AN ANTHROPOMETRIC AND BIOMECHANICAL COMPUTER MODEL OF MAN

by

Keith Case. B.Sc.

Thesis submitted for the degree of Doctor of Philosophy

in the Department of Production Engineering

and Production Management

Nottingham University

MAY 1975

CONTENTS

page

INTRODUCTION 3

Chapter 1 General Description of the SAMMIE System 5
Workplace Model 6
Work Task Language 10
The Man Model 13

Chapter 2 The Design Process 16

Chapter 3 Ergonomics and Design 30
Allocation of Function 31
Environmental Conditions 34
Psychological and Behavioural Patterns 35
Intelligence 35
Physiology 35
Anthropometry 36
Biomechanics 37
Data Availability for Ergonomic Evaluation 42

Chapter 4 The Anthropometric Model 49
The Link System 50
Open Chain Link System 52
The Link and Joint System for the SAMMIE Man Model 53
Joint Mobility 62
Mathematical Representation of the Anthropometric Model 66
Anthropometric Variables 71
Population Differences 72
Range of Dimensions within a Population 75
Correlation Differences 78
Data Provision for Anthropometric Model 79

Chapter 5	The Biomechanical Model	87
	Biodynamics	87
	Kinematics	88
	Trajectories	89
	Postures	93
	Indeterminacy and the need for a Kinematic Model	95
	Human Joints	98
Chapter 6	The Postural Algorithm	108
	Comfort Rating	115
Chapter 7	Joint Moments	120
	Fatigue	120
	Strength	124
	Dynamic and Static Force Exertion	125
	Strength Data	131
	Mathematical Model for Joint Torque Assessment	137
	Centre of Gravity and Balance Assessment	142
Chapter 8	Validation	148
	Validation as a Design Tool	148
	Validation of Man Model	151
	Segment Parameters	152
	Joint Model	155
	Joint Torque Model	158
	Postural Algorithm	163
Appendix I	Previous Work	169
	BOEMAN	173
	MTM Man	177
	COMBIMAN	181
	E.P.Hanavan's 'personalised model'	186
	UCIN	190
	Chaffin's Biomechanical Model	193
	Evershed's Man Model for the SAMMIE System	197

Appendix II Link Definitions 208

Appendix III Anthropometric and Biomechanical Data 211

Regression Equations for the Determination of Link Lengths 211

Derivation of Link Dimensions from External Dimensions 213

Formation of a Normal Distribution for Percentiles 214

Joint Range Data 216

Segment Parameters, Weights and Centres of Mass 218

Moments of Inertia about the Centre of Gravity of Body Segments 220

Appendix IV The 'Postural' Algorithm 221

General Principles 221

Data 221

The Algorithm 222

Appendix V Equations of Motion 231

Appendix VI Glossary of Terms 233

REFERENCES 236

SUMMARY

This thesis describes an anthropometric and biomechanical computer model of man which is an integral part of the SAMMIE workplace and work task design system.

Some aspects of the design process have been studied, especially with respect to the inclusion of human factors in the design process via the medium of computer graphics. A satisfactory way of achieving this objective is seen as being the provision of a pictorial model of man which facilitates the evaluation of important ergonomic design criteria concerned with the problems of reach, fit, movement patterns, strength, fatigue, comfort and balance.

A description is given of how such a model has been built, and linked with a similar model of the workplace to provide an integrated design and evaluation package.

ACKNOWLEDGEMENTS

The author would like to thank all the many people that have assisted him in a variety of ways in the last three years, and in particular,

Mr M.C. Bonney for supervision of the research work

The other members of the SAMMIE group, Mr Neil Kennedy, Dr Eileen Bisby, Mr Roger Williams, Mr Alan Parker, and Mr Stephen Barton.

The staff of the Computing centre at Warwick University

The Science Research Council for finance and continuing support for the project.

INTRODUCTION

The anthropometric and biomechanical model described here is an integral part of a computer aided design package known as SAMMIE (System for Aiding Man Machine Interaction Evaluation). As the acronym suggests the main objective of the system is to provide a design tool, (using the medium of computer graphics), which enables the analysis of some human factors aspects of workplace and work task design. The complete system is described very briefly in the next chapter and more fully in the references, but it is clear that before such a design tool can be built, it is necessary to make a brief study of the 'design process', and the significance of ergonomics to workplace design. Hence the second chapter considers three apparently divergent views of the design process, and attempts to identify those areas in which computer aids can be beneficial.

The third chapter investigates the use of ergonomics as a design criteria, although it is recognised that this is not the only criteria or necessarily the most important. Six major human factors of environmental conditions, human psychology, intelligence, physiology, anthropometry and biomechanics are identified, and means of including these factors in the design process are discussed. The conclusion is reached that anthropometrics and biomechanics form two aspects for which a computer model would be useful and relevant.

Hence the fourth chapter describes the way in which the human body can be represented by a link and joint system which is closely analogous to mechanical systems. Some of the problems inherent in the use of anthropometric data are discussed, and ways suggested in which relevant data can be acquired from the large volume available.

The fifth chapter is primarily concerned with the way in which the human body moves, and the extent of mobility at joints is used as the basis for the postural prediction algorithm described in chapter six.

Chapter seven is concerned with the biomechanical aspects of fatigue, strength and balance. A method of comparing the torques at joints due to muscle force exertion, with maximum attainable torques is discussed, thus enabling some estimation of the physical feasibility of a work task. The repercussions of the whole body centre of gravity due to the combined action of the weight of each segment are investigated with regard to a body posture being feasible so far as balance is concerned.

The final chapter illustrates the attempts made to validate the model, both as an integral part of a workplace design tool, and as a representation of various human functions.

The appendices include a description of other work in the field, including early man-modelling for the SAMMIE system, and also a glossary of terms, both of which it might be useful to study before reaching the body of this thesis.

CHAPTER ONE

GENERAL DESCRIPTION OF THE SAMMIE SYSTEM

General Description of the SAMMIE System.

The anthropometric and biomechanical man model, which is the main concern of this thesis, forms an integral part of a computer aided design system known as SAMMIE (System for Aiding Man-Machine Interaction Evaluation). The complete system consists of three inter-related parts:-

(a) a three dimensional workplace modelling system.

(b) a language to specify the operators' task.

(c) an anthropometric and biomechanical model of operators.

The aim of SAMMIE, is the provision of a tool which is useful in the consideration of human factors in the design of workplaces and work tasks. To implement this system, the medium of interactive computer graphics has been chosen because:-

(i) It enables the consideration of human factors at a much earlier stage in the design process (e.g. before any mock-up and fitting-test phase).

(ii) The need for sophisticated mock-ups can be reduced if not eliminated entirely.

(iii) The interactive nature of the graphics allows the consequences of a large number of design changes to be analysed in a comparatively short time.

(iv) The large volume of data handling required for ergonomic analysis is most efficiently handled by computer.

(v) The medium of graphics is easily understood and operated, and therefore the system can provide an effective method of communication between designers and users. (A fuller appraisal of computer graphics for these kinds of applications is given by Hughes (1972)).

A brief description of parts (a) and (b) above is given, with references to more detailed descriptions elsewhere, while the research into area (c) comprises the main part of the work undertaken by this author, and is expanded upon in later chapters.

(a) Workplace Model

The workplace model enables the designer to build up and modify a graphical representation of the operators' workplace, so that various designs can be presented for ergonomic evaluation. The aim has been to produce a three-dimensional model, with the minimum amount of data and its consequent preparation time. Objects are described in terms of a number of standard modules, such as cuboids, prisms, circles, lines, and points, with their relative orientations and positions specified by data input. In this way a desk could simply be defined as a rectangular plane supported in space by four lines, one at each corner. fig. (1.1). For some applications this simple symbolic representation might be sufficient, but for a more detailed investigation the user may wish to improve upon this by increasing the complexity of the model. This could be achieved for instance by the substitution of cuboids for the

Fig. 1.1 Simple Representation of a Desk.

planes and lines. Hence some impression of solidity in a visual sense would be given to the model, although any phenomena resulting from this 'solidity' cannot be detected by the system. i.e. there are no density and mass considerations, and physical interference between the operator and his workplace, or between different parts of the workplace can only be assessed visually.

Once the data has been specified the object can be displayed on the graphics screen at any required position and orientation, along with any other items so produced. Thus the table described above might be combined with a chair, a filing cabinet and a chest of drawers, to represent a simple office layout. fig (1.2). At this stage the control of the model is transferred directly to the designer using a lightpen for communication with the computer. There is now no need to prepare and input numerical data in the traditional sense, as modifications to existing data can be made interactively with the computer. In this way the items of furniture in the office layout, could be moved about the office, with a fresh display of the current situation being presented to the designer about once every second. Similarly the dimensions of the furniture can be changed in a pre-specified way with almost simultaneous redisplay, and without recourse to data preparation and input.

Furthermore the workplace can be viewed from any direction so that the traditional and often useful side elevations,

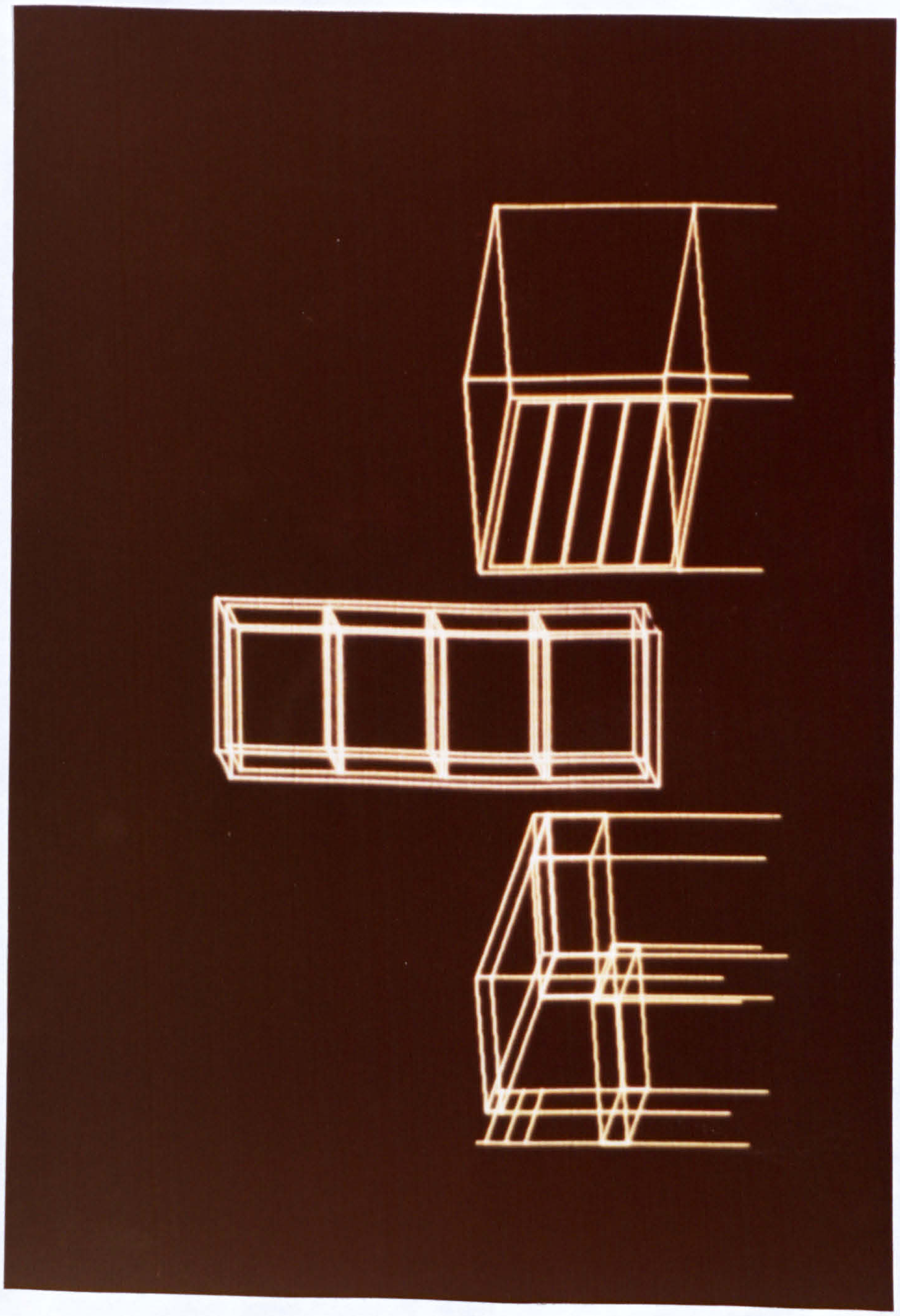


Fig. 1.2. Simple Office Layout.

front elevation, and plan view can easily be obtained, while intermediate positions give a three-dimensional representation in orthogonal projection.

A more detailed description of the workplace modelling system appears in Hughes (1972), and a manual for its use, Kennedy (1973).

(b) Work task language

The introduction of a model of an operator into the workplace model, requires a method of controlling its actions. As described later, the man model is essentially static, allowing the assessment of the effects of specific postures. However with a suitable control system these static frames could be displayed consecutively to produce an animated display of body movements (i.e. a kinematic model). In this way some 'pseudo-dynamic' aspects of the operator at his workplace could be investigated. For example it is often important to be able to assess not only whether a required point is within reach, but also whether in reaching to such a point, the moving limbs interfere with components of the workplace. Furthermore an operator may be required to work at several different positions in the workplace, so an additional requirement is that movement within the workplace can be managed in a satisfactory manner. Hence there are two major considerations:

(i) There should be a good representation of the paths taken by moving limbs, and also by the body when performing gross movements such as walking.

(ii) The instructions to perform such motions have to be communicated to the computer by the designer.

The first is solely a function of the man model, and is described later.

The second consideration, that of enabling the designer to control the movements of the man model, is met by the use of a 'work sequence language'. The objective of this language is to define the movements of the man in a manner which is intelligible to the designer, and unambiguous in its application to the model. The most immediately obvious way of meeting these criteria has been to pre-specify in the data input, points on each workplace component to which the man may be required to reach. These 'touch points' maintain the correct relative position during any change in the position, size, or orientation of the workplace component.

The left and right hands and feet can be requested to perform a reach movement, so an instruction in this simple 'touch point language' might be of the form PEDAL*RF*. This might simulate the operation of the brake pedal of a car with the right foot.

The simplicity of such a language for describing a work task, means that in some respects it is easy to learn, and fits well with any requirement for the production of MTM work study times, but it does impose certain limitations. The rigid structure of the language requires the specification of the touch points as data. This is not easily performed interactively at the screen, so it can become difficult to change a work sequence to enable the evaluation of a different arrangement of equipment in the workplace. In addition the language is very specific in its reference to the man model, so instructions of the kind PLACE BOOK ON SHELF are inadmissable, as the simple language structure can only cope with a hand or foot as the subject of a motion. Any situation where the subject and object of an instruction is not explicitly known, requires specification by the use of a syntax.

Hence to expand the use of the work sequence language and to make it more intelligible to the user, a new language is being developed, based on a subset of English. The language is of free form requiring no special symbols, as spaces act as word separators. The subject and object of any phrase are defined in terms of the workplace element name or limb of the body, and it is possible for the user to define the verbs which are to be used. A set of general purpose verbs are supplied however, and this collection will be added to as widely different tasks are investigated.

Each statement formed from nouns, verb and prepositional phrases can be executed or edited individually, so that a sequence of such tasks can be constructed. The syntax of all statements is checked automatically and in addition pre-specified conditional tests can be carried out before execution. In this way for example the user may specify that only one object may be held in each hand at any one time, a request to pick up further objects being ignored.

Further details on the work sequence language can be found in Kennedy (1973), and information regarding the earlier 'touch point' language is available in Hughes (1972).

(c) The Man Model

If the workplace modelling system described above can adequately represent the physical shape of the workplace and its components, it is then necessary to provide evaluative procedures, so that a proposed design can be critically compared with the design criteria. SAMMIE is mainly concerned with the ergonomic aspects of design, and hence it is considered that a man model, displayed on the screen with the workplace model and hence compatible with it, would be the most appropriate way of meeting this objective.

Hence the early SAMMIE model (Evershed 1970), was capable of performing certain anthropometric and kinematic evaluations of proposed designs. Designs could be tested for compatibility with the body dimensions of individual people, or with specified percentiles of populations, thus allowing the problems of fit and reach to be analysed. The 'natural planes' algorithm allowed the body postures to be assessed and displayed on the graphics screen, while the hand or foot followed a specified trajectory. A critical analysis of this prototype model is given in appendix I, the full description being available in

Evershed (1970).

For the reasons outlined in appendix I, it became clear that this model was inadequate as anything more than a prototype. Certain attempts were made to improve the model by enhancing the posture algorithm, improving the efficiency of the computer application, removing certain inconsistencies which existed between the man and workplace models, and by the inclusion of additional facilities. However it became obvious that the basic approach to posture modelling (i.e. the 'natural planes' algorithm), and the mathematical modelling of the link and joint structure, left very little hope for the future development of the model.

The prototype model was therefore abandoned and an entirely new model has been built as a replacement. This model is extensively described in later chapters, and repetition here is unnecessary, it being sufficient to say that it facilitates the evaluation of the following design criteria.

(i) Anthropometrics:-

(a) reach

(b) fit

(ii) Biomechanics:-

(a) motion paths of limbs

(b) extent of movement at joints ('comfort')

(c) strength

(d) balance

Development in these three main areas of workplace modelling, work task language and man modelling is continuing, along with the implementation of the system onto a dedicated mini-computer. It is hoped that the complete system will prove useful as a research tool for investigating the collection and application of ergonomic data, and as a design tool giving practical help in the early stages of the design process.

CHAPTER TWO

THE DESIGN PROCESS

The exact nature of the 'design process' is subject to a great deal of discussion and argument, both by theorists and practical designers, but it still remains somewhat nebulous. However, to enable a design system to be built, it is necessary to gain some understanding of the mental and physical processes employed by practising designers, so that assistance can be given by the computer in appropriate areas. Hence this chapter investigates the work of several authors concerned with the 'design process', and concludes with an assessment of areas in which a computer system will be of use.

The design process has been described by Jones (1970) as a three stage process of divergence, transformation, and convergence, using these terms to study design theory in its system rather than engineering or architectural design context.

The first of these stages, divergence, is the process of 'de-structuring the original brief while identifying those features of the design situation that will permit a valuable and feasible degree of change'. This is the 'brain-storming' aspect of the design process, where the original objectives of the brief are questioned, pre-conceived ideas removed, the boundaries of the problem investigated, and a large amount of information is gathered and absorbed, but no evaluation or decision-making is performed.

Transformation is 'the stage of pattern-making, fun, high level creativity, flashes of insight, changes of set and inspired guesswork'. Here the restrictions of reality are placed on the results of the divergent search, and value judgements made so that the process can proceed to the convergence stage. The objectives and boundaries which were not fixed in the first stage, now become fixed, and the problem split into sub-problems while remaining within the fixed boundaries and objectives.

The last stage of convergence serves to select the final design from the range of possibilities provided by the transformation stage. Hopefully this is achieved quickly and cheaply as the previous stage has structured the problem so that few iterations through the convergence stage are necessary.

Jones recognises the disintegrative nature of such a process, and the attendant dangers of lack of control in the all important transformation stage. However the advantages are thought to be that it reduces the tendency to select the first feasible solution found, and widens the designers' horizons in search of relevant information. The possibility of re-integrating the design process 'through the medium of on-line computing using graphical interfaces to speed up man-computer exchanges to the pace of thinking and conversation', is recognised, and this aspect is taken up again later in this chapter.

Beakley and Chilton (1973) give a somewhat more traditional view of the problem when considering the design process in the context of engineering design. They consider the design process to consist of iteration through the seven stages of problem identification, data collection, creation of ideas, simulation, analysis, experimentation, and solution, with a network of interacting feedback loops. (fig. 2.1)

Problem identification involves the defining of the problem boundaries, where these are found to be inadequate. Thus some design criteria will be specified, but it will usually be necessary to investigate what other factors are likely to affect the quality of a completed design.

Data collection is seen as a search for information relevant to the design problem. Normally it is impossible for this to be an exhaustive search due to an overabundance of information, but good problem identification reduces this problem to manageable proportions.

Perhaps the most important stage is the creation of ideas, or innovation. Methodologies can be proposed that stimulate the human brain into the channels of thought which are most likely to result in creative ideas, but there is no certainty of good results. A comprehensive list of such methodologies is given by Jones, while Beakley and Chilton mention checklists, value analysis, systematic search of design parameters, brainstorming, and synectics.

Simulation requires the building and testing of a model. The term model is used in its broadest sense to mean a representation by any means of the real life situation. Thus maps, catalogues of goods, and three-dimensional mock-ups, are all models, and serve to reduce a complex problem to a series of more easily understood sub-problems. The degree to which

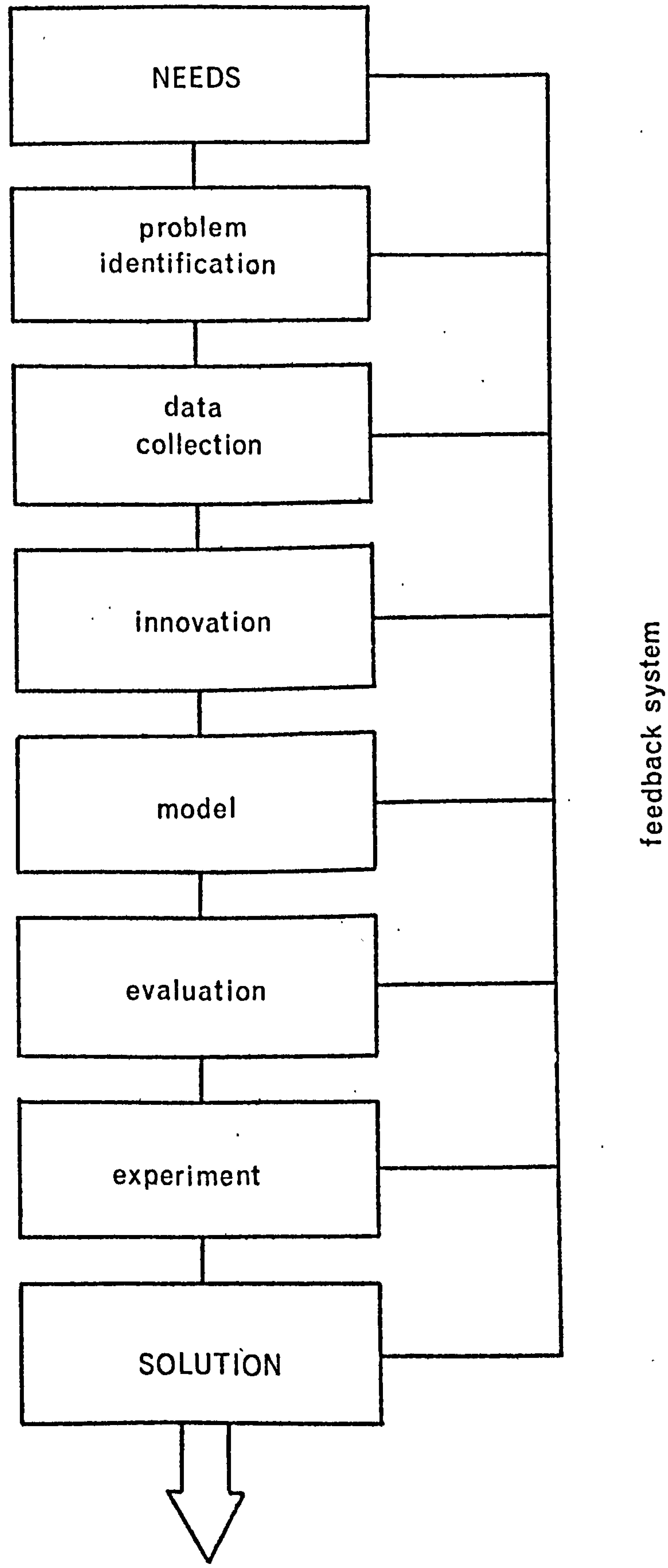


Fig. 2.1. A View of the Design Process. (adapted from Beakley and Chilton 1973).

the models correspond to their real life sub-problem is an indication of the validity of the model.

The analysis stage allows the designer to use his model to simplify the design so that it can be evaluated with respect to the stated design criteria. The model usually enables the problem to be stated in such a way that it can be solved by the application of mathematical techniques. Hence a free-body diagram may be the model that enables forces and moments to be calculated.

Any model which simplifies a complex situation, must do so by making assumptions. It is therefore necessary to test whether the assumptions are reasonable, and whether the model is sensitive to changes in these assumptions. i.e. the important assumptions as far as the model is concerned must be validated by experimentation.

The final stage of the design process, is the solution. This is the result of the analysis and experimentation stage, but probably will require presenting in the form of a report which compares the design achievements with the problem specification. The exact nature of this report, whether it be written, graphical, or verbal is obviously dependent on the individual design circumstances.

As figure 2.1 shows these seven stages are all interlinked by feedback loops, implying that it is an iterative process which converges on a solution. The extent to which any of the feedback loops are used is dependent on the type of problem being tackled. Designs with a high creativity content may require many iterations through the data collection and problem identification stages, while a simple routine re-design may be able to go through all seven stages with no back-tracking.

Archer (1973) sees design as 'the process of perceiving a problem in the external world, developing a cognitive model of the problem and possible solutions, externalising and testing this model, and then developing a set of instructions by which the model may be translated into real-world terms'.

A clear distinction must be drawn at each stage between reality and the designers' perception of that reality. Thus a model is a representation of the designer's perception of reality, but the model itself has to be perceived by the designer. This Archer describes as a two-stage mapping operation to represent reality by sketches, diagrams, mathematical expressions or whatever.

A 'problem-solution couple' exists, and it is the purpose of a design methodology to iteratively change, test and evaluate this couple until the 'misfit, malfunction or omission which constitutes the problem' is reduced to an acceptable level. Both sides of the couple make use of models, so it can be seen that models and human cognition comprise the essential features of the design process. In these terms the design process is described as:-

(a) perception of reality

(b) models of reality

(c) perception of problems

(d) models of problems

(e) perception of problem model

(f) concepts for solution

(g) models for solution concept

(h) perception of solution model

(i) outcome

(j) models of outcome

These three approaches to the description of the design process appear superficially to be considerably different, but certain features can be seen to be common to all three, and to most other theories of the design process.

(i) The most important of these, is the recognition by all the authors that there is a creative stage. This really is the essential feature of the design process, the other aspects being subsidiary in that they exist to enable creativity to take place.

(ii) The iterative nature of the process is recognised by most authors with a solution being found by convergence to a satisfactory rather than optimum answer. This is recognition of the fact that in most instances the number of possible solutions and routes to those solutions will be extremely large and incapable of consideration by current methods, as well as being outside the mental capacity of the designer.

(iii) Data collection and manipulation of this data in the form of a model.

(iv) Problem boundaries are defined, usually into design criteria against which the final design may be tested.

(v) Communication of the finished design to the sponsor.

If SAMMIE, or other such design tools, are to be useful in the context of the design process, they must aid the stimulation of creativity, but unfortunately it is difficult to envisage a methodology for creativity. The best approach is therefore to enhance the ability of the designer to cope with the subsidiary considerations numbered (ii) to (v) above. These are the functions which enable creativity to exist, but also tend to stifle and constrain that creativity by way of the time and effort expended by the designer.

SAMMIE is a model which hopefully helps to lighten the load of the designer in these respects, but only in the limited field of the application of ergonomic principles to workplace design. Implicit in this is that SAMMIE is only useful where human operators form part of a man-machine or man-environment design problem, where the anthropometric and biomechanical limitations of man are an important constraint. Other classes of design problem, such as those without human involvement, and those where mechanical and dynamic properties of machinery are important, would require models relevant to the particular situation, although the same general comments might apply.

SAMMIE then, can be seen as helping the design process in the four areas mentioned above. i.e.

(a) iterative searching for a solution.

(b) data collection and manipulation.

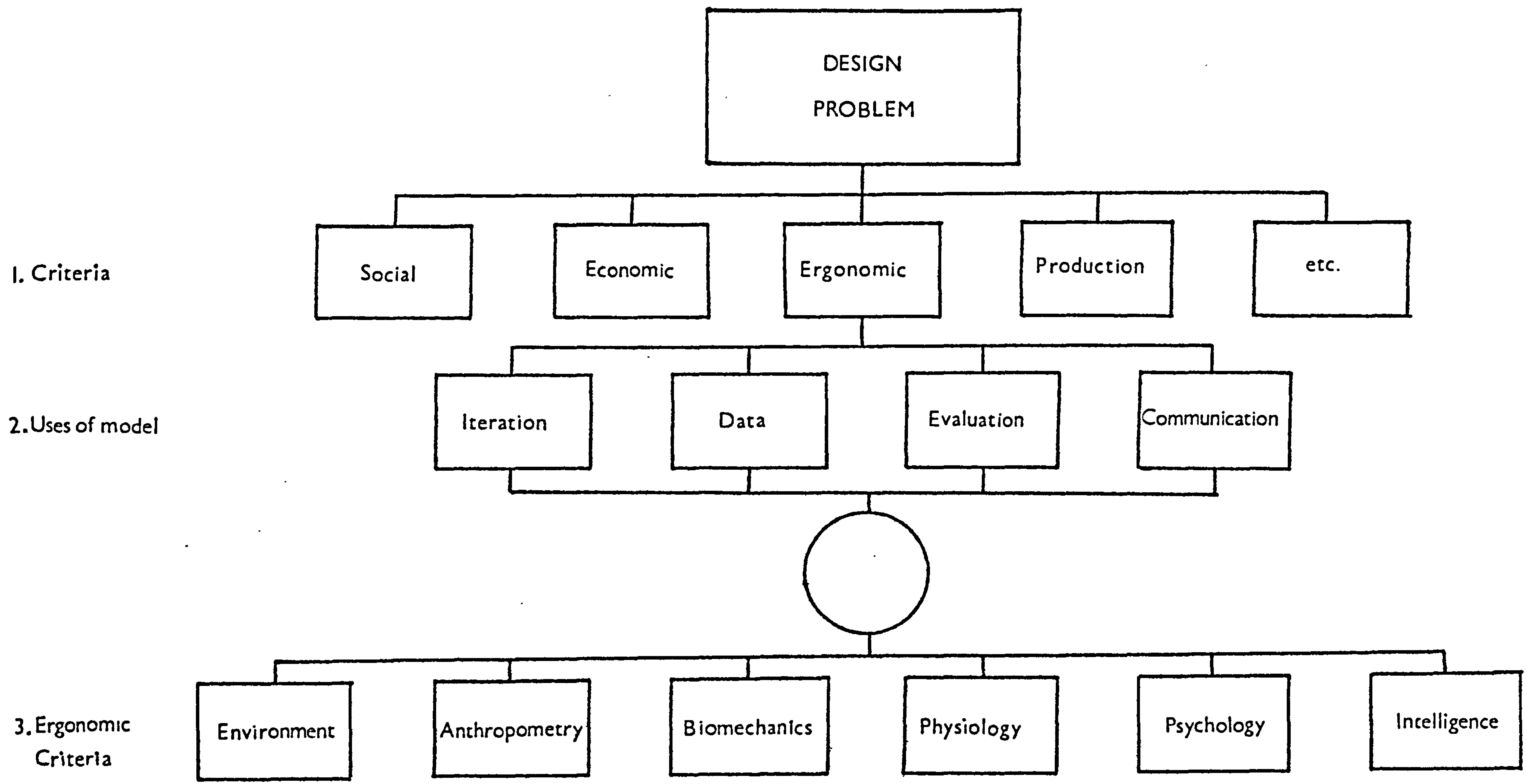
(c) testing a limited set of design criteria.

(d) provision of a medium for expressing the final and intermediate designs.

Figure 2.2 shows these aspects, where the first level indicates the type of problem, usually by reference to its most important design criteria. The second level shows the areas in which a model is useful, with the third level indicating the major ergonomic criteria and data.

The design situation is usually constrained by time and expense, resulting in satisfactory rather than optimum designs, although in certain closely defined situations, a computer system may be able to obtain an optimum solution. It is more likely however that a computer system, because of the infinite variety of possible solutions, will also only be able to find a satisfactory rather than optimum solution. However such a solution would be based on the evaluation and comparison of a much larger selection of solutions, and should thus have a greater chance of success than a manual method. The SAMMIE system is aimed at being at a midway position between a manual design system and a fully automated computer system. It attempts to use the attributes of the designer and the computer in a complementary way, leaving the designer free to concentrate on

Fig. 2.2. The Use of SAMMIE in the Design Process.



creative activity while the computer looks after the 'administration' of the design. In this way, solutions to a design problem are searched for by the human designer, the computer merely providing an effective medium for storing data, presenting designs in an appropriate form, and evaluating those designs against certain established criteria. No attempt has been made to give the computer any 'creativity', as this must involve either 'brute force' methods of evaluating every possibility, which is usually impracticable, or alternatively the building of general design algorithms which to be satisfactory must be applicable over a wide range of specific applications. Instead the computer is used to enhance the designer's ability to use his creativity, experience, and ability to manipulate qualitative rather than quantitative objectives.

In the first area of usefulness ((a) above), SAMMIE provides a capability of making many changes to a proposed design, at any stage of the design process. In comparison with the traditional drawing board method of engineering design, the interactive nature of computer graphics allows a great number of large or small modifications to be achieved with greatly reduced time and expense. Referring again to fig. 2.1 it is perhaps useful to consider the feedback loops as the major cost penalty, in that backtracking implies that cost and time penalties have been incurred. One view of the design process might be that final solution selection occurs when the cost/time penalty reaches an unacceptable level. Hence SAMMIE attempts to use interactive graphics so that design changes can be accommodated quickly and cheaply, allowing more and hopefully better designs to be evaluated.

In area (b), SAMMIE provides a facility for manipulating data for the complete man/machine system. Three-dimensional information about the workplace and its equipment is obtained from input data, and can be modified interactively on the screen of the graphics terminal. In this way any change in dimension, orientation or position of any part of the workplace can be achieved almost immediately. Human factors data in the form of a man model is also available for immediate use in evaluating the workplace design. It is the application of this human factors data to a particular design situation which can be time-consuming and frustrating for the designer trying to apply ergonomic principles in his design. The aim of SAMMIE is therefore to provide this data in a form compatible with the workplace information.

The testing of design criteria (c), is carried out in certain specific situations. Currently, the criteria available are the physical consequences of a workplace layout in its interactions with adjacent workplaces, interactions between components of the same workplace, and the effect of the equipment on its human operators. This can be summarised as an evaluation of the interaction of:-

(i) elements of the workplace

(ii) workplace and operators

(iii) operators and operators

Other design factors such as (Archer 1963/4):-

aesthetics

motivation

function

mechanism

structure

production

economics

are not specifically evaluated, not because they are necessarily considered to be of less importance than ergonomics, but because they are outside the scope of the SAMMIE system.

The use of SAMMIE as a communication medium (d) is highlighted when considering design by interdisciplinary groups. Archer (1971) describes design as '...necessarily a group activity' and goes on ' one of the causes of the very high failure rate....is the gross inadequacy of communication between the members of such groups'. An example of conflict and possible lack of commumication within a design group can be seen in the design of hospitals. The primary aim of the hospital system is presumably to provide for the medical needs of the population. To meet this design objective requires an interdisciplinary activity concerning architects, the medical profession, and hospital administrators. Conflicts of opinion may arise for example between the architects plans for room layouts, the medical requirements for the prevention of cross-infection, and the administrations' staffing problems. SAMMIE aims not necessarily to be able to eliminate these kinds of conflict, but to allow the consequences of any decision to be evaluated quickly and communicated through a common medium to all members of the design team.

However the design team exampled above may be incomplete, because the real users of the hospital would be the patients, nursing staff, doctors, and ancilliary staff. This aspect of the provision of a communication medium now becomes even more important, if such people are to be included in the design team, as otherwise people hitherto uninvolved in the design process will be required to express their ideas in terms alien to their training and experience.

In conclusion, the SAMMIE system has been built primarily to meet designers' needs for a tool which assists them in the evaluation of the human factors repurcussions of a proposed design. The need for a consideration of human factors and its relative importance to other criteria is discussed in the next chapter.

CHAPTER THREE

ERGONOMICS AND DESIGN

Ergonomics and Design

Until relatively recently ergonomics has been largely ignored as a design criteria, but this position is now changing rapidly. Much has been written in the literature concerning the history and roots of ergonomics (e.g. Chapanis (1959), Murrell (1965), and Woodson and Conover (1970)), and it is not intended to repeat it here. It is clear however that human factors were for many years subordinated to other design criteria such as productivity and economics, and that it was not until man's workplace became so complex that he himself became the limiting factor in any improvements, that the consideration of ergonomics became essential.

The Second World War was the greatest spur in this, as the development of complex aircraft and radar began to overload the human operator. Full employment after the war resulted in labour no longer being expendable (in the economic sense), so consideration of the operator's welfare assumed some importance. Finally the last decade has seen an acceleration in the introduction of government legislation concerned with the safety of operators at their workplaces, which has required the acquisition and inclusion in safety standards of information on human capabilities. This last point is discussed in considerable detail in a special edition of Human Factors (1972), where a number of authors repeatedly stress the difficulty of framing legislation in the context of inadequate knowledge of human capabilities.

The growth of ergonomics as an important consideration in workplace design, can then be seen to stem from these three factors:-

i.e.

(a) The complexity of modern equipment is such that the operator's ability to control it is being taxed.

(b) Staff shortages and high training costs increase the importance of providing good working conditions so as to retain labour.

(c) Government legislation protecting workers' welfare is increasingly being reflected in the design of workplaces.

<u>Allocation of Function</u>

The first of these three factors, that of the complexity of modern equipment, has led to the recognition of a problem known as the Allocation of Function. It has been realised that machines and man have widely differing attributes, which in complex man-machine systems have to be combined in such a way that the whole system functions in the desired manner. An early expression of this was contained in Fitt's List (1951), which compared some of the attributes of machine and man. An example of such a list appears as Table I.

Whitfield (1967) critisizes such lists as giving 'a fragmentary picture of human performance,....(suggesting that)...we must employ "whole" human operators and not merely assemblies of convenient human characteristics'. Jordan (1963) considers that making a comparison between man and machine is a fallacious exercise as we should be looking for areas where they are complementary and not necessarily comparable. He suggests that particularly in the context of responsibility and reliability in performing tasks, man should complement machine functions by being able to take over if the machine should fail. An important aspect of this is that operators of automatic equipment, can be given greater job satisfaction by the assumption of functions which could otherwise have been machine functions. Wulfeck and Zeitlin (1962) recognise that performance is not the only criteria, and in particular that cost/value data is of importance. Swain and Wohl (1961) conclude that 'there is no adequate systematic methodology in existence for allocating function between man and machine. This lack in fact, is probably the central problem in human factors engineering today.'

The conclusions that can be drawn from the argument are that:-

(a) The performance of human operators is important in all man-machine systems.

(b) Adequate data presented in the appropriate form is required before a solution to the allocation of function problem can be found.

(c) Criteria other than relative man-machine performance may be of importance.

Table I

Fitt's List

	Machine	Man
speed	Much superior	Lag 1 second
power	Consistent at any level Large, constant, standard forces	2hp for about 10 seconds .5hp for a few minutes .2hp for continuous work.
consistency	Ideal for repetition, routine, precision.	Not reliable, should be monitored by machine.
memory	Best for literal reproduction and short storage.	Large store multiple access. Better for principles and strategy.
reasoning	Good deductive	Good inductive
computation	Fast, accurate, poor at error correction.	Slow, subject to error, good at error correction.
input sensitivity	Some outside human senses. e.g. radioactivity	Wide range and variety of stimuli dealt with by one unit. e.g. eye deals with relative location, movement, and colour
	Insensitive to extraneous stimuli	Affected by heat, cold, noise and vibration.
	Poor for pattern detection	Good at pattern detection. Can detect signals in high noise level.
overload	Sudden breakdown	Graceful degradation
reliability	Good repetitive	Liable to random errors.
intelligence	None	Can deal with unpredicted and unpredictable. Can anticipate.
manipulative abilities	Specific	Great versatility

Hence it can be seen that, if the allocation of function is indeed 'the central problem in human factors engineering', then central to this problem is the provision of suitable human factors data presented in a manner compatible with the design methodology.

An examination of Fitt's List discloses that the important human factors to be considered are:-

(i) Response to environmental conditions.

(ii) Psychological and behavioural patterns.

(iii) Intelligence

(iv) Human physiology

(v) Anthropometry

(vi) Biomechanics

(i) Environmental conditions

The environmental conditions an operator finds at his workplace, can relate directly to his welfare and efficiency, and in extreme conditions to his safety. Industrial diseases, range from the well known and highly dangerous pneumoconosis of miners, asbestosis of asbestos workers, and radiation sickness of nuclear power workers, to the almost imperceptible loss of hearing in certain frequency ranges suffered by many people who work in very noisy surroundings. Similarily heat, light, humidity, noise, toxicity, vibration, and in space travel, weightlessness are all factors which should be considered in workplace design.

(ii) Psychological and Behavioural patterns

In situations where the operator performs the control function in a man-machine system, the psychological and behavioural aspects of his abilities assume greater importance than his physical attributes. Hence reaction time; motivation, and the ability to comprehend a complex situation and react to a wide range of stimuli in the appropriate way, become the limiting factors in the man-machine system. The place of ergonomics is then to arrange the workplace and task so that these functions can be performed in something approaching an optimum manner.

(iii) Intelligence

The related human attribute of human intelligence, enables an operator to arrange the use of his other facilities to their greatest advantage. Hence although inferior to machines in many ways, man can use his intelligence to control his own functions, and where necessary can employ inventiveness to cope with previously unexpected machine functions. Jordan's comments mentioned above, illustrate that this is a facility which the workplace designer should try to utilise, so that job satisfaction and hence motivation are enhanced.

(iv) Physiology

Human physiology is generally only an important criteria in manual work where the work content can be such that factors like heart rate, aspiration rate, sweat rate, and fatigue may limit man's ability to perform a task. The work content of such tasks is being progressively reduced by the replacement of man's manual attributes by machinery, but there are still a large number of industries where a great deal of human effort is required. This is true even of high technology industries such as coal-mining and steel manufacture where a significant proportion of the workforce can be found expending considerable manual effort, with added problems of adverse environmental conditions. Hence Pratt and Corlett (1970), in a study of vertical turret lathe operation have established that 'the heavy load due to the extreme postures demanded when operating these machines, requires 30% or 40% rest for operators. The physical capacity represented a limit on performance which prohibited any improvements in machining technology'. (also reported in Corlett (1973)).

Hence a knowledge of physiological factors can in some situations be essential so that suitable workloads and rest periods can be provided.

(v) Anthropometry

The anthropometry of the potential user population of a piece of equipment can have a considerable impact on the efficiency of the man-machine system. Kennedy (1972) has given many instances in the design of cockpits for military aircraft, where the inadequate application of anthropometric principles has resulted in some very undesirable and dangerous situations.

He quotes the case where 'as much as 25 percent of the navigator-bombadier trainees cannot adequately reach their ejection handle'. This example, and the many others that Kennedy mentions, are remarkable when it is considered that the military were among the first to realise the importance of the human element in any system, and that selection by size is an accepted method of recruitment.

In the industrial context, where there is a population of far greater variability due to differences in age, sex, occupation and nationality, there are many examples of mis-matching human anthropometrics to the machine. Singleton (1964) gives an excellent example of such a mismatch between a capstan lathe and its operator. (figs 3.1.a. and 3.1.b.). Figure 3.a. depicts an 'average sized subject' and the lathe controls, while the second figure shows a man designed to suit these controls. Obviously ergonomics played very little part in this design.

(vi) Biomechanics

Biomechanics attempts to draw an analogy between the moving parts of the human body, and the functioning of mechanical systems. Hence, depending on the closeness of the analogy, the equations of motion found in mechanics, can be used to describe certain human functions. In this way the force capability supplied by the muscles can be translated into movement of the limbs or the application of a force at some

Fig. 3.1.(a).

