THE DYNAMIC AND STATIC STRENGTHS OF ~~THE HUMAN IN~~ WHOLE BODY EXERTIONS IN THE HUMAN

by

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ABSTRACT

The characteristics of whole body manual exertions were investigated in both males and females under a wide range of conditions of posture, hand height, direction of exertion and task resistance. Many of these conditions were novel.

The many factors which influence force exertion were reviewed and a computerized bibliography on human strength was prepared. Two experimental studies investigated the influence and interrelationships of hand/handle interface, gravitational and musculo-skeletal limitations on the ability to produce maximal static forces. A third study introduced novel strength testing equipment, protocol, data processing and display techniques in order to extend the measurement and analysis into three dimensions. A final study compared static lifting strength with maximal one and two-handed dynamic lifting performance against a range of resistances on an isoresistive hydrodynamometer.

A good association was found between dynamic and static measures of whole body strength. However, different relationships between the two were observed in one and two-handed, and in male and female exertions. It was further concluded that dynamic and static measures of whole body strength cannot reliably be predicted on the basis of body weight and stature alone when the exerted force is directed along the line joining the foot and hand centroids. In other directions of exertion, where gravitational limitations play a more dominant role in the strength of exertion, reasonable predictions of whole body static strength may be obtained using a simple linear regression model with body weight and stature as independent variables.

Extension of the *Postural Stability Diagram* into three dimensions and dynamic models of lifting strength based on the results are discussed as possible aids for task analysis in manual materials handling.

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CHAPTER 1

INTRODUCTION

In order for a person to live a functionally independent life, he or she must be able to perform coordinated and forceful physical actions. The degree of forceful effort required depends on the type of task to be accomplished, and ranges from that needed to simply move a particular joint, to the maximum possible force which may be demanded under extreme circumstances.

The largest forces that an unaided individual may exhibit are most likely to occur during whole body exertions. These type of exertions are not confined to an isolated muscle group but require the active involvement of both the upper and lower limbs and trunk to retain postural stability and effect a desired action. The capacity of an individual to perform these type of exertions will influence not only their proficiency in recreational/sporting activities but also their ability to carry out daily routines at home and work.

Although modernisation has reduced the burden of many physically demanding tasks, numerous occupations still entail some form of manual materials handling. The whole body strength capability of the human is therefore a key element in dictating whether heavy manual tasks can be performed efficiently and safely.

With increasing legislation enforcing safe work practises in the occupational environment, various organisations concerned with health and safety have developed guidelines and regulations for manual handling activities (e.g. Health and Safety Executive 1988, NIOSH 1981, British Coal Ergonomics Group 1990). Although complex models exist, which predict the amount of physical stress on the human body for a given manual handling task (e.g. Garg & Chaffin 1975, NIOSH 1981), these models can only provide the roughest guidelines on the safety of manual exertions. This is partly due to the limited amount of epidemiological data available, linking given levels of exertion to risk of injury, and partly due to the limited number of conditions and many assumptions on which the human strength data has been derived to formulate these models. One class of activity for which there is a particular lack of information is that of single-handed whole body exertions.

In comparison to the large array of literature covering vertical two-handed lifting and horizontal pushing and pulling activities, only a hand_full of studies have investigated the strength of single-handed whole body exertions (McConville & Hertzberg 1968, Davis and Stubbs 1980, Warwick *et al.*, 1980).

It may be hypothesised that the lack of data on one-handed whole body strength capabilities may be the result of an assumption that heavy manual materials handling tasks will wherever possible be performed with two-hands.

In contrast to this assumption, it is easy to envisage many situations in which manual handling activities necessitate or preferentially dictate that a task, or a portion of a task, be performed one-handed rather than two-handed (e.g. airport luggage handling). Even if most heavy manual handling tasks are performed two-handed it does not necessarily follow that the load is shared equally between both hands. For example, an imbalance in load between the left and right hands may occur during manual handling of irregular shaped objects or those with uneven mass distribution. Consequently, there may be situations during two-handed exertions when the majority of the load may be moved or borne single_handedly.

In order to examine the likelihood of injury or the possibility of dropping the object during manovering of heavy loads, a logical first step would be to obtain information on the strength of single-handed exertions. Unfortunately, application of currently available one-handed whole body strength data to general situations encountered in the working environment is somewhat restricted.

