commonly used in the analysis of activities of daily living and sporting activities. In blast we consider the movement of the objects such as

blast fragments (secondary blast – see Chap. 6) and displacement or movement of the person due to blast and its interaction with objects such as vehicles (tertiary or solid blast – Chap. 6), where their movement is considered as *whole body* movement, or also takes into account the *relative* movement of different body parts.

Mass is how much matter an object contains. This remains constant regardless of location or gravitational conditions (for example, Earth, Mars or gravity in outer space). Weight, however, would vary under these three conditions. The importance of mass in blast biomechanics is that it represents the resistance to a change of linear motion (a speeding up or slowing down). This is important in blast when considering smaller fragments that are energised (small mass – secondary blast effects) by the blast when compared to larger items (a person or a vehicle – tertiary blast effects) that require more energy to get them moving. SI units of mass — kilogramme (kg).

A **Rigid Body** is an object that doesn't change shape. This is usually a major assumption in biomechanics, but serves to allow force analysis to be conducted (the subject of this chapter) prior to deformation analysis (the subject of subsequent chapters). Formally, a rigid body is a collection of particles that do not move with respect to each other. In a force analysis, the assumption is that however large a force may be, the rigid body does not deform. Obviously, this is an approximation in every case because all known materials deform by some amount under the action of a force. In the biomechanics of blast we tend to analyse the human body first as a series of rigid bodies (fore-arm, upper arm, head, trunk, shank, etc) that can move relative to each other and then secondly consider their deformation and failure.

Formulating problems in biomechanics in terms of the **Centre of Mass** (CoM) simplifies the problem to a single point. The CoM is the point on the rigid body that moves in the same way that a single particle containing all the mass of the object and is subjected to the same external forces would move. Therefore, when analysing

the body, we consider this as a series of rigid bodies, each with a constant CoM. Clearly, the whole person will have a varying overall CoM when independent movement of each of the joints is taken into account and this is where rigid body biomechanics moves into the realm of dynamics.

The **Centre of Gravity** (CoG) is the point at which the weight of the body or system can be considered to act. In other words, it is the point at which the weight of the body, $W = mg$, should be applied to a rigid body or system to balance exactly the translational and rotational effects of gravitational forces acting on the components of the body or system. The CoG and the CoM are coincident when gravity is constant and are thus frequently used interchangeably. These points are important in biomechanics as they are used as reference points for calculations.

The **Moment of Inertia** is the rotational equivalent of mass in its mechanical effect; it is the resistance to a change of state (a speeding up or slowing down) during rotation. This is dependent on the mass of the object and the way the mass is distributed,

$$I = mr^2$$

where m is the mass and r is the distance of the CoM of the object from the axis of rotation.

The SI unit of moment of inertia, I is the kilogramme metre squared (kgm^2).

The moment of inertia is especially important in high loading events where the forces that are applied to the person are not applied directly through the CoM. This means that the forces produce a turning effect and thus cause the person, or body segment, to rotate. A high moment of inertia will resist that rotation. For example, a coat hanger that supports two heavy bags hooked in the middle of the hanger will have a smaller resistance to rotation than a coat hanger with the same two heavy bags hooked on either side of the hanger.

A **Torque** or **Moment** is the turning effect of a force (Fig. 2.1). This is calculated in mechanics by multiplying the magnitude of the force by its **moment arm**, or **lever arm** which is the perpen-