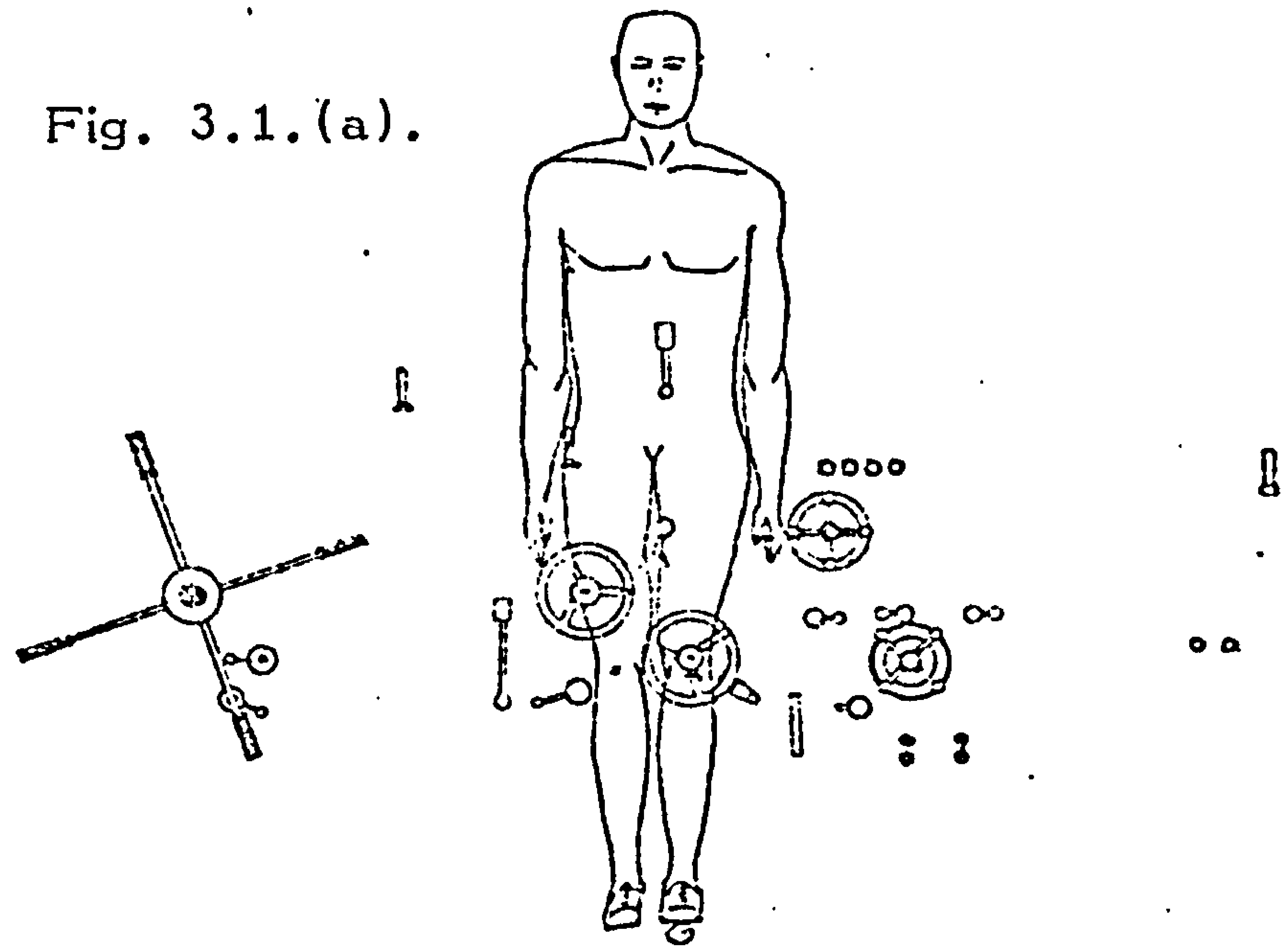
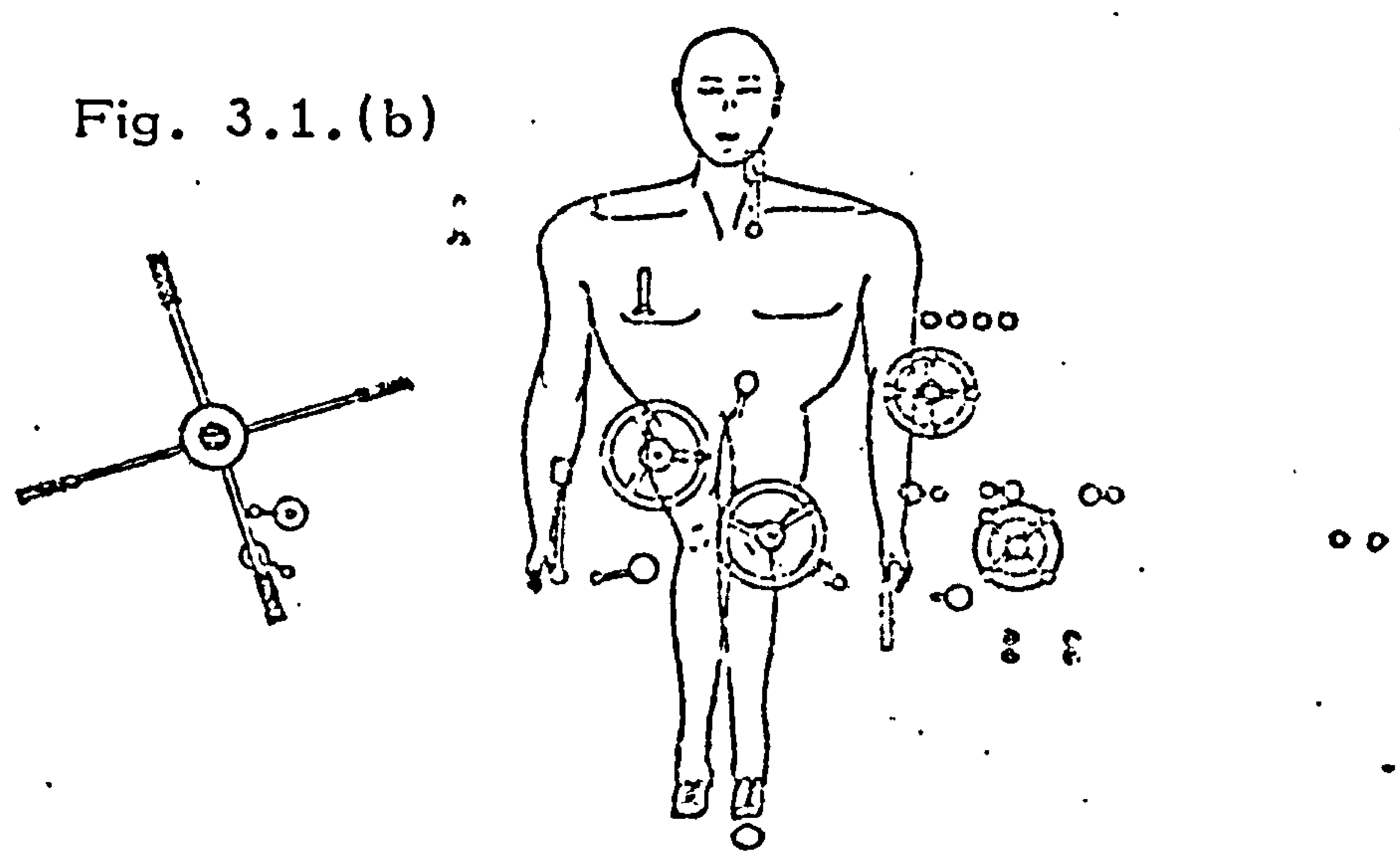


Fig. 3.1.(b)



Mismatch between a capstan lathe and its operator. Figure (a) shows an 'average sized subject and the lathe controls, while figure (b) shows a man designed to suit these controls. (from Singleton 1964).

distal part of the body. Alternatively the effect of the application of large external forces in the body can be investigated by a branch of biomechanics, known as biodynamics. Biodynamics is usually considered where the external forces overwhelm the internal muscle forces, so that the body can be considered as a collection of unconstrained masses susceptible to externally applied accelerations and decelerations. This is most useful where for instance the car crash or aircraft ejection situation is being considered. More useful in general workplace design problems however, are the aspects of biomechanics which deal with movement patterns (Kinematics), and the application of forces, in such situations as lifting, pushing or pulling. Here some of the physical capabilities of operators can be considered in the design of the workplace, and potentially fatiguing or dangerous situations can be avoided.

Fig. 3.2 illustrates these points, where the maximum forces exertable on a brake pedal have been derived for various pedal inclinations. (From a survey of 100 aircrew. Hertzberg and Burke (1971)). It can be seen that an inclination of 30° gives maximum forces which are approximately 50% higher than those obtained at the extreme conditions of 5 and 55 degrees. This is a direct result of the different postures involved, and clearly shows that an analysis of the lever system of the body (by biomechanics) can lead to improved workplace design.

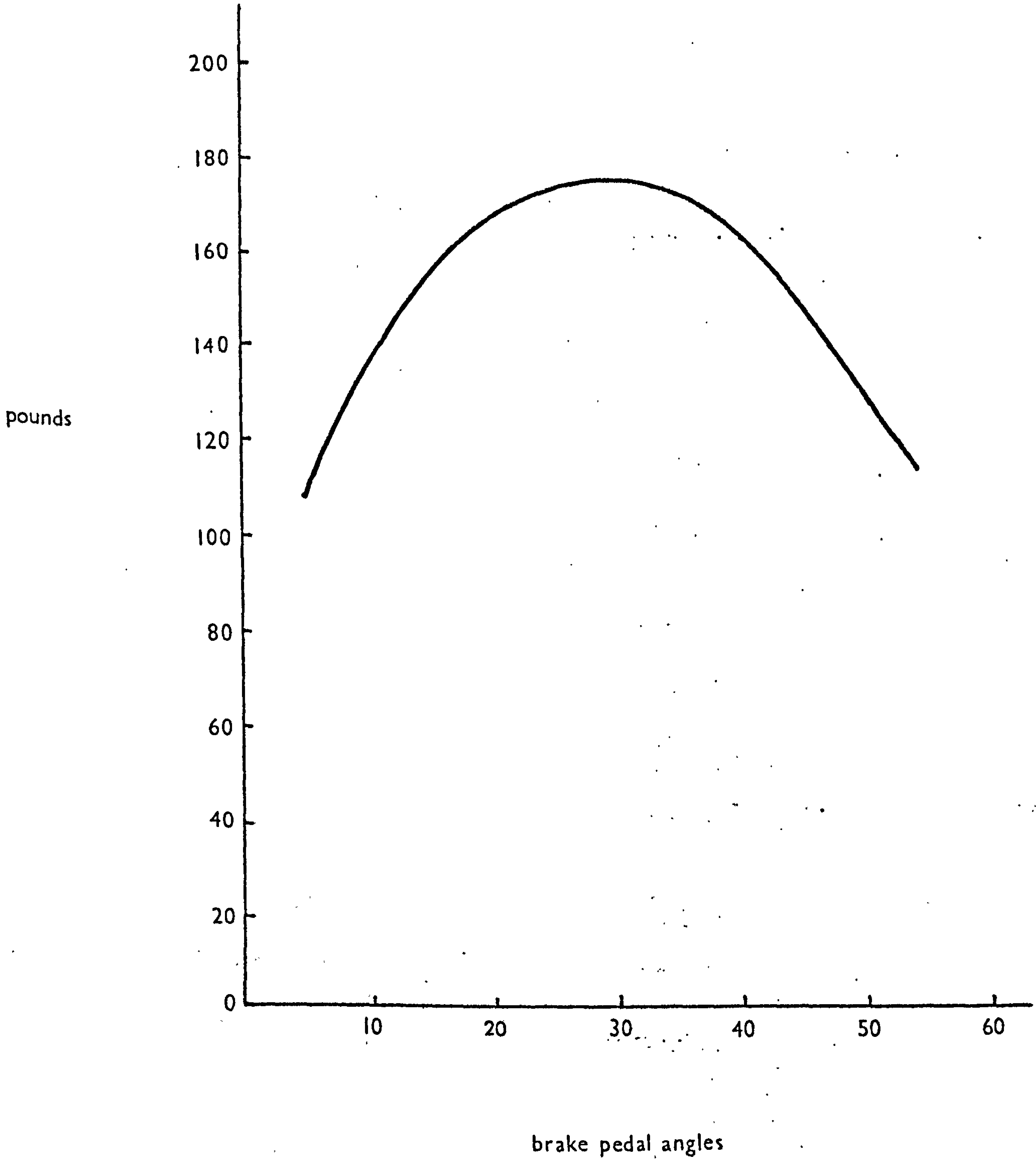


Fig. 3.2. Maximum forces exertable on a brake pedal at various inclinations (from a survey of 100 aircrew. Hertzberg and Burke 1971).

The six areas above cover the major ergonomic factors to be considered when designing man-machine systems, but there are undoubtedly many others of perhaps less significance in general, but which might assume considerable importance in specific circumstances. Among these may be included selection and training of staff, and the social interaction between operators.

Even a comprehensive list of criteria by which to judge the relative merits of designs, does not provide a complete solution to the problem of selecting a design of good ergonomic quality. Any realistic situation will involve several, if not all, of the factors mentioned above, but the relative importance of each factor may not be immediately obvious. As an extreme example, a control task will involve the operator in very little physical effort, but may well test his information intake ability. A design which managed to optimise the biomechanical content of the task, would do very little to meet the real problems encountered by the operator. In less extreme examples, the relative importance of the ergonomic factors may be such that a subtle compromise has to be found between conflicting pressures.

The first step in any determination of the overall ergonomic quality of a design, involves obtaining access to relevant data. Some of the difficulties in selecting data from the mass available are discussed later, but a few points specific to the areas of interest already indentified can be made here. In particular it is necessary to establish the availability, presentation and likely mode of implementation of such data.

Data Aviliability for Ergonomic Evaluation.

The environmental conditions found at the workplace, such as noise, heat, vibration etc. have been extensively studied, and many design recommendations given, very often with the backing of a professional institution. Examples can be found in the 'Recommendations for good interior lighting' published by the Illuminating Engineering Society London (1961), and the 'Guide for conservation of hearing in noise', published by the American Academy of Opthalmology and Otolaryngology (1957). Recommendations such as these are best included in the design process in the form of checklists, against which the design can be compared.

Unfortunately the psychological and behavioural aspects of man do not lend themselves to the deterministic treatment available for environmental conditions. Human performance in control tasks, which is the main area where a knowledge of man's psychological characteristics is important, is the predominant concern of modern human factors research. (As a brief study of recent editions of Ergonomics and Human Factors will confirm). However, despite the extensive study of a wide range of situations, a random selection of which might include Takakuwa's (1971) study of concentration as a measure of mental stress, Murrell's (1973) description of the work leading to the adoption of a British Standard in scales and indices and the more specific 'effects of platform fashion shoes on brake response time' (Warner and Mace 1974), it is evident that at the present time insufficient in known about the human brain and nervous system to enable general recommendations to be stated. This is particularly disturbing, as man is increasingly moving towards performing control functions rather than manual work, and information on his abilities in this context, should be of prime importance to the workplace designer. In this situation, the designer has to rely on the possibility that the area of interest to him has been the subject of study, so that directly relevant information is available. The only other alternatives are to initiate research studies, which will often be impractical, or perform somewhat dubious extrapolations from existing knowledge.

Brouha (1967), after many years of practical involvement in the consideration of human physiology in the industrial context, concludes that 'physiological techniques should be introduced in the methods of work analysis and work measurement...to improve machine and tool design and work space organisation'. He goes on to say however that physiology is 'still ignored in industrial practice', because of misdirection of effort by research laboratories, lack of awareness by management, and poor contact between physiologists and industry. This is rather a harsh indictment of a profession which is attempting to tackle the problems of industry, but it is true that this is an area which perhaps should be considered to have great potential, but little to show for the extensive effort expended to date. The physiology of humans is extremely complex, with many inter-related effects governing human work capacity. Hence although qualitative indicators of work capacity can be found in great number (e.g. oxygen consumption, blood lactate and sugar levels, pulse rate and blood pressure), it is difficult to relate these in a predictive way to the task being performed. Hence information for example relating heart rate to a lifting task may be difficult to find. If obtainable, such information may be of little value, because of lack of agreement as to what constitutes an acceptable heart rate. It is particularly important in physiology to consider the whole human system, and hence an 'acceptable' heart rate may depend on a large number of other factors e.g. fitness, rest periods allowed, and duration of work at that level.

This multi-variate nature of the data, tends to make it unuseable for practical purposes by the designer. Hence physiology is usually avoided as a design criteria unless circumstances make it absolutely essential (e.g. foundry work). Improvement in this situation will only come about, when the extensive research work currently being undertaken, can be compiled into data useful to the designer.

Anthropometric data is available in two distinct forms, which could be called basic and functional data. The basic data refers to the large number of linear and volumetric dimensions of the of the human body which have been collected for a wide variety of populations, while functional anthropometric data is related to the workplace or task. An example of the latter kind might be a reach contour which shows (for a specific population), the locus of all positions at which a button could be pressed. The relationship between functional data and the task is emphasised when it is realised that the reach contour used as an example, would have to be amended if the task involved was to grip a handle rather than push a button.

Currently it is functional data which is most commonly used by designers, as it provides a quick and easy way of determining such things as seat heights, work surface heights and control positions. There are however disadvantages in this approach, as once again the designer is relying on the availability of data which refers specifically to his type of problem and his potential user population. This is tantamount to the problem being already solved, in which case it is a data retrieval system which is required not a designer. More typically the problem will not have been previously solved, but the designer is left struggling in an attempt to manipulate function-specific data into a use for which it is not ideally suited.

The alternative of using the basic data is, at first glance, an even more distressing course of action for a designer to contemplate. Data retrieval of anthropometric dimensions for specific populations is simple enough, providing such data exists, but relating this to a three-dimensional co-ordinate geometry is sufficiently complex to render such an approach impossible without some kind of assistance from pre-determined computational operations. One aim of the anthropometric model described in later chapters is to provide this aid to the designer, through the provision of computer programs to handle the mathematical aspects of the analysis. A successful model of this type could be instrumental in improving the anthropometric aspects of designs, as it reduces the temptation to use inappropriate data merely because it is available, and gives the designer much greater flexibility in the type of evaluation that can be performed.

Biomechanical data can be thought of as basic or functional in a similar manner to anthropometric data. For example Hugh-Jones (1947) has shown that a seated operator can exert a mean isometric pull of about 80 lb when the hand grip is 230 mm above and 840 mm in front of the seat reference point. The contrasting approach involving the derivation of basic data has been used by several investigators who have established the torque levels available about certain joints (e.g. Chaffin 1971 and Pheasant 1974). Much the same comments can be made about the relative merits of basic and functional data in the context of biomechanics as were made in the context of anthropometrics. The same conclusion is also reached. i.e. that the use of basic data allows more flexibility over rigidly function-related data, but that the difficulties encountered in the practical application of basic data, requires that a computerised mathematical model be used. Such a model is described in later chapters.

It is evident then that ergonomics is a very broad and varied field, requiring considerable effort to achieve a comprehensive implementation into the design process. Potentially there is a vast amount of data concerning the human being and the way he functions, but for good ergonomic design, this data has to be collected, stored, recalled, interpreted, and manipulated for each particular design problem. Very rarely will a designer find the information in the exact form he requires, as it will probably refer to the wrong population, or for example the individual effects of heat noise and vibration may be known, but the aggregate effect of all three remains unknown.

There are thus two areas where ergonomics is lacking. The first of these, the incompleteness and inaccuracy of information, it shares with all the other active sciences. A complete knowledge of the functioning of the human body and brain is likely to elude us for some time yet, but advances are being made. The individual disciplines such as medicine, applied psychology and sociology, are thus providing ever more basic information for the ergonomist to relate to man's workplace and task.

The second and related point, is that with ever increasing amounts of data of greater complexity, a way has to be found to make the knowledge available to designers. Currently this has resulted in recommendations such as optimum working surface heights, the range of adjustments required for a typist's chair, and the load carrying abilities of man. Unfortunately for the designer, and the future users of his design, such specific information for a particular problem will very often not exist. In many areas such as anthropometrics and biomechanics, the basic data exists, but its conversion into a useable form is left to the designer. Hence one of the main aims of ergonomics should be to overcome this difficulty of the practical implementation of human factors data.

The approach to this problem taken in this thesis, is the building of a 'man' model which represents some of the main human functions. Of the six major areas of environmental conditions, psychological responses, intelligence, human physiology, anthropometry, and biomechanics, the last two are considered to be the most amenable to this treatment. Environmental conditions are perhaps best included by way of checklists, while the remaining three functions appear to be insufficiently understood at the present time to enable their accurate mathematical modelling.

The remainder of this thesis is thus concerned with the building of an anthropometric and biomechanical model of man which allows this human factors information to be manipulated in a way that is compatible with a workplace design model.

CHAPTER FOUR

THE ANTHROPOMETRIC MODEL

The Anthropometric Model

The need for an anthropometric and biomechanical model as identified in the previous chapter, can be satisfied by a mathematical model which can fully represent the three-dimensional geometry of the body in motion. Hence the anthropometrics of reach could be evaluated by reference to the linear dimensions of the various body segments, and their relative positions. The simple example of reaching forward with the body constrained not to move, illustrates that the distance of forward reach is dependant on the length of the upper arm, forearm and hand, and the relative orientation of each. (i.e. there are constraints to movement about joints; see chapter 5).

The problems of fit require a three dimensional representation of the flesh, and a method of manipulating these shapes into the correct position and orientation (i.e. posture) for display on the screen. Finally the modelling of the biomechanical features requires that the position of the end points of all the limbs are known, so that the various kinematic and strength analyses can be carried out (chapters 5,6 and 7).

The approach to this problem which has been accepted by most other investigators in this field, has been to build a three-dimensional link structure based on the work of Dempster (1955). Dempster proposed a functional link structure of the body, which adequately represents human anthropometry, while enabling the body to be treated as a mechanical or kinematic system. The next section describes the way in which Dempster developed the concept of links to represent and simplify the complex human bone structure.

The Link System

Human bones have many functions apart from the mechanical and kinematic ones, and the concept of a link is designed to remove those functions which are irrelevant to the anthropometrics and biomechanics of workplace design. Hence bones are approximated by straight rigid links between joint centres, although they are also 'recognised as calcium and phosphate deposits, as protective mechanisms because of their rigidity, as marrow deposits for blood cell formation, and as surfaces for muscle attachments'. (Dempster 1955).

The link does not attempt to represent the shape of the bone, but merely allows the determination of the spatial relationships between body segments, by reference to their end points. Hence for some bones such as the femur and the radius, the straight line link between the relevant joint centres, actually falls in part outside the physical volume of the bone. As Dempster says, 'a bone may flare out from or bend away from the core line between adjacent joint centres....(as a result of).....growth processes.....the genetic constitution of the species....and its mechanical function', but these functions are irrelevant in the current context.

The body segments are able to assume different relative positions (i.e. different postures), by movement about the joints which interconnect them. Hence to enable the essential feature of posture assessment to be performed, some representation of body joints has to be found.

Adjacent bones are held together by muscles and ligaments, but it is possible to identify centres of rotation for each link, which can be considered to act in the same way as pin-joints. Dempster (1955) has investigated the curvatures of the male and female articulating faces of the major joints of the body, and found them not truly reciprocating. In addition, 'the binding of ligaments may functionally change the position of joint centres'. However by the use of geometrical methods on dissected cadavers he was able to locate points on the skeletal frame about which all motion of adjacent links can be said to occur (appendix III). Hence pin-joints of this type are assumed for the anthropometric and biomechanical model. In some instances this approximation is a very close analogy to the functioning of human joints (particularly at the ankle and elbow), but at others, notably the shoulder joint, it is perhaps too gross an approximation. However the concept of pin-joints related to each other by straight rigid links, does enable the postural configuration of the body to be described in precise mathematical terms.

All movement of a link is thus rotational about the relevant pin-joint. This implies that the distal end of a link can only move through an arc of a circle relative to the joint centre, while the link itself sweeps out a plane surface. The extent to which such movements can be performed is dependant on constraints to this angular movement due to bony stops on the joints, ligaments and flesh interference (see chapter 5 for further details).

Open Chain Link System

The link and joint structure described in the preceeding section allows a potential of three degrees of rotational freedom for each link about its joint. As relative movement of adjacent links is possible only in a rotational sense, translatory movement of distal points can only be achieved by rotation at two or more joints. Hence it is impossible to move the hand relative to the wrist in anything other than a rotational sense. The addition of rotation about the elbow joint (or any combination of other relevant joints), however, enables translation of the hand through space.

These points have great significance both for the way in which the body functions, and for the approach made to man modelling. The crucial factor which gives man great flexibility in his movement patterns, and which also complicates the predicting of postures assumed when performing tasks, is that the link system so far described, forms an open chain. Mechanical systems are normally closed chain in that movement is always deterministic. The human link and joint system however has many degrees of freedom, so that most end positions of the hands for instance, can be attained by a large number of different postures. This indeterminacy due to redundant degrees of freedom at the joints gives rise to the open chain link system. The implications of this for man modelling are described in more detail in the next section, and in chapter 6 where the posture algorithm is described.

The Link and Joint System for the SAMMIE Man Model.

The earlier SAMMIE man model of Evershed (1970) which is briefly described in Appendix I utilised the thirteen links shown in figure 4.1. This model had no separate hands or feet, and the head was a rigid extension of a rigid one link spine. Such a model can be useful where the detailed operation of switches, levers and pedals is of no importance, where the trunk is constrained so as not to move, and where the orientation of the head bears no significance to the design. However it is felt that consideration of these features should be included in a more sophisticated model because:-

(i) The orientation of the hands and feet can have a profound effect on the posture which the rest of the body assumes. The different grip characteristics of say a crank and a lever will result in varying postures for the arm, and again, the shortening of the limb by forming the hand into a fist for grasping purposes results in a different functional reach characteristic

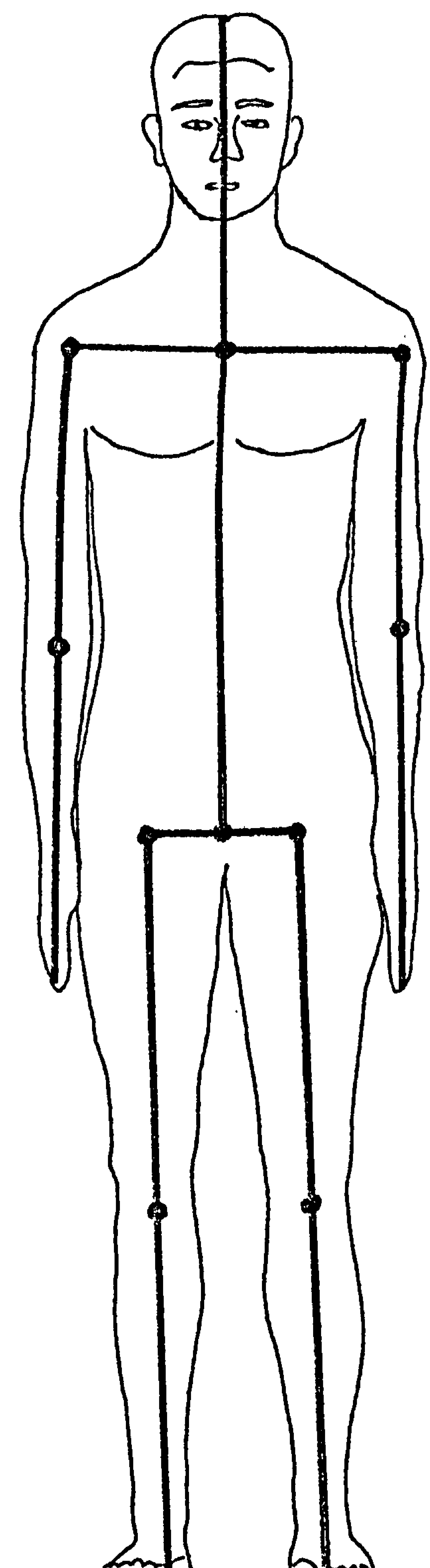


Fig. 4.1. Thirteen Link System of the Prototype SAMMIE man model. (Evershed 1970).

than that for a button pushed with the fingertip. (grip characteristics are not considered in the posture algorithm described in chapter 6, but the provision of hands makes this feasible at a later date).

(ii) Movement of the trunk generally plays an essential part in reach movements, and this cannot be adequately represented by a single rigid link. The spine is a very complex group of bones and joints, consisting of 25 separate vertebral links, but it has been found by Dempster (1955) that it can be functionally represented by two rigid links for the lumbar and thoracic portions. This is the representation adopted for the new SAMMIE model. Greater complexity of spine model is considered to be incompatible with the desire for a simple fast-acting model for interactive use by designers.

(iii) Movement of the head is an essential feature of a man model, if it is to be used to evaluate the progressively more common task of man controlling equipment. In this context the visual sense assumes high importance, and the mobility of the head and the consequent range of vision provided for the eye becomes a significant criterion. (Table II indicates the extra evaluation facilities afforded by extension of the number of links).

In consideration of these aspects, the current man model has been designed to have the 21 links and 17 joints depicted in Fig. 4.2. It is felt that this gives an adequate representation

Table II. Potential Value of Adding Extra Links to the SAMMIE model.

Uses	Comments
fingers	
Currently the hand is modelled, but not the individual fingers. The addition of fingers would assist the evaluation of intricate manipulative movements which can be a crucial aspect of the assembly, operation and maintenance of equipment.	Finger movement is considered to be outside the scale of the SAMMIE system. i.e. small scale as well as large scale design problems have not been tackled as other approaches are considered more appropriate.
interclavicular, clavicular, scapular	
Representation of the shoulder by these three links instead of a single rigid link would allow more accurate modelling of movement of the arm. (The 'shoulder' joint is one of the most mobile joint centres - see diagram of path of instantaneous centre of rotation of shoulder joint - Evershed 1970).	The use of a single link for the shoulder is one of the most unsatisfactory aspects of the current model, but its replacement by these three links, would add considerable complexity to the model. In addition the interelated action of the three joints does not lend itself to posture prediction.
many-segment, spine	
The current Lumbar-Thoracic spine model is adequate to represent the geometry of the body, but the representation of the spine by one link for each vertebral segment would be useful in considering back damage due to overloading (Fisher 1967) and in comfort assessment.	Apart from the enormous increase in the complexity of the model (a further 50 degrees of freedom), the many-segment spine is not necessary for the problems currently being tackled.
eye 'links'	
In problems of vision, eye links can be useful in allowing the movement of the eyes to be modelled, and hence the field of vision to be changed.	Although not a part of the man model, eye 'links' do exist in the SAMMIE system, in that the man's field of view is variable by control of the view displayed on the screen.

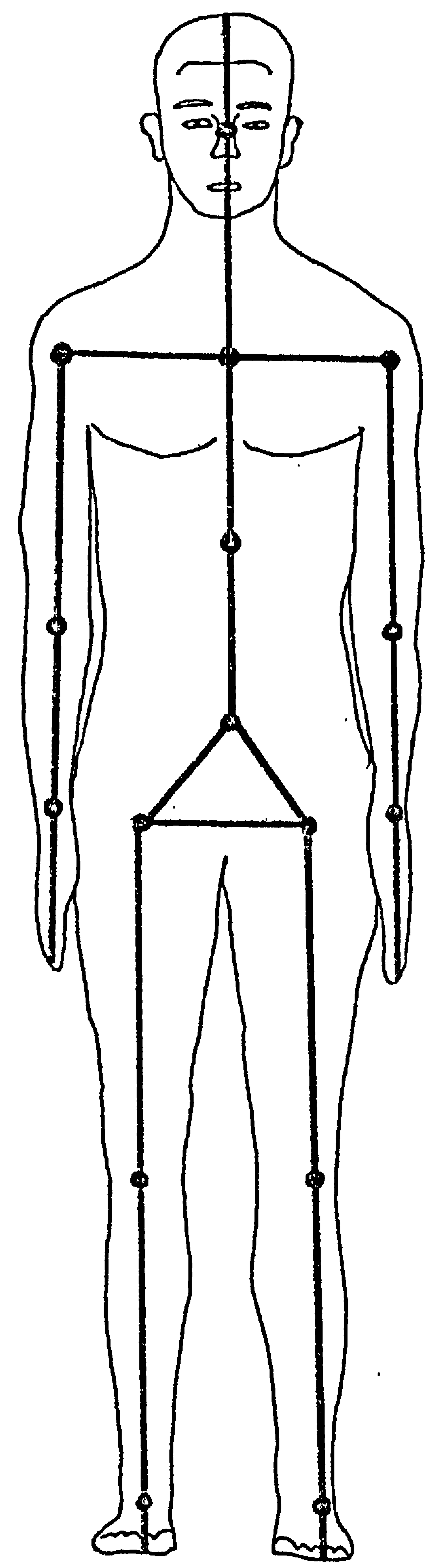


Fig. 4.2. Twenty-one Link System for the Current Man Model.

of the human anthropometry, and allows the necessary biomechanical and postural design features to be analysed, while retaining a relatively simple model amenable to computerisation and use by a designer. The obvious areas where such a link system may be thought to be deficient are in that it cannot cope with digit articulation, the complex structure of the shoulder is approximated by one rigid link, and the spine is far simpler than in reality.

This choice of 21 links appears to be consistent with the conclusions of the other workers in the field. Hence it is very similar to the original specification of the link system by Dempster, and as many of the other man models have been based on the ideas of Dempster's work, it is perhaps not surprising to find very similar link systems in BOEMAN, MTM Man, Cinci Kid and Chaffin's various models (see appendix I).

If the links shown in fig. 4.2. are to represent the anthropometry of specific populations, there are two essential requirements that must first be fulfilled.

(i) The link system must be described in unambiguous anatomical terms in order that the model can accept data collected in the same way.

(ii) The relationships between the external measurements normal in anthropometric surveys, and the internal link system must be established.

The first of these requirements is met in Appendix II where a definition of each link is given.

The second requirement is a realisation of the difficulty in relating the external measurements which are normally found in anthropometric surveys, to the proposed internal link system. A typical example might be the 'Hip Breadth' measurement shown in fig. 4.3. (Taken from Snyder, Chaffin and Schutz (1972).

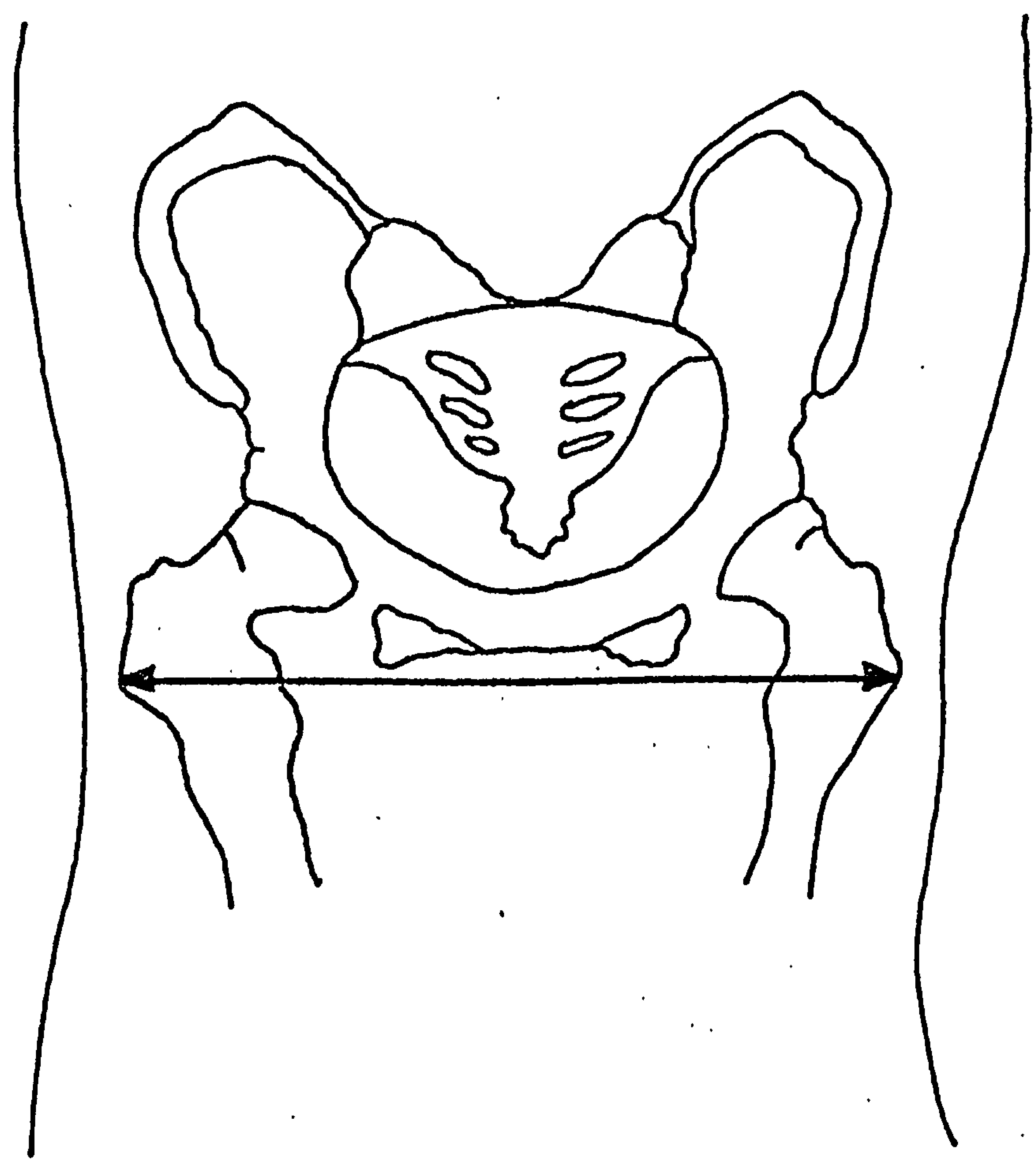


Fig. 4.3. A Typical External Measurement. 'Hip Breadth' (Snyder, Chaffin and Schutz 1972.)

It is clear that this external measurement, including as it does, a measure of the compressed flesh at the hip, can be related to an internal link, but because of the variability of flesh thickness, the relationship is likely to be more complex than a direct proportion. However given one specific set of experimental conditions, Dempster for example has managed to produce linear regression equations which relate the link dimensions to anthropometric data (shown as appendix III). This enables the link lengths to be derived from external measurements on the living subject, but it must be emphasised that this particular set of regression equations can become unsuitable in different circumstances.

In consideration of this problem, the link dimensions for SAMMIE can be input in two distinct ways.

i.e.

> the link dimension, if known can be entered directly into the model. This implies that some manual reduction of anthropometric data has previously been performed.
>
> or
>
> overall dimensions of the type shown in fig. 4.4 can be entered, in which case regression equations derived from the data of Dreyfuss (1967) are used to obtain the link dimensions (appendix III).

More information on the type and variability of such data is given later in this chapter, where attention is again drawn to the dangers inherent in the use of regression equations.

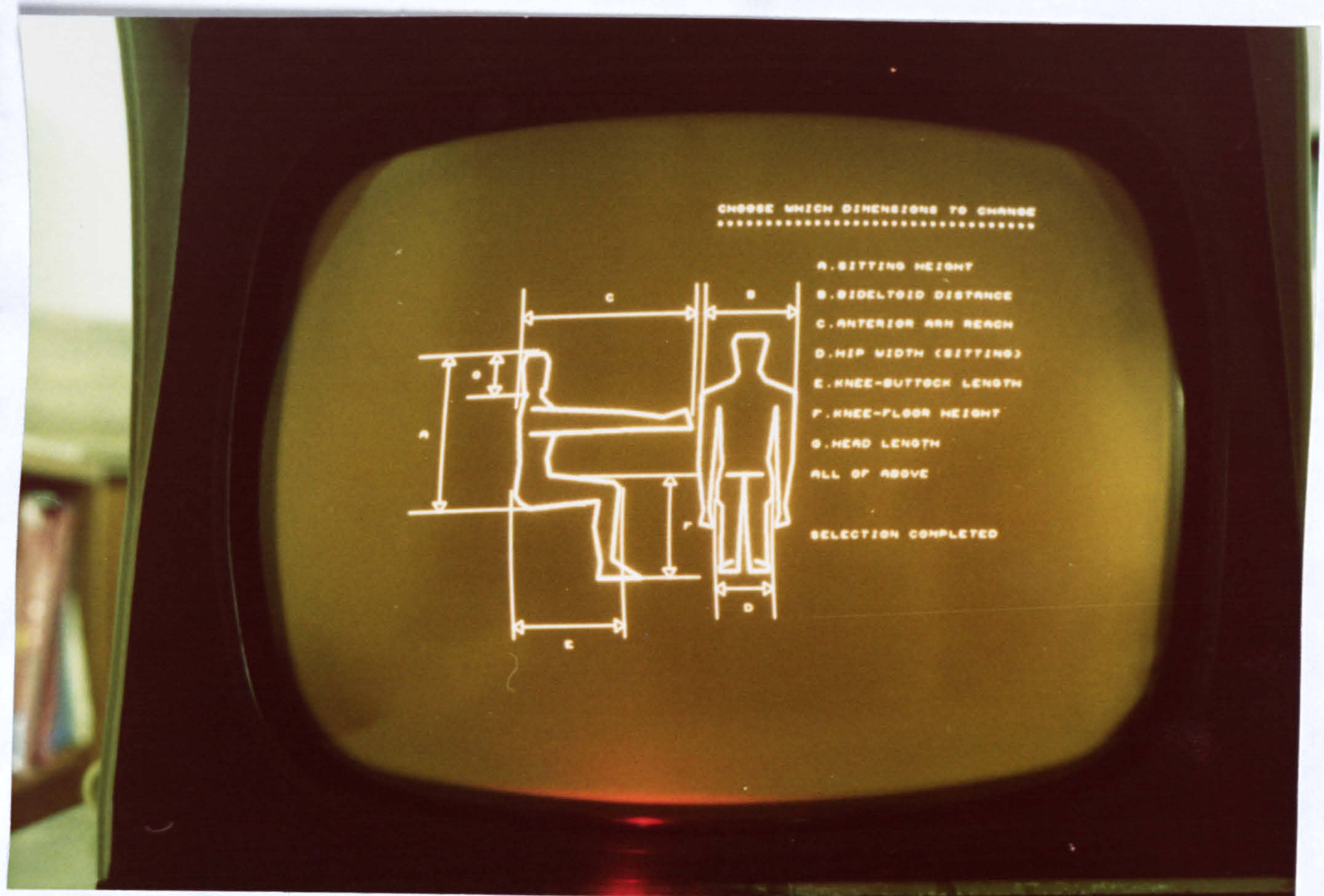


Fig. 4.4. External Dimensions can be specified on input, the link dimensions being derived from regression equations.

Joint Mobility

Having established the concept of a link system, it is necessary to incorporate a representation of the joints, so that the model can be manipulated to give any required posture. In order to achieve this the model recognises the potential three degrees of freedom which are apparent at each joint, so that in general a joint is modelled as in fig. 4.5. (a). Hence each joint is allowed a maximum of three degrees of rotational freedom, although in particular joints it may be necessary for some of these to be constrained.

The three angles θ,φ, and ψ form an Eulerian set which are indispensible when it comes to the mathematical construction of the complete link system, but there are some difficulties involved in using these angles for comparison purposes with data on joint range mobility. The example of the shoulder joint displays the necessary points of interest.

For the shoulder then

θ is the 'angle of latitude' which determines the inclination of the upper arm to the vertical

φ is the 'angle of longitude' which determines the position of the upper arm in the horizontal plane

ψ is the 'angle of twist', which determines the lateral-medial rotation along the upper arm.

It can be arranged so that the neutral position (with the arms hanging vertically by the side of the body) is represented by a zero value for all three of these angles with the axes so arranged that the YZ plane is equivalent to the saggital plane, and XZ to the transverse plane. In this case variation of one of the angles results:-

flexion - extension of the upper arm (for changes in θ)
abduction - adduction of the upper arm (for change in φ)
lateral - medial rotation (for change in ψ)

These are the measurements of range of joint movement which are normally presented in the literature, so that in this particular instance the data in the literature could be applied directly to the model.

