A TEXTBOOK OF
BIOMEDICAL ENGINEERING

edited by

R. M. KENEDI

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Preface

THE APPLICATION OF ENGINEERING IN MEDICINE IS THE OUTCOME OF A technological revolution in medical practice that has occurred over the last thirty years. It arose from a growing realisation that a range of disciplines outwith medicine can offer assistance to benefit its practice. The trend is now worldwide, with particular emphasis on multidisciplinary clinic teams. These are generally headed by the medical clinician directly responsible for the patient. Team members are collected from those disciplines which the clinician feels can contribute to an understanding and solution of the problems of his patients and so assist him in making his diagnostic decision and choice of therapy speedily and reliably.

In this context it is important to realise that to talk of Bioengineering as a *new and distinct discipline* is nonsense: the activity is the application of well established principles, concepts and techniques of engineering to the world of living systems. Of course, the assessment of living systems is a field relatively new to engineering and has two somewhat unusual characteristics. *Firstly*, the *extent* of the field of activity is enormous—it is at least as large as the whole of medicine and the whole of engineering combined. *Secondly* (and perhaps it is this that makes the incursion of engineering into medicine so attractive), the engineering problems of living systems are *especially difficult* as problems go; in their simplest appearing form living systems are challenging and stimulating to all—even to the best of engineers. Among the most beneficial effects of teamwork in this field have been the results produced by the direct interaction of individuals trained in the disciplines of medicine and engineering. The cross-fertilisation of ideas produced working hypotheses and practical techniques which, within the context of either of the disciplines alone, would have been regarded as too unconventional to consider.

The activities popularly understood as "Bioengineering" can conveniently be classified under four headings (This classification is neither unique nor exclusive—it happens to be that of the editor!):

BIONICS—the study of the engineering mechanisms of the biological processes and their applications in engineering
APPLIED BIOLOGY—the application of the biological processes on an industrial scale
BIOMEDICAL ENGINEERING—the applications of engineering to medicine in two categories: the engineering study of the human body in health and disease, and the development of engineering instrumentation and devices for medical research and practice
ENVIRONMENTAL HEALTH ENGINEERING—the engineering of the environment in closed (space capsule, submarine) and open (houses, cities) systems, to ensure the health and comfort of the inhabitants.

The above will be seen to cover a range of activity sufficient to ensure a fully satisfying (and remunerative) career for all engineers likely to be attracted to the bio-field!

While the literature of bioengineering, and even that of biomedical engineering alone, is prodigious, it consists primarily of specialist articles published in a great variety of medical, life and physical science and engineering journals. Books on the topic are few, and are either generalist and diffuse, or specialist and narrow. The time appears right for the publication of the kind of "text" book which this volume aspires to be. It will be obvious to the reader that to produce such a book for the potential whole of Biomedical Engineering alone would result in an encyclopaedic collection of tomes. It follows that any realistic attempt requires to be clearly oriented and correspondingly limited.

This particular volume is designed as a "text book" for medical undergraduates, as a possible "primer" for graduate medicals and life scientists unacquainted with Biomedical Engineering, and as a book of pertinence for certain of the para-medics—the professions supplementary to medicine. It is based on the contributors' professional competence as actually applied, highlighting those aspects which have proved of direct value in clinical and laboratory practice, research and teaching. Although the contents may at first sight appear to have been selected somewhat arbitrarily, the contributors' experience has shown that they form a highly relevant collection of "what every good doctor should know".

Differences in style as between contributions are unavoidable in a multi-author volume. It is believed, however, that these differences, by providing a degree of stylistic variety, are likely to add rather than to detract from reader acceptability.

The contributors are all present or past associates of the Strathclyde Bioengineering Unit. The Editor thus has the pleasant task of thanking them also as colleagues for their expertise, patience and forebearance so freely given during the collation of this volume. Last, but most certainly not least, particular thanks are due to Miss Jane Bowen, another colleague, who prepared all the illustrations.

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Contents

CHAPTER ONE

HUMAN BODY BIOMECHANICS

1.1 ENGINEERING MECHANICS

Basic concepts

Engineers view, express, analyse and synthetize the world at large in terms of three measurable concepts: force F, length L and time T. In the physical world, a *change of force* invariably produces a *change of length* (deformation, motion, etc.), both these changes being in general time-dependent.