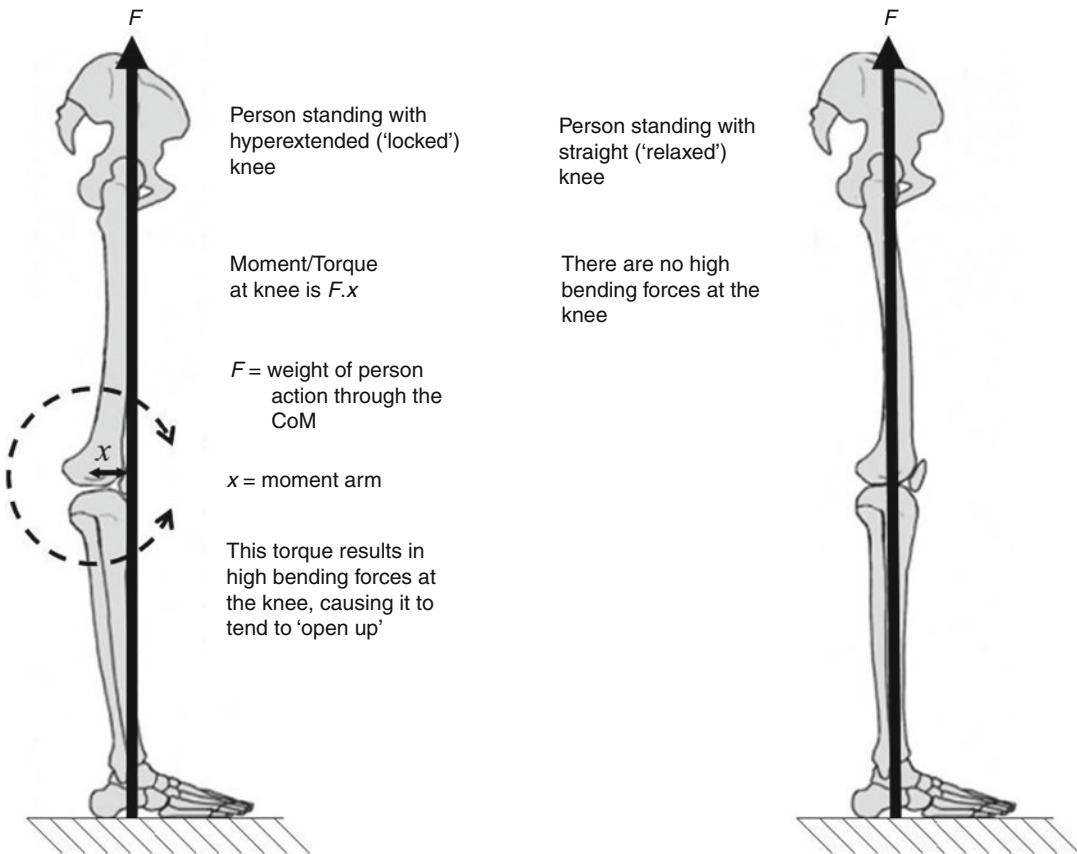


Fig. 2.1 Moment at the knee joint for different loading conditions

dicular distance from the point of application of a force to the axis of rotation. Therefore, a large force and a large moment arm will result in a large moment. As the forces in blast are extremely high, only a small moment arm will result in a large moment and thus cause angular (or rotational) acceleration of the person or body segment. In vector terms, the calculation is the vector (cross) product of force and distance. The SI unit of moment is the Newton metre (Nm).

Scalar quantities in biomechanics have magnitude only. For example, mass, length, or kinetic energy (described later) are scalar quantities and can be manipulated with conventional arithmetic.

Vector quantities in biomechanics have both direction and magnitude (Fig. 2.2). A force, for example, is always described by its magnitude

and by the direction in which it is acting. Velocity is also a vector quantity because it expresses the rate of change of position in a given direction. This is experienced when going round a corner; a satellite orbiting at a constant speed (scalar) around the earth has a changing velocity (vector), because the direction of travel is moving.

This means that when performing calculations with vectors, ordinary arithmetic will give the wrong answers; therefore, vector addition and other types of vector algebra must be used.

Acceleration is the rate of change of velocity with respect to time (the first time derivative of velocity or the second time derivative of displacement). Acceleration is a vector quantity. Taking the satellite described above, the constant speed going round the earth reflects a change in velocity with respect to time and is, thus,