However in general a link (e.g. the upper arm) will assume a position such that rotation in the θ, φ and ψ senses all contribute to the posture of the link. The implication of this is that the limits to movement at a joint are generally of the form

$$\text{constraint} = f(\theta, \varphi, \psi)$$

This functional relationship is, as far as the author is aware, almost entirely uninvestigated apart from some early German and Swiss investigations on a limited number of cadavers (e.g. Braune and Fischer (1887), Langer (1865), Albert (1876), Stasser and Gassmann (1893), reported in Dempster (1955)). The normal approach has been to measure movement only in the saggital and transverse planes of figure 4.5.(a), and also in the ψ sense. This results for example in there being very little knowledge on the extent of abduction of the upper arm which is possible while the arm is also partially extended.

It is outside the scope of this author's work to initiate data collection procedures, and so as a result of the shortage of suitable data, some rather extreme assumptions have had to be made.

i.e. that

(i) The angle of flexion - extension at a joint is represented by the angle between the projection of the link onto the YZ plane and the Y axis (angle α fig. 4.5.(b)).

(ii) The angle of abduction - adduction at a joint is represented by the angle between the projection of the link onto the XY plane and the X axis (angle β fig. 4.5.(b))

(iii) The angle of medial - lateral rotation is equivalent to angle ψ.

Furthermore it is assumed that if all three joint angles individually fall within the single variable limits provided by data in the literature, then that is a feasible posture for the joint. Implicit in this is the assumption that the three variable angles are independent and not functionally related as has been previously suggested. This is extremely unlikely to be true in the general case, although it can be seen that at joints such as the ankle where two of the angles (φ and ψ) are constrained to zero, the assumptions are valid. At joints with two or three degrees of freedom it is considered that the assumptions give an adequate approximation to the situation, and that if functional

Fig. 4.5. (a)

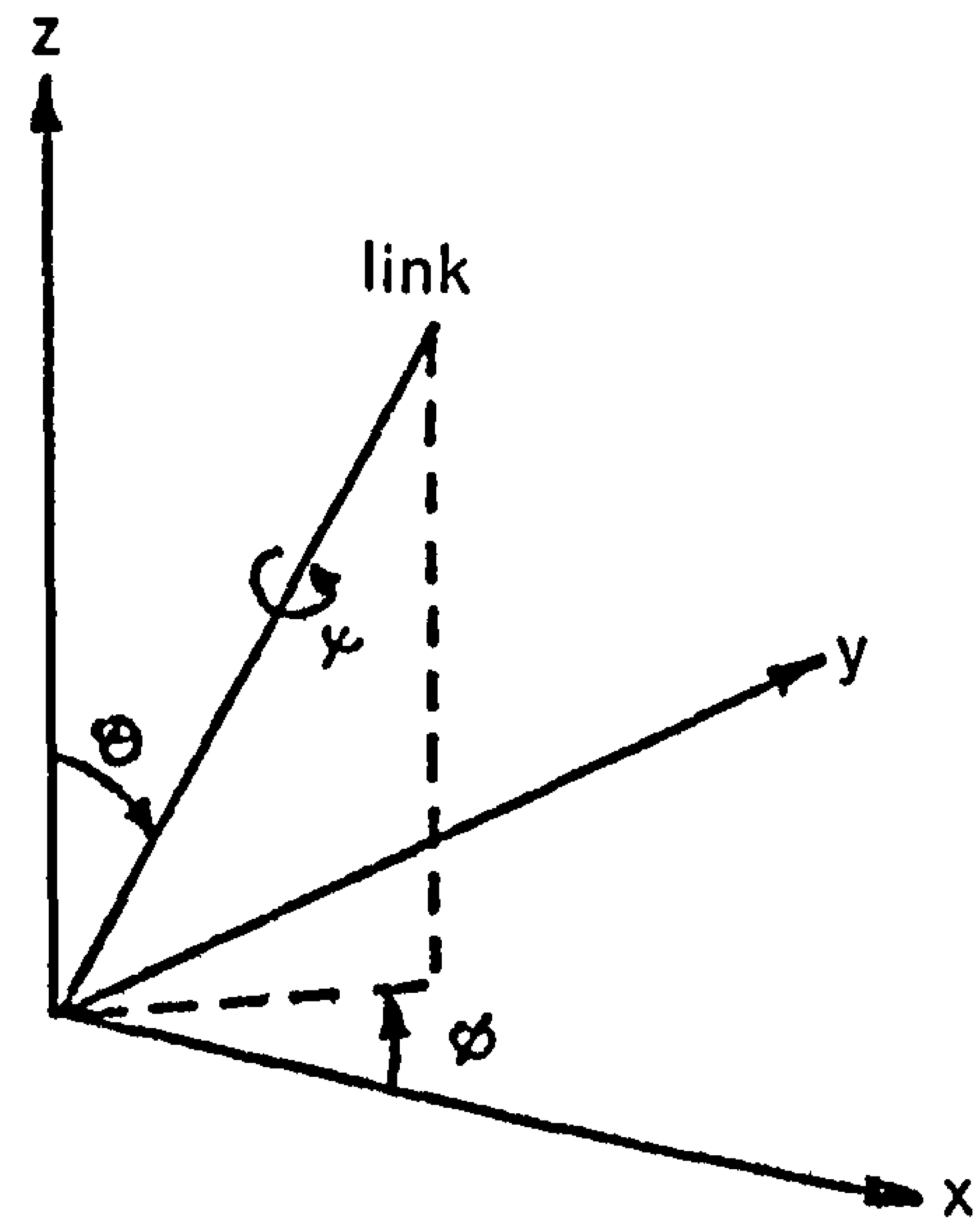


Fig. 4.5. (b)

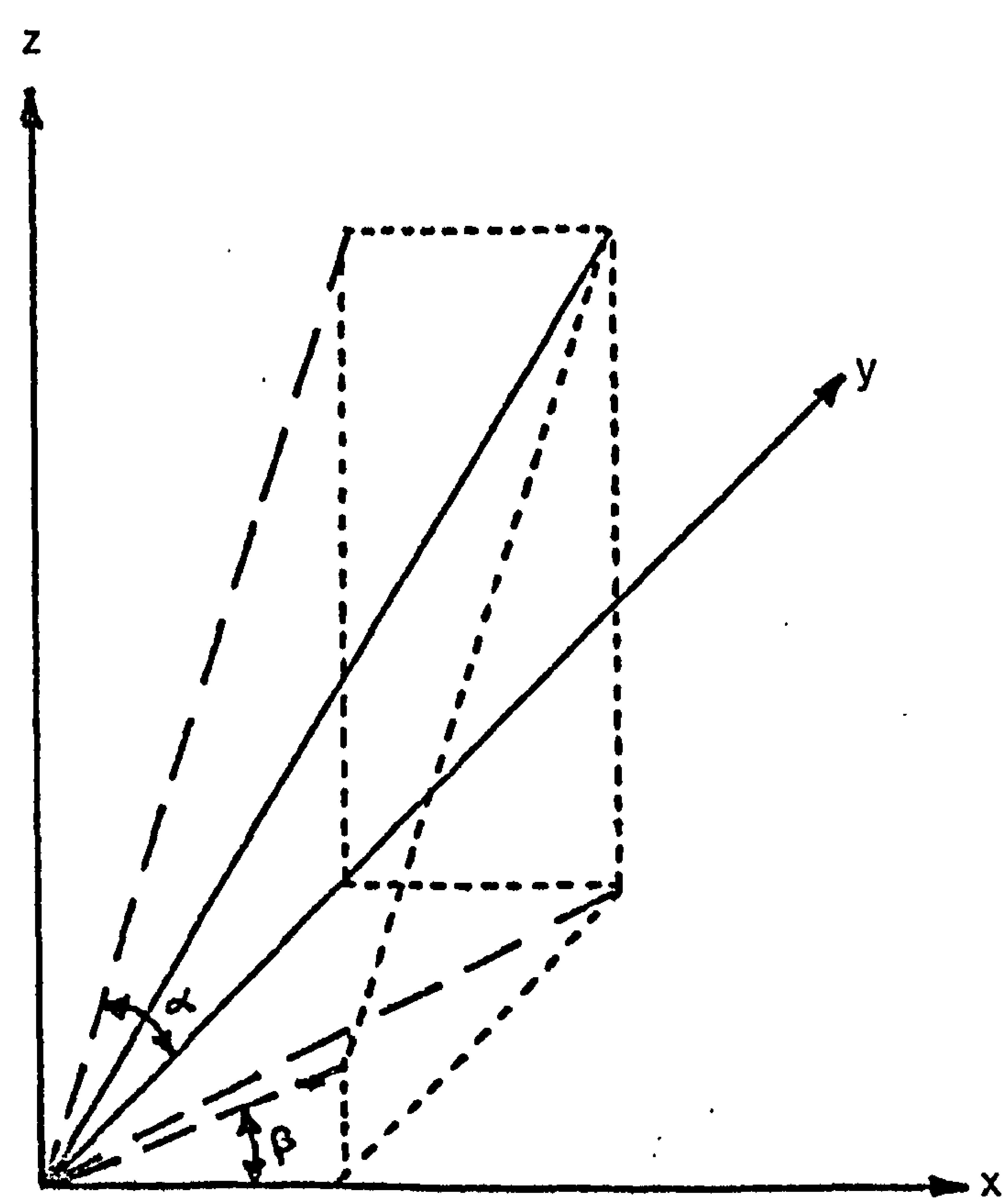


Fig. (a) General Joint Model

Fig. (b) Projection of Orthogonal Angles relationships are derived in the future, then these could easily be incorporated into the model.

The way in which the body takes up configurations within the angle constraints is a biomechanical feature, so this aspect is investigated more fully in Chapter 5. The joint model is however a part of the mathematical construction which enables the link system to be manipulated into specific postures ready for anthropometric assessment. Hence its description thus far has been a necessary prelude to the explanation of the mathematical representation of the link and joint system.

Mathematical Representation of the Anthropometric Model

The axes system adopted for the joint model has already been defined by fig. 4.5., and some mention has been made about the suitability of an Eulerian set of axes for this kind of application. Euler angles are merely a set of three 'independant parameters specifying the orientation of a rigid body' (Goldstein (1950)). Hence the three angles represent the minimum amount of information required in order to construct the orthogonal transformation matrix which relates a given cartesian coordinate system to another. The necessity of performing such a transformation will become apparent later.

The Euler angles then, allow the transformation between axes systems to be performed by three successive rotations in a specific sequence. Figure 4.6. adapted from Goldstein (1950) illustrates such a sequence of rotation using the angles φ , θ

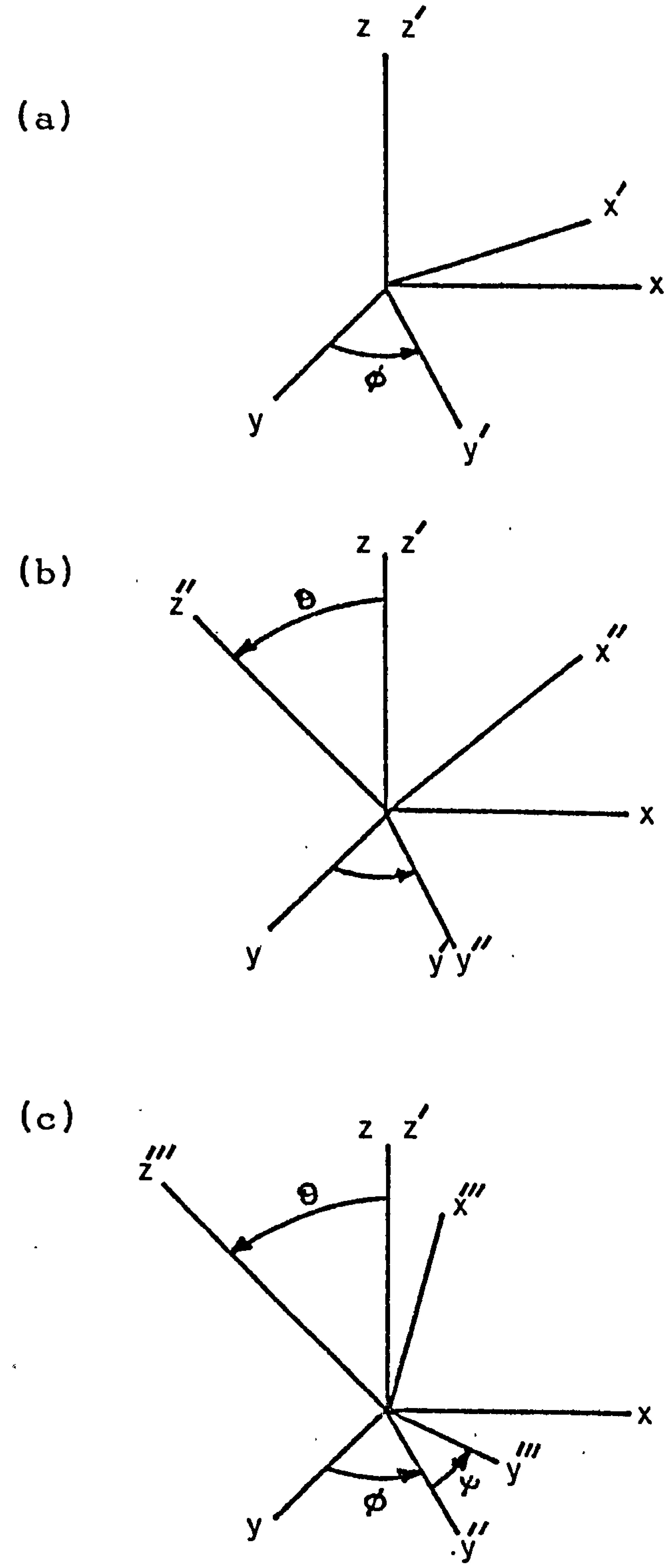


Fig. 4.6. Transformation of Axes System by the Use of Euler Angles.

and ψ as defined above.

The initial system of axes (XYZ) are first rotated anticlockwise about the Z axis by the angle φ, resulting in the X'Y'Z' axis system shown in fig. 4.6.(a). These intermediate axes (X'Y'Z') are then rotated anticlockwise about the Y' axis by the angle θ to produce the axes X"Y"Z" depicted in fig. 4.6.(b).

Finally these X"Y"Z" are rotated anticlockwise by the angle ψ about the Z" axis, giving the set of X'''Y'''Z''' axes shown in fig. 4.6.(c).

The three angles φ, θ and ψ then completely specify the orientation of the X'''Y'''Z''' set of axes relative to the XYZ set.

Using matrix notation the whole process can be achieved by the use of a single transformation matrix which, acting as a vector in the original axes system, will describe that vector in terms of the new set of axes. Hence

Transformation matrix T = CBA

where A = the rotation matrix for φ about Z

B = the rotation matrix for θ about Y'

C - the rotation matrix for ψ about Z"

This is equivalent to

$$T = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

resulting in the final transformation matrix

$$T = \begin{bmatrix} \cos\psi\cos\theta\cos\varphi - \sin\psi\sin\varphi & \cos\psi\cos\theta\sin\psi + \sin\psi\cos\varphi & -\cos\psi\sin\theta \\ -\sin\psi\cos\theta\cos\varphi - \cos\psi.\sin\varphi & -\sin\psi\cos\theta\sin\varphi + \cos\psi\cos\varphi & -\sin\psi\sin\theta \\ -\sin\theta\cos\varphi & -\sin\theta\sin\varphi & \cos\theta \end{bmatrix}$$

The value of such a transformation matrix is that it enables all the links in the open chain system to be related to each other. Defining each link by its length and the three Euler angles means that the whole system can be related to one set of space axes. This is an essential requirement for posture assessment and for display on a graphics terminal.

Referring again to fig. 4.2. the space axes adopted for the model have been chosen to correspond with the link axes for the lower spine, so that the base of the spine becomes the origin for the coordinate system used to describe the man's overall position and orientation. These space axes will then correspond with the space axes of the workspace model, enabling for instance, hand trajectories and workplace elements to be described in a unified co-ordinate system. A hand position is however a consequence of the orientation of all the links in the chain (in this case the lower and upper spine, shoulder, upper arm, forearm and hand). It is the transformation matrix for each link which facilitates the twin objectives of

(i) Specifying extremity positions in terms of a space set of axes compatible with the space axes of the workplace model, while

(ii) retaining information concerning the orientation of a link relative to its own local set of axes, and thus enabling this posture to be compared for feasibility with angle constraints.

The specification of an extremity orientation relative to the space axes is then given by

$$R_n = T_n T_{n-1} \ldots\ldots\ldots T_2 T_1 \qquad \text{—— (A)}$$

n = link number of extremity

where R_n = the final transformation matrix for link number n

$T_{1\ n}$ = the transformation matrices for each link.

In the case of the right hand this would be equivalent to

$$R_{\text{right hand}} = T_{\text{right hand}} T_{\text{right forearm}} T_{\text{right arm}} T_{\text{right shoulder}} T_{\text{upper spine}} T_{\text{lower spine}}$$

which would give the angular orientation of the right hand to the space axes.

In order to complete the specification of the hand position, it is also necessary to sum the translation vectors along the link system in a similar way. Hence the complete specification of the hand position relative to the coordinate system of the space axes would be

$$X'_n = R_n X_n + (X'_1 + X'_2 + \ldots\ldots X'_{n-1}) \quad \text{———(B)}$$

where n = link number of hand

X'_n = coordinate vector of link n

R_n = see equation A

equation B can be expressed alternatively as:-

$$X'_n = R_n X_n + R_{n-1} X_{n-1} + \ldots\ldots R_2 X_2 + R_1 X_1 \quad \text{— (C)}$$

Such a mathematical model enables any body posture to be described in terms of the link and joint geometry in a way which is compatible with the workplace model.

The inclusion of suitable data concerning link lengths and specific angles at joints, makes this mathematical model a suitable method for the evaluation of postures. The manner in which the angles are determined for a specific task, using the postural algorithm is described in chapter 6. Before the link lengths can be included, it is necessary to have an adequate understanding of the manner in which human anthropometry varies between different people, and this aspect is studied in the next section.

Anthropometric Variables

Variability in anthropometric variables arises from three sources:-

(i) Population differences

(ii) Range of dimensions within any population

(iii) Correlation between limb dimensions.

(i) Population Differences

Anthropometric data is collected for specified populations, and can only be used for those populations. The population can be defined in terms of any factor which has a characteristic effect on body dimensions, and some of the important variables are identified below.

Murrell (1965) and Damon, Stoudt and McFarland (1966) suggest that the most important factors affecting anthropometry are

(a) Nationality

(b) Race

(c) Sex

(d) Occupation

(e) Age

(Damon et al also include body build, diet, level of physical activity, posture, voluntary changes, time of day and clothing).

Nationality and race are very often linked in that usually people of the same nationality will be of the same race, but there are however notable exceptions such as the cosmopolitan population of the United States. Here there are two major racial groups, white and negroid, which exhibit significantly different anthropometric features (e.g. white American soldiers of World War II were taller than their negro counterparts (Army Services Data (World War II))). Differences between Asiatics and Western races are even more pronounced, not only in overall measurements, but in the relationships between various dimensions. (Asians tend to have forelimbs which are more than proportionately short). See Fig. 4.7. which shows the effect of nationality on the stature of various groups of airmen.

Females are generally smaller than males of the same race, although Western women may be found to be larger than Asiatic men. The relative proportions of the dimensions of females may also differ from males, notably that women generally have wider hips. (the 50%ile female has a hip width of 363 mm compared with 305 mm for the 50%ile male. Dreyfuss(1967)).

Occupation and body dimensions appear to be correlated, but it is not always possible to distinguish between cause and effect. In some instances the occupation itself changes in some way the body dimensions. Hence dentists can very often be found to have a 'rounded' back directly attributable to a lifetime of bending over patients. In other instances it appears to be a mechanism other than an effect of the occupation. There is evidence for example showing that British company directors are approximately 100 mm taller on average than men from social classes III, IV and V. (May and Wright (1961) and Kensley (1950)). It is difficult to see any way in which the occupation of company director can cause an increase in height, so the conclusion must be that there is some correlation between height and class or business ability.

Age is also of considerable importance, although once again it is difficult to assess the relative effects of two different

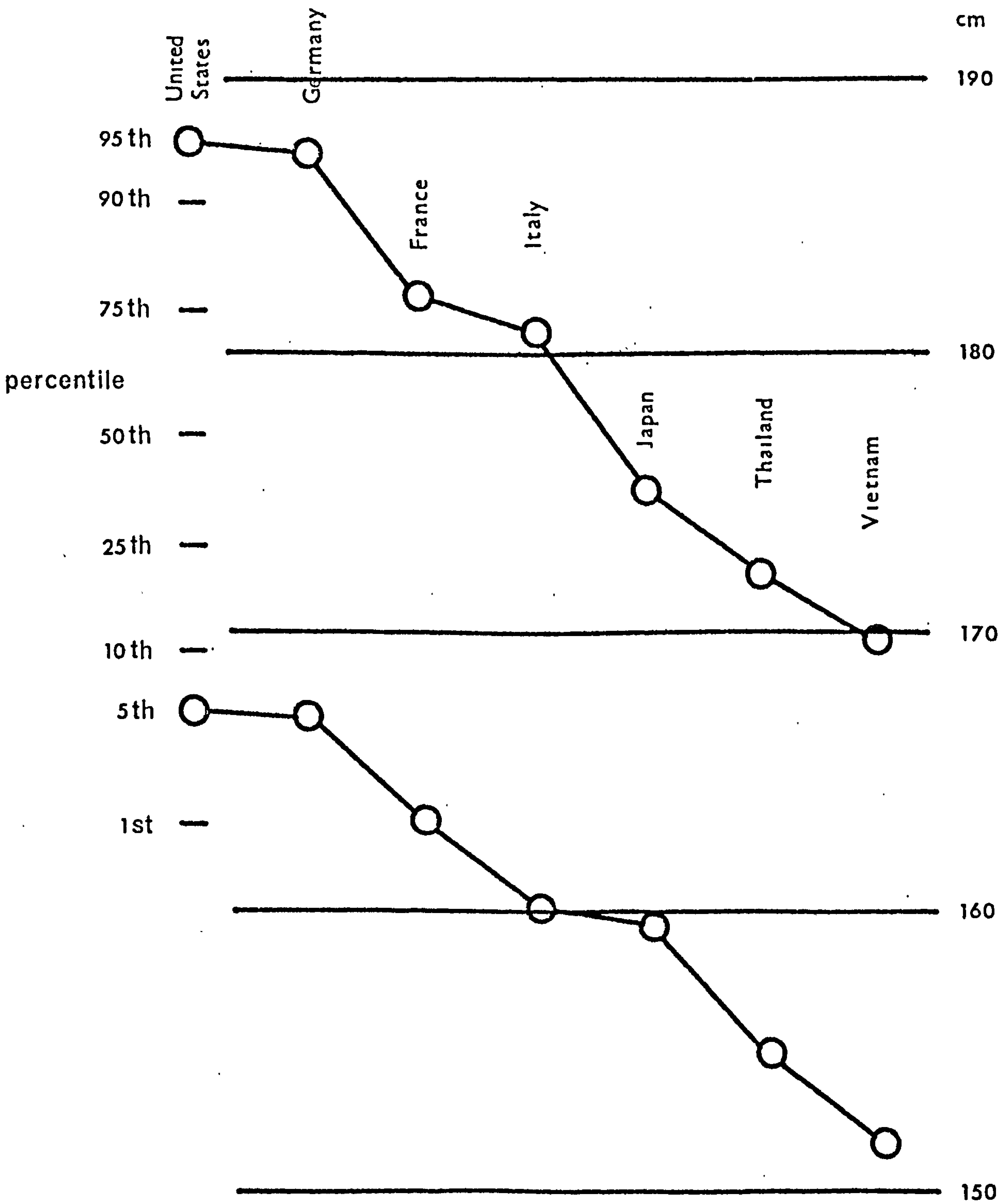


Fig. 4.7. Effect of Nationality on Stature. (from Kennedy 1972).

processes occurring with time. Clements (1954) has discovered that height reaches a maximum at the age of 20 for men, and then decreases by about 0.08 mm per year. Kemsley (1957) however has identified a difference of 33 mm between women of 23 and those of 51 years old. It is difficult to assess how much of this difference is attributable to the ageing process and child-bearing in the case of women, and how much is due to differences between generations possibly because of improved social conditions.

Nationality, race, sex, occupation and age are usually considered to be the most important criteria by which to define a population, but they are by no means the only ones. They are sufficient however to show that careful consideration must be made of the factors influencing a particular set of data.

(ii) Range of Dimensions within a Population

To a certain extent, the definition of a population determines the variability of dimensions within that population. A population that included every human being on the planet would have a range of variability from the smallest female pygmy to the largest male African Nilotic Negro (Damon, Stoudt , McFarland , 1966). Indeed this might be the required population if the design of some ubiquitous article were contemplated, but normally the potential user population can be substantially reduced in numbers. A closely defined biological population, such as a sample of American women 95% of whom are between the ages of 18 and 39 could be expected to exhibit a range of variation of dimensions that approximated very closely to a normal distribution (fig. 4.8.)

A functionally defined population however, such as the users of a geriatric hospital, might include the different biological groups of young female Asiatic nurses, old female patients and young male doctors. Such a lack of homogeneity within the population would lead to considerable distortion of the normal distribution, there probably being a distribution which is essentially a compound of the normal distributions for each biological sub-group. To cope with this situation, population data is usually expressed in terms of percentiles. Hence a statement such as the height of the 97.5 percentile male is 1880 mm conveys the fact that 97.5 percent of the population have a height of 1880 mm or less. In an homogenous population, this percentile can be related back to a normal distribution, by the usual mathematical methods

$$\text{e.g.} \quad (x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{1}{2}t^2} dt$$

where x is the probability (= %ile/100) that a measurement will lie in the range $-\infty$ to x.

However no such implications can be drawn from a non-normal distribution, where for example the 50th percentile (or median) value, need not be the 'average' or mean value. To summarize, within a particular population, there might be a large or

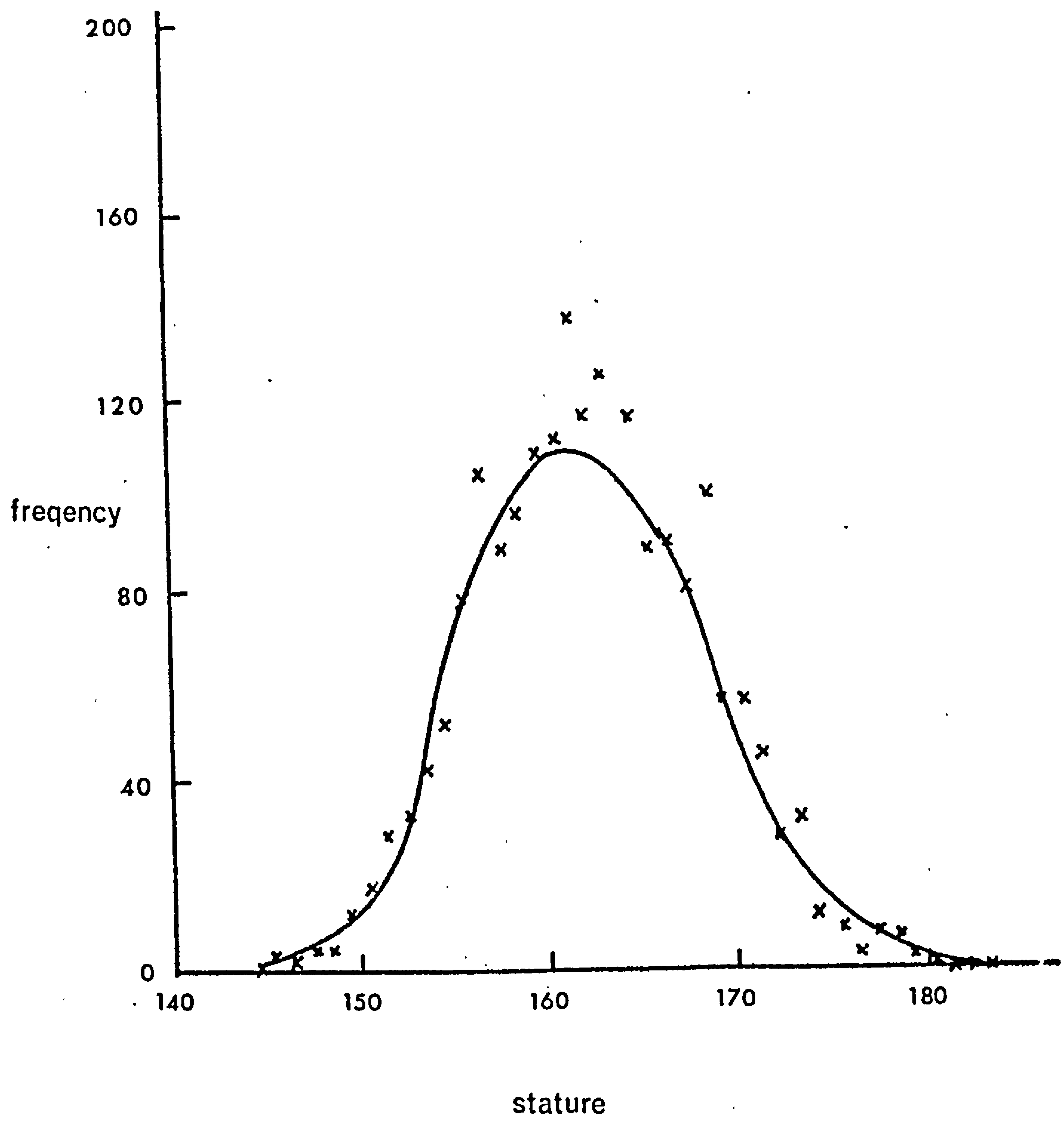


Fig. 4.8. The Normal Distribution of Stature shown in a Survey of Air Force Women. (Clauser et al. 1972)

small range of variability of dimensions, and this variability might be readily predicted by mathematical constructs such as normal distribution, but for a non-homogenous group little can be said about the distribution of dimensions.

(iii) Correlation Differences.

The final source of complexity in the use of anthropometric data is that correlation between various dimensions of the body can be very poor. Hertzburg (1960) reports that in a survey of over 4000 Air Force personnel, there were no examples of men who fell within the 30 percent central (average) range on all of a series of ten measurements. That is to say that the man who is average in all dimensions, and thus an 'average' man, just does not exist, because the correlation between different dimensions is not sufficiently high. This is obviously just as true for other percentiles, and the effect is emphasised where the population is not an homogenous one (Hertzburg's population of young, healthy Air Force men could be considered to be very homogeneous).

Little has been said so far about volumetric measures such as chest circumference, waist circumference and so on, but these dimensions are more susceptible to poor correlation than linear dimensions. Hence Barkla (1961) found very good correlation between sitting height and standing height for males, where the maximum difference from the average ratio was about 1%. However men of average height may have waist circumferences which quite commonly vary from 750 mm to 1000 mm, and in extreme cases much more.

Data provision for Anthropometric Model.

From the above necessarily brief discussion of the variability of anthropometric data, it is clear that at the present stage of development, SAMMIE cannot hope to provide a data base for a particular design problem. Each design problem is likely to involve a different user population and hence a different set of anthropometric data. It may be possible to build a general data structure such that a complete range of information according to sex, nationality, age, occupation etc could be available, but its practical value may be less than would seem immediately obvious. The technical problem of building the data structure so that the dimensions for any required population or sub-population could be obtained, is in itself quite feasible, although a major undertaking.

However it is likely to be difficult entering data into this structure, because of the nature of anthropometric data, which is inherently 'inaccurate' for a number of reasons. Discrepancies between different sets of data often arise from the different measurement techniques being used, so that for instance stature can vary depending on the erectness of the spine. Some investigators may consider that the subject should be asked to fully erect the spine so that all subjects are measured under the same conditions, whereas others might consider that this would induce an unnatural posture, and hence irrelevant information, e.g. 'subject stands erect, head in the Frankfurt plane, heels together, and weight distributed equally on both feet and .... while taking a deep breath stretches to maximum stature and the vertical distance from the standing surface to the top of the head is measured (Clauser, Tucker, McConville, Churchill, Laubach 1972). Additionally samples vary in size and quality, so that some (usually American and European military) surveys involve several thousand subjects (or as many as 385,937 in the U.S. World War II survey (Karpinos (1958))) while less than 100 subjects are sometimes considered sufficient. The sample size effects the quality of the sample, as the larger samples are likely to be more representative. Hence comparison between different surveys requires that the larger surveys are favourably weighted.

For these kinds of reasons, the inconsistancy between measurements can be as large as those found by Barkla (1961) and reproduced in table III.

Table III Maximum dimensional differences found in various anthropometric surveys. Barkla (1961)

Dimension	British		American	
	Men	Women	Men	Women
stature	86mm	33mm	43mm	43mm
sitting height	58		20	10
buttock-knee length	53		18	

Hence for example the stature of 50^{th} percentile British men apparently varies by as much as 86 mm depending on which data source is used. As the difference between the 95^{th} percentile and 50^{th} percentile British male is only 125mm (Warren Spring Laboratory 1964), it can be seen that this is a highly significant discrepancy.

Perhaps more important than the inaccuracies of data when building a data bank, are the gaps that currently exist in anthropometric data. Most effort has in the past been directed at easily accessible populations such as military or student subjects, whereas designers may wish to design for the old, females, specialist occupational groups and so on. Although SAMMIE is intended as a general purpose workplace design tool it is felt that each particular design situation requires considering individually as far as the use of anthropometric data is concerned. This may then result in the initiation of a data collection program, or more hopefully the relevant information could be found in the literature. The provision of a data bank containing such information is thought at the present time to be a misdirection of effort. This effort is better used to provide a flexible and easy way of manipulating the data once it has been obtained. Hence the anthropometric model contains very little data, but provides a data manipulation ability as shown in fig. 4.9.

Referring to figure 4.9., the user of the model must first decide whether the population with which he is concerned

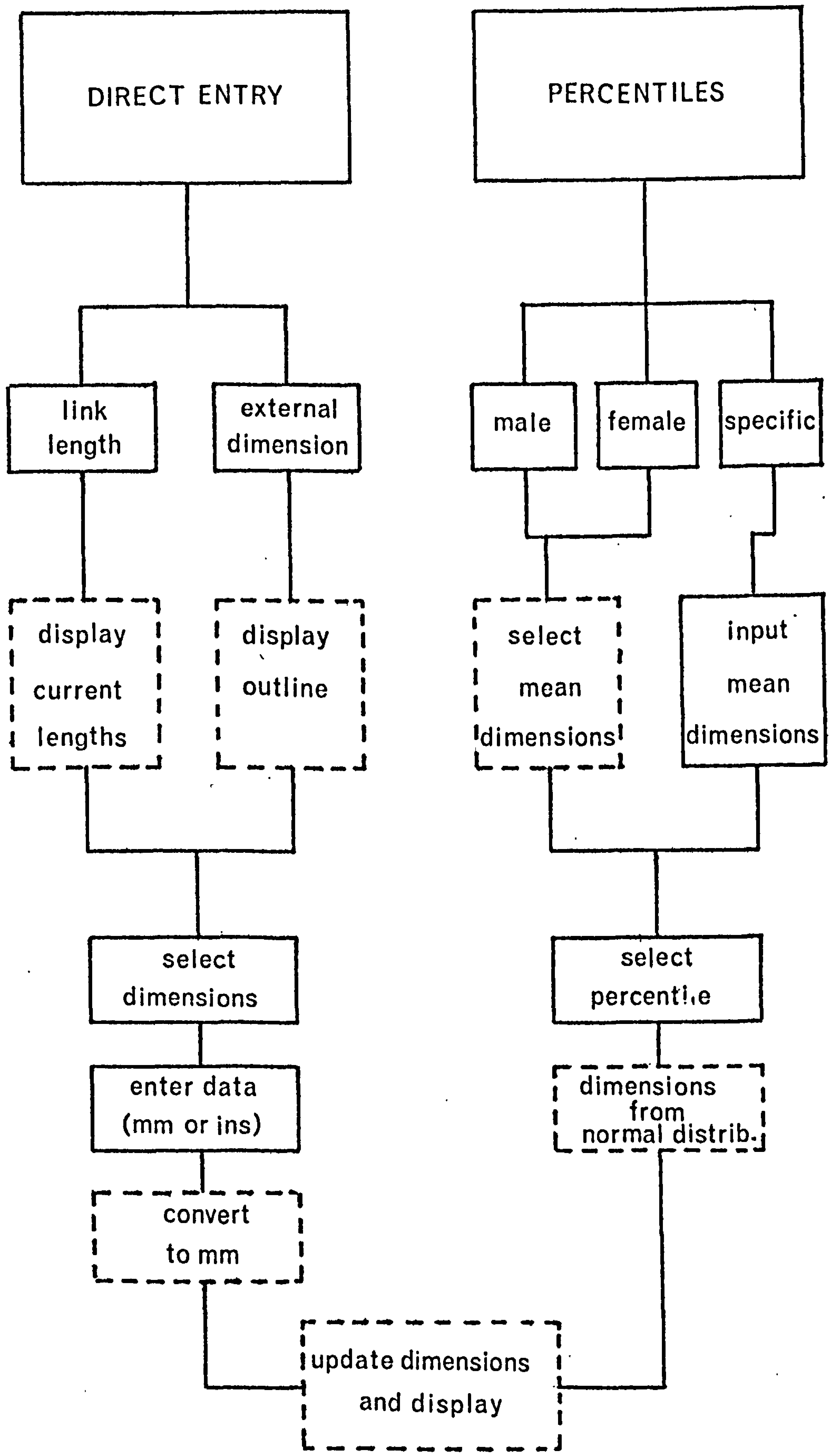


Fig. 4.9. The Various Methods of entering Anthropometric Data into SAMMIE. (dashed boxes indicate computer functions).

is homogeneous or not. Homogeneous populations are amenable to mathematical treatment as a normal distribution as shown in the right hand side of the figure. However for a non-homogeneous population, or for the investigation of individual subjects, it is necessary to consider the left hand side of the figure, and refer more explicitly to limb dimensions.

The 'Direct Entry of Dimensions' allows the link lengths to be expressed in the two ways mentioned earlier, i.e. either as the link dimension or as external measurements from which link measurements are derived. In the latter case, an outline sketch of a man is displayed on the screen (see fig. 4.4.) together with a menu from which any or all of the external dimensions can be selected for change. Similarly, if changing the link lengths directly, a menu for doing so is displayed along side an indication of the current values (fig. 4.10.). Entry of the numerical information is via a teletype and can be in either inches or millimetres, inches being automatically converted to millimetres on input.

The changing of the link lengths by the use of percentiles, requires first that the population be selected and defined. As a data bank is not included within SAMMIE at present, the user of the system has to supply this information himself. For development and demonstration purposes the male and female data from Dreyfuss (1967) have been made available. Normally however it is necessary to input a 'specific' set of 50th per-

Fig. 4.10. Changing of Limb Lengths by Menu Control

centile link dimensions relating to the required population. These 50th percentile data are input using the same method as for the 'direct entry of dimensions' and are equivalent to the mean of the distribution (the median and mean of a normal distribution are identical). Inclusion of standard deviations for each dimension, allows a normal distribution to be defined, from which any percentile can be obtained. As a default mechanism, the standard deviations derived from Dreyfuss (1967) can be used so as to reduce the data input. (appendix III). Care should of course be exercised in using a short cut such as this, as the Dreyfuss data relates to a specific population (American), and it may be found that other populations show significantly different distributions about the mean.

Using this percentile facility thus enables any percentile from a given population to be obtained quickly and easily, although it should be remembered that its accuracy is limited by the need for homogeneous populations.

The anthropometric model is thus a facility which allows the manipulation of data concerning the most important dimensions of the human body. The data is represented visually on the computer graphics screen in the form of a three dimensional 'man' model (fig. 4.11.) allowing the assessment of the various anthropometric design criteria mentioned in the previous chapter.

It also assists in the assessment of posture and movement patterns which are the subject of the next chapter.

CHAPTER FIVE

THE BIOMECHANICAL MODEL

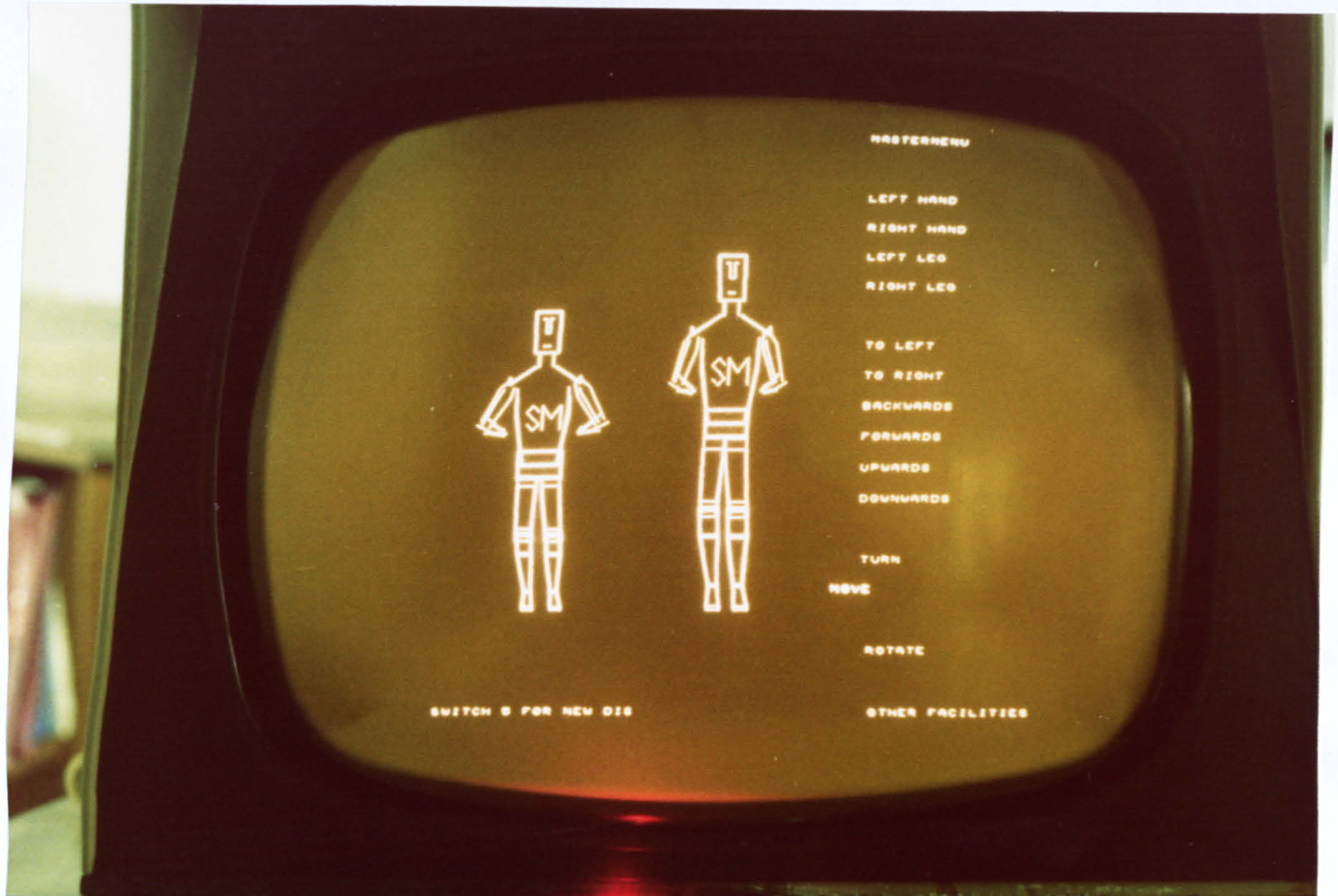


Fig. 4.11. The Three Dimensional Man Model.

The Biomechanical Model

Biomechanics is the study of the human body's range and speed of movement, and the ability of the bone, muscle and flesh structure to exert and withstand forces. For convenience biomechanics can be subdivided into:-

(a) biodynamics

and (b) kinematics

(a) Biodynamics

Biodynamics is concerned with the application of force by, or on the human body, while kinematics is solely concerned with the resulting movement patterns. Both aspects are worthy of consideration in workplace design, as they respectively enable the study of the implications of externally or internally applied forces, and analysis of the interaction between the operator and his workplace.