It is interesting to note that engineering mechanics divides into its branches depending on the way in which the relationship between the time-dependent change of force and the time-dependent change in length is defined. For example, if the postulated relationship is between change of force and change of length (say the force on a spring and its extension), the study is that of the Mechanics of Materials. If, however, the change of force is related to a change in velocity (i.e. the rate of change of length with time) the study is that of the Mechanics of Fluids.

Units. Throughout the text internationally agreed units will be used as follows:

Length L	metre, m
	centimetre, cm (1 cm = 10^{-2} m)
	millimetres, mm (1 mm = 10^{-3} m)
Time T	second, s
Force F	newton (kg m/s^2). 1 newton (N) is the force which, when applied to a mass of 1 kilogram, produces an acceleration of 1 m/s^2.

Vectors

A force acts along a certain line and in a certain direction. To define a force fully, its *magnitude*, *line of action* and *direction* must be specified. Such a quantity is called a *vector* quantity, as opposed to *scalar* quantities which possess *magnitude* only. Length (and its derivatives) is also a vector quantity, while time is regarded as a scalar quantity.

A vector may be represented as shown in figure 1.1.

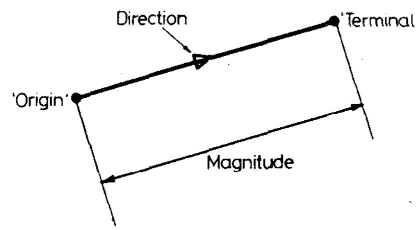
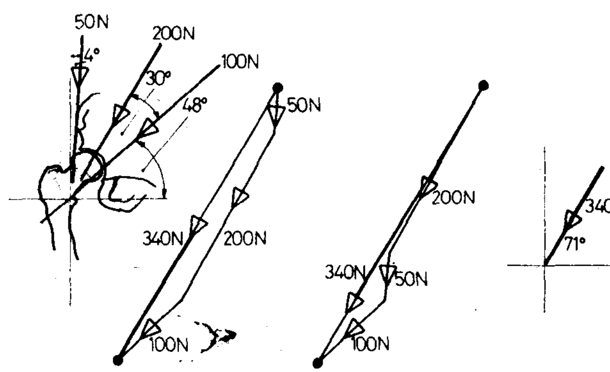


Figure 1.1

To *add* vectors (graphically) they are drawn in any order, the origin of each successive vector being placed at the terminal of the preceding one. The *resultant* vector (the vector sum) is given by the vector whose origin is the origin of the first vector and whose terminal is the terminal of the last vector.

Example 1.1 In a particular action, the three hip abductor muscles controlling the pelvis in the frontal plane have the values and lines of action shown. Find the resultant force on the pelvis.



The individual vectors, drawn to scale, are *added in any order, giving the vector resultant* $R = 340$ N at 71° to the horizontal.

Note: To subtract vectors, the addition procedure can be used, provided the direction of the vectors to be subtracted is *reversed* prior to carrying out the addition (figure 1.2).

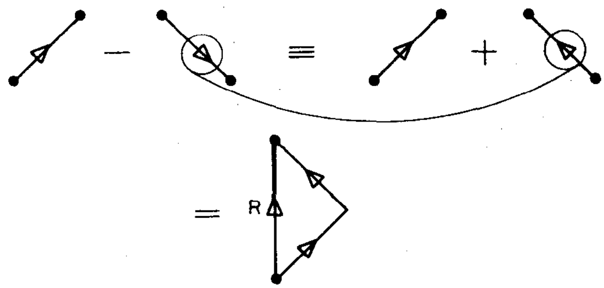


Figure 1.2

In the same way as a group of vectors can be replaced by their vector sum or resultant *R*, any single vector may be replaced by any group of vectors whose sum is the given single vector (figure 1.3).

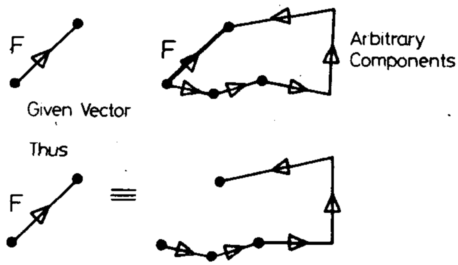


Figure 1.3

For convenience, it is usual to replace any given vector by two component vectors only, these generally being taken along two reference directions at right angles to each other (figure 1.4).