A common feature of most studies on whole body exertions is that of rigidly defining foot and hand placement thereby limiting the choice of posture available to the subject. In addition, few researchers apart from Grieve and coworkers (Grieve 1979a, 1979b, Grieve & Pheasant 1981; Pheasant & Grieve 1981; Pheasant *et al.*, 1982) have explored directions of exertion beyond the purely vertical or horizontal. As a consequence, whole body strength data have been more representative of the conditions imposed by experimental constraints than of the real strength capabilities of human beings in freely chosen postures and directions of exertion they would normally use in real world working tasks.

Experimental procedure and strength testing protocol are therefore important factors to consider when interpreting and applying the various data on human strength. Because of the use of different apparatus, techniques and conditions under which human strength has been measured much of the data in the literature can not be directly compared. Furthermore, the absolute strength of an individual performing a given task can vary widely according to the exercise conditions under which the individual is tested.

In order to appreciate the general attributes of strength of an individual, rather than that specifically attributable to the nature of the task involved, direct comparisons of strength tests performed under different exercise modes are needed. Experiments of this nature are particularly required to assess the reliability of using static measures of whole body strength to predict dynamic capabilities.

In summary, there are a multitude of factors which may limit an individuals capacity for forceful effort. The primary concern of the present work, however, is directed towards the role of a number of anthropometric and biomechanical factors in the determination of maximal whole body exertions in the healthy human. The main objective of the thesis was to investigate the influence of these factors on whole body strength capabilities under conditions and directions of exertion that have been previously unexplored.

General Aims of the Study

The main aims of the thesis were to:

(1) Describe and compare the dynamic and static strengths of single-handed and two-handed whole body exertions in the human.

(2) Determine the influence and relative importance of sex and a number of anthropometric, interfacial and musculoskeletal factors on force exertion.

The thesis approaches these general aims in several stages. The first stage involves a review of the literature and presentation of the theoretical framework used in the analysis of whole body exertions. The second stage involves the experimental work and is comprised of four studies which incorporate and develop the theoretical analysis through the complexities of one, two and three dimensional analysis of whole body static strength, to the dynamics of whole body lifting strength. Concluding remarks summarizing the findings of the experimental work are provided in the final Chapter of the thesis.

Definition of Human Strength

As "strength" is a term that is used in many different ways in everyday life, it is necessary to define its precise meaning in the context of the present work.

In the past several authors have reviewed the literature on human strength and presented some of the many definitions that have been proposed (Kroemer 1970, Atha 1982, Kulig *et al.*, 1984). Three examples illustrating the general form of these definitions have described strength as:

> "the maximal force muscles can exert isometrically in a single voluntary effort" (Kroemer 1970).

> "the ability to develop force against an unyielding resistance in a single contraction of unrestricted duration" (Kulig *et al.*, 1984).

> "the strength of a muscle or homogeneous muscle group (i.e. a group of muscles that have neighbouring attachment sites, share a functional role, and act simultaneously) is the magnitude of the variable force that this contractile entity exerts on the skeletal system at the attachment sites of interest" (Kulig *et al.*, 1984).

A common failing of these definitions are that they are too restrictive to be of general use considering the wide variety of present-day strength testing environments.

In the first and the third definitions the action of muscles is given primary importance in force production. As shown by Dempster (1958) and more recently by Pheasant (1977) and Grieve (1979) there are many situations in which a subject's effective strength is not primarily dependent on the capacity of muscles to develop forces. According to Dempster (1958) the strength of 'static' whole body pulling actions are predominantly dictated by the distribution of body mass and postural stability. Under these circumstances the action of muscles simply maintain joint postures in order to allow body weight to be effectively deployed (Pheasant 1977).

Although the second definition avoids this problem by omitting any reference to "muscular" force, its application is limited as in the first definition to a particular state of muscle activity, namely static contractions. In comparison, the third definition defines strength as a scalar variable which may change with time and is not associated solely with one particular state of muscle activity (e.g. isometric, concentric or eccentric contractions) (Kulig *et al.*, , 1984). Unfortunately, this latter definition is only applicable to localized single joint actions, and requires either a quantitative knowledge of the internal geometry of the particular joint of interest, or a direct measure of force at the muscle attachment site.

As direct measures of muscle force in the human are rarely performed (Komi 1990 is one example), the quantity actually measured is usually a net torque about a given articulation. In most measures of strength the nature of the testing device and the point of attachment of the force sensor to the limb/body (relative to the axis of rotation of the limb or task in question) plays an important role in the subsequent output of a given action.

In view of the above issues it was decided to adopt a revised version of the definition of strength originally proposed by Pheasant (1977). In his PhD thesis Pheasant defines the strength of an action as "the maximal steady force or torque which an individual can voluntarily exert on an external test object under given conditions". In order for this definition to be applicable to the present work, slight modifications are required to deemphasise static exertions and include a reference to other exercise conditions. The following definition of strength is therefore proposed.