The external application of force to the body, often through accelerations in increased g conditions, or possibly through vibration, is usually of less importance in the context of industrial design. Extreme conditions of acceleration or vibration are rarely found, except in such areas as aircraft ejection or car-crash situations, where such conditions will be of crucial importance. A survey of models primarily aimed at this type of application can be found in Van Gierke (1971), but it is not the intention that SAMMIE be used in such a manner at this time.

Instead SAMMIE is designed to allow the evaluation of certain kinematic aspects of the workplace and task. For example interference between the operator's moving limbs and elements of the workplace can be avoided by a knowledge of the 'dynamic' anthropometry. Supplementary to this, the assessment of torque capabilities about the joints and certain aspects of balance in normal gravity conditions, can be investigated using the model.

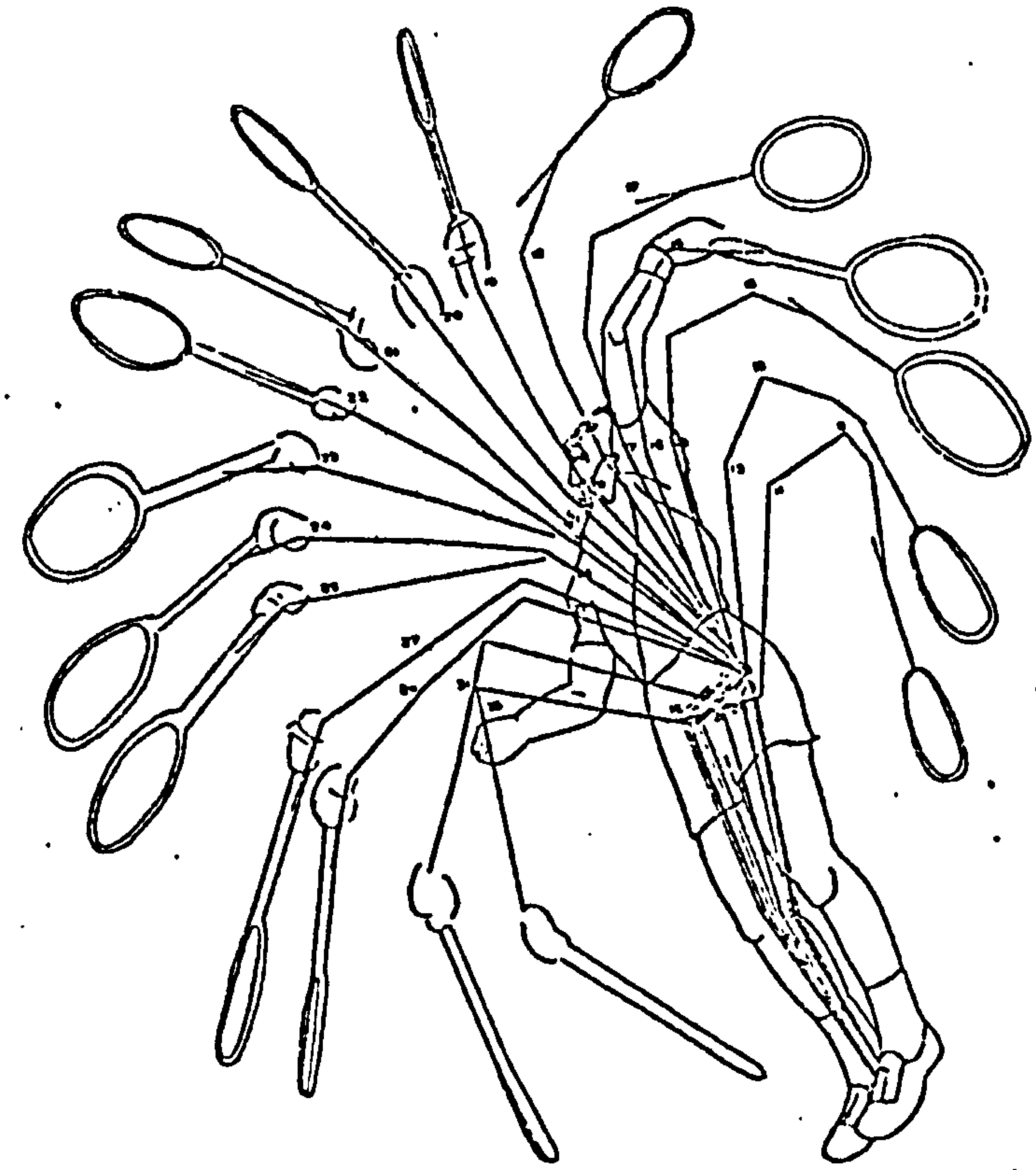
(b) Kinematics

Kinematics is solely concerned with the relative positions of the various body segments resultant on a particular task being performed. The trajectory of the end member (e.g. hand) may be 'machine' defined in that the task constrains such a movement in a particular way, or alternatively it can be an unconstrained movement from one point to another. Hence rounding a bend in a car requires that the hands remain on the steering wheel and move in an arc of a circle, but preparing to change gear only requires that the hand starts at the steering wheel and finishes at the gear lever, the intermediate trajectory being undefined. In both cases the posture assumed by the rest of the body is generally unconstrained, there being many feasible configurations because of the indeterminate nature of the human link system (as explained in the previous chapter). Before a kinematic assessment of work tasks can be made, it is therefore necessary to devise a method of modelling the trajectories of the end members (hands, feet or any other point that is required e.g. head in vision problems) before the consequent postures can be evaluated.

Trajectories

Apart from the constrained situation, very little is known about the trajectories which human beings adopt to perform tasks. This is probably because the wide range of movements which the body is able to execute, leads to there being no generally identifiable pattern of motion. So many factors can influence such movements, that although it may be possible to derive a feasible trajectory, this may not be the natural movement for a majority of human operators. Hence motivation, avoidance of obstacles, minimisation of effort, preparation for the next movement, and speed are only a few of the possible factors affecting movement patterns. Because of this extreme variability, the experimental work to date tends to be either of a very specific nature in the way that certain athletic movements have been closely analysed and recorded, or alternatively rigid laboratory conditions have been studied which are unlikely to be encountered in practical situations. Hence Plagenhoef (1971) has used photographic methods to analyse the movements involved in many sporting activities including gymnastics, swimming, kayaking, tennis and golf. The tennis services of Rod Laver and Ken Rosewall (fig. 5.1.) illustrate the point that even motions performed by two top class and highly trained athletes

(a)



(b)

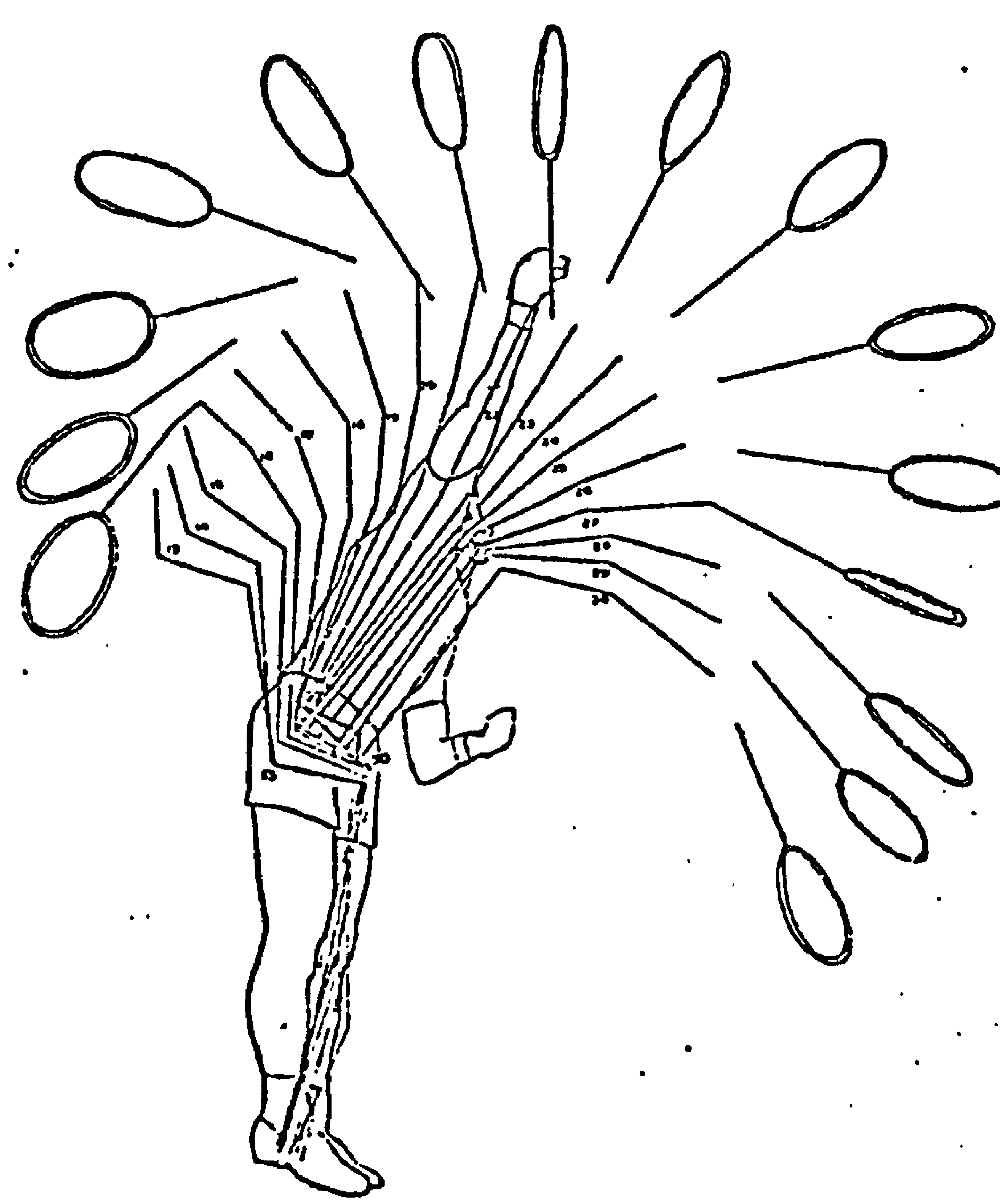


Fig. 5.1. The Tennis Services of Rod Laver (a) and Ken Rosewall (b) (from S.C. Plagenhoef 1971).

attempting to reach a substantially similar objective, do not withstand close comparison as far as the hand trajectory is concerned.

In laboratory conditions Kattan and Nadler (1969) have attempted by using the Doppler effect of ultrasonic waves, to provide predictive equations of three-dimensional motion paths for a set of simple hand motions involving different distances and directions of motion. An example of one particular movement of this kind is shown as fig. 5.2.

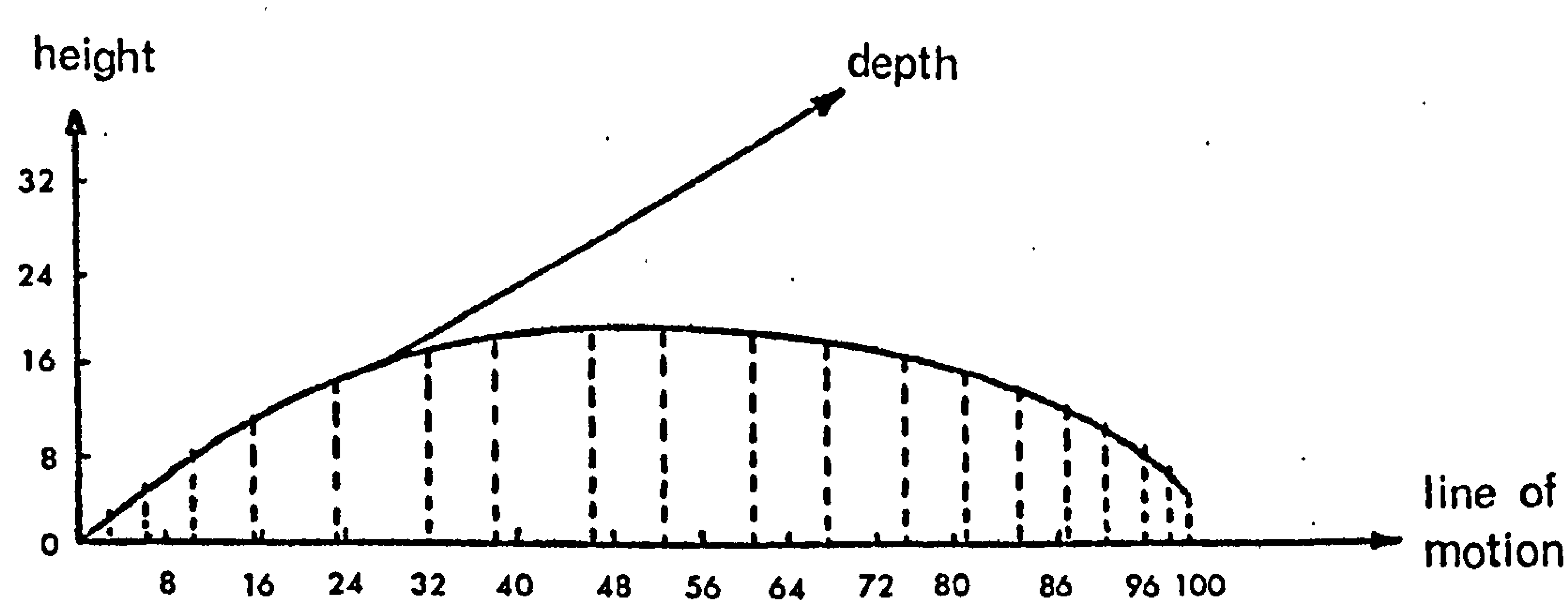


Fig. 5.2. Movement Path for a Simple Hand Motion in Saggital Plane. Units are % of Linear Movement Distance (from Kattan and Nadler (1969).

Kattan and Nadler conclude that the trajectory between two points is essentially a straight line, although a measurable parabolic curve effect is present which taken over a range of directions increases the mean motion path to 104.25% of the linear path. Such equations might be useful where the work situation agrees closely with the experimental one, which in this case could be for example the assembly of small components at a well-laid out workbench. However as only distance and direction variables are considered, this is not a satisfactory basis for the formulation of a general functional relationship between task and (hand) trajectory.

It appears in conclusion that there exists a wide variety of measuring techniques including electromyography, Corser (1974), electrogoniometry, Michelson (1974), mechanical methods (Paradise 1974), and photogrammetry (Bullock and Harley 1972) which are available for recording motions, but as yet there has been no satisfactory analysis of these results to give predictive equations of hu.nan motion.

This lack of reliable experimental data on hand (and foot) trajectories constitutes a difficult problem when there is a requirement to model man's movements. In early versions of the SAMMIE model, the parabolic paths of Kattan and Nadler have been used to derive intermediate points on a trajectory between known starting and finishing points, but this resulted in computational penalties while little additional information was obtained. Currently movements are defined as straight line paths in three-dimensional space, with the designer being required to explicitly build up complex trajectories in terms of three-dimensional co-ordinate geometry. Kennedy (1974) has devised a language with which to control both the movements of the man model and changes in the workplace layout. The language (briefly described in chapter 1) is currently in the development phase, and its use for controlling the man model not yet implemented, but it is hoped that eventually it will provide a common link between the designer, the man model and the workplace model. At this later stage it will be possible for example to detect interference between the workplace and the trajectories implicit in a work task described by the language, and automatically amend the trajectory using algorithmic methods so as to avoid its occurrence.

However at the current time a rather unsatisfactory situation exists where, because of the lack of predictive equations concerning human movement, the designer, if he wishes to accurately represent all facets of a work task, can be faced with extensive manual constructions of hand trajectories.

Postures

Analysis of the postures assumed by the human body while a task is being performed, suffers from the same problems as analysis of trajectories except that there is an even higher probability that postures will be indeterminate because they are generally unconstrained. Any movement of the body except an extremely artifically constrained one will result in there being redundant degrees of freedom at the joints and hence an infinite number of feasible postures. Once again measuring techniques are available and have been abundantly used, but while there exists 'a need for an analysis of human motion,....no such analysis exists'. (Nubar and Contini (1961)). This statement is still true fourteen years later.

Nubar and Contini in comparing the human body to a mechanical system see the unknowns in predictive equations of motion as being:-

(a) the coordinates of a definite point in the body relative to a reference set of axes.

(b) the orientation of all the body segments relative to the reference axes.

(c) the joint moments at the end of the segment.

(d) the reactions at all but one of the support points.

and the known quantities as:-

(e) the applied forces.

(f) physical characteristics of the segments (length, mass, centre of gravity, moments of inertia).

(g) the initial values of (a) and (b) above.

The resulting equations of motion exceed the number of primary unknowns by precisely the number of joint moments which are constrained by outside factors such as speed, direction etc.

If the number of joint moments is m and the number of known constraints is n there still remains an (m-n) indeterminancy. At this point in the argument, Nubar and Contini choose to hypothesise a minimal principle that 'a mentally normal individual will, in all likelyhood, move (or adjust his posture) in such a way as to reduce his total muscular effort to a minimum, consistent with the constraints'. Hence although they proceed to produce a model for human motion based on energy minimisation, such a model, although complete in the mathematical sense, fails to include some of the important factors influencing movement. The choice of energy minimisation as what Kroemer (1973) calls the 'driving' function may be extremely useful in tasks with a high manual work content, but is rather lacking in other situations.

Similarly all other attempts (such as Ayoub's (1974) power minimisation and the joint angle optimisation of Luming and Krause (1974))must fail to a greater or lesser extent until such time as the 'driving function' can be more closely defined. Such a time appears to be a long way off as yet.

Indeterminacy and the need for a kinematic model.

The need to build a kinematic model is present, because an important feature of a workplace design tool is that the operator's movements need to be related to his equipment and environment so that any mismatch can be identified and eliminated. However it has been made clear that the current level of knowledge is not adequate to fully predict the trajectories and postures involved in human motion, which unfortunately leads to the conclusion that algorithmic methods have to be employed. (It is possible for specified motions, to define the movements by data, but the quantity of data involved renders this approach too cumbersome for a general model.) If this situation is accepted, then it is necessary to build models so that any information forthcoming on the 'driving' or objective function which controls human movement will be readily assimilated into the model. One approach to this problem might be to build an algorithm based on the maintainance of all joints at feasible and reasonable positions in space. This three-dimensional co-ordinates geometry method has been utilised by Evershed (1970) for his 'natural planes' algorithm, which uses simple geometric considerations combined with stored data to predict postures. (see appendix I). Such methods are however found to place severe restrictions on the usefulness of the man model, as the algorithm is completely abstract and does not attempt to imitate the way in which the body functions, but only the end result.

A better physical characteristic which provides a mechanism for controlling bodily motions, is the angles at the joints. As has been explained previously all body motions are combinations of angular movements about joints, so a model which provides adequate control over these joint angles is useful for kinematic analysis. Potentially this would enable consideration of:-

(i) The position of a joint relative to 'comfort' angles.

(ii) The position of a joint relative to absolute constraints.

(iii) The relationship between forces to be exerted and maximum or normal torques available at joints.

(iv) The angular velocity and acceleration of body segments about joints.

(v) The inertial effects of limbs about joints.

(vi) The work done or energy expenditure during movement leading to the assessment of physiological factors.

The eventual inclusion of all the above items into the man model is one of the aims of SAMMIE, although at present only the first two are included in the 'postural' algorithm. The algorithm, described more fully later, controls the joint angles and hence the postures, by attempting to maintain all joints within their absolute physical constraints or preferably within their normal range of motion. Information concerning items (iii), (iv) and (v) is not at present included in the predictive algorithm, but has been made available as 'after the event' analyses. Hence the postures predicted during a task do not depend on the dynamic effects of forces, accelerations and velocities of limbs, but on completion of a task it is possible to ascertain whether any of these constraints have been exceeded. Item (vi), concerning energy expenditure is at present excluded completely from the analysis, and is a matter for future development.

This approach is of course open to criticism on exactly the same grounds as the methods of Nubar and Contini, Ayoub and Luming and Krause, in that it does not adequately cover all the human functions which together comprise the 'driving' function for body movement. In particular it does not consider external effects such as avoidance of objects in the workplace, although some improvements in this area may be forthcoming from development of the work sequence language.

However because the algorithm is directly concerned with the movement mechanism which is used by the body, it does hold more hope for future development than some of the other methods that have been employed, i.e. it is a fact that all motion is rotational about joints, and that there are definite physical constraints to such motion. It is the manner in which it is decided which particular posture to adopt from the infinite number that are feasible, that is unknown, but it must at least be compatible with the proposed algorithm.

As the range of motion available at joints is crucial both to human motion, and to further description of the postural algorithm, it is necessary to investigate the functioning of the joints in more detail, before proceeding with further descriptions of the biomechanical model.

Human Joints

Some of the mathematical problems associated with modelling joints have already been described when discussing the link system for the anthropometric model, but little has been said of the physical nature of joints.

Body joints are formed wherever two or more bones are connected by ligaments and tissue. Only joints where articulation is possible are of interest here, the immovable joints like those of ths skull being irrelevant in the current context. The degree of articulation is dependant on the geometry of the male and female surfaces, and the constraints formed by bony stops, ligaments, and in some cases flesh interference. Muscle forces, although capable of initiating or stopping movement about a joint, at any point in its range, do not act as absolute constraints to movement.

Three distinct types of joint can be identified; hinge joints, pivot joints and ball and socket joints, each allowing a characteristic type of movement (Damon, McFarland and Stoudt (1966)). Hence the knee is an example of the hinge type, the elbow is a pivot joint, and the shoulder and hip are representative of the ball and socket.

The important features as far as mathematical modelling is concerned are the constraints to movement, and the type of joint (and hence the degrees of freedom). It has already been indicated in figure 4.3. that adequate representation of the link and joint model can be obtained by modelling the following joints.

(a) wrist

(b) elbow

(c) shoulder

(d) neck joint

(e) thoracic joint

(f) lumber joint

(g) hip

(h) knees

(i) ankle.

Each of these joints has its own peculiar characteristics, so it is useful to briefly describe each one individually.

(A glossary of standard terms used in describing joint motion appears as appendix VI).

(a) wrist

A pivot joint with one degree of restraint, allowing movement in the flexion-extension and abduction-adduction senses. Negligible amounts of longitudinal rotation possible.

(b) elbow

A hinge and pivot joint allowing one degree of freedom in the flexion sense and also forearm pronation and supination. Also negligible amounts of abduction-adduction possible.

(c) shoulder

A ball and socket joint allowing all three degrees of freedom i.e. abduction-adduction, flexion-extension and medial and lateral rotation of the upper arm.

(d) <u>neck joint</u>

A mathematical construct equivalent to a ball and socket allowing dorsal and ventral flexion, right and left flexion and right and left rotation of the head, and protraction-retraction and elevation-depression of the shoulder.

(e) and (f) <u>thoracic and lumber joints</u>

A simplification of the multi-jointed spine which is able to move in flexion-hyperextension, lateral bending and rotation. Motions of this type occur to varying extents at each of the spinal vertabrae, but representation by only two joints enables the major movements to be represented while retaining simplicity in the model.

(g) <u>hip</u>

Ball and socket joint permitting three degrees of freedom for the upper leg, i.e. abduction-adduction, flexion-extension, and lateral and medial rotation.

(h) <u>knee</u>

Hinge joint allowing flexion-extension and medial and lateral rotation of the lower leg.

(i) <u>ankle</u>

Pivot joint permitting two degrees of freedom in dorsiflexion-plantarextension and inversion-eversion.

The complete model thus has 41 degrees of freedom at its joints, allowing the foot 7 degrees of freedom relative to the pelvis, and the hand 15 degrees of freedom relative to the base of the spine.

Information regarding the type and range of motion possible at each joint, has been obtained either by the study of cadavers or by measurement of living subjects. The early cadaver work was carried out largely by German investigators, notably Braune and Fischer (1887) and Fick (1904-11), but more recently, with the advent of better instrumentation most studies are made on living subjects allowing a larger and more representative sample to be used. Thus Sinelnikoff and Grigorowitsch (1931) took measurements on 100 males and 100 females using a protractor type goniometer, and Glanville and Kreezer (1937) used a pendulum device for their sample of ten males. Dempster (1955) used photographic techniques to study a sample of 39 young men of varying body builds, and his work has been statistically re-analysed by Barter, Emmanuel and Truett (1957). The data used for the biomechanical model is largely taken from this last source, as it is considered the most reliable (see appendix III for details). Where gaps exist in this data, the data of Glanville and Kreezer has been used, and certain of the 'normal' as opposed to absolute ranges of joint motion are from Ryan, Springer and Hlastala (1970).

The situation regarding information on range of joint movement is very unsatisfactory, because of the relatively few studies that have been carried out, and the small samples involved. Many of the comments made earlier when considering anthropometric data apply equally well here, in that joint range is dependent on the population considered and varies between individuals within such populations.

The factors most likely to affect motion at the joints have been listed by Damon, Stoudt and McFarland (1966) and can be seen to be comparable with the factors which influence anthropometry. The important factors are briefly described below, but the shortage of experimental investigation into these aspects, leaves us with little quantitative information.

(a) age. Between the ages of 20 and 60, mobility decreases slightly, and will decline by a further 10 percent in the next ten years. (West (1945)).

(b) sex. Women have greater mobility at all joints but the knee, the greatest difference being 14° (at the wrist) (Sinelnikoff and Grigorowitsch, 1931).

(c) body build. Dempster's (1955) study showed that obesity can markedly reduce joint mobility.

(d) exercise. Lack of exercise tends to lead to restricted movement and conversely increased exercise can extend the normal range of mobility.

(e) occupation. Certain occupations can lead to particular joints being exercised and hence their mobility is increased.

(f) Arthritis, poliomyelitis and other similar diseases can render a joint totally inoperative or only partially mobile.

(g) motivation. Increased effort can increase joint range, and forcing of the joint beyond its voluntary limit can result in significantly higher passive ranges (Glanville and Kreezer 1937).

(h) body position. A distinction has to be made for instance between the pronated and supinated hand when considering wrist flexion.

(i) clothing. Bulky winter clothing or specialised clothing such as pressure suits can severely limit mobility.

Although the above factors have been shown experimentally to affect joint mobility, very few large scale surveys have been conducted, so it is difficult to relate joint mobility to a particular population in anything other than a qualitative way. The model currently uses the data of appendix III for all populations, although there is no reason why variability should not be accounted for in much the same way as the link lengths of the anthropometric model. Given joint range data for a particular population, it would of course be possible to explicitly change the input data, but such data is not likely to be readily available.

Once suitable data has been obtained for limits of joint motion, it is possible to describe body postures in terms of the angles at the joints, and compare these with the limits, so that feasibility can be ascertained.

At this point it is possible to return once again to the question of posture prediction during simulation of a work task.

Postures

The term postures is used to refer not only to the static positions of the body segments, but also to those instantaneous 'frames' of a kinematic movement. The underlying problem in the formulation of a kinematic model is to predict these postures for a wide range of movement. A critical analysis of other attempts in this area of posture prediction is given in appendix I, but the general difficulty encountered arises from the complexity of the mathematical methods required. Most serious attempts to model the 'driving' function have resulted in the use of optimisation techniques designed to minimise an objective function whilst having regard for the physical constraints to movement imposed internally by the body. Hence in the case of BOEMAN (Ryan, 1971), the objective function is the minimisation of the effort required to maintain a posture, leading to an optimisation of the Euler angles for each joint within joint angle constraints. The mathematical method employed is a gradient search technique involving the minimisation of a non-linear objective function with non-linear constraints. Evaluation times of three minutes have been reported for the prediction of just one posture using this technique, and this is when using a powerful CDC6600 machine. Reducing the model to a spine and arm model, removing the effort objective function and reducing the accuracy of the minimisation techniques has enabled the evaluation time to be reduced to nine seconds, but only at the expense of model performance.

The same general comments apply to all models using this kind of mathematical technique, and this is of great significance to the design of the SAMMIE model. SAMMIE is intended as a practical design tool for use in the interactive graphics mode, and hence

(a) for a designer to feel that he is in control of the system, changes in the workplace or man model position which are initiated by interactive control at the screen, should be implemented almost simultaneously.

(b) the proposed development of SAMMIE is intended to be implemented on a dedicated mini-computer, as this is seen as being the most economic method for its eventual use as a design tool. Benwell (1974) has indicated that such machines are likely to be some five times slower in operation than the CDC6600, implying that methods of the kind used in BOEMAN would give intolerable time penalties in the region of 15 minutes per evaluation for a full model, and 45 seconds for the simplified model. It does not seem possible to significantly improve these times by more efficient programming, as a 5000% improvement is necessary.

To summarise the objectives of posture prediction techniques:-

(i) The method used should reflect the functioning of the human body as far as possible. This enables the progressive extension of the facilities of the model, as any new facilities will be compatible with the original model.

(ii) The method should be able to cope with the indeterminate nature of the human link system, in such a way that the postures presented are representative of actual human postures, i.e. the derivation of a feasible posture is not sufficient.

(iii) The use of the model as an interactive design tool must be considered, and this implies a requirement for computation which does not result in excessive evaluation times.

To meet these objectives, the man model described in this thesis uses a 'postural' algorithm which is described in the next chapter.

CHAPTER SIX

THE POSTURAL ALGORITHM

The Postural Algorithm

To meet the objectives listed at the end of the last chapter, the 'postural' algorithm has been kept as simple as possible, and is based on a work study principle of motion economy which is constrained by the limits to motion about joints.

The foregoing description of the joints, demonstrates that each joint has definite limits to its range of motion, so that all motions of the human body are limited by these constraints and the link anthropometry. The algorithm is used to predict a posture which is consistent with natural human movement and at the same time feasible within these constraints.

This has been achieved by a combination of a proposal by Barnes (1963) which requires that the least significant links be moved first, and a hypothesis that links tend to arrange themselves so that joint angles are kept within a normal or 'comfort' range of movement.

Barnes, in formulating some general guidelines on motion economy as a way to improving work methods, has suggested that a task should be performed in such a way that body motions are confined to 'the lowest classification with which it is possible to perform the task satisfactorily'. For movements involving the top half of the body, he gave the following classifications.

1. hand
2. hand, forearm.

3. hand, forearm, upper arm.

4. hand, forearm, upper arm, shoulder.

5. hand, forearm, upper arm, shoulder, spine.

Hence in the context of work economy, lower classifications are considered preferable, and the higher classifications should only be used when essential for reach purposes.

A criticism of this view however is that the human body tends to function much more as a total system, and therefore links of higher classifications will often be utilised when not essential to the motion. In this way, although it might be feasible to reach a desired position with the arm alone, it will often be found that the spine also contributes to the movement. This would seem to indicate that the absolute constraints to movement about the joints do not dictate the sequence of introduction of body links in normal situations. Instead, it would appear that normal or 'comfort' joint constraints exist, and that movement of an extra link is preferable to violation of these constraints.

There is very little experimental evidence to support this assertion, although some preliminary work carried out in conjunction with Michelson at Loughborough University, supports it in a qualitative way (fig. 6.1.). It can be seen from this simple forward motion of the hands to place a tray on a horizontal surface, that the spine moves well before the elbow or shoulder joints are fully extended.

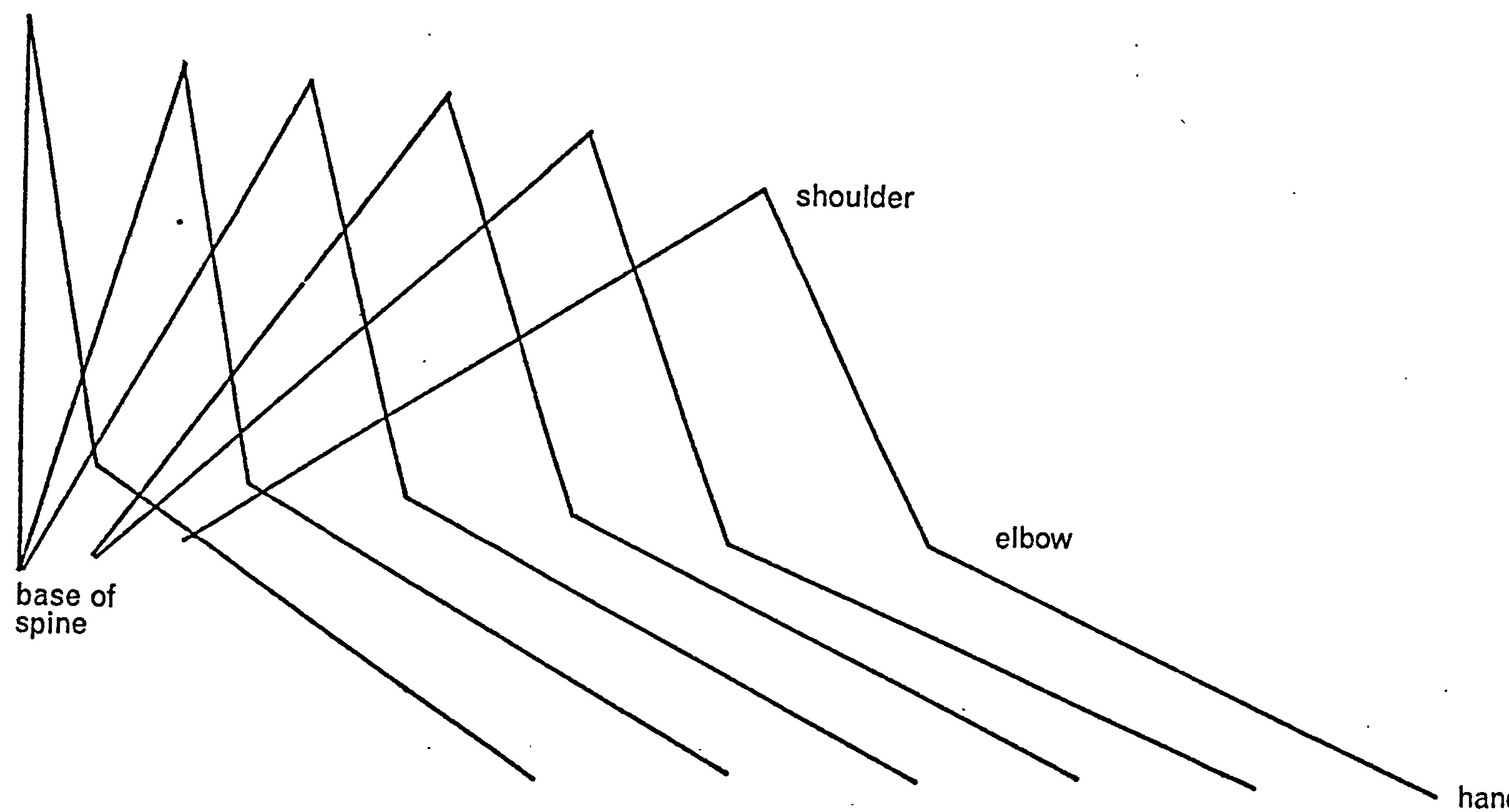


Fig. 6.1. Experimental Work Showing the Movement of the Spine before the full extension of the arm.

Hence to represent this situation, the 'postural' algorithm superimposes a series of joint constraints over Barnes' motion economy principle. Each degree of freedom at a joint is seen to consist of four constraints and a neutral point. In this way for example, movement of the arm in the saggital plane is constrained not only by the maximum extent of flexion and extension, but also by inner limits of normal flexion and extension (fig. 6.2.).

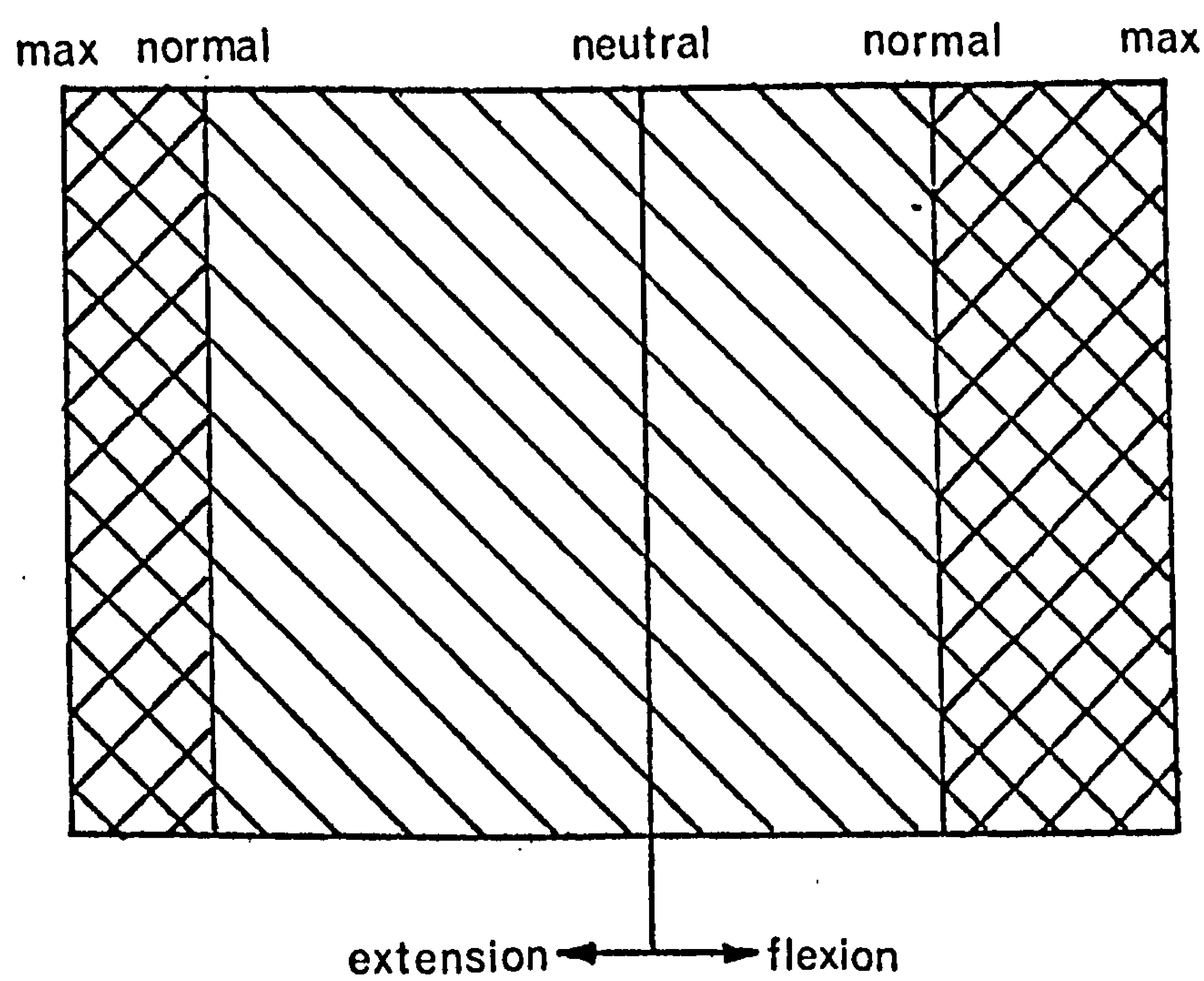


Fig. 6.2. The Relationships between Angle Constraints at Joints

It is assumed that the body tends to optimise its posture so that all joints are as close as possible to their neutral or rest position. (The neutral position is defined as 'standing upright with arms hanging at the side, palms inward' Murrell

1965). Murrell states that such a neutral position for the unsupported body results in minimum muscle activity and such a posture is 'therefore the least fatiguing and probably the most comfortable'. It should of course be remembered that when the body is supported, as when lying down, there will be a relative improvement in comfort and fatigue.

The 'postural' algorithm allows movement away from the neutral position for the relevant joint, until the normal constraint is reached. At this stage the next significant limb is introduced. Extension of the limbs continues in this way until all the relevant joints are approaching their normal constraints. If further movement is required, the least significant joint is allowed to move into the region between the normal and maximum constraints. Once all relevant joints are at their maximum constraints, the position is deemed to be out of reach.

This general method of limb introduction has to be modified in places, where for example the spine often moves before the shoulder, but it does provide a way of predicting a reasonable solution from the infinite number of feasible ones.

Detailed description of the algorithm is provided by the flow diagram for the upper half of the body (fig. 6.3.), and an explanation of this diagram is contained in appendix IV.

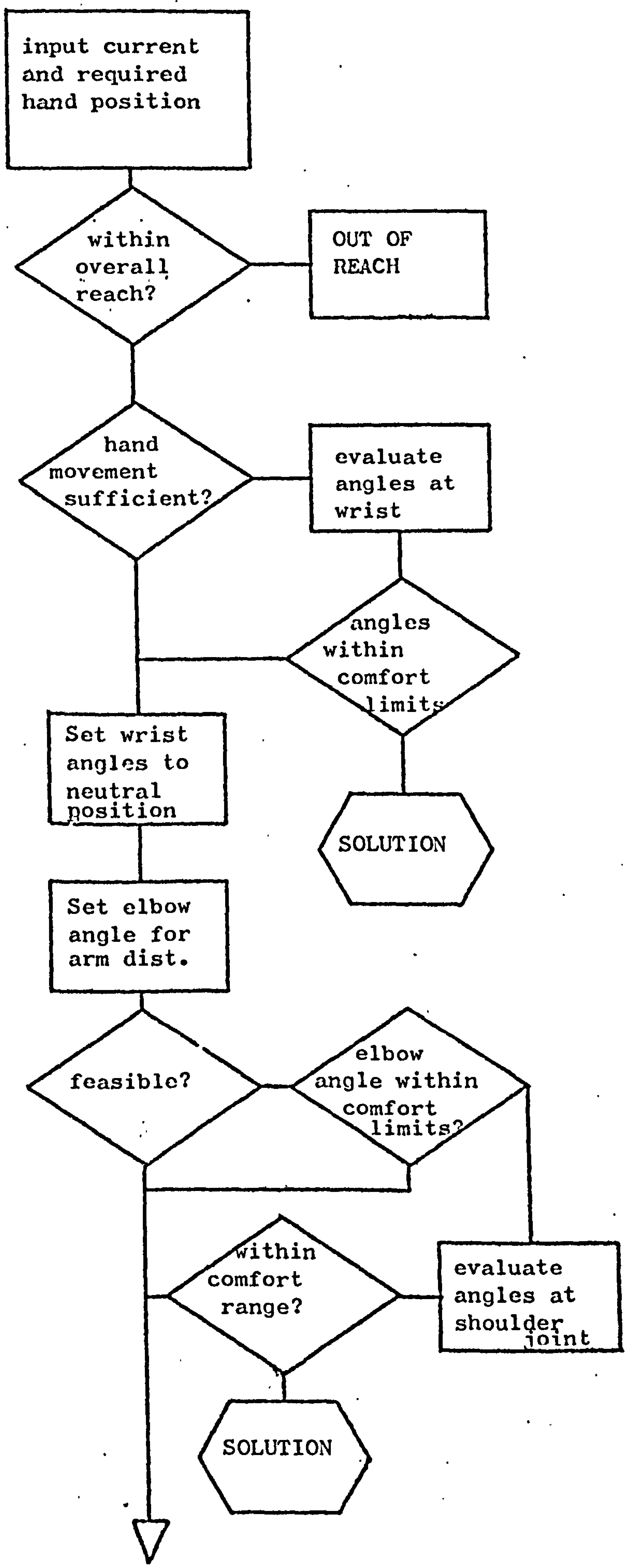


Fig. 6.3. Flow Diagram for Postural Algorithm.

Fig. 6.3. continued

Comfort Rating.

A subsidiary advantage gained from the use of joint angles for posture prediction, is that it is possible to derive an approximate measure of 'comfort' for a given posture. The model contains information concerning the limits to normal movement at joints, as well as the absolute limits, and thus any joint posture can be defined in terms of these constraints. Hence referring again to fig. 6.2. three distinct states of a joint can be identified

i.e. (i) at neutral or rest position

(ii) within constraints to normal movement

(iii) within constraints to maximum movement

In addition Barnes' postulation that the lowest classification of movement should be used to obtain energy expenditure minimisation, can be extended to relate in the same way to comfort. It can then be assumed for example that the spine posture is more important than the hand posture as far as overall comfort is concerned.