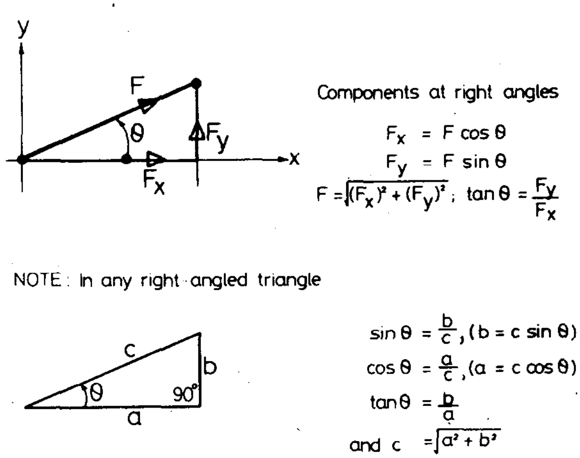


Figure 1.4

Noting that vectors acting in the same line can be summed directly as *scalar* quantities, the technique of component analysis of a vector system to obtain the resultant of the system is as follows:

Two reference axes are chosen at right angles, x and y.

All vectors are resolved into components along these axes (figure 1.4), giving F_x and F_y values.

The algebraic sum of the components ($\sum F_x$ and $\sum F_y$) is determined.

The resultant R is then given by $\sqrt{(\sum F_x)^2 + (\sum F_y)^2}$ in magnitude and by $\tan\theta = \sum F_y / \sum F_x$ in direction, where θ is the angle of inclination of R to the reference direction x.

Example 1.1, solved by component analysis.

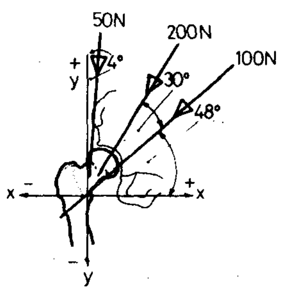
$$\sum F_x = -100 \times \cos 48^\circ - 200 \times \cos 78^\circ - 50 \cos 86^\circ$$
$$= -112\text{N}$$

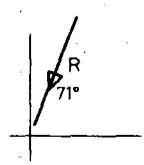
$$\sum F_y = -100 \times \sin 48^\circ - 200 \times \sin 78^\circ - 50 \sin 86^\circ$$
$$= -320\text{N}$$

$$R = \sqrt{(\sum F_x)^2 + (\sum F_y)^2} = 340\text{N}$$

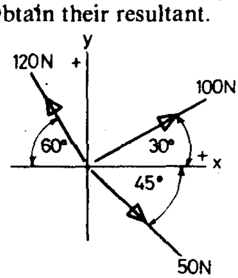
$$\tan\theta = \frac{\sum F_y}{\sum F_x} = 2{\cdot}86$$

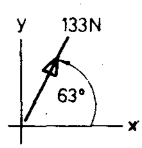
for which $\theta = 71^\circ$ (approximately)





Example 1.2 Three forces of magnitude and direction as indicated act at a point as shown. Obtain their resultant.





(Answer 133N at 63° to x-axis.)

The vector jargon of elegance

Replacement of vectors by components along directions at right angles can be taken a step further, by introducing a notation which immediately identifies the direction of a vector in mathematical terms. The advantage of this is most clearly evident when working with vectors in three dimensions, but it is introduced here partly to show the potential elegance of mathematical notation and partly as the commencement of producing a properly "rounded" biomechanician. The whole concept is based on the meaning of the so-called "imaginary" quantity $\sqrt{-1}$, usually denoted by i or j.

Until the Arabs introduced the symbol for zero, no meaning could be attached to the negative value of numbers. In a similar manner, it was only about the seventeenth century, with the rise of mathematicians such as Euler and D'Alembert, that the imaginary quantity j was interpreted as an *operator*. This was a completely new concept comparable in importance to the introduction of the symbol zero. It opened up the way to a completely new mathematics, the so-called *operational* mathematics which is one of the important tools of physical science and engineering.

In mathematical notation a^n means the number a to the power n (for example $2^2 = 4$), where n is the *index*. a^{-n} means the reciprocal of a^n, i.e. $1/a^n$. To multiply powers of the same number, the indices are added. Thus $a^n \times a^m = a^{n+m}$ (for example $2^2 \times 2^3 = 2^5 = 32$), similarly $a^n \times a^{-m} = a^{n-m}$ (for example $2^2 \times 2^{-3} = 2^{-1} = \frac{1}{2}$), consequently

$$a^n \times a^{-n} = a^0$$

$$\text{or} \quad a^n \times a^{-n} = \frac{a^n}{a^n} = 1$$

$$\text{Hence } a^0 = 1$$

Thus the value of any number to the power zero is 1.