THE STRENGTH OF AN ACTION IS THE MAXIMAL FORCE OR TORQUE WHICH AN INDIVIDUAL CAN VOLUNTARY EXERT ON AN EXTERNAL TEST OBJECT UNDER A PARTICULAR SET OF ENVIRONMENTAL AND EXERCISE CONDITIONS.

As pointed out by Pheasant (1977) the above statement is a purely operational definition which makes no prior assumptions about the biomechanical or physiological determinates of human strength. However, as the current work deals with both static and dynamic activities further clarification is required to define strength under these different exercise conditions. The following section therefore deals with conventions and definition of terms which are referred to throughout the various chapters of this thesis.

Conventions and Definition of Terms

Static Strength: Refers to the steady maximum voluntary force or torque an individual can exert on an external test object when no apparent observable movement or external work occurs. Also termed ***isometric strength***, these exertions involve muscular contractions in which the overall length of the active muscles remain fairly constant.

As static strength may be measured over varying time periods several authors have proposed a standardized protocol (Caldwell *et al.*, 1974, Chaffin 1975) for its measurement. For the purpose of the present work steady maximum strength is defined as the mean force observed over the last few seconds of a maximum effort maintained over a five second duration. The largest force observed over this time period, (excluding observations clearly attributable to jerking actions) is termed the peak strength. All observations of whole body static strength reported in Chapters 4 and 5 of this thesis conform to this latter strength measurement.

Dynamic Strength: Refers to the maximum force or torque an individual can exert on an external test object during a single voluntary effort when some overt movement can be observed and measurable work is performed. During dynamic exertions the muscles may contract concentrically (i.e. the overall length of the muscle shortens during contraction) to produce positive work, or contract eccentrically (i.e. the overall length of the muscle becomes longer while contracting) to produce negative work.

Because of the large array of strength testing devices currently available, dynamic strength has been assessed in many different ways. Listed below are the various measures of dynamic strength classified according to the type of task resistance.

Isokinetic Strength: The maximum force or torque an individual can exert during a single voluntary effort against an external test object constrained to move at a preset constant velocity.

Isoinertial Strength: Measures the ability of a person to overcome the inertia of a freely movable mass by measuring the maximum amount of weight he or she can handle and move to an assigned point at a freely chosen speed (Ayoub & Mital 1989).

Isoresistive Strength: The maximum force or torque an individual can exert during a single voluntary effort against an external test object constrained to operate at a preset resistance, in which the ratio of the measured force/velocity^{X} is constant.[1]

One other class of strength measurement that has been employed by early investigators is that of the ***breaking strength*** (Lovett & Martin 1916, Hunsicher & Donelly 1955, Rasch & Pierson 1960). Breaking strength refers to the maximum amount of force or torque which an individual can exert in order to resist a forceable extension of the limb or muscle group in question. Due to the limited application of this particular measure of strength to everyday activities, current practice has been to measure actively exerted forces rather than actively resisted forces. Consequently, measures of breaking strength have fallen from general use in the literature.

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[1] By using an analogy with electronic theory, the ratio of force/velocity^{X} may be considered as a measure of the resistance of an exertion. The power to which the velocity is raised will depend on the particular physical characteristics of the strength testing device. If the resistance to motion is provided by the movement of a piston through a fluid, the main factor on which the value of X is dependant will be the viscosity of the fluid contained in the device.

Absolute Strength: Measurements of strength may be expressed in absolute terms by values in kilograms of force (kgf) or in Systeme International d'Unités (SI) of force (i.e. Newtons (N)). The corresponding units of torque are therefore kgfm or Nm.

Normalised Strength: Alternatively, strength measurements may be normalised by dividing by the individuals body weight. If both the strength and body weight are expressed in the same units, the resulting normalised strength is a simple dimensionless ratio. Strength may therefore be expressed as a percentage of body weight.

Other terms and abbreviations used in the thesis are listed below.

Postural Stability Diagram (PSD): A graphical medium for presentation and analysis of co-planar forces at either the hands or the feet during whole body static exertions (see Grieve 1979a ,b).

The Maximum Advantage of using a Component of Exertion (MACE): For a given force vector plotted on the PSD, a circle can be described around it representing the maximum components that are possible in each direction. If this procedure is repeated for all force vectors on the PSD envelope a new envelope is described representing the maximum components that are possible in each direction. The MACE, in a given direction is defined as the ratio of the maximum available component compared with the directed resultant in that direction.