Some aggregation of the comfort rating at each joint, with the more significant joints being given appropriate weighting, will give an approximate rating of overall comfort. The three states in which joints can be found (numbered (i) to (iii) above), provide a step function for comfort at each joint (see fig. 6.4.).

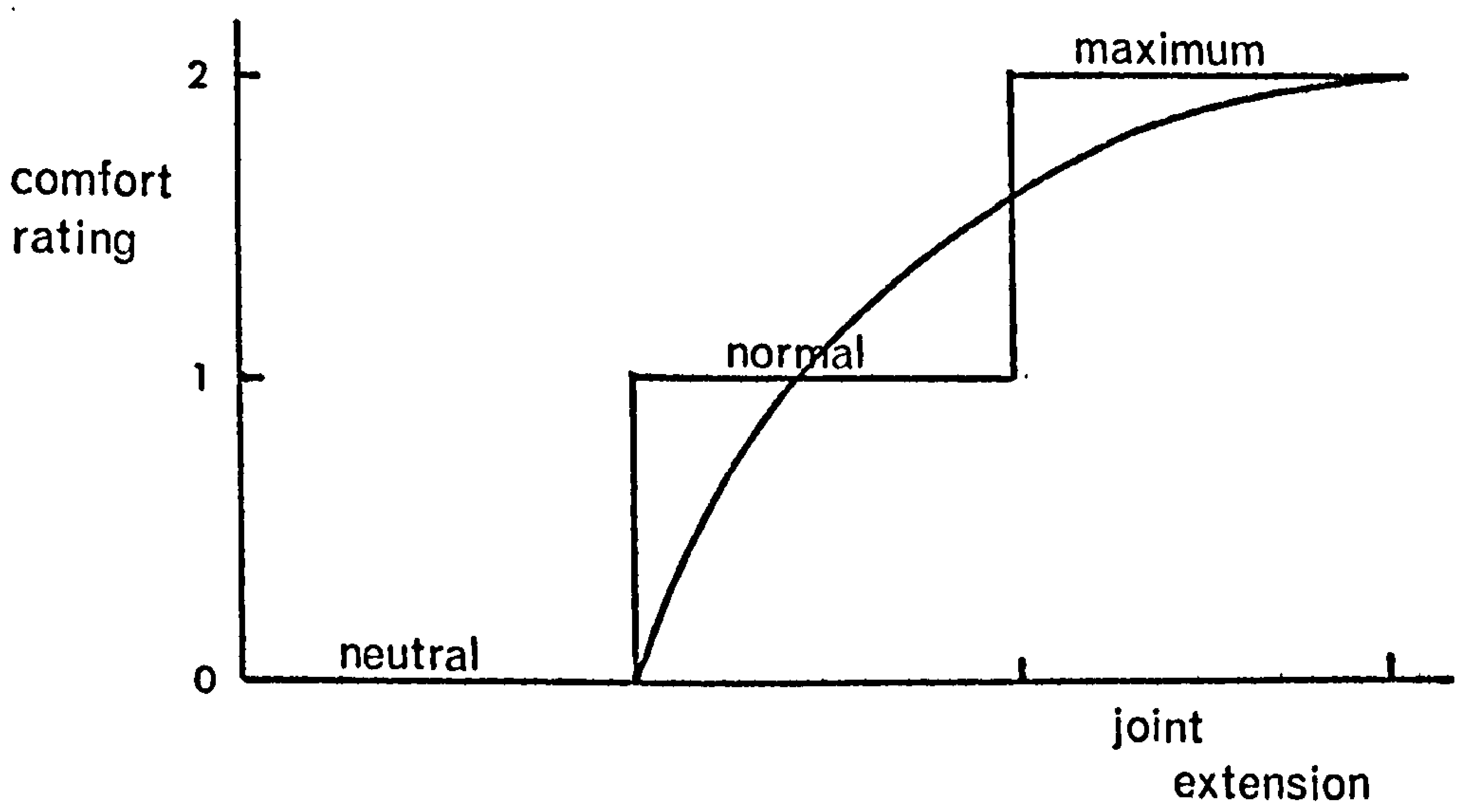


Fig. 6.4. 'Comfort' at each Joint

Currently this step function is used to define a comfort rating at zero, one or two for each joint, although it would be a simple extension to provide a continuous scale related to a curve such as that shown in fig. 6.4.

Then, for the top half of the body, the comfort ratings of the wrist, elbow, shoulder, thoracic and lumbar joints are given weightings of one to five. As an example, if the wrist is fully extended, the elbow within normal range, and all other joints at their rest position, the comfort rating would be formed as follows:-

$$\text{Overall Comfort Rating (OCR)} = CR_{wrist} + 2 \times CR_{elbow} + 3 \times CR_{shoulder} + 4 \times CR_{thoracic} + 5 \times CR_{lumbar}$$

then

$$OCR = 2 + 2x1 + 3x0 + 4x0 + 5x0 = 4$$

Higher values of OCR then indicate progressively more uncomfortable postures.

This OCR index is intended solely as an easily obtainable measure of comfort which allows rapid comparison of postures, and must be used with great caution for several reasons.

(i) Comfort is influenced by many factors other than joint angles. Thus the time for which a posture has to be held, and the effort required to do so (e.g. if lifting a weight) can be more important than the angles themselves.

(ii) The assignment of values is somewhat arbitrary, as for example, in some circumstances extension of the spine into its maximum range may be preferable to extension of the elbow.

(iii) The function is not linear, so that a value of 50 is not 'five times more uncomfortable' than a value of 10.

The comfort rating thus represents a spin-off from the postural algorithm which has not yet been fully developed or exploited.

The 'postural' algorithm fulfils some of the criteria for posture prediction in that its relative simplicity results in computation times that are compatible with the need for a fast-acting interactive system. Hence it has some advantage over the complex mathematical techniques used in other models, which can result in evaluation times that are unacceptable for practical design work.

Although the algorithm is simple it does not necessarily imply that the postures predicted are any less 'correct' than those predicted by more sophisticated methods. In terms of feasibility both approaches are exactly comparable, as within the limits of the quality of the data, both are able to accurately predict whether a posture is physically possible. The difficulty arises in determining whether the postures are typical of normal movement patterns. The physical, physiological and phychological factors which together determine movement patterns appear at the present time to be too complex for any unifying functional relationship to be defined. Hence although it is accepted by Ayoub, Walvekar and Petrumo (1974) for example that 'man acts to optimize some criterion of performance in carrying out a movement', the exact nature of that criterion remains unknown. Ayoub proposes power minimisation as the criterion, using the principles of dynamic programming for model solution, but it is clear that such an approach is only realistic where physical effort is the major component of the task. Hence even though sophisticated mathematical techniques have been used, this model is still not suitable for a large proportion of tasks. Hence as our ability to manipulate complex mathematical functions far exceeds our ability to understand the functioning of the human body, the existence of a sophisticated mathematical technique is no proof of the quality of the posture prediction.

The 'postural' algorithm is of course open to similar criticism in as much as it is an incomplete representation of human movement. Hence it is currently only truly applicable where movements are considered which are not constrained by external effects such as interference with workplace elements, and where movement patterns are not affected by certain internal effects (e.g. no consideration is made of the effort required to perform a task). However the construction of the algorithm will allow extensions in the future which will allow several internal factors to be considered (see previous chapter) and the developments in the work sequence language will potentially enable evaluation of a considerable number of external factors.

Preliminary investigation of two of the internal factors have shown them to be potentially useful for later inclusion in the algorithm, although at the current time they are only available as separate analyses. Hence the assessment of balance, and some of the dynamic properties of the body leading to muscle strength evaluation have been studied, and the work reported in the next chapter, but these criteria are not included in the predictive algorithm.

CHAPTER SEVEN

JOINT MOMENTS

Joint Moments

The anthropometric and biomechanical model thus far described is potentially useful for studying the static or pseudo-dynamic implications of a workplace design. The attributes of the model allow the following kind of criteria to be examined.

(i) static

(a) reach

(b) fit

(ii) pseudo-dynamic

(a) interference caused by the workplace while executing tasks (using the man and workplace models in conjunction).

(b) assessment of movement patterns implicit in the work task, possibly leading to improved method (work task) or improved workplace design.

However there are a range of criteria which would enable better assessment of man's physical capability of performing a task. Among these can be included strength, fatigue, balance, work capacity and energy expenditure, but at the current stage of development only the first three of these have been investigated.

Fatigue

Human fatigue 'is an important aspect with respect to ergonomics or occupational health, since it determines the working capacity of individual workers and is at the same time also one of the first concerns for their well-being.' (Hashimoto 1971). However fatigue is a highly complex phenomenon linked to many physiological and psychological aspects of work. The Kyoto Symposium on 'Methodology in Human Fatigue Assessment (ed. Hashimoto, Kogi, Grandjean 1971) identified many such psycho-physiological factors including:-

monotony

environment (illumination, climate, noise)

intensity and length of manual work

phsychic factors (responsibility, worries, conflicts)

illness and pain, eating habits

Grandjean and Kogi (1971) state that fatigue has three major components (or symptoms)

(i) sensation of bodily tiredness and drowsiness

(ii) sensation of weakened motivation or concentration towards the task

(iii) a group of physical complaints pertaining to psychosomatic disorders

It is evident then that the level of fatigue induced by a work task can have significant effects on the efficiency with which a task is carried out, and as Saito et al. (1971) have shown, (fig. 7.1.), absenteeism, usually due to psychomatic disorders such as headaches, giddiness , palpitations and indigestion, increases as workload is increased. It would

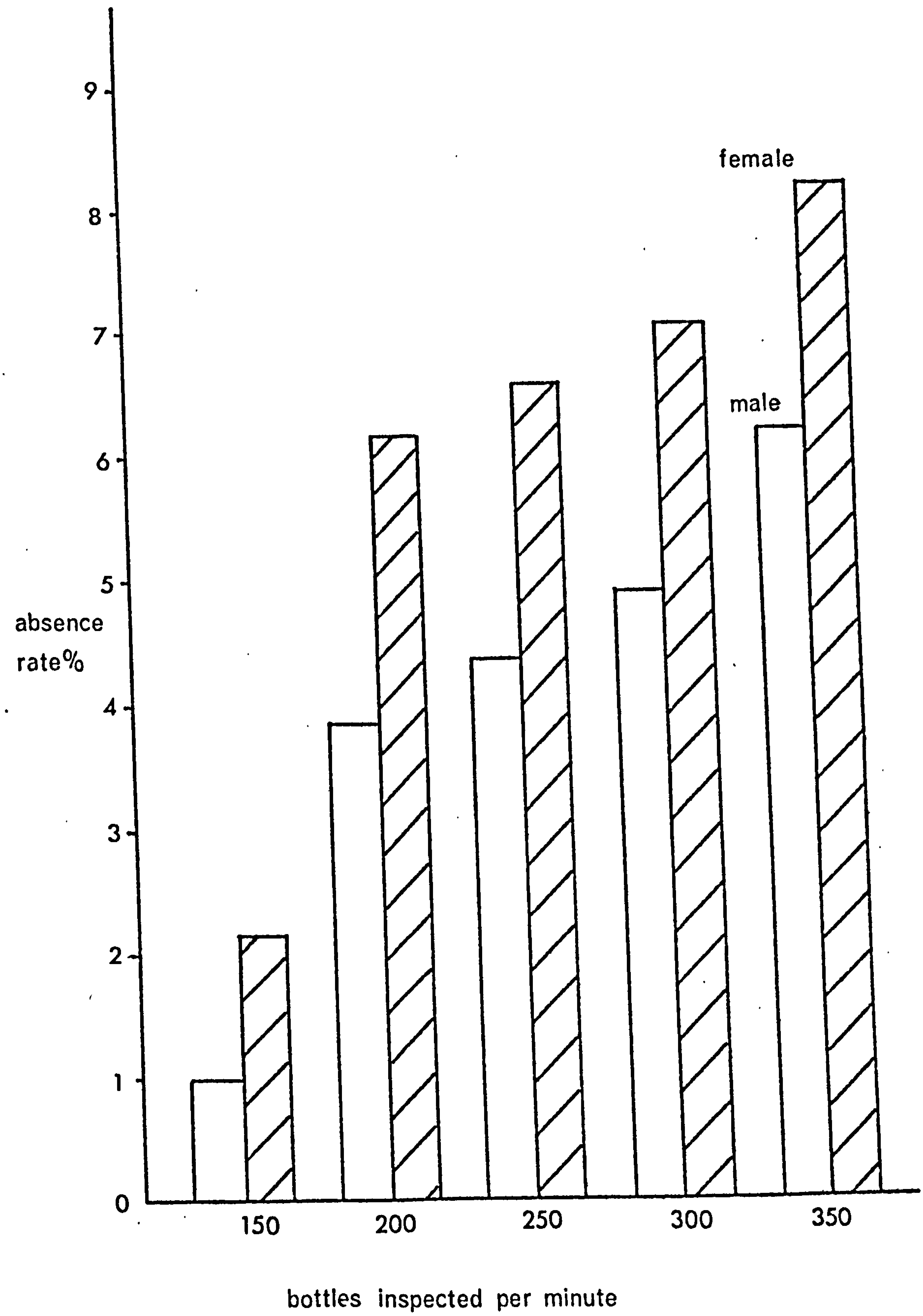


Fig. 7.1. Effect of Workload on the Absence Rate of Bottle Inspection Workers. (Saito et al. 1971).

thus seem desireable to include an analysis of fatigue in the man model so that both work task and workplace designs could be directed towards minimising fatigue. Unfortunately, not only is there a large number of factors to be considered, but because of the 'whole system' nature of fatigue it is also impossible to separate the effects of individual factors in any quantitative way. However for the limited area of muscle fatigue, or as Chaffin (1969) calls it, 'human physical fatigue', this constraint can be relaxed so that some kind of assessment of fatigue is possible. Hence Morioka <u>et al</u>. (1971) have established that for certain kinds of operations, muscle force is kept to within 10-20% of its maximum. Kroemer (1970) reports the work of Monod (1956), Rohmert (1960) and Caldwell (1964) which can be summarised by the curve shown as fig. 7.2.

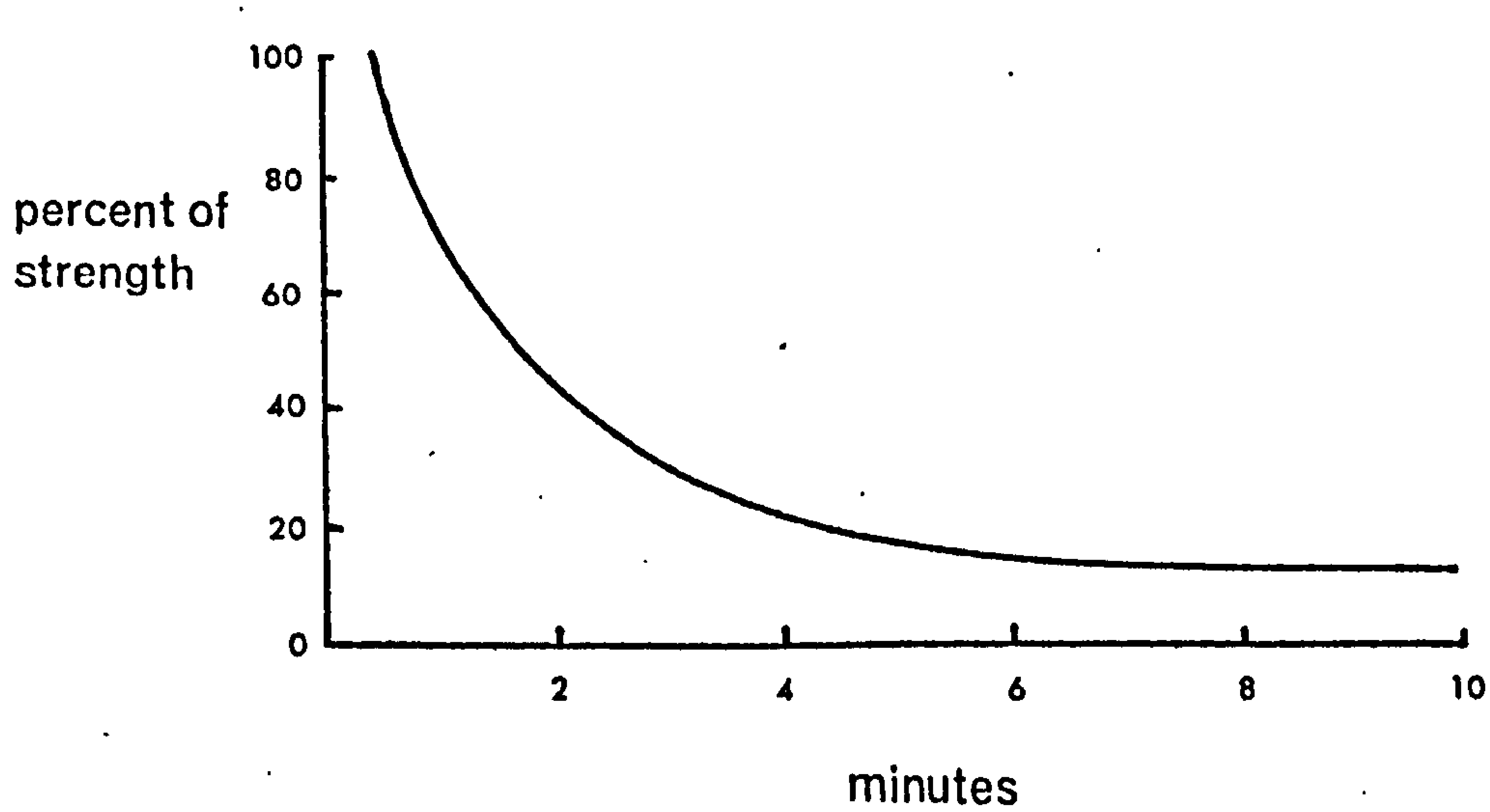


Fig. 7.2. Degradation of Strength with Time (Kroemer 1970)

It can be seen that maximum strength (defined as the maximum force muscles can exert), can only be held for a few seconds, there being a gradual degradation with time until the point where if a force is required to be maintained for several minutes, it cannot exceed 20% of the maximum strength.

The conclusion to be drawn from this is that the commonly accepted view that the forces required to operate controls need only be within the maximum limits, needs considerable modification when these forces have to be maintained for anything longer than a few seconds.

Strength

The situation where forces are only required for a few seconds, can however arise in many work tasks, and in this case it is useful to know the strength of the various muscle groups used to apply the force. Then tasks can be designed so that the maximum force required does not for example exceed that available to an operator with 5th percentile strength. This would ensure that the majority of operators could perform the task, although it might be preferable to relate the task to strengths which can be attained without undue effort, rather than maximum effort. Chaffin (1969) states that the central nervous system contains a protective mechanism which prevents strain on the musculo-skeletal system exceeding certain 'learned' limits. Hence the body will normally only exert strength up to 80% of the value at which injury occurs. Chaffin however, goes on to say that this 'learned' limit is not effective where

(i) the back is used in a lifting task

(ii) very rapid jerky movements are used

(iii) motivation such as fear causes maximum limits to be exceeded

(iv) co-ordination has been lost due to muscle exhaustion.

The need thus arises for a model capable of describing and analysing muscle strength, so that these various factors can be considered.

Muscles

The human body applies forces by the use of muscles, sometimes combined with the action of gravity. The detailed description of the physiology of muscles with their conversion of calorific energy into mechanical energy is not important here, it being sufficient to state that they are capable of exerting forces by contraction. The manner in which these forces are transmitted to the skeletal frame is however of considerable interest, as it leads directly to a method of modelling some of the dynamic as well as static aspects of force exertion.

Dynamic and Static Force Exertion.

Forces can be said to be applied statically, when very slow movement, or no movement of the body results from the application. Typical of this kind of situation is the holding of a weight, where the muscles are doing work to maintain their contracted state against the effects of gravity (on the limbs as well as the weight), but no movement occurs.

Dynamic forces result in movement of parts of the body, and therefore inertial forces also have to be supplied or withstood by the muscles. In addition static forces maintaining the postures of the non-moving parts of the body will almost always be present when dynamic forces are applied.

In either case, muscle force is usually applied by the linear contraction of a muscle being utilised to give a torque about a joint. Hence muscles normally connect two adjacent body segments as depicted in fig.7.3. (from MacConaill and Basmajian 1969).

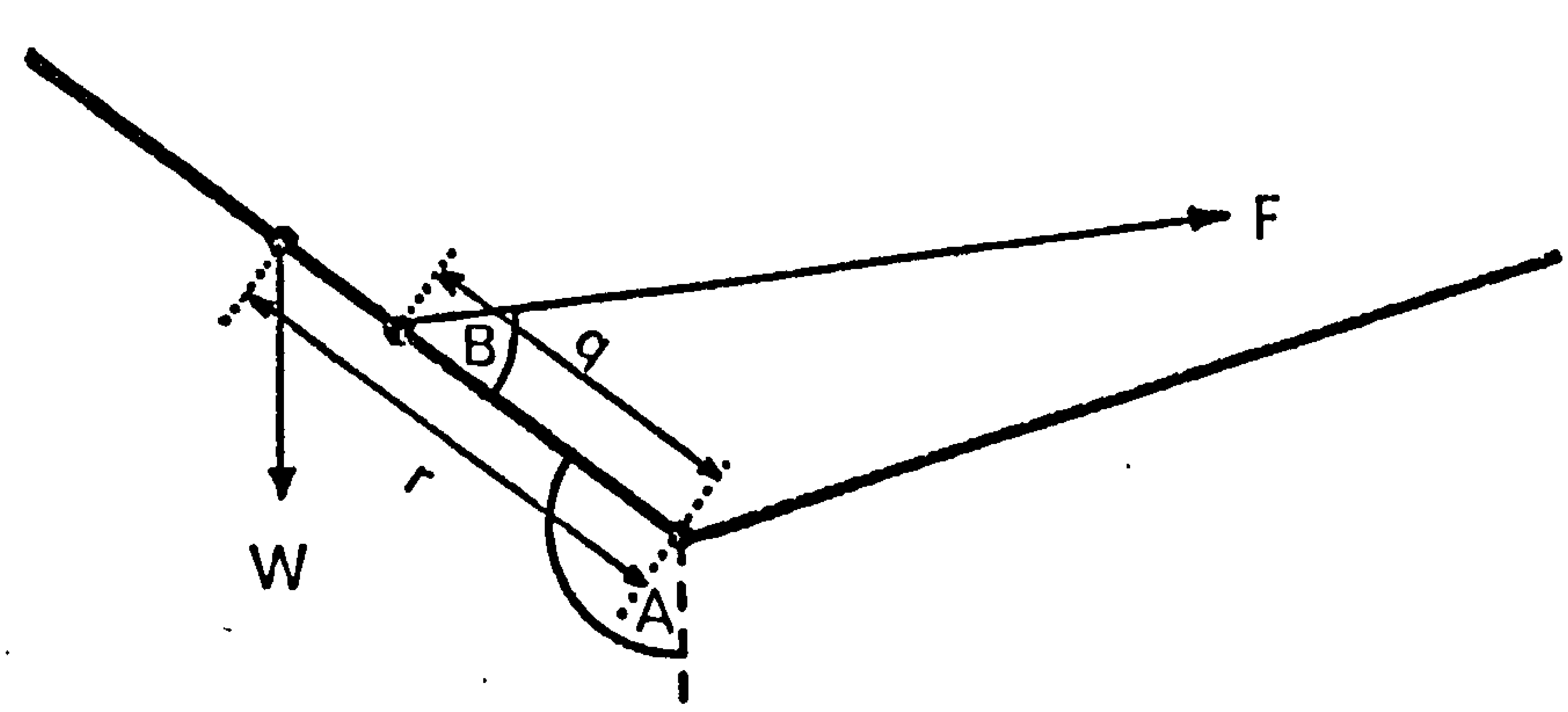


Fig. 7.3. Muscle Action (from MacConaill and Basmajian 1969)

The magnitude of the torque supplied is then dependent on (in the static situation)

(i) the amount of internal muscle force (F)

(ii) the distance between the joint and the location of the muscle or tendon attatchment to the bone. i.e. the lever arm q.

(iii) the pull angle between the vector of muscle force and the limb B

(iv) the gravity force associated with the segment tending to be moved W.

The dynamic situation where movement of body segments takes place, is further complicated by the inertial forces connected with the rotational acceleration and deceleration of segments. Hence fig.7.4. from Plagenhoef (1971) shows the free-body diagram for two segments in motion. The additional forces present here are

(v) tangential forces due to the angular acceleration of each segment

(vi) radial forces due to the angular acceleration of each segment

(vii) the Coriolis force due to the rotation of a segment about an axis which is itself rotation.

It can be seen then that the action of muscles is extremely complex, although the final result of any muscle contraction can be said to consist essentially of a torque about a joint,

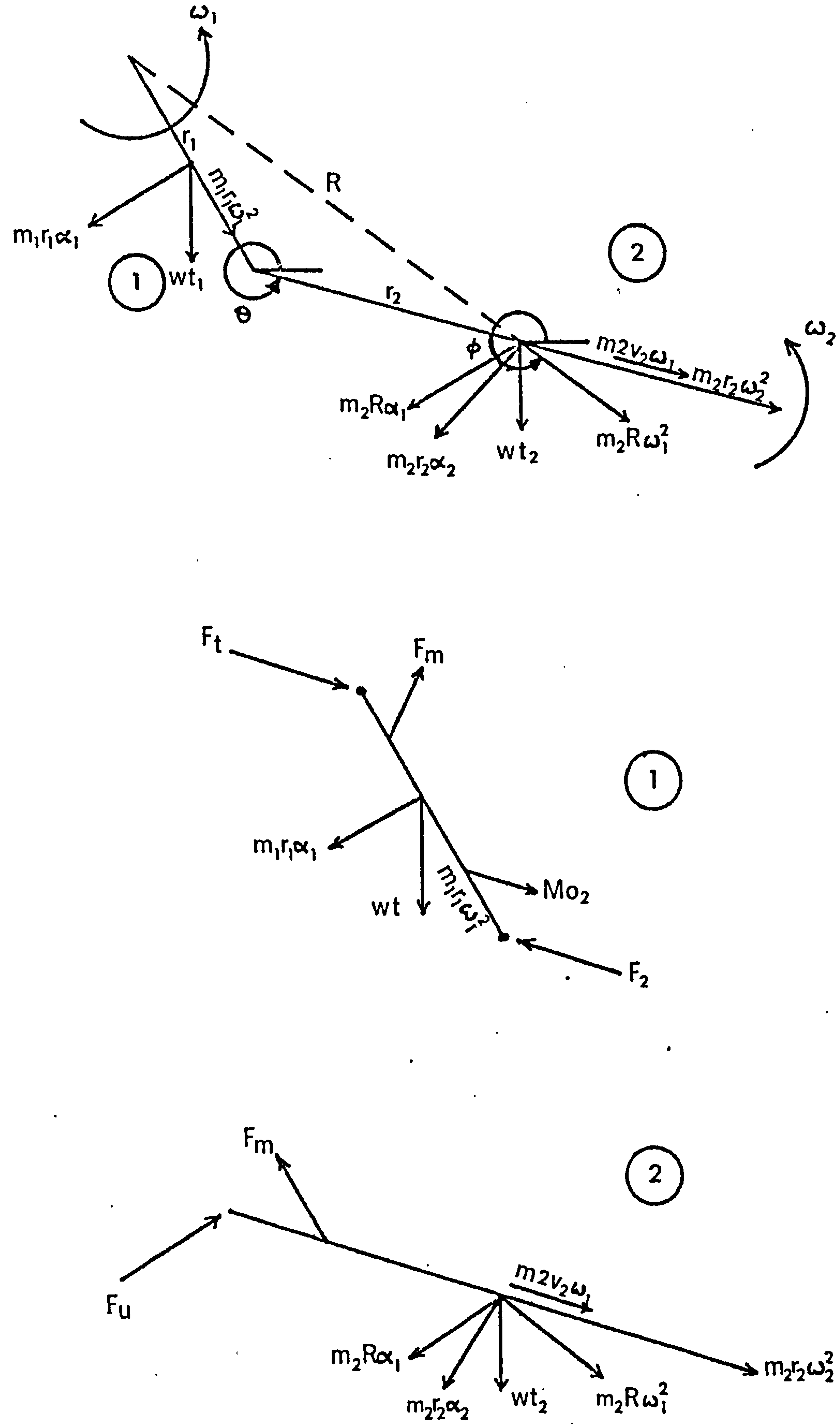


Fig. 7.4. Free-body diagrams for a two segment motion. (Plagenhoef 1971).

and a force across the joint.

The force across the joint may tend to compress or pull apart the joint, but it has been shown (MacConaill and Basmajian 1969) that the muscle/joint system is so arranged that no internal muscle force can damage a joint. Joints can of course be damaged by separation due to the action of external forces, but this need not concern us for the moment. The torques at the joints, provide us with essential information about the strength of the muscles, as the torque and strength are directly related. The nature of the relationship is however extremely difficult to derive, largely because of the complexity of the factors listed (i) - (vii) above. It is difficult for example to find the length of the lever arm in the human body. This is because the length of the lever arm is determined by the point of attatchment of the muscle to the bone, and most motions involve several groups of muscles depending on the geometry and mechanics of the situation. Hence Plagenhoef (1971) states that:-

(a) The total joint muscle action adjusts constantly during a motion, attempting to maintain a stable joint (compressive rather than shearing action at the joint).

(b) The muscles that have their long axes closest to the resultant force vector direction are called on to the greatest extent.

For these reasons the simple movement of flexing the elbow could involve the use of the biceps, triceps and brachioradialis, the extent to which each individual muscle is used being very difficult to ascertain. Some useful indications as to the likely ways in which muscles are used in a wide variety of movements is given by MacConaill and Basmajian (1969) and Basmajian (1959,1962), but such complicated analysis will not be attempted in the current model.

Instead the resultant torques at the joints are used as indicators of strength. Experimental data concerning the maximum torque possible at each of the relevant joints can be compared with the torques required for a particular motion, so that feasibility can be assessed without direct reference to the action of the muscles which provide the torque. The validity of such an approach is dependant on satisfactory strength data being available, and the formulation of a model which adequately represents the mechanics of movement (i.e. the equations of motion for the limbs). The later requirement is met by the use of Plagenhoef's (1969) method of obtaining kinetic data on human motions, (described later), but the provision of comparative data on torques at joints is fraught with all the usual difficulties encountered when dealing with anthropometric and biomechanical data.

Strength Data

The strength capabilities of human operators are subject to similar variations to those found in anthropometry and joint range data. Strength will vary between different populations (defined in any of the normal ways such as by nationality, age, sex, occupation etc), and also between individuals within these populations. A more fundamental problem however, is concerned with the inconsistencies that exist in the literature, due presumeably to different experimental techniques. Thus Kroemer (1970) in reviewing some of the literature is drawn to the conclusion that 'the scientific value of such (strength) tests is rather dubious'. This condemnation is based on inconsistencies such as

'10,000 British workers exerted on the average 363 lb in static backlift' (cathcart 1935)

while '900 United States Air Force personnel exerted a mean static pull-up force of 520lb in backlift'(Clarke 1945). Kroemer sees these inconsistencies to have arisen mainly out of the incorrect use of terminology in describing experimental conditions. Strength is defined (by Kroemer) as the 'maximal force muscles can exert isometrically in a single voluntary effort, meaning constant muscle length, and implying static force exertion. Difficulty often arises out of confusing this term with isotonic which implies that a muscle is under constant tension. A constant force exerted at some external point does not necessarily mean that the muscles are being used either isometrically or isotonically because body segments may be moving, in which case dynamic effort is being applied.

A further complication arises out of the experimental technique involved in many studies. Clarke (1966) for example, reports the strength of most segment movements, but omits to state the length of the lever arm involved. A tensiometer was used to find for example the strength of hip flexion, but the point of application to the thigh is unspecified making the result of a mean strength of 108.88 pounds rather meaningless. (fig.7.5.)

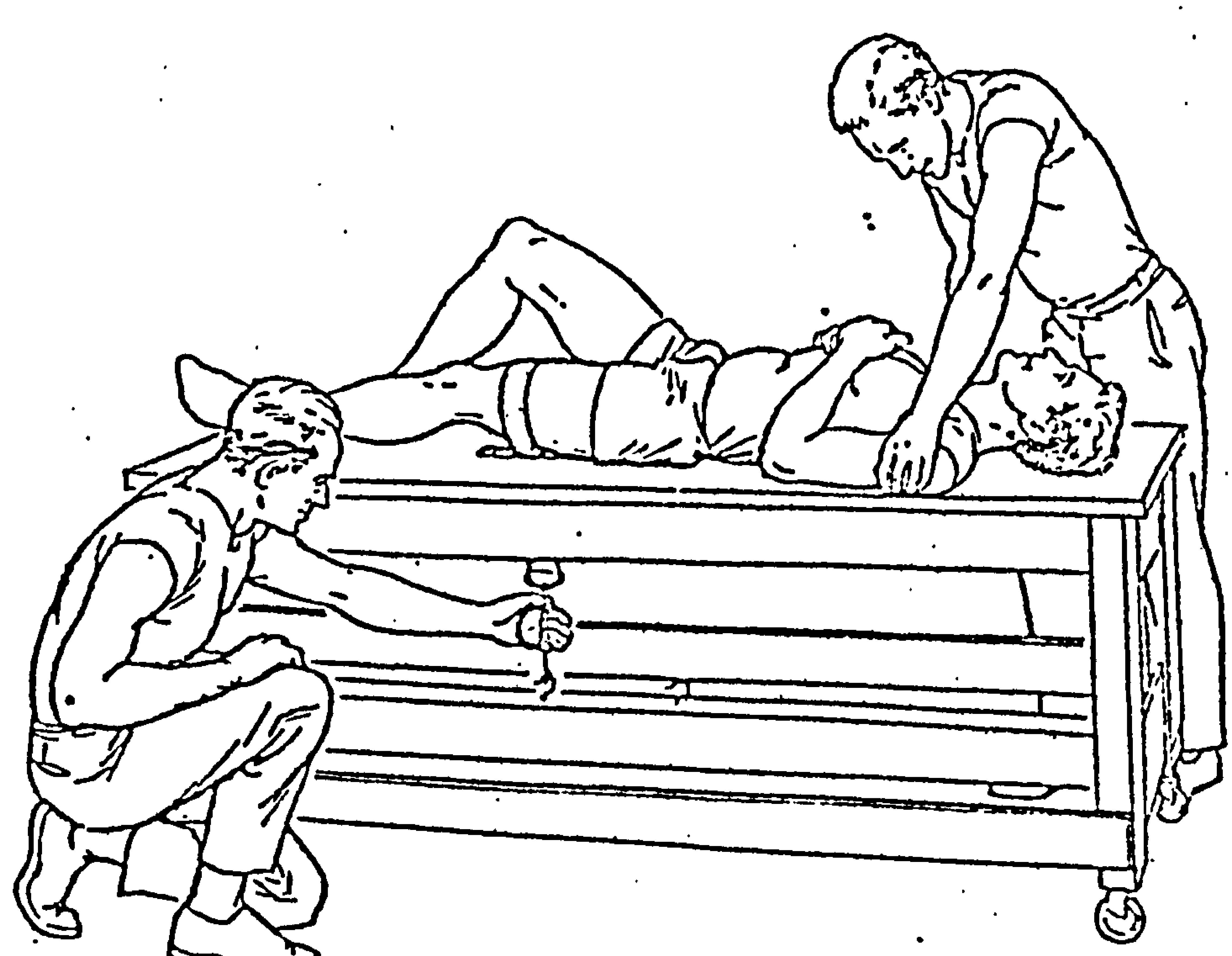


Fig. 7.5. Clarke's Method for measuring the Strength of Hip Flexion.

The artifical nature of strength tests, such as those by Clarke, where force application is by one segment only, has led other investigators to publish data concerning functional force exertions. Hence Thordsen, Kroemer and Laubach (1972) have established force capabilities of U.S. Air Force personnel at a wide range of aircraft control locations. Chaffin (1971), using male and female industrial workers, has generalised this approach into force contours (e.g. Fig.7.6.), which allow the prediction of strength capabilities at any point in a specified three dimensional space. In producing these functional contours, Chaffin has established basic data concerning the maximum torque values at the major joints, (Tables IV and V), and it is suggested that these values are used for companitive purposes in the current model.

Tables IV and V refer to data collected from a sample of 100 men and women at the Western Electric Kansas City works, with the anthropometric dimensions as shown, and with the following experimental conditions (Chaffin 1971)

(a) both hands are equally loaded and in front of the body.

(b) the object is stationary or being moved very slowly (i.e. static force exertion)

(c) the person is free to select body configuration (i.e. no obstructions)

(d) the load is applied for a period of less than four

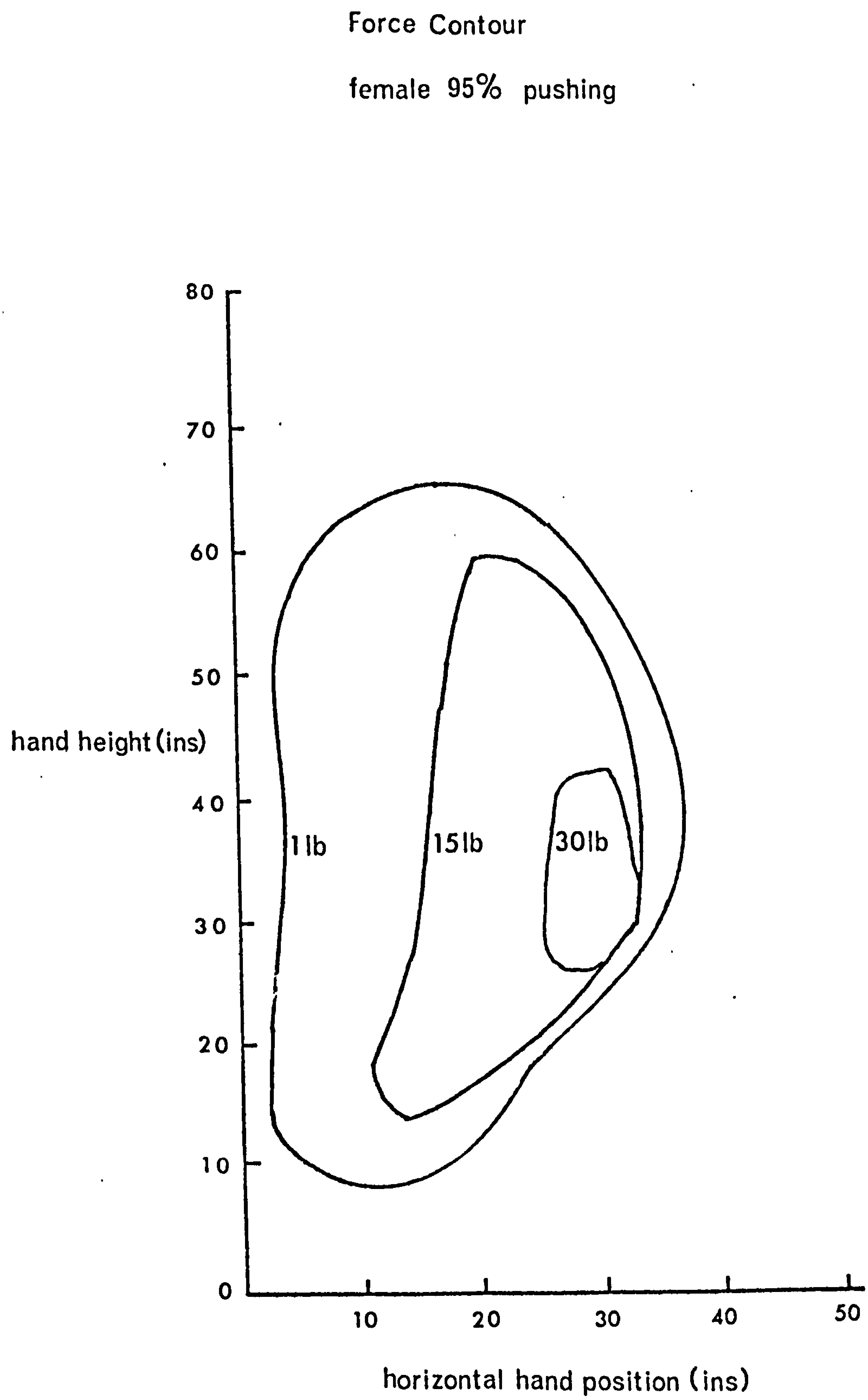


Fig. 7.6. Force Contours from the Data of Chaffin (1971)

Table IV Male Torque Capabilities (From a survey of 100 industrial workers at the Western Electric-Kansas City Works. D.B. Chaffin (1971).

Torque (inch-pounds)	Percentile		
	95%	50%	5%
Elbow Flexion	436.1	616.0	821.3
Elbow Extension	281.5	379.5	491.3
Shoulder Flexion	517.9	743.7	1001.3
Shoulder Extension	521.0	738.2	986.1
Hip Flexion	1029.1	1358.6	1734.4
Hip Extension	1652.7	2988.7	4512.8
Knee Flexion	354.9	455.7	570.7
Knee Extension	1019.6	1614.3	2292.8
Plantar Flexion	1118.5	1969.8	2941.0

Table V Female Torque Capabilities (From a survey of 100 industrial workers at the Western Electric - Kansas City Works. D.B.Chaffin (1971))

Torque (inch-pounds)	Percentile		
	95%	50%	5%
Elbow Flexion	134.4	251.9	386.1
Elbow Extension	85.9	132.3	185.3
Shoulder Flexion	156.0	256.6	390.6
Shoulder Extension	156.8	261.9	381.8
Hip Flexion	274.2	417.9	581.8
Hip Extension	433.7	918.1	1470.7
Knee Flexion	108.5	195.8	295.4
Knee Extension	300.9	704.6	1165.2
Plantar Flexion	442.3	973.5	1579.6

seconds, and is repeated less frequently than every five minutes (i.e. no accumulated muscle fatigue)

These stringent constraints on the suitability of this data for use in the biomechanical model are necessary if valid predictions of human strength are to be obtained. For this reason the mathematical model for obtaining the values of torque at the joints (described below), does not proceed as far as checking feasibility of a task, by the comparison of torques predicted by the model with known maximum torques. It is left for the designer to make manual comparisons with data known to suit the particular circumstances. The scarcity of such data however would probably lead to Chaffin's data being deemed suitable for most static force exertion.

Mathematical Model for Joint Torque Assessment

It has already been indicated (e.g. fig.7.4.(b)) that the equations of motion of the body segments, while performing dynamic force exertions, can be extremely complex. They are however comparable in every way to the equations governing the motion of mechanical equipment (so long as the assumptions and approximations implicit in the joint and link model are acceptable). It is therefore possible to build a mathematical model, able to quickly and accurately provide the required torques at the joints which represent the dominant muscle forces.

Such a model has been built by Plagenhoef (1966), and forms the basis of the model used within the SAMMIE system. The model is capable of analysing static or dynamic situations, and provides information on the velocities and accelerations of body segments, and also the forces and torques at joints.

Such a model were it to be considering the relative motion of five body segments, would involve the analysis of 38 inertial forces, but this level of complexity is reduced in the current model by limiting the analysis to three moving segments only. This constraint, although desireable for practical purposes, is thought to be compatible with the likely requirements, allowing as it does, the consideration of movements involving the upper and lower arm and the spine, or alternatively movements by the foot, lower leg and thigh.

The free-body diagrams for a three segment motion can be found in Plagenhoef (1971) and are similar to those for two segment motion (fig.7.4.). The relevant equations of motion are included in appendix V.

Plagenhoef identifies seven essential steps for the analysis of joint torques.

(i) determine the length of each body segment

(ii) determine the weight of each body segment

(iii) photograph the desired motion

(iv) make a composite tracing of the total movement

(v) locate the centre of gravity and radius of gyration of each segment

(vi) determine the instantaneous angular velocities and accelerations of each segment, the desired number of times during the whole movement.

(vii) determine the joint forces and moments of force.