Note further that the index n may be a fraction—this by definition means the root of the number. Thus $a^{1/n} = \sqrt[n]{a}$, i.e. the n^{th} root of a. Hence $a^{1/2} = \sqrt{a}$, $(-1)^{1/2} = \sqrt{-1}$, etc.

Consider a vector r acting along the reference axis x, as shown in figure 1.5.

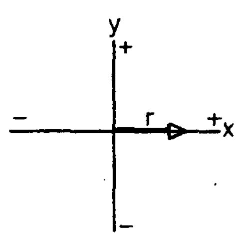


Figure 1.5

This can be written as

$$r = r \times 1 = r(-1)^0 = r(-1)^{0/180}$$

since 0/180 or for that matter 0/(any number) is equal to 0.

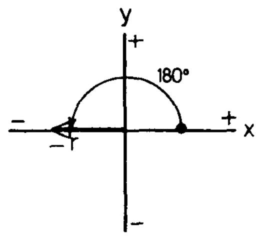


Figure 1.6 $-r = r(-1)^{180/180}$

In a similar way, the vector $-r$ shown in figure 1.6 can be written as

$$-r = r \times (-1) = r(-1)^1 = r(-1)^{180/180}$$

Multiplication of r by the quantity $(-1)^{180/180}$ can therefore be interpreted as *rotation* of the vector r in an anticlockwise direction through an angle of 180° from its original position along the reference.

By analogy, $r(-1)^{\theta/180}$ can be interpreted as the vector r rotated through an angle θ from its original position, as shown in figure 1.7.

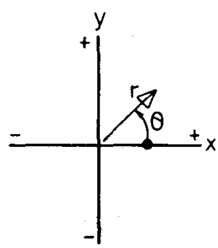


Figure 1.7 $r(-1)^{\theta/180}$

Thus the quantity $(-1)^{\theta/180}$ is an *operator*, multiplication by which leaves the magnitude of the vector unaltered but changes its line of action.

Clearly when $\theta = 90°$, the quantity $(-1)^{\theta/180}$ becomes

$$(-1)^{90/180} = (-1)^{1/2} = \sqrt{-1} = j$$

Then $$r(-1)^{90/180} = jr$$

means the vector r rotated through an angle of 90° anticlockwise from its original position (figure 1.8).

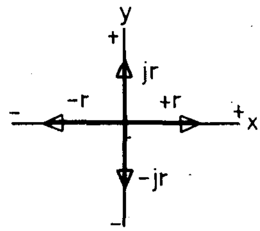


Figure 1.8 Interpretation of the imaginary quantity $\sqrt{-1} = j$ as an operator.

Thus the resultant R of a system of vectors whose x and y components are $\sum F_x$ and $\sum F_y$ can be described in a simple elegant statement as

$$R = \sum F_x + j\sum F_y$$

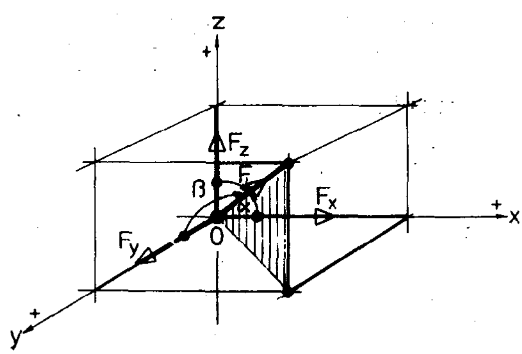
This one operator statement is fully equivalent to the previously derived algebraic statements that

$$R = \sqrt{(\sum F_x)^2 + (\sum F_y)^2}$$

at angle θ to the reference axis x given by

$$\tan\theta = \frac{\sum F_y}{\sum F_x}$$

So far we have considered vector resolution and summation in two dimensions (or directions) only. Real life takes place in three-dimensional space. Thus it is usually necessary to consider components of vectors in three directions (x, y, z) which, for convenience, are normally taken to be mutually perpendicular.



Angle between line of F and axis x is α
Angle between line of F and axis y is β
Angle between line of F and axis z is γ

Figure 1.9