The anthropometric and biomechanical model described to date, if the assumptions and approximations it contains are acceptable, is suited to the provision of a major part of this information. The lengths and weights of the body segments are already contained in the model as part of the data base. The need to photograph a movement is removed, as the movement can be simulated by the postural algorithm, or alternatively the man model can be manipulated into any of the required instantaneous postures. There is also no need to trace the movement as all the relevant parameters can be accumulated within the computer. The centres of gravity of the body segments and the moments of inertia (taken from Clauser et al. (1969) and Dempster 1955 respectively, see appendix III) have been made available as stored data. With this information, Plagenhoef's adapted model allows the determination of the joint forces and joint moments of force and also the segment velocities and accelerations required for intermediate calculation.

The combined Plagenhoef and SAMMIE model is lacking in data in one area only. The current SAMMIE model has no time base, and it is a requirement of the Plagenhoef model (if used in dynamic mode) that the instantaneous body postures, which together constitute a description of the movement, should be taken at equal time intervals. Currently the man model assesses postures at equal distance increments, so that a movement of 500 mm might involve five 'frames' being displayed at 100 mm intervals. This is only consistent with motions performed with uniform velocity, which is a comparatively rare situation in body movements, as it is more normal for movements to go through the acceleration-constant velocity-deceleration stages. Future developments will enable the modelling of trajectories by time as well as displacement, but currently the torque model can only be used in static situations unless the posture information is obtained from sources other than the postural algorithm.

Useful information concerning the time-dependency of motions, can be found in Bailey and Presgrave (1958), or relationships of the kind shown below might be of use.

Time-displacement relationship due to Slote and Stone (1963)

$$D_t = \frac{Dmax}{2} \quad \frac{2\ t}{T} \quad - \quad \sin(\frac{2\ t}{T})$$

where D_t = Displacement in direction of motion at time t

D_{max} = maximum displacement

T = total time

t = time

Further detailed description of the torque model is not considered appropriate here, as the many publications of Plagenhoef (1966, 1968a, 1968b, 1971), provide an extensive explanation of all aspects of the model. It is clear however that the model which has primarily been used by Plagenhoef to analyse sporting activities, also has great potential in the industrial context, where there is a need to predict the likely strength requirements and fatigue involved in manual tasks. The absorbtion of the model into the SAMMIE system brings this goal nearer to fulfilment.

Centre of Gravity and Balance Assessment

Interest in the location of the centres of gravity of the body segments has recently been revived with the need to study the dynamics of the human body in various situations. Hence Hanavan (1964) studied the inertial properties of the body in weightless conditions when considering the design of a Self-Manoeuvring Unit for manned space travel (appendix I). Deprived of the use of gravity and friction forces, the human being is not well adapted for locomotion unless a directed external force is supplied. Analysis of the required direction and magnitude of that force requires a knowledge of the inertial properties of the body in any posture, which leads directly to a requirement for information concerning the centres of gravity of all of the moveable segments of the body.

Again the increased sophistication in prosthetic devices requires a greater knowledge of the segment parameters. Modern devices are far removed from the 'wooden leg' concept, where the main function was either simply to support the body or to provide some cosmetic treatment for a missing limb. Attempts are now made to substitute devices which are capable of reproducing many of the other functions of the limbs in walking, applying forces and in manipulating tools (pens, cutlery etc). This usually requires that hitherto unused muscles are used to control an independant power source which operates the prosthetic device.

These two rather specialised uses of information regarding the body segment centres of gravity and other dynamic factors, are outside the present research activities of the SAMMIE system, but a third use is found in the assessment of balance resultant on particular postures.

Many social and industrial situations can be found where balance of the body, perhaps while carrying a load, is of importance in the work task or workplace design problem. Industrially, quite considerable loads have to be lifted and positioned, when for example bulky parts are taken from a store and placed onto a machine. It is quite possible that a combination of the anthropometry of the operator and spatial layout of the machinery may make this a dangerous if not infeasible task, simply because it is not possible to maintain adequate balance.

Study of the body segment parameters (weight, volume, centre of gravity and moments of inertia) have taken three distinct forms. A considerable amount of effort has involved the dissection of cadavers with subsequent measurement of the relevant parameters. This method has been employed notably by Braune and Fischer (1887), Fischer (1906), Dempster (1955), (re-analysed by Barter et al 1957), and Clauser, McConville and Young (1969), but is susceptible to the usual sources of error when cadavers are studied. (e.g. many cadavers will be considerably older than a normal population, will often be diseased, and some changes after death will almost certainly have occurred.)

The other main alternative of measuring the living has been adopted by Harless (1860), Bernstein (1931), Basler (1931), Cureton (1943) and Cleveland (1955), enabling much larger samples of a more representative nature to be analysed, but the practical problems involved can cast some doubt on the accuracy of such work. The techniques used are either hydrostatic weighing or the use of a Borelli platform to measure reaction change, but both are liable to errors due to incorrect or inconsistent positioning of the subject.

Finally mathematical models have been used by Whitsett (1962), Hanavan (1964) and McHenry and Naab (1966), where the irregular shapes of the human body segments are represented by geometric solids of uniform density. A fuller description of Hanavan's model and its limitations is given in appendix I.

The foregoing description of the experimental work has been rather brief, but a more detailed survey of the methods and data can be found in Clauser, McConville and Young (1969).

Of the work mentioned above, the cadaver dissection of Clauser et al (1969), with its careful selection of subjects according to age at death, overall physical appearance, evidence of disease or accident before death, body weight and stature, appears to be the most suitable of the recent studies, and this has been used as a basis for the SAMMIE model.

Appendix III(e) shows the ratio of segment weight to body weight, and the centre of mass to segment length ratio respectively (reproduced from Clauser et al (1969)). The results from earlier studies are included for comparison purposes only, the data of Clauser et al being used exclusively. The information included in these two tables plus the data supplied by the anthropometric model on the segment lengths and the body posture, when combined with a knowledge of the total body weight, are sufficient to locate the overall centre of gravity of the model. This is achieved by assuming the whole weight of a segment to act at the segment centre of gravity, with simple moment equations enabling the overall centre of gravity to be located in any or all of the three orthogonal planes of the body (saggital, transverse and coronal).

Currently, location of the overall centre of gravity (and its display on the graphics screen), is the end point of the analysis. No attempt has been made to assess whether a particular location implies that imbalance has occurred, as this is left for the designer to decide. A free-standing position would allow computer analysis of balance, as it could be assumed that the weight of the body has to act downwards through the feet for proper balance. However the most commonly met situations involve reaction forces at points other than the feet. Hence part of the body weight will often be supported by the arms (e.g. climbing a ladder), or the subject will be seated, making a balance analysis unnecessarily complicated when it can be more easily assessed visually from the screen.

One particular exception to this exclusion of external (reaction) forces is that it is possible to apply vertical loads to one or both of the hands, so that a very simple load carrying operation can be simulated. Such loads are considered to be acting at the centre of gravity of the hand segment, and this can be very simply included in the moment equations.

The modelling of the centre of gravity is thus a useful, if limited, addition to the biomechanical model which facilitates the assessment of balance when carrying loads in an unconstrained posture, but it plays no part in the limb positioning algorithm.

The biomechanical model described in the last three chapters simulates the important biomechanical features of the body, through the kinematic representation of movement, and the assessment of joint torques and balance, while fatigue and 'comfort' have been introduced indirectly. Hence the biomechanical features most likely to be useful for workplace and work task design are contained within the model, although other possibly useful criteria (e.g. energy expenditure) have been left for future development.

been left for future development.

CHAPTER EIGHT

VALIDATION

Validation of the anthropometric and biomechanical model is required at two levels i.e.

(i) as part of a design tool

(ii) as a representation of certain physical aspects of human beings.

The first of these requirements sets the context for the second, as the man model is seen as an evaluative design tool, which has very little intrinsic value, outside of its use in a design system.

(i) Validation as a Design Tool

The complete SAMMIE system, including the workplace model, man model, and work task language is intended to assist the process of ergonomic design. The value of such a system is therefore dependant on the quality of resultant designs, and the economics relative to other methods. Hence SAMMIE is likely to be useful where

(a) cost savings in the design or operation of equipment can be made.

Cheaper design costs are likely to occur when the frequent design or re-design of equipment is undertaken. One such situation exists in the design of jigs and fixtures for the car industry, where several dozen slightly different designs might be in use. Small savings in unit cost of finished articles can give rise to considerable aggregate savings where mass production is concerned. Hence even if the cost of using SAMMIE is high, this can be met by spreading over a large volume of articles. Again where the initial cost of design is high or where design mistakes can be expensive, the use of computer techniques might be justified,

(b) the human operator is the limiting factor in successful operation of the equipment.

In many situations human factors take precedence over economics, and this well particularly be noticeable in military of safety contexts. Hence SAMMIE is relevant to the design of equipment such as aircraft cockpits where there are complex inter-relationships between the operator and his equipment and where deficiency in the design can have disastrous consequences.

Unfortunately it is difficult to ascertain whether or not SAMMIE meets these two criteria of cost and design quality, because at this development stage of the project, it has been impossible to tackle the complex problems which are typically found in industry. Added to this is the difficulty in assessing design costs and the set up and running costs of equipment designed either by SAMMIE or manual methods.

An even more taxing problem is the evaluation of the quality of designs. Even if subjective opinion can be removed, there is no way of inter-relating those objective measures of effectiveness which do exist. Thus a manual design might satisfy production criteria in a better way than the SAMMIE system, whereas the reverse might be true for anthropometric considerations. However the relative importance of anthropometricsand productivity can only be established subjectively and hence an overall objective assessment of the design is not obtainable.

For these reasons the usefulness of the system can only be assessed in a subjective manner. Hence the considerable upsurge of interest in the SAMMIE type of modelling approach can be taken to indicate that industry sees that the demand for new methods of ergonomic design could be satisfied in this way. At present, the unproven economics has resulted in most interest being found where the ergonomic quality of the design is the important criteria. Hence the other work in this field, described in appendix I is found to be concerned with military aircraft cockpit design (BOEMAN), weightlessness in space travel (Hanavan), prevention of industrial injuries (Chaffin), car-crash simulation (Cinci Kid) and only Kilpatrick's MTM Man is primarily concerned with the reduction of costs. (It attempts to improve industrial methods and times by the use of MTM analysis).

Interest in the SAMMIE system has been shown in the design of hospital bed areas, fork lift trucks, military equipment, welding equipment for car production, car seat design, layout of dental surgeries, and steel mill pulpits. Once again in all these areas it is the safety or efficiency of operation which is of interest, rather than the reduction of costs by cheaper initial design, more efficient operation or improved methods.

In conclusion then, the economic validity of the modelling approach is unproven, but a requirement for the inclusion of ergonomic factors in design appears to exist. The attempts of other researchers in the field, and the interest shown by potential users of SAMMIE, although mainly subjective in nature, indicates that the approach might well be valid from the aspect of the ergonomic quality of design.

(ii) Validation of Man Model

At the second level of validation, it is necessary to show that the anthropometric and biomechanical features of the model correspond closely to the same human attributes. However the use of the model must be borne in mind, as the accuracy required of this correspondence is determined by the nature of the design problem encountered (see Table II). Hence for example the description of joints, muscles and the skeletal frame needed for a model used to investigate medical problems, would require much greater accuracy than that contained in the current model.

Subjective assessments indicate that many essential human attributes can be communicated to the designer via the display on the graphics terminal. Hence the symbolic representation of three-dimensional flesh is sufficient to convey the impression of a human model, while the movement of limbs and the postures adopted appears reasonable. However for the purpose of more objective evaluation of the model, four areas can be identified for which some kind of validation is required.

i.e. (a) segment parameters (limb lengths, weights, centres of gravity, moments of inertia)

(b) joint model

(c) joint torque model

(d) postural algorithm

(a) Segment Parameters.

The segment parameters are all introduced to the model as input data, and therefore their validity is entirely dependant on the data source. As the model provides no data of its own, but merely manipulates data with which it has been provided, it is the user that has to ensure that the data is reliable and correct for the particular application. A great deal has already been said in earlier chapters about the inadequacies of anthropometric and biomechanical data, and the necessity to clearly identify the user population being considered. Having regard for this problem, the sources of data which are considered to be the most reliable have been mentioned, and have been used for illustrative purposes in the development of the model. However the relevance of the data available needs to be thought satisfactory or otherwise data will have to be supplied by the user.

The link model into which limb length data is entered, makes several assumptions concerning the skeletal frame of the human body. These assumptions have been described earlier in chapter 4, but no evidence has so far been produced which shows that the link lengths are compatible with the body dimensions which they represent.

Dempster (1964), the originator of the concept of links to represent the major dimensions of the human body, has, in recognition of this problem, investigated the correlation between the dimensions of the bones of the arms and legs, and their respective links. His re-analysis of the work of Trotter and Gleser (1952,1958), provided the regression equations contained in appendix III. The work of Trotter and Gleser is particularly notable as they 'were able to correlate measurements of stature made on military personnel, <u>during life</u> with measurements on dried skeletal bones of the <u>same</u> individuals <u>after death</u>'. Dempster (1955,1964) gives sufficient detail of this work, and similar investigations of his own, to indicate that the link system concept is valid, when used to represent certain anthropometric and biomechanical functions, and also that anthropometric data concerning external body dimensions combined with regression equations, can be used to accurately define the link system. It should of course be noted that these studies were concerned with young white and Negro American military personnel, and therefore the regression equations are likely to be suitable only for similar populations. However the likelihood is that the equations would be suitable approximations for most populations consisting of western races. Whether or not the regression equations can be related to other populations, they do show that in general internal link lengths can be accurately derived from external body dimensions.

It should be noted however that this accuracy of representation is only true of measurements concerned with the long dimensions of bones. For functional reach problems this is sufficient, but where the volumetric effects of the human body have to be considered, the model can only give an indication of the situation. Hence the typical cockpit type of problem, where man also has to be able to fit into his workplace (e.g. car, fork lift truck, aircraft cockpit) cannot be considered in its entirety. The 'flesh' surrounding the link structure of the model is currently designed to symbolically represent a person with a 'normal' body shape. Hence no information can be derived concerning the problems which may be encountered by operators whose body shape differs from this norm. However future developments may include both more sophisticated graphical techniques for drawing realistic flesh contours, and variable flesh shape generated from somatotype data. Some preparatory work for the inclusion of somatotype as a parameter of the man model, has been carried out by A.D. Parker under the supervision of the author, so that future versions of the model will be able to represent the degree of ectomorphy, mesomorphy, and endomorphy present in the man model, i.e. the degree of obesity, muscularity and thiness (for a description of somatotyping, see Sheldon (1940)).

(b) Joint Model

Data concerning the range of motion available at joints is supplied by the user, and therefore its validity is once again dependant on the consideration given to the problem by the user. However unlike anthropometric data of which there is an abundant supply, data on range of joint motion is severely limited. For this reason either new data must be collected for a particular application, or use must be made of the most reliable data currently available.

The only satisfactory way out of this dilemma is for data to be collected on user populations before design work commences. However the tediousness of this approach would probably make this impractical unless long term design studies were envisaged. If it is considered to be impractical, then the alternative suggested is that the data of Barter Emmanual and Truett (1959) or Silnelikoff and Grigorwitsh (1931) be used.

Whichever source of data is used, its implementation into the joint model can only be made if certain assumptions can be shown to be valid. These assumptions can be found elsewhere in this thesis, but the essential points are contained in fig. 8.1. Here the model's constraint values for a joint with two degrees of freedom, are compared with experimental data from an early study by Braune and Fischer (1887). It can be seen that the simple form of linear constraint found in the model, approximates very closely with experimental data, except where the joint is close to its maximum range in both directions (the 'rounded-corner' effect). This suggests that the model may permit slight over-extension at a limited number of extreme positions. Joints with three degrees of freedom show a similar close correspondance between the simple linear model constraints and the experimental curves.

Although these experimental results show that the model's linear representation of the joints ranges is satisfactory, it must be remembered that this study of Braune and Fischer was based on the cadaver investigation of a very limited sample, and the numerical values may not be very reliable.

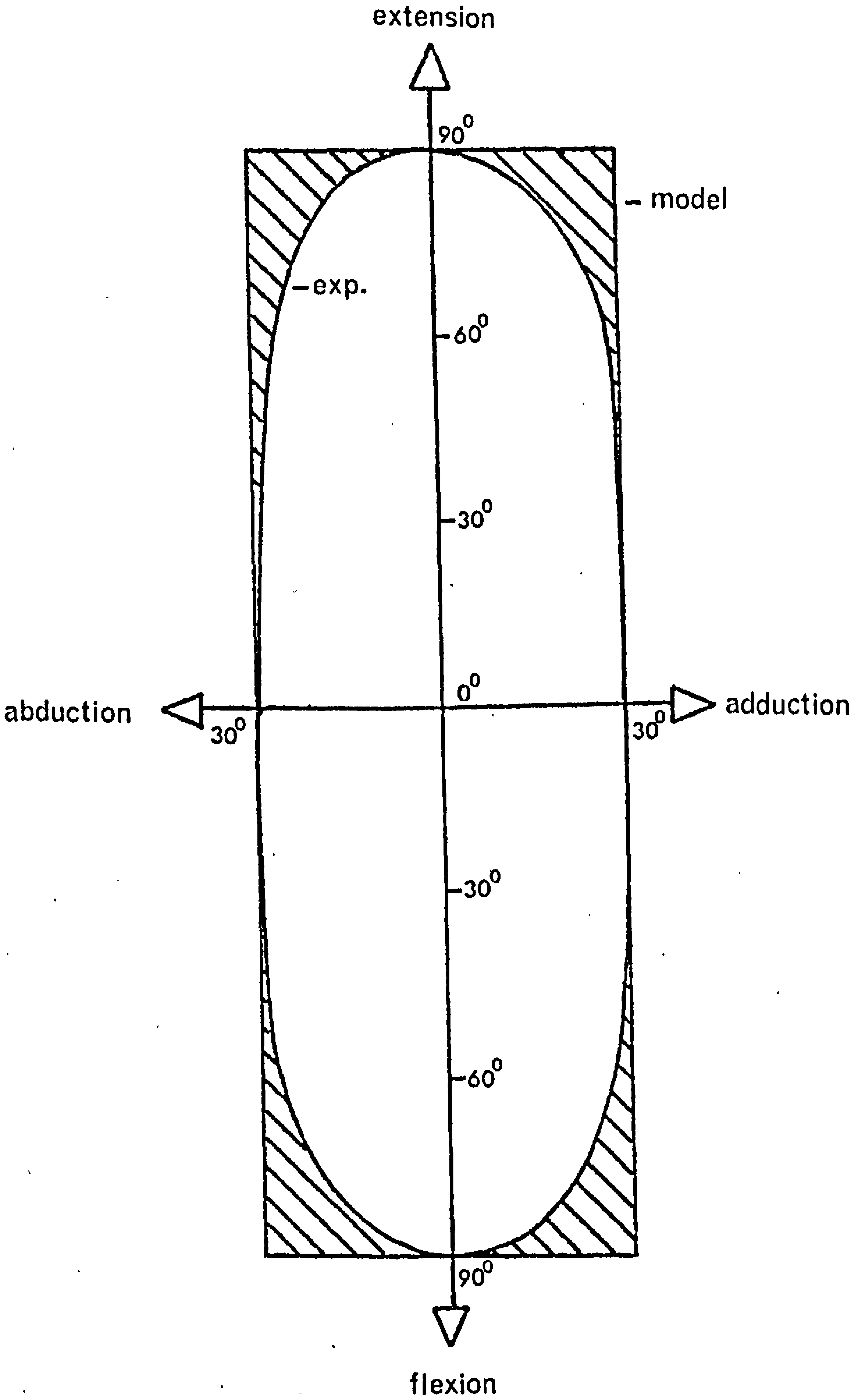


Fig. 8.1. Comparison of Model's Angle Constraints with Experimental Data from Braune and Fischer (1887).

(c) Joint Torque Model.

The evaluation of torques at the joints can be considered to be valid if the assumptions of the link model are valid. Hence acceptance of the link and joint model as a sufficiently good representation of the major features of the human skeletal frame, implies that the equations of motion derived from engineering mechanics can be applied to the model. The close analogy between mechanical systems and the link system implies that joint torques can be found, by well-proven mathematical techniques.

The only area of contention might be in the assumption that these joint torques represent the dominant muscle forces which are useful in predicting the feasibility of a task. Hence the assumption that fatigue and strength capability can be assessed by the comparison of predicted torques with experimentally derived maximum attainable torques, is once again dependent on the quality of data available. The problem lies in the fact that joint torque is dependant on joint posture, so any maximum torque measured at a joint will refer to one specific configuration of the muscles about the joint. This problem has been explained more fully in chapter 7 and in the references (Plagenhoef (1968), MacConaill and Basmajian (1969)).

Evidence that the model's estimates of strength compare with experimental results is however available. Thordsen

Kroemer and Laubach (1972), have investigated the maximum isometric forces that male subjects could exert at six locations of hand operated aircraft controls. The vertical force that can be exerted on the control stick has been chosen for comparison with the SAMMIE model. The experimental situation is shown in fig. 8.2., along with the major results.

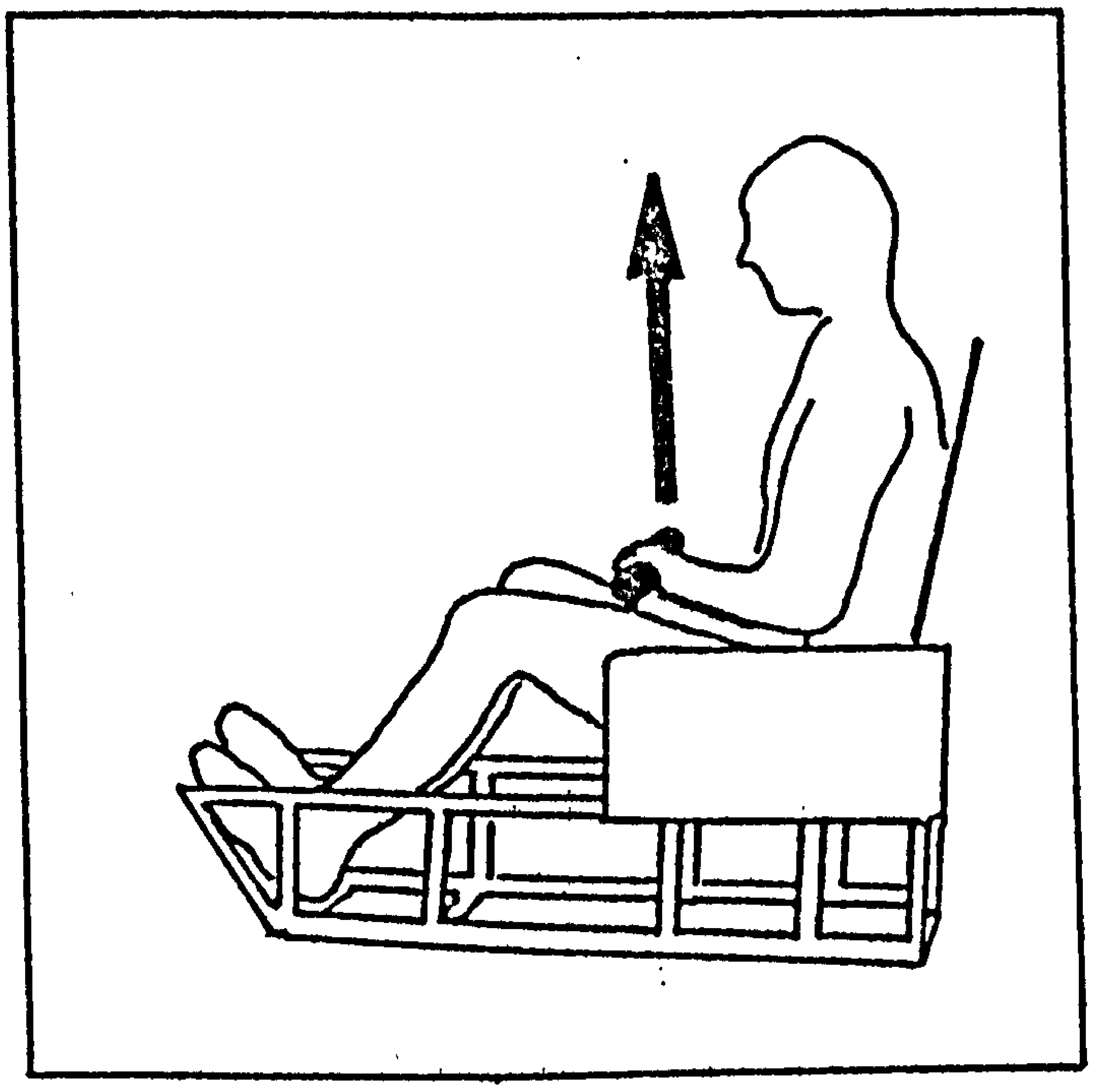


Fig. 8.2. Investigation of the Vertical Force that can be Exerted on a Control Stick. (Thorsden, Kroemer and Laubach 1972).

Reproducing this situation by using the SAMMIE model to represent the anthropometry and posture, and the joint torque model to analyse the torques at the shoulder and elbow joints, reveals that:-

in exerting an upward force of 290.9 Newtons (the 50th percentile maximum force from Thordsen et al.)

(i) the torque at the elbow = 600,000 gm-cm

(ii) the torque at the shoulder = 832,000 gm-cm

Chaffin and Baker (1970) have investigated the maximum voluntary torques available at various joints, for a small sample of 19 males and 5 females, and a summary of their conclusions is shown as table VI. (Later work by Chaffin (1971) with a sample of 100 males and 100 females, has already been mentioned with a summary included in Tables IV and V).

Table VI

max. voluntary torque at test angle	male (gm-cms)	
	mean	std. dev.
elbow (90°)	694000	172,000
shoulder (+30°)	836,000	212,000
hip (90°)	2,930,000	877,000
knee (120°)	1,931,000	586,000
ankle (90°)	1,870,000	446,000

If Chaffin's data is used to predict the maximum possible torque at the elbow and shoulder, it can be seen that agreement with Thordsen's result is as close as 0.02 standard deviations at the shoulder, and 0.55 standard deviations at the elbow.

Further corroboration is supplied by Chaffin and Baker, in their use of a model similar to Plagenhoef's (1966) (on which the SAMMIE joint torque model is based). Their investigation of male and female industrial workers performing lifting tasks, showed that link models using the classic equations of motion were able to accurately predict actual lifting capability. Hence figure 8.3. (reproduced from Chaffin and Baker (1970)) shows the close relationship between experimental force capabilities, and those derived from a predictive model.

Such depth of investigation has not been performed with the SAMMIE model, but the close agreement with Thordsen's experimental data, and the work of Chaffin and Baker using a very comparable model, are sufficient to show the approach to be valid.

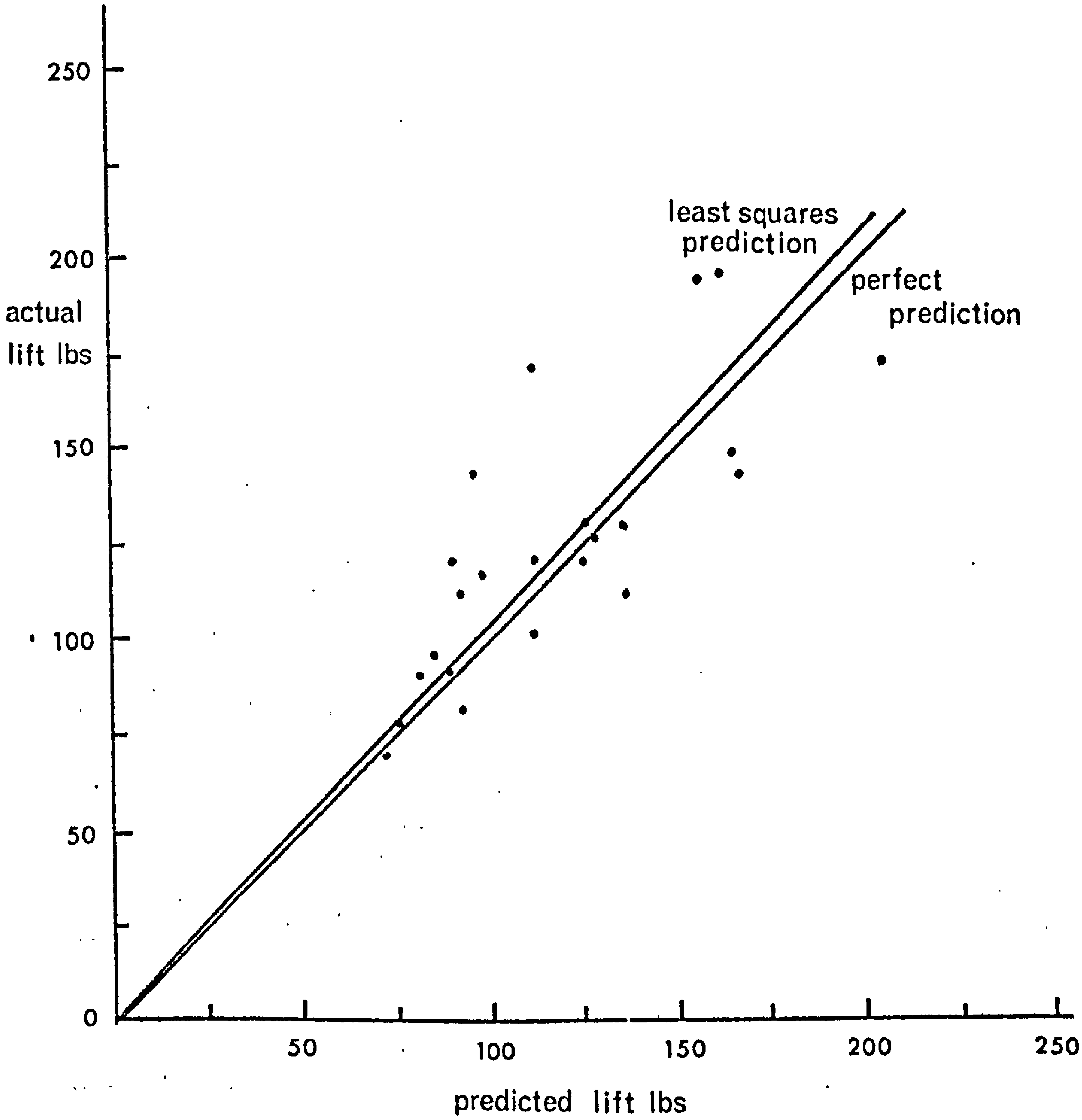


Fig. 8.3. Comparison of Experimentally derived Force Capabilities, and those Predicted by a Mathematical Model. (Chaffin and Baker 1970).

(d) Postural Algorithm

The postural algorithm described in chapter six is intended to derive positions of the link model, which give a reasonable indication of postures that would be assumed when performing tasks. As explained in earlier chapters, the link system of the human body enables hand or foot positions to be reached with an infinite variety of postures. Hence for validation of this aspect of the model, necessarily constrained experimental conditions must be used for comparison purposes. Indeed highly constrained situations are usually the only ones that have been studied in any detail. Thus for example Bullock and Harley (1972), Kennedy (1972), and King, Morrow and Vollmer (1947), have all studied cockpit situations where much of the link system is constrained, so that only the arms (and occasionally shoulders) are permitted to move. Additionally only extreme reach positions are investigated, as here the infinite posture variability problem is avoided. That is to say that at the extreme reach position, there is only one feasible posture that can be adopted.

Hence the attempts to validate the postural algorithm have been restricted to comparison of computer derived 'contours of reach', with those derived experimentally. The more general comparison of postures derived for points within the contour of reach has not been investigated as:-

(i) The postures would be extremely task-dependant, and the model is not sufficiently well developed at this stage for meaningful results to be obtained. Hence the handling characteristics of tools, workplace components and work-pieces for example, have a profound effect on the postures adopted during a work task, whereas the model can only represent unconstrained movement.

(ii) Extreme variability is found in the way in which different people perform the same task, making comparison with the computer model a difficult task.

(iii) The experimental data available is very sparse, and usually related to specific tasks because of (i) above.

The experimental work of King, Morrow and Vollmer (1947) has been selected for the comparison of reach contours, although any other well-documented work would be equally suitable. The full description of their work can be found in the reference, but briefly they investigated the maximum extent of reach in areas to the front of the body, and at eleven different levels. A military population of 139 subjects was used for the survey, and measurements were described in sufficient detail for input into the computer model.

The experimental results at several different heights above the seat reference point are reproduced as figure 8.4., and the equivalent computer derived results are shown as an

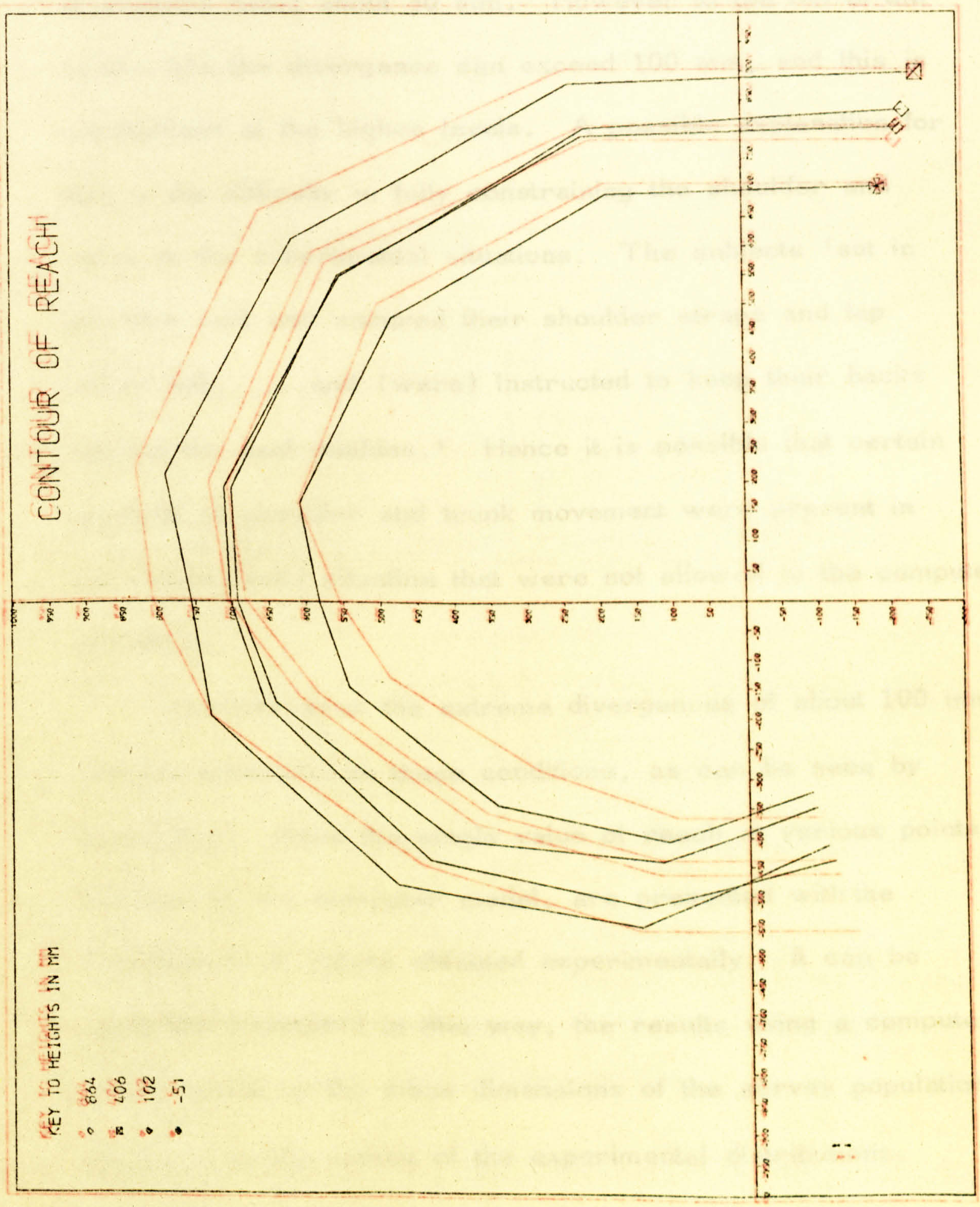


Fig. 8.4. Contours of Reach at Various Heights from the Work of King, Morrow and Vollmer (1947), with the SAMMIE Model Results overlaid.

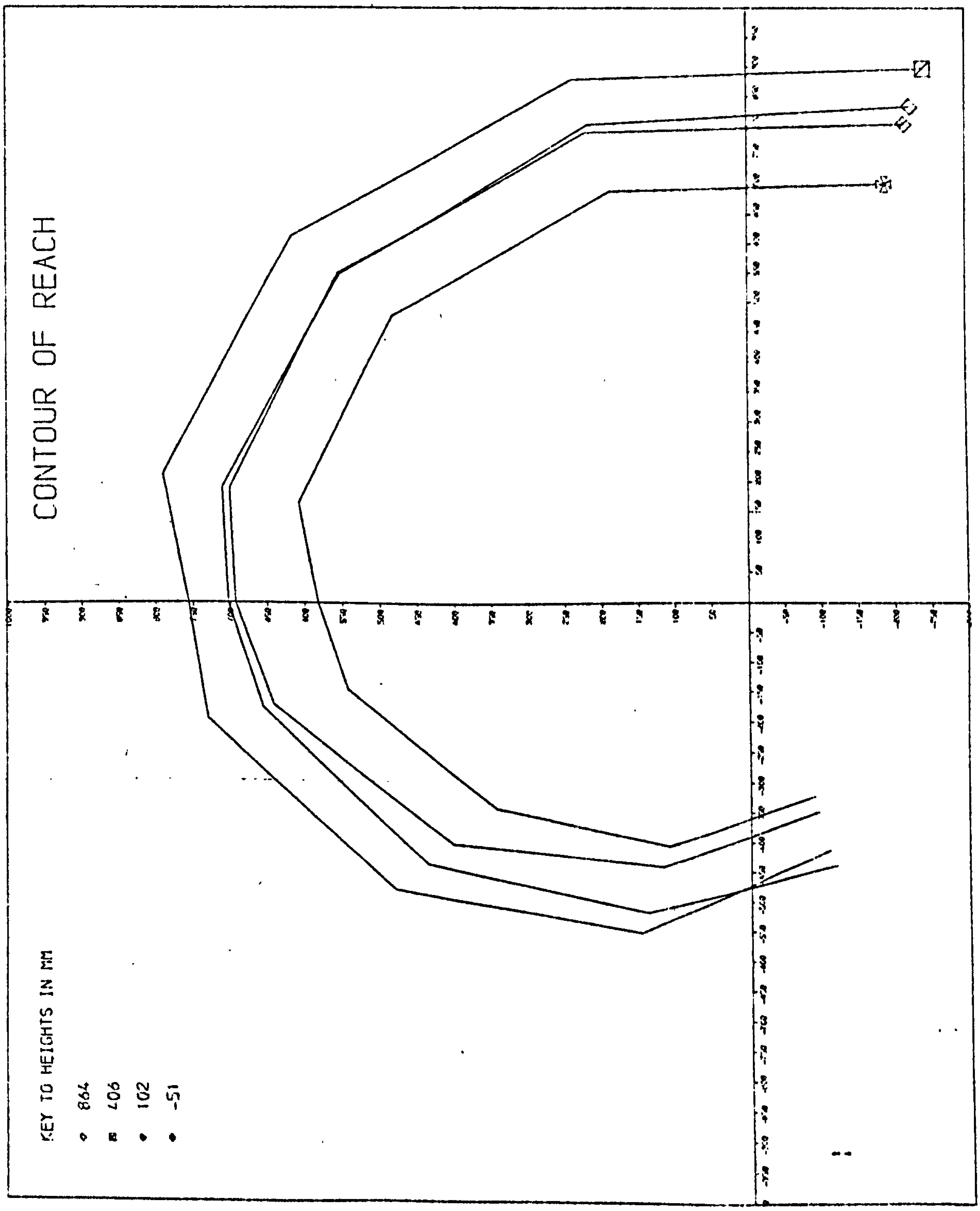


Fig. 8.4. Contours of Reach at Various Heights from the Work of King, Morrow and Vollmer (1947), with the SAMMIE Model Results overlaid.

overlay. The agreement between the two different sets of data varies depending on the region of comparison. Generally the two sets of curves appear to agree extremely well in regions to the right of the body centre-line, the maximum divergence being about 50 mm. However to the left of the centre-line the divergence can exceed 100 mm, and this is emphasised at the higher levels. A possible explanation for this is the difficulty in fully constraining the shoulder and spine in the experimental situations. The subjects 'sat in the pilot seat and secured their shoulder straps and lap safety belt,.....and (were) instructed to keep their backs against the seat cushion.' Hence it is possible that certain amounts of shoulder and trunk movement were present in the experimental situation that were not allowed in the computer evaluation.

However even the extreme divergences of about 100 mm are not excessive in these conditions, as can be seen by figure 8.5. Here the single value of reach at various points obtained by the computer model, are presented with the distributions of values obtained experimentally. It can be seen that presented in this way, the results using a computer model based on the mean dimensions of the survey population fall close to the means of the experimental distributions.

The computer model has thus been shown to give a sufficiently good agreement with the experimental evidence,

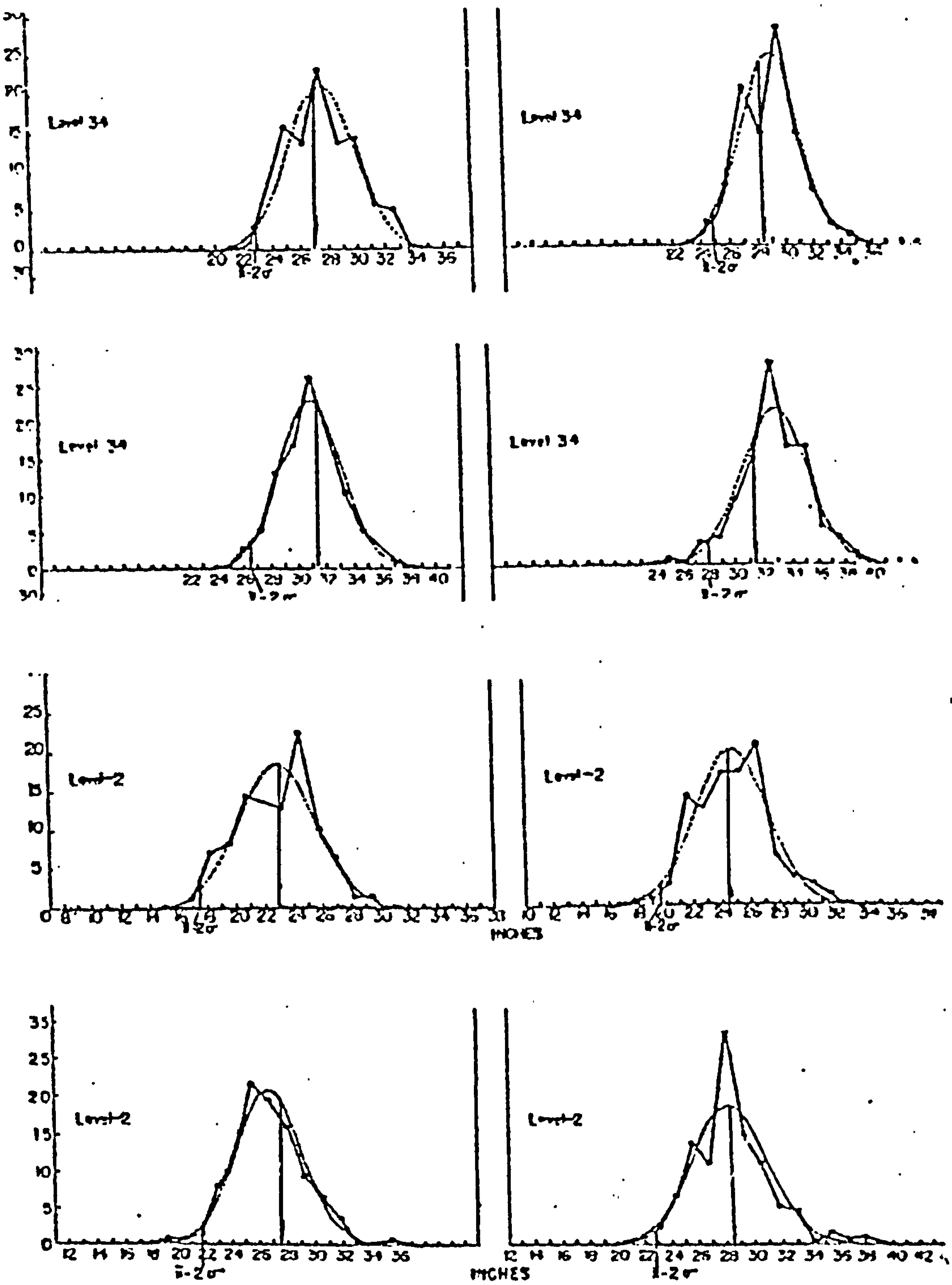


Fig. 8.5. Percentage Frequency Distributions for Arm Reach at 0°, 15°, 45° and 75° with fitted Normal Distribution Curves. (from King, Morrow, and Vollmer 1947), also showing SAMMIE Model Prediction (as a vertical straight line).

to show that the model is capable of dealing with these situations. It must be recognised however that these constrained conditions are unlikely to be met in normal workplace design (except in cockpit design for cars, trucks and aircraft), and thus it is possible that in other situations the postural algorithm will not behave as well.

APPENDIX ONE

PREVIOUS WORK

Previous Work

Kroemer (1973) has surveyed the field of man modelling in recent years and concludes that there are two distinct classes of man model. The category described as 'external biodynamic', are those where the overall passive response of the body to certain external conditions is the prime concern. These are listed and briefly described in Von Gierke (1971). It can be seen that the models are usually developed to study the response of the human body to the application of large external forces which overwhelm the muscle strength of the human body (the 'internal' forces), and therefore the models can be considered as being 'external'. The inertial effects of the various parts of the body assume greater importance as the models are used for example to study the response to 'windblast and airstream following emergency escape', Payne (1970), aircraft and car crashes, McHenry (1971), and other rapid deceleration or acceleration situations. In addition to these external force applications, models of the biodynamic type are also used to study the response of the body and its internal organs to varying levels of vibration and pressure which could lead to injury.

The external biodynamic models are thus concerned primarily with extreme environmental conditions, which although important for the safety of the operator, do not relate to the less critical but nevertheless important conditions which an operator would normally find at an industrial workplace. For this reason biodynamic models of this type are excluded from any further discussion, except that the work of Hanavan and Huston, Hassel, and Passerello is described in a little more detail, to serve as examples of this category of model.

Kroemer's second category, is models of the 'internal' type, where the important features are the anthropometry, kinematics, dynamics and energy capabilities of the body. It is to this category that this author's work belongs, and hence some examples of 'internal' models are described in this appendix.

Within this group, the important differences which should be considered when comparing the various models are:-

(a) Purpose of model.

(b) Design of model.

(c) Mode of implementation.

The objectives of the models vary from the very specific Work Study application of MTM Man (Kilpatrick (1970)), to the more general approach of COMBIMAN (Kroemer (1973)), BOEMAN (Ryan 1971), and SAMMIE (Bonney et al. 1974), where workplace and task design, is studied in the context of human factors.

The design of the model is obviously dependent on its purpose, but the essential differentiating factors are the dimensionality (two or three dimensions), stick model or with flesh representation, static, kinematic or dynamic, and the method of posture prediction.

Ryan (1970) suggests that there are three possible approaches to posture prediction

(i) Stored Data Model.

This is the simplest approach in concept but is virtually impossible in practice. It depends on the collection and storing of an infinite amount of data which covers all feasible or likely movements. It can be useful however to store some such data so that an algorithm can relate this data to specific circumstances (e.g. Evershed's 'natural planes').

(ii) Specific Algorithm Model.

The specific algorithm approach is in common use in man models as it uses explicit mathematical procedures for moving the link system to perform a given task. Here the limbs are moved in prespecified ways which are relevant to the application envisaged.

(iii) The General Algorithm Model.

In this case 'a general mathematical problem-solving technique, as opposed to specific link-system motion algorithm' is used.

The mode of implementation is restricted here to computer applications, thus excluding physical models, but within this constraint, the model may be under interactive control, where the designer 'converses' with the computer, or it may be batch mode where the model is limited to evaluating predetermined situations. In addition the method of representation, can take the form of numerical tabular output, graphical output to a plotter, or presentation on a visual display terminal.

Table VII, adapted from Kroemer (1973) shows how the various models describ ed below fit into these categories.

Table VII Model Characteristics

MODEL	Dimensions	Links	Joints	Volume	Mass	Static	Kinematic	Dynamic	Displacement	Strength	Work	Power	Equipment	Environment	Task
BOEMAN	3	23	22	x	x	x	x	-	x	-	-	-	x	x	x
MTM Man	3	8	7	-	-	x	-	-	x	x	-	-	x	-	-
COMBIMAN*	3	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hanavan's	3	18	13	x	x	x	-	-	x	-	-	-	-	-	-
Chaffins	3	18	17	-	x	x	-	-	-	x	-	-	x	-	-
SAMMIE Prototype	3	13	11	x	-	x	x	-	x	-	-	-	x	x	x

* Largely unimplemented at present.

BOEMAN

BOEMAN is the name given to a man model developed by the Boeing Company under a contract for the Joint Army-Navy Aircraft Instrumentation Research Program (JANAIR), and as implied has been developed to assist in the evaluation of the cockpit design of military aircraft.

Work beganon a projected six phase project in January 1968, each phase being of one year's duration, but an additional seven month phase was introduced in 1970. This additional phase took the form of a period in which to consolidate the previous achievements, and in the light of this to reassess the future program.

In fact this reassessment resulted in the abandonment of the project by Boeing, the work to that date being transferred to the Aerospace Medical Research Laboratories of the USAF (known as COMBIMAN) and to the U.S. Navy. Publications of the BOEMAN group give a good indication of the ambitious nature of the project, and indeed it appears that it might have been the complexity of the proposed final model which led to its eventual abandonment.

The work completed and published by Boeing provided a 'baseline' man-model with three-dimensional flesh contours added. Anthropometry was represented by rigid links forming the 23 major segments of the body, and an algorithm was available for posture prediction. The geometry of the model's workspace (cockpit) could be input to the computer, enabling checks to be made for physical and visual interference.

The parts of the program not yet executed, include facilities to evaluate the effect of joint centre excursion, digit articulation, force capabilities, energy expenditure, and a flexible flesh description with interference analysis. The man model as it stands at the current stage of development, provides a useful insight into the building of an algorithm which simulates to an adequate degree the motion patterns of humans.

BOEMAN uses the General Algorithm approach to posture prediction, although certain elements of the other two approaches are used as well. The trajectory of the leading segment (e.g. hand or foot) is first defined, and then subdivided into motion steps. At each step the body configuration is derived from optimisation of the Euler angle problem. i.e. the final configuration is expressed in the form of Euler angles for each segment, the solution being the result of the minimisation of a non-linear objective function with non-linear constraints. The objective function is the amount of effort required to maintain a body configuration, while the constraints are the required positions of the leading segments, and the joint angles beyond which motion about the joint is impossible. In this way joint angles (Euler angles) are maintained as close as possible to 'preferred angles' while still performing the task.

This General Algorithm approach is the most satisfactory in many ways in that it is intuitively obvious that the body does in fact optimise some objective function while remaining within certain constraints. In the case of BOEMAN, the constraints are predominately physical in that they are the limits of angular movement at the joints, or objects to be avoided etc. This makes then relatively easy to define, although it must be remembered that there may well be intangible constraints such as motivation and intelligence. On the other hand, the objective function to be optimised may well be outside the domain of man modelling and more involved in artificial intelligence. However it may be that this is a necessary extension of the field of man modelling, as once the purely physical aspects of the body have been sufficiently well described, the methods by which these physical parts combine to perform operations in a workspace is the next logical requirement for improved representation of man's movements.

The current level of algorithm building as exemplified by BOEMAN's minimum effort algorithm and its extension in COMBIMAN may then be seen as a first step towards a more 'complete' man model. Unfortunately this ambitious approach in the context of current computer technology has resulted in a model which is impractical as a design tool. The full BOEMAN model is reported as taking three minutes on a very powerful machine to evaluate just one position for the model. As the prime aim of a computer-aided design system is usually to allow the evaluation of a large number of possibilities, with the designer in interactive control of the outcome, this time figure is unacceptable. At the expense of reducing the scope of the algorithm (and hence drawing back from the long term objective of an 'intelligent' model), this evaluation time has been reduced to about nine seconds. However for a satisfactory dialogue between the designer and the computer, almost simultaneous response of less than a second is required.

MTM Man

As its name implies, MTM Man, developed at the University of Michigan by K.E. Kilpatrick (1970), is a man model with the prime aim of assisting workplace design with respect to the methods and times taken for tasks performed. (MTM- Methods-Time Measurements is the name given to a pre-determined motion time system in common use in American and European industry (MTM Association for Standards Research 1964).

MTM is itself suited primarily to industrial tasks where some degree of skill has been attained and also where the work involves repetitive short cycles, with limb rather than body movements predominating. The ideal situation for an MTM analysis is therefore where a skilled operator is performing a well defined repetitive industrial task whilst sitting at a workbench. This is the type of design situation where Kilpatrick states that the 'large volume of designs makes the cost of small inefficiencies potentially costly'. Contrasting with this is for example the small volume production of aircraft cockpit designs which however involve big costs in re-design or in operational failure.

Kilpatrick's model with its high dependance on motion times for its measures of design effectiveness is obviously intended mainly for industrial design, although it shares many of the capabilities of the military models such as BOEMAN and COMBIMAN. The model consists of two parts, a Task Time Prediction Model (TTP) and a Biokinematic Model, the former providing the motion-time information consequent upon a work sequence executed by the Biokinematic Model. The TTP model will not be described here, a full description being available in 'A model for the Design of Manual Work Stations'. K.E. Kilpatrick (1970).

The Biokinematic or Man Model consists of twelve rigid links and eleven joints representing the upper half of a seated operator. This stick man or a model with flesh contours added can be viewed simultaneously in front or side elevation along with a description of the task being performed. The output medium can either be a graph plotter or a storage tube type of graphics terminal.

Once again the interesting feature of this model is the manner in which the joint centres are located for various hand positions. Kilpatrick states that one objective is to produce an 'economical interactive workplace design evaluation tool', using 'simple heuristics to locate joint centres' rather than 'time consuming iterative procedures'. To this end the mathematical minimisation approach of Boeing was rejected, and simpler Joint Excursion Envelopes developed. For each joint a geometric shape (e.g. an elliptical cone for the wrist)was generated which represented the maximum 'normal' extent of available movement. Heuristic rules based on regression equations relating to experimental human body configurations, enable the body segments to assume positions which are within the feasible limits of the excursion envelopes.

Orthogonal photogrammetry techniques were used to collect data and to validate the model, and although a very small sample was used, the results indicate that the model is able to represent body configurations to a degree of accuracy which is acceptable for most industrial design situations.

The major limitations of the model are a result of its own limited objectives. Hence it is restricted to a seated operator. This may be sufficient for a large class of industrial design problems, but would preclude a perhaps larger class where body movement is involved, resulting in greater interaction between man and his environment. The choice of MTM times as the major measure of design effectiveness covers a need in industry where this is a common method of assessing the work content of a task. However this is only one criterion of many, and although the biokinetic model also considers some aspects of static anthropometry, it is otherwise somewhat lacking in evaluative procedures.

However the important objective of designing a simple model so that it can be used interactively appears to have been met very well. Although it is not made clear how the task description is related to required hand positions, once such information is available to the computer, it is able to evaluate different body configurations at the rate of about one every two seconds. This compares very favourably with the much greater time taken by BOEMAN, even though less powerful equipment was used.

COMBIMAN

COMBIMAN, (Kroemer (1973)), is a potentially far-reaching proposal by the USAF to develope a man model to be used in cockpit design. Currently only the software obtained from the BOEMAN project is available, but if the other proposals are implemented the ultimate result could be a model which would be very useful in many workplace design problems.

Kroemer identifies the model as having three parts:-

(i) a reservoir of body form information (Anthropometric Analog)

(ii) a representation of body mechanics (Biomechanical Analog)

(iii) an ergonomic model of man at his work station (Ergonomic Analog)

The first of these the 'anthropometric analog' is at present the most developed of the three parts. The reservoir of anthropometric data enables standard anthropometric data of nude subjects to be compiled, stores data on subjects wearing special equipment in common working positions, and calculates changes in anthropometric descriptors produced by variations in posture, garments, equipment, task requirement or g-environments. Fast access to this data is provided for any specified population or sub-sample, the data being displayed on a CRT, or in the form of computer print-outs, drawings or tables.

The 'biomechanical analog' is at present at the stage of planning, but some interesting thoughts on the method of approach have been accumulated. In common with most other investigators in this field, the need is recognised to model the link system, to incorporate data on the range of movement at the joints, and reach capabilities, and also to consider the segment weights. The major advance that COMBIMAN hopes to achieve is the combination of these factors, and information on the active dynamics (i.e. muscle force, torque, energy and power capabilities) into an objective or 'driving' function. Ultimately it is hoped to produce an internally driven model such that the trajectories of, for example the arm, are derived by the model using algorithms based on the dynamic capabilities of man. To achieve this it is proposed that the model should initially be built with external driving functions, such as prespecified hand trajectories, allowing the model to derive the internal effects of this trajectory on the body dynamics. Comparison with experimental data would then indicate the feasibility of such a movement. At a later stage of model development, this 'external-internal' model could be reversed into an 'internal-external' model, so that body dynamics become the driving function.

The final part of COMBIMAN, the 'ergonomic analog' is designed to simulate man at his work-station. It is proposed that the equipment is modelled using two-dimensional panels and three-dimensional blocks which could be varied in size and location. These could be defined as rigid, deformable, solid or penetrable, and any number of workplaces or items of equipment could be so described. A more difficult problem is seen to be the description and execution of a work-task at that workplace. To simulate how a task might be carried out implies a knowledge of the driving function for the 'biomechanical analog'. Hence a reach motion might be driven for example by a minimum energy function, or by a maximum comfort function. In general however the likelyhood is that it will be an amalgam of many such functions. Furthermore this optimisation may have to be carried out over a whole series of movements, and not for each individual reach. To overcome this problem COMBIMAN proposes to use simple heuristic rules, allowing for the addition of more complex performance criteria in the future as more experimental data becomes available.

COMBIMAN then is planned as a far reaching development encompassing most other attempts in the field of man modelling. Its extension into the area of an internally driven model, will be its contribution to the science, as at present other man models have avoided this aspect as far as possible. The desireability of such an extension is self-evident, as it will enable designers to have at hand a tool which could quickly and accurately indicate future usage of his design. The practical difficulties to overcome before such a state is reached however may prove to be extremely arduous. The collection of the necessary data on dynamic movements of man may itself prove to be a very long process, while the relating of this data to human capabilities in the form of algorithms will at best only result in approximate solutions, which consider only the major elements of the driving function. More fundamental perhaps is the implicit assumption that the human being is in some way predictable. It is true that in the limited sense of performing a well defined work-task, certain end points of movement can be precisely defined. However the many various intermediate postures may depend not only, or even primarily, on some optimum function of the dynamics of the human body, but may be concerned more with external conditions. This implies the necessity to model the human brain as well as the human body, thus imparting some artificial intelligence to the model. In this way it could for example move to avoid obstacles, dangerous situations and otherwise undesireable body motion paths, could operate so as to maintain good vision, could model different motivation levels and so on, ultimately resulting in a complete human behavioural model.

This approach may well be possible and desireable in the future, but at present appears to be a rather ambitious task. It should be added that this problem is recognised by the developers of COMBIMAN, and their phasing of the work ensures that this ideal and complete model is approached via simpler models using heuristic rules.

E.P. Hanavan's 'personalised model'

This model developed by the United States Air Force, is an early attempt at modelling the inertial properties of the human body, to facilitate the design of a Self-Maneuvering Unit for manned space flight. To meet this objective it was considered necessary to have a knowledge of the following:-

(a) the location of the centre of mass of the body.

(b) the moments of inertia and the products of inertia about axes through the centre of mass.

(c) the principal moments of inertia about the principal axes through the centre of mass.

(d) the orientation of the principal axes.

A torque about a principal axis will produce rotation only about that axis, while a torque about any other axis will produce rotation about more than one axis. In the context of a Self-Maneuvering Unit working in reduced g-conditions, rotation about axes other than the principal axes is wasteful on fuel and makes the maintenance of a stable body attitude more difficult. The location of the principal axes of the human body is then the major task to which the model directs itself. Secondary considerations essential to this primary aim, were the distribution of mass and the anthropometric data of the individual person.

Hence Hanavan constructed a mathematical model which represented a human being by a set of rigid bodies of simple geometric shape and uniform density. The mass of each segment was derived from the regression equations presented by Barter (1967). Each limb was allowed to rotate about fixed pivot joints, enabling the body to change position.

The geometric shape usually chosen to represent a limb is a frustrum of a cone, or a right elliptical cylinder, the hands and head being the only exceptions. The dimensions of each of these shapes were defined with reference to anthropometric data derived by Santschi et al. (1963) and Hansen and Cornog (1958), although in actual use the model would require data for specific astronauts or for a limited population. With the constricted mobility caused by full pressure suits, the need for movement of the head and torso was not envisaged so that only the limbs are allowed to change position.

For each body segment, the simple geometric shape and the uniform density allows the centre of gravity and the moments of inertia of each individual segment to be calculated from the straightforward equations of dynamics. The relative orientation of the segments is specified by the use of two Euler angles for each moveable limb. The third Euler angle is unnecessary as all the limbs are represented by solids of revolution, and are thus symetrical about their long axes. The Euler angles are used to relate the inertial properties of each segment to the body axes located at the centre of mass of the whole body. Hence the required principal moments of inertia about the principal axes and the orientation of those axes can be derived from the standard methods of dynamics.

The model was compared with the experimental data of Santschi for a range of body configurations, and the predicted centre of gravity found to be within 18 mm, and the moment of inertia within 10%, of the experimental results.

Although this study appears to give good comparison with a set of experimental data, it is limited in its application for several reasons.

(a) It is essentially a static model, whereas the interesting and difficult problems in this field are dynamic, i.e. when the body is changing position while having the force of the Self-Maneuvering Unit applied to it.

(b) Only the limbs are allowed to change position, the head and torso must always remain stationary. The head and torso combined comprise almost 60% of the body's total mass (Clauser, McConville and Young (1969)), and hence any movement of these, even if only slight because of the constraining action of the pressure suit, would lead to significant changes in the inertial properties.

(c) The mathematical model itself needs some improvement to represent the human body in a more general form. The assumption that all the segments are symetrical solids of revolution, and the resulting insignificance of the third Euler angle, may be an adequate approximation for the static positions investigated in the study, but for any further development this would need improvement. It seems somewhat unnecessary to use the geometrical representation with its consequent limitations, as it is only needed to derive centres of gravity and moments of inertia, which can quite adequately be obtained from various experimental data sources (e.g. the cadaver dissection work of Dempster (1955) and the later work of Drillis and Contini (1966).

Some of these limitations have been tackled by a group at the University of Cincinatti, where Hanavan's model has been extended. Known as UCIN the model is described below.

UCIN

UCIN is a 'three-dimensional, restrained human body dynamics model' developed at the University of Cincinnati by Huston, Hessel, and Passerello (1974). The model uses an extended version of Hanavan's model (described above), which in addition to the considerations of force effects on the limbs, also includes the head and torso, resulting in a model with 31 degrees of freedom. The main areas of development have been in the mathematical implementation of the dynamics analysis, and in the production of a user-orientated computer package.

The model's environment (typically a car interior or an aircraft cockpit), is modelled only to the extent that it is assigned a reference set of axes, the motion of which in its six degrees of freedom, is usually known. The body segments are related to a reference set of axes in the lower torso. The objective of the model is then to be able to analyse the reaction of individual body segments to motion imparted by movement in one of the six degrees of freedom of the environment reference axes. This is an important addition to Hanavan's model which was only capable of assessing the effects of external forces on specific body configurations and not the dynamic effects of individual body segments.

To achieve this, Hanavan's representation of the body (in an extended form) is used in conjunction with a dynamical analysis based upon Lagrange's form of d'Alembert's Principle. This approach is necessary because of the complex nature of a system with 31 degrees of freedom. The traditional approach using Newton's Laws or Lagrange's Equations involve the calculation of a great deal of redundant information. A detailed description of the method can be found in Huston et al. (1974) where reference is also made to standard dynamics texts.

In the context of providing a useable tool for studying the dynamic effects of forces applied to the human body, the UCIN package is designed to provide graphical output which completely describes the motion of the segments of the body. Hence a head-on car crash can be simulated with the occupant either restrained or unrestrained by seat belts. Given the deceleration of the vehicle, it is possible for example to plot curves showing acceleration, displacement and rotation of the head in three dimensions. This could be used to study the effect of whiplash and the provision of seat belts.

Hanavan's model and the UCIN extension, are examples of a whole series of models of the 'external' type which study the effects of external forces on the whole body. These models are very often dynamic, and are usually directed at a specific problem, weightlessness and car crash simulation being the most common uses. The significance of these models to the building of an internal dynamic model is that they provide a framework within which the important muscle forces and speed of voluntary motion can be considered.

Chaffin's Biomechanical model

The biomechanical model developed at the University of Michigan by D.B. Chaffin (1969) is primarily concerned with assessing whether a task is within an operator's physical capabilities. A gradual degradation of performance over time (fatigue) is not considered but rather the situation where 'a load is applied for less than four seconds and repeated less frequently than every five minutes (i.e. no accumulated muscle fatigue)'.

Currently the model, based on similar work by Plagenhoef (1968), consists of seven rigid links in the saggital plane. The type of force applications considered are thus limited to symmetrical two-handed situations such as lifting, pushing and pulling in the saggital plane. Furthermore only static forces are analysised, so the force application must not result in movement, (or very slow movement where acceleration effects become negligible are acceptible as an approximation.) The aim of Chaffin's work has been to compute torques at six of the major articulations of the body, (wrist, shoulder, hip, knee, elbow and ankle), so that they can be compared with experimentally derived maximum values, to assess whether a task is within an operator's abilities.

In addition an assessment of spinal stress is included, as it is believed that this is an important contributor to the problem of low-back injury. The spine is represented by 18 links after Fisher (1967) using the dimensions of Fick (1904) and Lanier (1939), the curvature being derived from the data of Dempster (1955). Intra-abdominal pressure contributes to relieving compression on the lumbar spine (Morris, Lucas and Bresler (1961)), and the details of the way in which this was utilised can be found in the various works of Chaffin (1969a, 1969b, 1970).

The experimental technique involved subjects in applying maximum voluntary articulation torques at the various joints, by applying push or pull forces against load cells. In this way maximum torque limits were obtained at various joint angles for:-

(i) elbow flexion and extension

(ii) shoulder flexion and extension

(iii) hip extension

(iv) knee extension

(v) ankle plantar flexion

Using the model to predict the maximum lifting ability of a small sample provided some interesting results. Firstly it displayed graphically the effects of limb dimensions on the ability to perform a lift. Differences in limb dimensions require the adoption of different body configurations, and hence as muscle strength is a function of the geometrical manner in which the muscle acts, lifting ability will be effected. Secondly it showed that the limit of lifting ability may be partially attributed to the subjects' sensing of imminent back injury, rather than any exceeding of the individual muscle strengths. This is illustrated by the fact that knee extension torque ranged from 75% to 95% of its maximum, while hip extension torque reached only 18% to 75% of its maximum.

The model has enabled the identification of values of spinal compressive forces, which should not be exceeded in lifting tasks, although the small sample employed means that they cannot be used as a performance limit. Furthermore it has been found that these forces remain relatively constant, subjects varying their postures and torques at joints so as to 'optimise' the compressive forces in the spine. Differences are however noticed between subjects of different ages and sex.

The model, although it only acts in two dimensions, thus giving an incomplete picture of the biomechanics of the human body, is useful as it demonstrates the necessity for a computer model where there is a wide range of variability in human capabilities. In an attempt to transfer some of this information into graphical form, Chaffin has published (1971) a series of force contours (e.g. fig. 7.6.). The difficulty in doing so is shown by the large number of curves required, as a different family of curves is needed for each sex, type of task and size of person. More appropriate is a model of man in his working position, where the individual muscle strength requirements and the effects of different limb lengths can be evaluated.

Evershed's Man Model for the SAMMIE System

The work of Evershed (1970) resulted in the prototype man model for the SAMMIE system. The current author's work has been to replace this model with a more realistic and useable one, and this is described elsewhere in this thesis. The prototype is of interest here as it provided the groundwork for the current developments embodied in the current author's work.

Evershed's model considers man as a system of rigid linkages (after Dempster (1955)), recognising that an assumption of straight rigid links is only an approximation, but nevertheless an adequate one for the applications envisaged. Links of this kind are used to represent the upper half of the body by a rigid spine, upper and lower arms, and the shoulders, with five further links for the upper and lower legs and a rigid pelvis. The head is included as a rigid extension of the spine, making a thirteen link ten joint model. The joints themselves are depicted as being the centres of rotation for the adjacent limbs, the implicit assumption being that this instantaneous centre does not move during rotation of a limb. This assumption is seen as being acceptable at certain joints such as the knee and elbow, but is only an approximation at such complex joints as the hip and shoulder.

Flesh contours are added to the basic stick and joint assembly so that a more realistic three-dimensional display of the model can be obtained on a visual display screen. The flesh shape is defined as polygon-faced prisms, which approximate to the shape of a 50th percentile male of 'normal' shape.

As in all man models the major difficulty is in deciding which of an infinite number of possible body configurations is a representative one for a specified task. The approach adopted is to specify a sequential introduction of links, with algorithms and stored data determining the resultant joint and limb positions. The introduction of limbs is based on the work study principle of motion economy proposed by Barnes (1967), where movement was classified as follows:-

(i) hand

(ii) hand and forearm

(iii) hand forearm and upper arm

(iv) hand forearm, upper arm and shoulder

(v) hand, forearm, upper arm, shoulder and trunk.

The principle implies that the lowest order of classification feasible should be used for a body movement. Hence the model (as it has no separate hand), first assesses whether reach with the arm alone is feasible. Movement of the shoulder and then the spine, would be included only should it prove necessary. In this way the problem of calculating the joint positions is reduced to a two link system, as all distal limbs must be fully extended. Both extremity coordinates (distal and proximal) of the two link system are known leaving only the intermediate joint coordinates to evaluate. This evaluation of intermediate joint positions is taken up again later when discussing the 'Natural Planes' algorithm.

Evershed admits that this sequential introduction of limbs is somewhat unsatisfactory, as it requires that peripheral limbs must be fully extended before inner ones are introduced, whereas the natural and more comfortable configuration may for example call for earlier trunk movement. In addition it is possible to exceed maximum joint angle constraints, if the constraint is passed before a two link system is fully extended. This means that some infeasible body configurations are presented because of the limitations of the link introduction decision model. An obvious example of these limitations appears when the arm alone is unable to reach a specified position, and the shoulder is required to move. In this situation it is probable that humans would in fact move the spine in preference to shoulder movement alone. However the model will not allow the spine to move until the shoulder and arm are fully extended. As a consequence the model will sometimes take up infeasible positions, for example when reaching to the left with the right arm, the shoulder will rotate up to 180 degrees before spine movement is introduced.

One further complication arises when the required positions of both hands would imply that spine movement is necessary. This is known as the tripod situation and is the one exception to the two link method of solution. In this case, the position of the 'intermediate' joint (the top of the spine) is considered to be the point of intersection of the three spheres:-

(i) centre left hand; radius left lower and upper arms.

(ii) centre right hand; radius right lower and upper arms.

(iii) centre base of spine; radius spine.

The solution to the two link system has similarities in that the locus of possible positions for the intermediate joints is represented by the intersection of two spheres. The spheres are of radius equal to the length of the two links, with centres at the distal and proximal ends of the two link system. This locus is a circle, any of an infinite number of positions on its circumference being mathematically a feasible solution. Some of these positions would be outside the range permitted by limb mobility at the joints, but the problem remains to find one solution which is representative of a normal human posture.

This problem of selecting the most likely solution from an infinite choice is inherent in most methods of mathematical representation and as mentioned earlier, there are in general three approaches used to arrive at a solution.

(a) stored data

(b) specific algorithms

(c) general algorithms

The approach taken is to combine the stored data and algorithmic methods, resulting in the 'natural planes' algorithm. This method 'defines 'natural planes' in which the linkage system should lie for the hand in a particular volume in space'. The plane cuts the locus of possible solution in two places, and further tests have to be carried out to establish which is the preferable joint position.

Considering again the example of the arm, where it is required to find the elbow position, the coordinates of the hand and shoulder are known, so that if the 'natural plane' is defined by data, the elbow position can be found by simple mathematical techniques (Evershed (1970) appendix two).

The 'natural planes' data has been collected for reach requiring two, three, or four limbs, by dividing the models environment into one foot cubes, for each of which a natural plane number is stored. The hand position is itself a parameter of the 'natural plane', so the equation of the plane varies within each cube even though the natural plane number remains constant.

Evershed recognises the difficulty in obtaining 'natural plane' data from large populations, and also that it will have many more parameters than just hand position. Some other possible variables are considered to be:-

(a) the weight of the arm

(b) the weight held in the hand

(c) the speed and direction of movement

(d) the resistance to motion

(e) the required hand orientation

(f) restrictive clothing

(g) restrictions imposed by the surroundings

Also the possibility of improving the model by reducing the size of the cubes is recognised, but the associated data collection problems are considered to outweight any improvements in accuracy obtained. A worthwhile improvment however is envisaged if a mathematical function could be fitted to the natural planes data so that:-

(a) more parameters could be introduced (see above)

(b) the discontinuity of the boundary between two natural planes cubes could be eliminated.

(c) computer storage of data could be vastly reduced.

The major inadequacies of the model stem from the limitations imposed by the 'natural planes' approach to finding joint positions coordinates. 'Natural planes' is only applicable in the two link context, as three or more links would imply that the link system is located in a three-dimensional volume rather than in a plane. This limitation leads directly to the limb introduction model described above, resulting not only in an unrealistic movement pattern, but also allowing infeasible positions to be taken up by the model. Movement may be impossible due to bony stops on the joints, muscle and ligament constraints, or interference with adjacent limbs, but this aspect is not modelled. The only exception in this respect is that the twist in the upper arm is compared with constraint values to assist in selecting the best solution from the two possible solutions supplied by the 'natural planes' algorithm.

However section 4.1. of Evershed's thesis refers to angle constraints expressed in the form of spherical polar coordinates. He states that these are 'angles which can readily be measured for limits of movement'. This is obviously untrue because as fig. 4.5.(a) shows, θ is a function of φ and ψ, and is thus extremely difficult to measure in any comprehensive way. Indeed this is born out by the fact that virtually all the researchers in this field (e.g. Barter, Emmanuel and Truett, Dempster, Glanville and Kreezer) have chosen to relate angular mobility to an orthogonal set of axes. This allows angles to be more easily defined and expressed in familar terms such as the extent of abduction, adduction, flexion and extension. The source quoted for Evershed's spherical polar coordinates is Barter, Emmanuel and Truett (1957), but on examination it is clear that this contains only values for ψ for the upper arms, all other data being expressed in the form of orthoganal angles.

It is necessary therefore for each limb to have its own orthoganal axis system with the origin at the proximal end of the limb, so that the limb angles can be compared with constraints. Furthermore it is also necessary to relate each limb to the other limbs in the link structure so that the total body configuration can be defined. To do this an Eulerian system of angles such as an extended spherical polar coordinates system similar to that mentioned above must be used.

The total incompatibility of the use of angle constraints with the 'natural planes' algorithm, casts some doubt on the validation of the model by the use of contours of reach. It will be noticed that the contours of reach presented in figures 12-20 of Evershed's thesis represent the very constrained conditions of arm movement only, with the shoulder and spine not allowed to move. Hence the man model is reduced to an arm model which can more reasonably be considered as a two link system (assuming the hand to be a rigid extension of the lower arm). This situation corresponds quite closely to the constrained conditions in an aircraft cockpit, which was the situation being investigated by King, Morrow and Vollmer (1947) (with whose experimental data Evershed compared the models capabilities). However for use in 'workspace assessment', such constraints would seem unrealistic, and the shoulder and spine should be allowed to move. As previously explained this would result in either

(a) the 'natural planes' algorithm being unuseable because of the three dimensional link system.

or (b) the exclusion of angle constraints at the joints so that multi-link systems can be reduced to a two link system.

Alternative (a) implies that the natural planes algorithm would have to be abandoned. Alternative (b) results in an unrealistic model where the locus of reach for the hand is merely a sphere of radius equal to the sum of the lengths of the upper and lower arms, the shoulder and the spine, with centre at the base of the spine. In addition intermediate joint positions in certain circumstances could bear little relation to any realistic postures adopted by human beings.

It appears that alternative (b) was the one chosen by Evershed for the implementation of his man model. This is borne out by the fact that inspection of the model in action on the visual display screen amply illustrates the lack of angle constraints. In addition, closer investigation into the derivation of the contours of reach (Evershed figs.12-20), reveals that the envelope of reach for one hand is dependant on four major factors:-

(i) the mathematical resilience of the model

(ii) the position of the other hand

(iii) the natural planes algorithm

(iv) the limb dimensions

Re-analysing the model in an attempt to reproduce the contours of reach shows that the above four factors are all active.

It was shown that 38% of the positions deemed to be infeasible, are a result of mathematical inconsistencies within the model. These usually take the form of complex roots to equations.

A further 40% of infeasible positions were due to the position of the other hand. The position of the other hand cannot be ignored by the model, as it is one of the factors included in the link introduction decision model. Hence for the purposes of obtaining the reach contours the other hand has been made to perform the mirror image of the movements required of the hand under test. As a consequence while the left hand moves away from the body to the left, the right hand moves away to the right, and vice-versa. This results in some very strange test positions where for example the arms are crossed with the hands attempting to reach in the opposite direction to that which would normally be expected. It is not surprising that many such positions were infeasible.

The third category of infeasible positions, those relating to the natural planes algorithm, and representing 11% of the total, arise from the solution selection by reference to the angle of twist in the upper arm. Some of these might represent truly infeasible positions, where the hand position requires an angle of twist which is outside obtainable limits. However in most cases it merely reflects the inadequacy of the natural planes algorithm to arrive at reasonable solutions.

The final category which accounts for 11% of the total, represent positions which are outside the geometric capabilities of the limbs i.e. the position is out of reach because the total length of arm shoulder and spine is insufficient.

It can be seen then that the contours of reach bear little relationship to the capabilities of the model (because of the inadequate control of the other hand position), and far less to the capabilities of a human being.

It is for these reasons of fundamental faults in the original model, plus the desire to extend the scope and useability of the model which have resulted in the current author's attempts at man modelling.

APPENDIX TWO

LINK DEFINITIONS

Link Definitions

Chapter 4 has defined links as being the straight line between adjacent joint centres. The joint centres are internal to the body and thus generally inaccessable for measurement purposes. Nominal joint centre positions have however been defined by Dempster (1955) which allow measurement from surface landmarks, and these are reproduced below:-

Sternoclavicular joint center. - Midpoint position of the palpable junction between the proximal end of the clavicle and the sternum at the upper border (jugular notch) of the sternum.

Claviscapular joint center.- Mid point of a line between the coracoid tuberosity of the clavicle (at the posterior border of the bone) and the acromioclavicular articulation (or the tubercle) at the lateral end of the clavicle); the point, however should be visualized as on the underside of the clavicle.

Clavicular link.- The direct distance between the two joint centers listed above.

Glenohumeral joint center. - Midregion of the palpable bony mass of the head and tuberosities of the humerus; with the arm abducted about 45°, relative to the vertebral margin of the scapula; a line dropped perpendicular to the long axis of the arm from the outermost margin of the acromion will approximately bisect the joint.

Scapular link. - The distance between the centers of the foregoing mean clavicapular and glenohumeral joints - an unsatisfactory measurement - approximately 3.5 cm.

Elbow joint center. - Midpoint of a line between (1) the lowest palapble point of the medial epicondyle of the humerus, and (2) a point 8 mm above the radiale (radio-humeral junction).

Humeral link. - The distance between the glenohumeral and elbow joint centers.

Wrist joint center. - On the palmar side of the hand, the distal wrist crease at the palmaris longus tendon, or the midpoint of a line between the radial styloid and the center of the pisiform bone; on the dorsal side of the hand, the palpable groove between the lunate and capitate bones, on a line with metacarpal bone III.

Radial link. - The spanning distance between the wrist and elbow joint centers.

Center of gravity of the hand (position of rest). - A point on the skin surface midway in the angle between the proximal transverse palmar crease and the radial longitudinal crease in line with the third digit; flattening or cupping the hand changes the relative location of this point very little, except to change the position normal to the skin surface.

Hand link. - The slightly oblique line from the wrist center to the center of gravity of the hand.

Hip joint center.-(Lateral aspect of the hip). A point at the tip of the femoral trochanter 0.4 inch anterior to the most laterally projecting part of the femoral trochanter.

Knee joint center.- Midpoint of a line between the centers of the posterior convexities of the femoral condyles.

Femoral link. - Distance between the foregoing centers.

Ankle joint center. - Level of a line between the tip of the lateral malleolus of the fibula and a point 5 mm distal to the tibial malleolus.

Leg link. - The distance between knee and ankle centers.

Center of gravity of the foot. - Halfway along an oblique line between the ankle joint center and the ball of the foot, at the head of metatarsal II.

Foot link. - The distance between the ankle joint center and the center of gravity of the foot.

APPENDIX THREE

ANTHROPOMETRIC AND BIOMECHANICAL DATA

(a) Regression Equations for the Determination of Link Lengths

In chapter 4, a link model was described, which enabled the building of an anthropometric model. Link length is defined as the straight line distance between two adjacent centres of rotation. As these centres of rotation are generally located internal to the body, the relationships between links and externally palpable points needs to be derived so that the introduction to the model of anthropometric data is facilitated. Dempster (1964) has however derived a set of regression equations which are capable of providing this information, and they are presented below.

	Standard Error of Estimate	Correlation coefficient
Ulna length - 23.7922 + (0.9810 x Radius length)	4.58	.94
Humerus length = 64.4829 + (0.9683 x Radius length)	9.97	.81
Forearm-link length = 1.0709 x Radius Length*	-	-
Arm-link length = 58.0752 + (0.9646 x Radius length)	8.92	.94
Radius Length = 7.9728 + (0.9002 x Ulna length)	4.39	.94
Humerus length = 74.0856 + (0.9688 x Ulna length)	11.07	.76
Forearm-link length = 0.9870 x Ulna length *	-	-

Arm-link length = 66.2621 + (0.8665 x Ulna length)	9.90	.94
Femur length = 125.6879 + (0.9067 x Tibia length)	18.39	.73
Fibula length = 31.3653 + (0.9252 x Tibia length)	5.28	.97
Shank-link length = 1.0776 x Tibia Length *	-	-
Thigh-link length = 132.8253 + (0.8172 x Tibia length)	16.57	.73
Femur length = 101.8815 + (0.9629 x Fibula length)	11.45	.87
Tibia length = 8.6266 + (1.0119 x Fibula length)	5.53	.97
Shank-link length = 8.2184 + (1.0904 x Fibula length)	5.95	.97
Thigh-link length = 92.0397 + (0.8699 x Fibula length)	10.34	.87

* Derived from ratios of link length of bone. length as below.

Ratio of lengths	cadaver sample size	mean(%)	standard deviation (%)
Arm-link/humerus	32	89.44	1.59
Forearm-link/ulna	32	98.70	2.66
Forearm-link/radius	26	107.09	3.53
Thigh-link/femur	32	90.34	0.88
Shank-link/tibia	33	107.76	1.81

From:- Conversion Scales for Estimating Humeral and Femoral Lengths and the Lengths of Functional Segments in the Limbs of American Causosoid Males.

W.T. Dempster. L.A. Sherr. J.E. Priest (1964)

(b) Derivation of Link Demensions from External Dimensions.

Section (a) of this appendix has already described one way in which link dimensions can be derived from external measurements. When entering data via the facility illustrated in figure 4.4. a slightly different approach is used to define the link lengths. Relationships between external functional measurements and link lengths have been derived from the data of Dreyfuss (1967), and these are reproduced below.

Spine-Link = Sitting Height x 0.50

Shoulder Link = Bideltoid Distance x 0.40

Upper Arm Link = Anterior Arm Reach x 0.34

Forearm Link = Anterior Arm Reach x 0.52

Pelvis Link = Hip Width x 0.35

Thigh Link = Knee-Buttock Length x 0.71

Lower Leg Link = Knee-Floor Height x 0.91

From:- The Measure of Man. H.Dreyfuss 3rd Edition 1967.

(c) Formation of a Normal Distribution for Percentiles

Chapter 4 describes how anthropometric data can be described in terms of percentiles. The user of the system merely has to state which percentile is required, and supply the mean dimension, and then the program is able to derive the dimension of the link. Hence if the user were to ask for the upper arm length of the model to be changed to the 97.5 percentile value, he would simply input the mean value of this dimension as say 280 mm, and the 97.5 percentile value of 305 mm would be computed. Computation is by way of a normal distribution which can be defined in terms of the mean and the standard deviation. The mean is supplied by the user, and the standard deviation is stored data which has been derived from Dreyfuss (1967).

For convenience the distribution for each dimension, are all related to one master distribution shown in fig. A.1. (Defines percentiles in terms of the number of standard deviations from the mean).

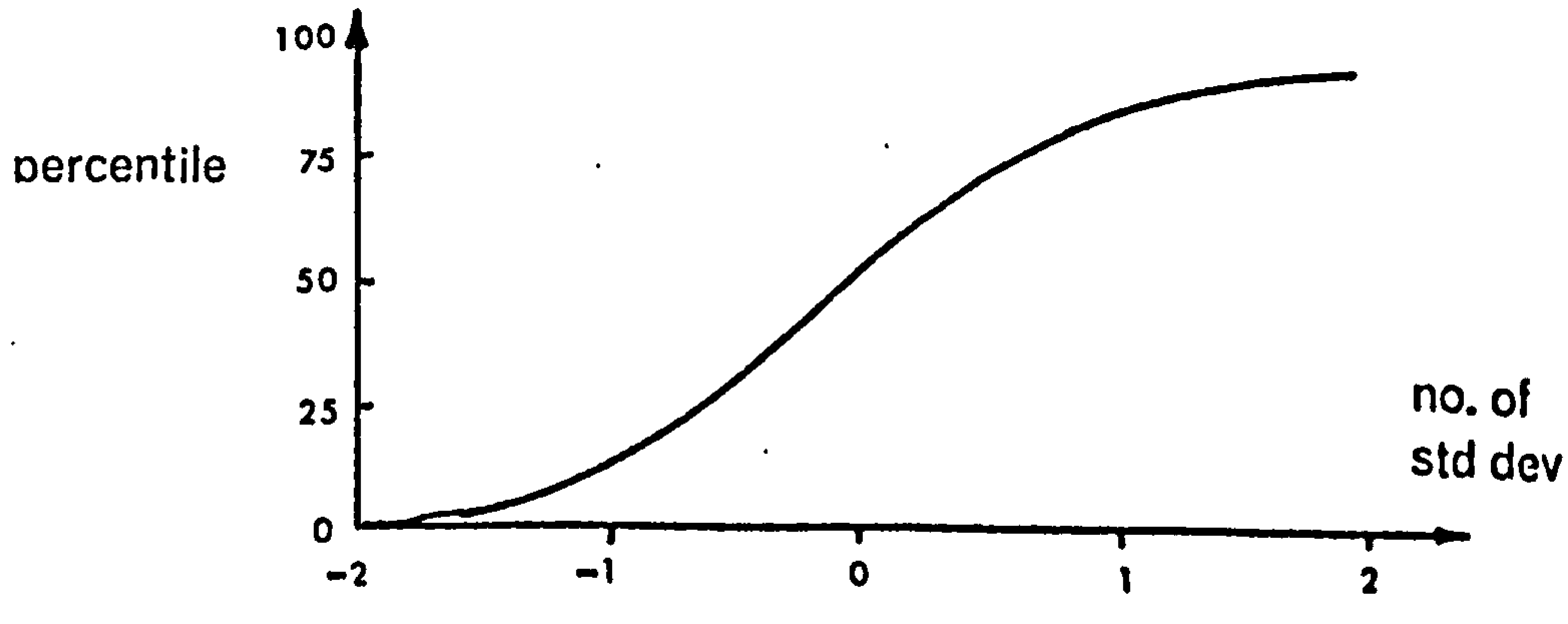


Fig. A.1. Master Normal Distribution.

The individual dimensions are derived from this distribution from the relationships shown below.

Spine Link = m_s + SD x 0.068

Upper Arm Link = m_u + SD x 0.034

Lower Arm Link = m_l + SD x 0.051

Shoulder Link = m_{sh} + SD x 0.065

Head Link = m_n + SD x 0.017

Thigh Link = m_t + SD x 0.047

Lower Leg Link = m_{la} + SD x 0.068

Pelvic Link = m_p + SD x 0.054

where m_s = mean spine length etc.

SD = No. of standard deviations required for percentile.

Derived from:- The Measure of Man H.Dreyfuss 3rd Edition (1967).

(d) Joint Range Data

The data below is from a re-analysis of data published by Dempster (1955).

Leading characteristics of the sample population are:-

sample size = 39 College Students		
	mean	standard deviation
age:	21.1 yrs	3.3
weight:	169.7 lbs	36.3
stature:	70.5 inches	2.8

Joint and type of movement	mean (degrees)	standard deviation
Wrist		
flexion	90	12
extension	99	13
abduction	27	9
adduction	47	7
Forearm		
supination	113	22
pronation	77	24
Elbow		
flexion	142	10
Shoulder		
flexion	188	12
extension	61	14
abduction	134	17

adduction	48	9
medial rotation	97	22
lateral rotation	34	13
Hip		
flexion	113	13
abduction	53	12
adduction	31	12
medial rotation	39	10
lateral rotation	34	10
Knee		
flexion	125	10
medial rotation	35	12
lateral rotation	43	12
Ankle		
flexion	35	7
extension	38	12
Foot		
inversion	24	9
eversion	23	7

From:- A Statistical Evaluation of Joint Range Data
J.T. Barter. I. Emanuel. B. Truett (1957)

(e) Segment Parameters: Weights and Centres of Mass

Segmental Weight / Body Weight Ratios.

(from various cadaver studies)

source	Harless (1860)	Braune and Fischer (1889)	Fischer (1906)	Dempster (1955)	Clauser et al. (1969)
sample size	2	3	1	8	13
Head	7.6%	7.0%	8.8%	7.9%	7.3%
Trunk	44.2	46.1	45.2	48.6	50.7
Upper arm	3.2	3.3	2.8	2.7	2.6
Forearm	1.7	2.1	-	1.6	1.6
Hand	0.9	0.8	-	0.6	0.7
Thigh	11.9	10.7	11.0	9.7	10.3
Calf	4.6	4.8	4.5	4.5	4.3
Foot	2.0	1.7	2.1	1.4	1.5

First four columns for comparison only

From C.E. Clauser et al. (1969)

Centre of Mass / Segment Length Ratios

(from various cadaver studies)

source	Harless (1860)	Braune and Fischer (1889)	Fischer (1906)	Dempster (1955)	Clauser et al. (1969)
Head	36.2%	-	-	43.3%	46.6%
Trunk	44.8	-	-	-	38.0*
Upper arm		47.0	45.0	43.6	51.3
Forearm	42.0	42.1	-	43.0	39.0
Hand	39.7	-	-	49.4	18.0*
Thigh	48.9	44.0	43.6	43.3	37.2*
Calf	43.3	42.0	43.3	43.3	37.1
Foot	44.4	44.4	-	42.9	44.9

*Variation in definition of segment length.

All ratios from distal end of segment.

From:- Clauser et al. (1969)

(f) Moments of Inertia About the Centre of Gravity (I_{CG}) of Body Segments

A full set of data from the study of eight cadavers is available in Dempster (1955). Only a representative sample is given here.

	I_{CG}
Arm	$.112 \times 10^6$
Forearm	$.050 \times 10^6$
Hand	$.003 \times 10^6$
Thigh	$.610 \times 10^6$
Leg	$.340 \times 10^6$
Foot	0.33×10^6

From W.T. Dempster (1955).

APPENDIX FOUR

THE POSTURAL ALGORITHM

The 'Postural' Algorithm

The objectives of the 'postural' algorithm have been described in chapter 6 and the logic included in a flow diagram (fig. 6.3.). A more detailed step-by-step description is given here.

General principles.

The algorithm attempts to predict a posture which is a reasonable representation of human movement. This is achieved by the sequential introduction of links, and the use of angle constraints. Hence the algorithm is designed to keep the angles at all joints as close as possible to the rest position, and within normal rather than absolute constraints.

Data

Each degree of freedom at a joint has four constraint values associated with it (fig. 6.2.), which are contained in the program as stored data. The user will not normally be required to supply this data, unless a special population or a special condition such as arthritis, is being considered.

The position of the man model relative to the workplace model is assumed fixed at the current stage of development (i.e. the base of the spine, as the reference point of the man model, cannot move relative to the workplace model). Hence action such as walking to another point in the workplace, cannot be initiated from within the postural algorithm, and is only possible before use of the algorithm. This situation may change with the implementation of the new work sequence language.

The only information which the user of the system has to supply, is the required hand position. This may be achieved in one of two ways.

(i) by use of the work sequence language.

Movement commands emanating from the work sequence language pre-specify the end point of a movement (the 'touchpoint') and intermediate evaluation points on the hand trajectory.

(ii) by menu control

Incremental movement along specified axes can be performed by the use of menu commands. Hence either hand (or foot) can be instructed to move by a pre-set distance along any one of three orthoganal axes (i.e. forwards-backwards, right-left, and upwards-downwards with respect to the front-facing position of the man).

The link lengths will have been specified, in one of the several ways mentioned in chapter 4, so that data base if complete, and a description of the algorithm now follows.

The algorithm

(i) Test overall reach ability. The distance between the required hand position and the base of spine is compared with the sum of the relevant link lengths.

e.g. if this distance is greater than the sum of the lengths of the hand, arm, shoulder and spine, the position is considered to be out of reach and posture prediction is not attempted.

(ii) Test reach ability with hand alone. If the hand position can be reached by movement of the hand alone, without violating the normal range of movement at the wrist, then this wrist posture is used with the rest of the body maintaining its current posture.

(iii) If step (ii) does not result in a solution, then the hand is assumed to become a rigid extension of the forearm, i.e. the wrist joint is set at its neutral position.

(iv) Movement of the forearm (with the hand extension), is not considered to occur solely about the elbow joint. As the elbow joint has only one degree of freedom (flexion), forearm movement can only result in hand movement in one plane, i.e. the hand can only move through a circular arc. This is unlikely to provide a solution, so movement about the elbow is only considered in conjunction with movement at the shoulder.

(v) Set elbow angle of flexion to give correct hand to shoulder distance.

i.e. elbow angle = $\cos^{-1}(((\text{upper arm length})^2 + (\text{forearm})^2 - ((xx-x)^2 + (yy-y)^2 + (zz-z)^2)) / 2 \times \text{upper arm} \times \text{forearm})$

(xx, yy, zz) = required hand position. (x, y, z) = shoulder position. (cosine rule)

(vi) Test this angle against angle constraints. If the normal angle is exceeded, spine movement is necessary, so proceed to step (viii).

(vii) Determine angles at shoulder which together with the angle of flexion at the elbow define an arm posture which gives correct hand position. This is an indeterminate situation as the three degrees of freedom available at the shoulder joint, allow the correct hand and shoulder positions to be maintained while the elbow takes up any number of positions on a circular arc. Abduction-adduction and flexion-extension at the shoulder joint are normally used to position the arm, the ability to rotate the arm medially and laterally usually being reserved for special purpose motions such as the use of a screwdriver. Hence an attempt is made to find angles of abduction-adduction and flexion-extension, which are within the normal range of motion, and which represent a realistic and not only feasible location of the elbow joint. This is best approached using Euler angles, rather than the orthogonal angles. Hence the problem is to find the Euler angles φ and θ for the upper arm (fig. 4.5.).

The basic equation relating required hand position (xx,yy,zz) to the Euler angles is:-

equation A

$$\begin{bmatrix} xx \\ yy \\ zz \end{bmatrix} = RM_{I-2} \begin{bmatrix} O \\ O \\ -L_{I-2} \end{bmatrix} + RM_{I-2}RM_{I-1} \begin{bmatrix} O \\ O \\ -L_{I-1} \end{bmatrix} + RM_{I-2}RM_{I-1}RM_{I} \begin{bmatrix} O \\ O \\ -L_{I} \end{bmatrix}$$

where RM_I = rotation matrix for joint I

L_I = length of Link I

I = hand

I-1 = forearm

I-2 = upper arm

Where arm movement is used, the hand is a rigid extension of the forearm, and hence:-

RM = I (identity matrix)

and equation A becomes

equation B

$$\begin{bmatrix} xx \\ yy \\ zz \end{bmatrix} = RM_{I-2} \begin{bmatrix} O \\ O \\ -L_{I-2} \end{bmatrix} + RM_{I-1} \begin{bmatrix} O \\ O \\ -L_{I-1}-L_{I} \end{bmatrix}$$

RM_{I-1} is constant for a given elbow angle, such that in general

$$\begin{bmatrix} \cos\varphi_{I-1}\cos\theta_{I-1} & \sin\varphi_{I-1} & \cos\varphi_{I-1}\sin\theta_{I-1} \\ -\sin\varphi_{I-1}\cos\theta_{I-1} & \cos\varphi_{I-1} & -\sin\varphi_{I-1}\sin\theta_{I-1} \\ -\sin\theta_{I-1} & O & \cos\theta_{I-1} \end{bmatrix}$$

by definition of the elbow joint $_{I-1}$ = 90°

Hence

$$RM_{I-1} = \begin{bmatrix} O & 1 & O \\ -\cos\theta_{I-1} & O & -\sin\theta_{I-1} \\ -\sin\theta_{I-1} & O & \cos\theta_{I-1} \end{bmatrix}$$

in equation B put

$$\begin{bmatrix} 0 \\ 0 \\ -L_{I-1} \end{bmatrix} + RM_{I-1} \begin{bmatrix} 0 \\ 0 \\ -L_{I-1} - L_I \end{bmatrix} = \begin{bmatrix} XP \\ YP \\ ZP \end{bmatrix}$$

hence

$$\begin{bmatrix} XX \\ YY \\ ZZ \end{bmatrix} = RM_{I-2} \begin{bmatrix} XP \\ YP \\ ZP \end{bmatrix} \qquad \text{equation C}$$

assuming $_{I-2} = 0$ and expanding C

$$XX = \cos\varphi_{I-2}\cos\theta_{I-2}XP + \sin\varphi_{I-2}YP + \cos\varphi_{I-2}\sin\theta_{I-2}ZP \quad (i)$$

$$YY = -\sin\varphi_{I-2}\cos\theta_{I-2}XP + \cos\varphi_{I-2}YP - \sin\varphi_{I-2}\sin\theta_{I-2}ZP \quad (ii)$$

$$ZZ = -\sin\theta_{I-2}XP + \cos\theta_{I-2}.ZP \quad (iii)$$

putting $_{I-2} = T$ and $_{I-2} = P$

then (iii)

$$ZZ = -XP.\sin(T) + ZP.\cos(T)$$

now

$$a\cos\eta + b\sin\eta = k\sin(\eta+\lambda) \quad \text{where } k = \pm\ (a^2+b^2), \quad \lambda = \tan^{-1}(a/b)$$

hence $ZZ = \pm\ (XP^2+ZP^2)\ \sin(\theta + \tan^{-1}(\frac{ZP}{-XP}))$

$$\theta = \pm \sin^{-1}(ZZ/N(XP^2+ZP^2)) - \tan^{-1}(^a/b)$$

Two values of θ are found, the correct value being found by back-substitution in (iii)

φ is found using a similar technique on equation (i).

i.e.

put $A = XP\cos\theta_{I-2}$ $B = YP$ $C = ZP\sin\theta_{I-2}$

in (i)

$$XX = A.\cos(P) + B.\sin(P) + C.\cos(P)$$

$$XX = N((A+C)^2 + B^2)\sin(\varphi + \tan^{-1}((A+C)/B))$$

$$\varphi = \pm \sin^{-1}(XX/N((A+C)^2 + B^2)) - \tan^{-1}((A+C)/B)$$

back substitution in (i) finds correct value for φ

Hence the Euler angles for the upper arm are found, and the orthoganal angles of abduction-adduction and flexion-extension can be derived from the two equations below. (with certain qualifiers to ensure that the correct octant is chosen).

$$\alpha = \tan^{-1} ((-\sin\theta \sin\varphi)/\cos\theta.)$$

$$\beta = \tan^{-1}((\cos\varphi .\sin\theta)/\cos\theta)$$

Angles α and β are checked against constraint values, and if the normal constraints are exceeded then spine movement has to be introduced.

(viii) Spine movement. The objective of the spine location procedures is to locate the position of the spine in such a way that the required hand position is reached by the combined movement of the spine, upper arm and the forearm. The hand remains rigidly fixed to the forearm, and the shoulder is not permitted to move at this stage.

Once again the problem is to determine two Euler angles, this time for the spine. φ is found by the projection of a straight line between the base of the spine and the hand position onto the horizontal plane, with due consideration being given to which quadrant it lies in. The hand position (XX, YY, ZZ) relative to a set of axes which have been rotated through an angle φ is then found.

i.e.

$$\begin{bmatrix} AX \\ AY \\ AZ \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} XX \\ YY \\ ZZ \end{bmatrix}$$

Figure A.2. illustrates a projection of the link system onto the φ -plane.

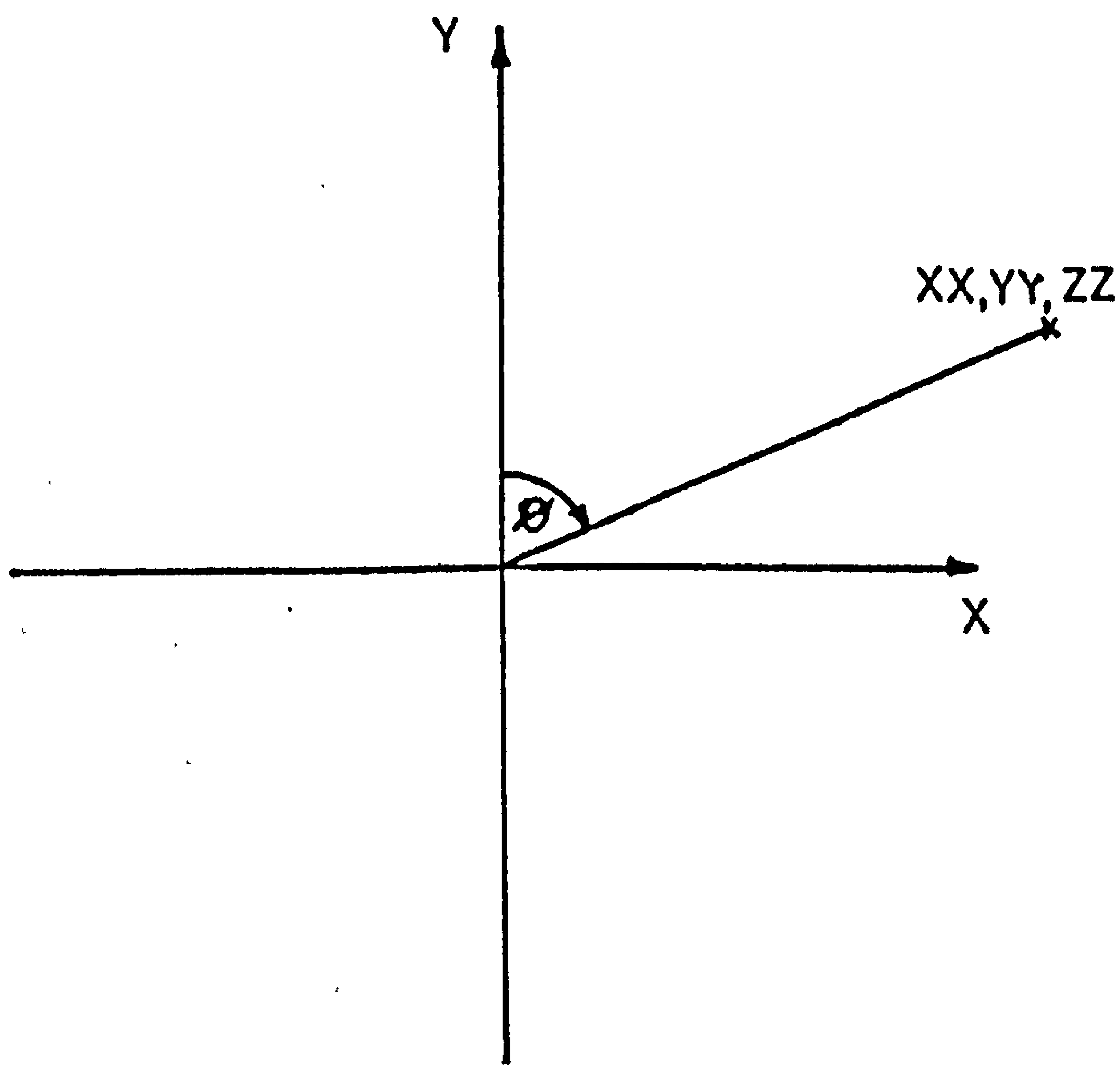


Fig. A.2. Determination of Euler Angles in Spine Movement.

To find θ, BY and BZ are first determined by the intersection of the two circles

radius: PAR   centre: (AY,AZ)

radius: spine length   centre: (0.0)

i.e. $(BY-AY)^2 + (BZ-AZ)^2 = PAR^2$ (i)

$BY^2 + BZ^2 = (\text{spine length})^2$ (ii)

from (i) and (ii) the quadratic

$N.BZ^2 + P.BZ + Q = 0$ is obtained

where $N = -4AY^2 - 4AZ^2$

$P = -4AZ.M$

$Q = 4AY^2.(\text{spine length})^2 - M^2$

Of the two solutions available from the quadratic, the one implying the most upright spine is chosen.

is then given by

$\theta = \tan^{-1}(BY/BZ)$ having due regard to which quadrant it lies in. The orthoganal angles are found as before from φ and θ, and compared with constraint values. If within normal constraints, the shoulder angles are determined as in stage (vii), and provided they are within normal range, the solution is found.

(ix) If the spine location described above results in either the shoulder joint or spine being out of the normal range of movement then the algorithm becomes an iterative one, returning to stage (v), but this time extending the degree of elbow flexion into the normal to maximum range.

(x) If extension of the elbow joint still does not allow a solution to be found, then the angles at the shoulder joint are allowed to exceed their normal constraints and the process repeated.

(xi) With elbow and shoulder joints fully extended, the spine is permitted to move into its maximum range of movement. If a solution is not possible at the full extent of elbow, shoulder and spine extension, then the required hand position is deemed to be out of reach.

The above description of the 'postural' algorithm is of necessity very brief, but it is mainly intended to convey the general principles and some of the mathematical techniques, and is not intended as a detailed technical report.

APPENDIX FIVE

EQUATIONS OF MOTION

Equations of Motion

Chapter 7 discussed the use of Plagenhoef's (1966) model for the determination of joint moments. The equations of motion used in that model for a three degment motion, are presented here.

Segment 1 is rotating about a fixed point, and segments 2 and 3 are rotating about moving axes.

The force and moment equations are as follows

Segment 3

$$F_{y3} = -WT_3+m_3r_3\alpha_3\cos\theta_3+m_3r_3w_3^2\sin\theta_3-m_3R_1\alpha_1\cos\varphi_1+ m_3R_1w_1^2\sin\varphi_1+m_3R_2\alpha_2\cos(180°-\varphi_2)+m_3R_2w_2^2\sin(180°-\varphi_2) +m_3(2w_1V_2+2w_1V_3+2w_1w_3r_3)\sin\theta_3-m2w_2V_3\sin\theta_3$$

$$F_{x3} = -m_3r_3\alpha_3\sin\theta_3+m_3r_3w_3^2\cos\theta_3+m_3R_1\alpha_1\sin\varphi_1+m_3R_1w_1^2\cos\varphi_1 +m_3R_2\alpha_2\sin(180°-\varphi_2)-m_3R_2w_2^2\cos(180°-\varphi_2) +m_3(2w_1V_2+2w_1V_3+2w_1w_2r_3)\cos\theta_3-m2w_2V_3\cos\theta_3$$

$$M_{o3} - WT\cos\theta_3r_3+m_3k_3^2\alpha_3+m_3R_1w_1^2\sin(\varphi_1-\theta_3)r_3-m_3R_1\alpha_1\cos(\varphi_1-\theta_3 +m_3R_2w_2^2\sin(\varphi_2-\theta_3)r_3-m_3R_2\alpha_2\cos(\varphi_2-\theta_3)r_3 =0$$

Segment 2

$$F_{y2} = -WT_2+m_2r_2\alpha_2\cos(180°-\theta_2)+m_2w_2^2\sin(180°-\theta_2) -m_2R_1^1\alpha_1\cos\varphi_1^1+M_2R_1w_1^2\sin\varphi_1^1-m2V_2w_1\sin(180°-\theta_2)+F_{y3}$$

$$F_{x2} = +m_2r_2\ {}_2\sin(180°-\theta_2)-m_2r_2w_2^2\cos(180°-\theta_2)+m_2R_1^1\alpha_1\sin\varphi_1^1 +m_2R_1w_1^2\cos\varphi_1^1+m2V_2w_1\cos(180°-\theta_2)+F_{x3}$$

$$M_{o2} + WT_2\cos(180°-\theta_2)r_2 - m_2k_2^2\alpha_2 - m_2R_1^1w_1^2\sin(\theta_2-\varphi_1^1)r_2$$
$$-m_2R_1^1\alpha_1\cos(\theta_2-\varphi_1^1)r_2 + F_{y3}l_2(\cos180°-\theta_2)$$
$$+F_{x3}l_2(\sin180°-\theta_2) - M_{o3} = 0$$

Segment 1

$$F_{y1} = -WT - m_1r_1\alpha_1\cos\theta_1 + m_1r_1w_1^2\sin\theta_1 + F_{y2}$$

$$F_{x1} = +m_1r_1\alpha_1\sin\theta_1 + m_1r_1w_1^2\cos\theta_1 + F_{x2}$$

$$M_{o1} - WT_1\cos\theta_1r_1 - m_1k_1^2\alpha_1 + F_{y2}l_1(\cos\theta_1) + F_{x2}l_1(\sin\theta_1) - M_{o2} = 0$$

APPENDIX SIX

GLOSSARY OF TERMS

Glossary of Terms

Computer and SAMMIE system terms

SAMMIE

An acronym, System for Aiding Man-Machine Interaction Evaluation, used to identify the suite of computer-aided design programs developed at Nottingham University.

Interactive Graphics

A terminal attached to a computer that enables the operator to 'converse' with the computer through the medium of graphical in addition to alpha-numeric information.

Lightpen

A device attatched to the graphics terminal, which allows the identification of specific points on the screen.

Modules

The basic 'building blocks' of the environment model. A set of 3-D shapes from which a wide range of items can be built up.

Natural Planes Algorithm

A mathematical method of obtaining coordinate positions of joints. Used in the prototype SAMMIE model, but now abandoned.

Touchpoints

Identified points within the workplace model, to which the man model may be required to reach.

Work Task Language

A means of specifying the actions of the model.

Anthropometric Terms

Abduction

Movement of a limb away from the body centreline.

Adduction

Movement of a limb towards the body centreline.

Flexion

Bending or decreasing the angle of a joint.

Extension

Straightening, or increasing the angle of a joint.

Hyperextension

A continuation of extension backwards.

Pronation

Movement (of the hand) into the (palm) downward position.

Supination

Movement (of the hand) into the (palm) upwards position.

Medial Rotation

Turning toward the midline of the body.

Lateral Rotation

Turning away from the midline of the body.

Eversion

Turning outward

Inversion

Turning inward

Saggital Plane

Vertical longitudinal plane dividing the human into right and left halves.

Transverse Plane

Vertical latitudinal plane dividing the human into front and back halves.

Coronal Plane

The horizontal plane forming a mutually perpendicular set of axes with the above two.

Distal

The end of a limb furthest away from the trunk.

Proximal

The end of a limb closest to the trunk.

Goniometer

An angle measuring device.

REFERENCES

REFERENCES

ALBERT. E.
Zur Mechanik des Huftgeleukes. Med. Jahrb. K.K. Gesellsch. d'Arzte (Wien) 1876.

ARCHER L.B.
Technological Innovation - a Methodology Science Policy Foundation Special Publication Series Infolink Ltd. Science Policy Foundation 1971

ARCHER L.B.
Systematic Method for Designers. Reprint originally published as a series of seven articles in Design. 1963/4.

ARCHER L.B.
Development of Mathematical Modelling Techniques for Application in Equipment Design. Pilot Study: outline for final report. Unpublished Draft Report to Science Research Council. September 1973.

ARMY SERVICES DATA (World War II)
Height and Weight for men inducted into the Army and for rejected men. Report No. 1-BM. Office of the Surgeon General Medical Statistics Division.

AYOUB M.M. WALVEKAR A. PETRUNO M.
A Biomechanical Model for the Upper Extremity using Optimisation Techniques. Paper presented to Automotive Engineering Congress - Detroit. February 1974.

BARKLA D.
The Estimation of Body Measurements of British Populations in Relation to Seat Design. Ergonomics 4. 123. 1961.

BARNES R.M.
Motion and Time Study. Sixth Edition. Wiley International London 1968.

BARTER J.T. EMMANUEL I. TRUETT B.
A Statistical Evaluation of Joint Range Data. WADC Technical Note 57-311. Wright-Patterson Air Force Base, Ohio. 1957.

BASLER A.
Die Lage des Schwerpunkter in lebenden Menschen Fortsch. Med. 11. 1931.

BASMAJIAN J.V.
'Spurt' and 'Shunt' Muscles: an Electromyographic Confirmation. J. Anat. 93. 551-553. 1959.

BEAKLEY G.C. CHILTON E.G.
Introduction to Engineering Design and Graphics. The Macmillan Company. New York. 1973.

BAILEY G.B. PRESGRAVE R.
Basic Motion Timestudy. McGraw-Hill. New York 1958.

BENWELL N.
Benchmarking and its Many Real-Life Problems. Computer Weekly. September 26th 1974.

BERNSTEIN N.A. SALZGEBER D.A. PAULENKO P.P. GURVICH N.A.
Determination of Location of the Centres of Gravity and Mass of the Links of the Living Human Body. All-Union Institute of Experimental Medicine - Moscow. 1931.

BONNEY M.C. CASE K. HUGHES B.J. KENNEDY D.N. WILLIAMS R.W.
The SAMMIE Computer Aided Workplace and Work Task Design System. Paper presented to the Automotive Engineering Congress. February 1974.

BRAUNE W. FISCHER O.
Untersuchungen uber die Gelenke des menschlichen Armes: 1. Das Ellenbogengelenk (O. Fischer); 2. Das Handgelenk (W. Braune. O. Fischer). Abh. d. math.-phys. Cl. d. K. Sachs Gesellsch. d. Wiss. Vol. 14(2). 1887.

BROUHA L.
Physiology in Industry: Evaluation of Industrial Stresses by the Physiological Reactions of the Worker. International Series of Monographs in Pure and Applied Biology. Vol. 4 2nd ed. Pergamon Press. N.Y. 1967.

BULLOCK M.I. HARLEY I.A.
The Measurement of Three-Dimensional Body Movements by the use of Photogrammetry. Ergonomics vol. 15. 1972.

CALDWELL L.S.
The Load-endurance Relationship for a Static Manual Response. Human Factors 6(1). 1964.

CATHCART E.P.
The Physique of Man in Industry. Industrial Health Research Board. Medical Research Council. Report No. 71. 1935.

CHAFFIN D.B.
A Computerized Biomechanical Model - Development of and Use in Studying Gross Body Actions. Paper presented to Biomechanical and Human Factors Conference, Ann Arbor, Michigan. 1969.

CHAFFIN D.B.
Lifting, Pushing and Pulling Strength Predictions. Report by Department of Industrial Engineering. University of Michigan. March 1971.

CHAFFIN D.B.
Physical Fatigue: What it is - How it is Predicted. The Journal of Methods - Time Measurement vol. XIV No. 3 1969.

CHAFFIN D.B. BAKER W.H.
A Biomechanical Model for Analysis of Synthetic Saggital Plane Lifting. AIIE Transactions Industrial Engineering Research and Development Vol 11 No. 1. March 1970.

CHAPANIS A.
Research Techniques in Human Engineering. John Hopkins Press. Baltimore. 1959.

CLARKE H.H.
Analysis of Physical Fitness Index Scores of Air Crew Students at the close of a Physical Conditioning Program. Research Quarterly 16(1). 1945.

CLARKE H.H.
Muscular Strength and Endurance in Man. Prentice-Hall Englewood Cliffs N.J. 1966.

CLAUSER C.E. TUCKER P.E. McCONVILLE J.T. CHURCHILL E. LLOYD L.L.
Anthropometry of Air Force Women. Wright-Patterson Air Force Base. Ohio. Report No. AMRL-TR-70-5. April 1972.

CLAUSER C.E. McCONVILLE J.T. YOUNG J.W.
Weight, Volume, and Center of Mass of Segments of the Human Body. Wright-Patterson Air Force Base, Ohio. Report No. AMRL-TR-69-70. August 1969.

CLEMENTS E.M.B.
Body Measurements of the Working Population in:- Human Factors in Equipment Design (eds. Floyd W.F. Welford A.T.) 1954.

CLEVELAND H.G.
The Determination of the Centre of Gravity of Segments of the Human Body. Dissertation - University of California. Los Angeles. 1955.

CORLETT E.N.
Human Factors in the Design of Manufacturing Systems. Human Factors 15(2). 1973.

CORSER T.
Temporal Discrepancies in the Electromyographic Study of Rapid Movement. Ergonomics Vol. 17. No. 3. May 1974.

CURETON T.K.
Warfare Aquatics, Course Syllabus and Activities Manual Stipes Publishing Co. Champaign. I 11. 1943.

DAMON A. STOUDT H.W. McFARLAND R.A.
The Human Body in Equipment Design. Harvard University Press. Camb. Mass. 1966.

DEMPSTER W.T.
Space Requirements of the Seated Operator. W.A.D.C. Technical Report. Wright Patterson Air Force Base Ohio. July 1955.

DEMPSTER W.T. SHERR L.A. PRIEST J.G.
Conversion Scales for Estimating Humeral and Femoral Lengths and the Lengths of Functional Segments in the Limbs of American Caucasoid Males. Human Biology Vol. 36. 3. 1964.

DREYFUSS H.
The Measure of Man - Human Factors in Design. Whitney Library of Design. 2nd ed. 1967.

DRILLIS R. CONTINI R.
Body Segment Parameters. New York University Research Dev. R.TR. 1166.03. Sept. 1966.

EVERSHED D.G.
A Computer Model of Man for Workspace Assessment. Ph.D. Thesis. Dept. of Production Engineering and Production Management. Nottingham University. October 1970.

FICK R.
Handbuch der Anatomie und Mechanik des Gelenke. G. Fischer. Hena. 1904-11.

FISCHER O.
Theoretische Grundlagen fur eine Mechanik der lebenden Korpes. B.G. Teubner. Berlin. 1906.

FITTS P.M. et al.
Human Engineering for an Effective Navigation and Traffic Control System. Washington D.C. National Research Council. 1951.

FISHER B.O.
Analysis of Spinal Stresses During Lifting. M.Sc. Thesis University of Michigan. 1967.

GIERKE H.E. Von
Biodynamic Models and their Applications. Journal of the Acoustical Society of America. 50. 6 (Part 1) 1971.

GLANVILLE A.D. KREEZER G.
The Maximum Amplitude and Velocity of Joint Movement in Normal Male Human Adults. Human Biology 9. 1937.

GOLDSTEIN H.
Classical Mechanics. Addison-Wesley. Mass. 1950.

GRANDJEAN E. KOGI K.
Introductory Remarks to 'Methodology in Human Fatigue Assessment' (editors Hashimoto K. Kogi K. Grandjean E.) Proceedings of the Kyoto Symposium . Taylor & Francis Ltd. London. 1971.

HANAVAN E.P.
A Mathematical Model of the Human Body. M.Sc. Thesis U.S.A.F. Institute of Technology. 1964.

HANSEN R. CORNOY D.Y.
Annotated Bibliography of Applied Physical Anthropology in Human Engineering. WADC Technical Report 56-30. Wright-Patterson AFB Ohio. May 1958.

HARLESS E.
Die Statischen Momente der Menschlichen Gliedmassen. Abh. d. math-phys. Cl. d. Konigl. Bayer Akad. d. Wiss. Vol. 8. 1860.

HASHIMOTO K. KOGI K. GRANDJEAN E.
Methodology in Human Fatigue Assessment. (editors Hashimoto K. Kogi K. Grandjean E.) Proceedings of the Kyoto Symposium on 'Methodology of Fatigue Assessment'. Taylor & Francis, London. 1971.

HERTZBERG H.T.E.
Dynamic Anthropometry of Working Positions. Human Factors Vol 2, No. 3. August 1960.

HERTZBERG H.T.E. BURKE F.E.
Foot Forces Exerted at Various Aircraft Brake Pedal Angles. Human Factors 13 (5). 1971.

HUGHES B.J.
A Computer Graphics Approach to Modelling and Evaluating Workspaces. Ph.D. Thesis Dept.of Production Engineering and Production Mangement. Nottingham University. October 1972.

HUGH-JONES P.
The Effect of Limb Position in Seated Subjects on their Ability to Utilize the Maximum Contractile Force of the Limb Muscles. Journal of Physiology 105. 1947.

HUMAN FACTORS
(Special Edition on Human Factors and Law). 1972.

HUSTON R.L. HESSEL R. PASSERELLO C.
A Three-Dimensional Vehicle-Man Model for Collision and High Acceleration Studies. Paper presented to Automotive Engineering Congress. Detroit. 1974.

JONES J.C.
Design Methods: Seeds of Human Futures. London Wiley. 1970.

JORDAN N.
Allocation of Functions between Man and Machine in Automated Systems. Journal of Applied Psychology 47. 1963.

KARPINOS B.D.
Height and Weight of Selective Service Registrants Processed for Military Service during World War II. Human Biology. 30. 292. 1958.

KATTAN A. NADLER G.
Equations of Hand Motion Path for Workspace Design. Human Factors Col. 11(2). 1969.

KEMSLEY W.F.F.
Womens' Measurement and Sizes. H.M.S.O. London (Published by B.O.T. for Joint Clothing Council Ltd.). 1957.

KEMSLEY W.F.F.
Weight and Height of a Population in 1943. Ann. Eugenics. 15. 161. 1950.

KENNEDY D.N.
Preliminary Specification for a Work Task Description Language. Internal paper, Dept. of Production Engineering and Production Management. Nottingham University. 1973.

KENNEDY D.N.
'The SAMMIE System'. Workspace Modelling Manual. Internal Report. Dept. of Production Engineering and Production Management. Nottingham University.

KENNEDY K.W.
Anthropometry and Kinematics in Crew Station Design. Wright-Patterson Air Force Base. Ohio. AMRL. TR 72-75. also published in Proceeding of Inter-Agency Conference on Management and Technology in the Crew Systems Design Process. Sept. 1972.

KILPATRICK K.E.
A Model for the Design of Manual Work Stations. Ph.D. Thesis. University of Michigan. 1970.

KING B.G. MORROW D.J. VOLLMER E.P.
Cockpit Studies - The Boundaries of the Maximum Area for the Operation of Manual Controls. Naval Medical Research Institute. Bethsesda Maryland 1947.

KROEMER K.H.E.
COMBIMAN. Computerized Biomechanical Man-Model. Wright-Patterson Air Force Base, Ohio. Report No. AMRL-TR-72-16. April 1973.

KROEMER K.H.E.
Human Strength: Terminology, Measurement, and Interpretation of Data. Human Factors 12 (3). 1970.

LANGER C.
Lehrbuch des Anatomie des Menschen. Wilhelm Braumuller. Wies. 1865.

LANIER R.R.
Presacral Vertebrae of White and Negro Males. American Journal of Physical Medicine 25. 1939.

LUMING H. KRAUSE H.E.
A Model of Reach Capabilities of Man. Paper presented to the Automotive Engineering Congress. Detroit. February 1974.

MACCONAILL M.A. BASMAJIAN J.V.
Muscles and Movements - A Basis for Human Kinesiology. Williams and Wilkins. Baltimore 1969.

MAY J. WRIGHT H.B.
Heights and Weights of Business Men. Trans. Ass. Med. Off. 11. 143. 1961.

McHENRY R.R.
Multidegree, Nonlinear Mathematical Models of the Human Body and Restraint Systems. Applications in the Engineering Design of Protective Systems. Wright-Patterson A.F.B. AMRL-TR-71-29-7. 1971.

McHENRY R.R. NOAB K.N.
Computer Simulation of the Crash Victim - A Validation Study. Cornell Aeronautical Laboratory Inc. Buffalo N.Y. 1966.

METHODS-TIME MEASUREMENT ASSOCIATION.
Methods-Time Measurement, Application Training Course. Ann Arbor Press Ann Arbor 1964.

MICHELSON D.L.
CODA. Instrument for 3-D Movement Recording. Loughborough University of Technology. Report No. 145. October 1974.

MONOD H.
Contribution a l'etude du travail statique. Paris. These Medicine. 1956.

MORIOKA M. NUMAJIRI K. ONISHI N. SASAKI N.
Mechanical and Physiological Efficiency at Muscular Work with different Muscle Groups. Proceedings of the Kyoto Symposium. (eds. Hashimoto K. Kogi K. Grandjean E.) Taylor & Francis London. 1971.

MORRIS J.M. LUCAS D.B. BRESLER B.
Role of the Trunk in Stability of the Spine. Journal of Bone Joint Surgery Vol. 43A 1961.

MURRELL K.F.H.
Applied Psychology in the Production of a British Standard. Applied Ergonomics 4.1. 1973.

MURRELL K.F.H.
Ergonomics. Man in his Working Environment. Chapman and Hall. 1965.

NUBAR Y. CONTINI R.
A Minimal Principle in Biomechanics. Bulletin of Mathematical Biophysics. vol. 23. 1961.

PARADISE M.G.A.
Low Cost System for the Measurement of Posture. Undergraduate thesis. Dept. of Production Engineering and Production Management. Nottingham University. 1974.

PAYNE P.R. BAND E.G.U.
Development of a Dynamic Analog Anthropometric('Dynamic Dan') for Aircraft Escape System Testing. Wright-Patterson ARB Ohio. AMRL-TR-71-10. 1970.

PHEASANT S.
Plantar-flexar Torque: An Applied Anatomical Study. Paper presented to the Ergonomics Research Society Conference. Cambridge. April 1974.

PLAGENHOEF S.C.
A Kinetic Analysis of Running. Journal of U.S. Track Coaches Association. Quarterly Review. October 1968.

PLAGENHOEF S.C.
Computer Programs for Obtaining Kinetic Data on Human Movement. Journal of Biomechanics 1. 1968.

PLAGENHOEF S.C.
Patterns of Human Motion. A Cinematographic Analysis. Prentice-Hall. New Jersey. 1971.

PLAGENHOEF S.C.
Methods for Obtaining Kinetic Data to Analyse Human Motions. The Research Quarterly 37.1. 1966.

PRATT F.M. CORLETT E.N.
The Ergonomics of Vertical Tower Lathe Operation. Applied Ergonomics 1 (5). 1970.

ROHMERT W.
Ermittlung von Erholungspausen fur statische Arbeit des Menschen. Internationale Zeitschrift fur angewandte Physiologie 18. 175.190(a) 1960.

RYAN P.W.
Cockpit Geometry Evaluation. Phase II-A. Final Report. Vol 1. - Program Description and Summary. Janair Report 701213. November 1971.

RYAN P.W. SPRINGER W.E. HLASTALA M.P.
Cockpit Geometry Evaluation. Phase II. Final Report. Vol. II - Human Data. Janair Report 700202. February 1970.

SAITO H. KISHIDA T. ENDO Y. SAITO M.
Studies on Monotonous Work (II) Comparison of Different Work Control Systems. Journal of Science of Labour 47 1971.

SANTSCHI W.R. et al.
Moments of Inertia and Centers of Gravity of the Living Human Body. Wright-Patterson AFB, Ohio. AMRL-TR-63-36. May 1963.

SHELDON W.H.
The Varieties of Human Physique. Harper & Bros. New York. 1940.

SINELNIKOFF E. GRIGOROWITSCH M.
Die Beweglikeit der Gelenke als sekundares geschlechtliches und konstitutionelles Merkmal. Zeitschrift fur Konstitutions-lehre 15. 1931.

SINGLETON W.T.
A Preliminary Study of a Capstan Lathe. International Journal of Production Research. Vol. 3. No. 3. 1964.

SLOTE L. STONE G.
Biomechanical Power Generated by Forearm Flexion. Human Factors Vol 5. No. 5. 1963.

SNYDER R.G. CHAFFIN D.B. SCHUTZ R.K.
Link System of the Human Torso. Wright- Patterson Air Force Base, Ohio. AMRL-TR-71-88. August 1972.

STRASSER H. GASSMANN A.
Hulfsmittel und Normen zur Bestimmung und Veranschaulichung des Stellungen, Bewegungen und Kraftwirkungen am Kugelgelenk, insbesondere am Huft- und Schultesgelenke des Menschen. Anat. Hefte. Vol. 2 (617). 1893.

SWAIN A.D. WOHL J.G.
Factors Affected Degree of Automation in Test and Checkout Equipment. Dunlop and Assoc. Stamford. Conn. 1961.

TAKAKUWA E.
Maintaining Concentration (TAF) as a Measure of Mental Stress. Paper in the Proceedings of the Kyoto Symposium on 'Methodology in Fatigue Assessment' (eds. Hashimoto K. Kogi K. Grandjean E.). Taylor & Francis Ltd. London 1971.

THORDSEN M.L. KROEMER K.H.E. LLOYD L.L.
Human Force Exertions in Aircraft Control Locations.
Wright-Patterson Air Force Base, Ohio. AMRL-TR-71-119.
Feb. 1972.

TROTTER M. GLESER G.C.
A re-evaluation of Estimation of Stature based on measurements of stature taken during life and of long bones after death.
American Journal of Physical Anthropology 10. 1952.

TROTTER M. GLESER G.C.
Estimation of Stature from Long Bones of American Whites and Negroes. American Journal of Physical Anthropology 16. 1958.

WARNER H.D. MACE K.C.
Effects of Platform Fashion Shoes on Brake Response Time. Applied Ergonomics 5.3. 1974.

WARREN SPRING LABORATORY
Anthropometric Data for Designers. A Critical Evaluation.
Research Report No. RR/ES/58. May 1964.

WEST C.C.
Measurement of Joint Motion. Archives of Physical Medicine 26. 1945.

WHITFIELD D.
Human Skill as a Determinate of Allocation of Function.
Proceedings of the Conference on the Human Operator in Complex Systems. Tayor & Francis Ltd. London. 1967.

WHITSETT C.E.
Some Dynamic Response Characteristics of Weightless Man.
M.Sc. Thesis Air Force Institute of Technology. Wright-Patterson Air Force Base, Ohio. AMRL-TR-63-18.
AD 412 541). 1962.

WOODSON W.E. CONOVER D.W.
Human Engineering Guide for Equipment l: Designers. Second Edition. University of California Press. 1970.

WULFECK J.W. ZEITLIN L.R.
Human Capabilities and Limitations (in) Psychological Principles in System Development. (edited by R.M.Gagne)
New York. 1962.

The I.E.S. Code. Recommendations for Good Interior Lighting. Illuminating Engineering Society London. 1961.

Guide for Conservation of Hearing in Noise. The American Academy of Opthalmology and Otolaryngology. Los Angelus. 1957.