The conventions used to denote the sign, direction and movement action of whole body forces in three dimensions is presented in Figure 1.1. The movement action conventions are based on single-handed whole body exertions performed on the left-handed version of the dynamometer described in Chapter 5.

The terms medial-lateral and lateral-medial exertions refer to movement actions in the transverse plane performed away and towards the midline of the body respectively. The labelling of these terms in Figure 1.1C will of course be reversed whenright-handed exertions are measured.

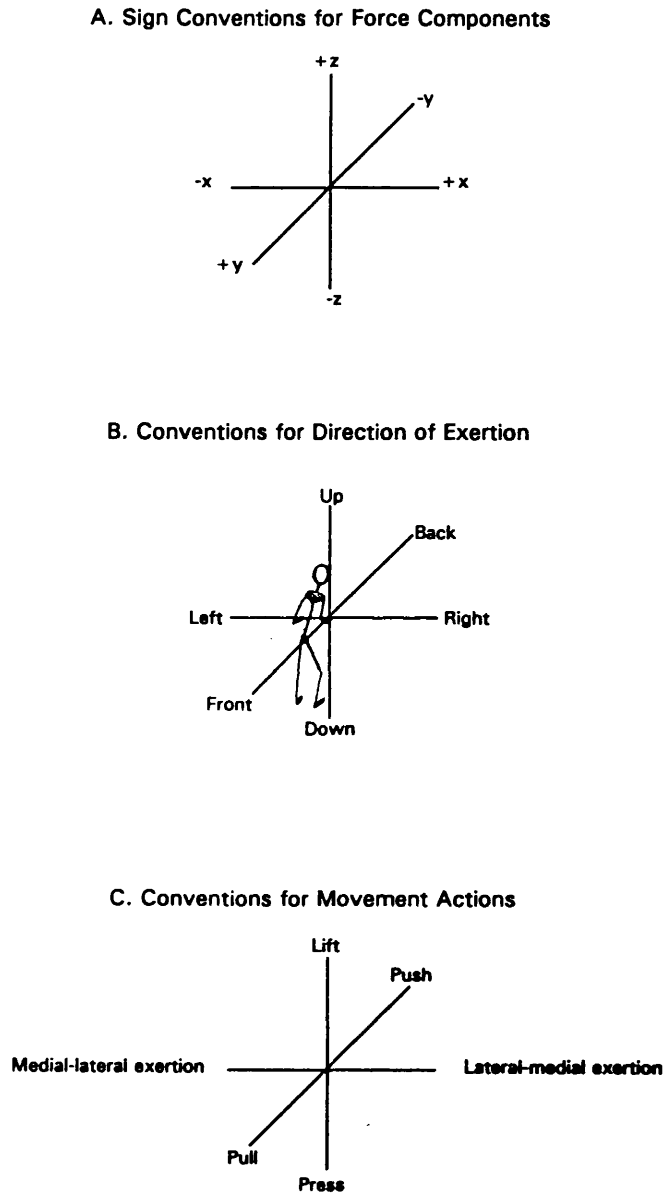

Figure 1.1: Conventions used to denote the sign of manual forces (A), directions of exertion (B), and movement actions of whole body exertions in three dimensions (C). The location of the subject with respect to these axes is shown in the centre figure.

CHAPTER 2

A SUMMARY OF THE LITERATURE ON HUMAN STRENGTH

Introduction

Research into human strength has been carried out not only within the traditional disciplines of anatomy, physiology, medicine, psychology, engineering, but also among the more recent multi-disciplinary areas of biomechanics, psychophysics, ergonomics and kinesiology. Even within the relatively new field of biomechanics, subdisciplines are developing (i.e. sports biomechanics, orthopaedics and occupational biomechanics) which approach the study of human strength with different concerns and objectives. Consequently, the scientific literature on human strength is spread across a cornucopia of books and journals.

In the field of manual materials handling, the growing need to collate this information has been recognised by several authors. As a result, several comprehensive texts have been published covering much of the scientific literature on human strength in this field (Brown 1972, Chaffin and Andersson 1984, Ayoub and Mital 1989).

The above texts are specifically directed towards the problems and hazards of manual materials handling and to providing ergonomic solutions for alleviating them. Consequently, there is minimal reference to work on human strength published in other fields. It was intended therefore, that the literature on human strength be collated from a broader base so that different perspectives and emphases on performance measures of human strength may be represented.

In order to satisfy this objective, the literature review was divided into two sections. The first section deals with the design and implementation of a computerized bibliography in which much of the current knowledge on human strength is contained. The second section of the literature review focuses on the literature directly relevant to the issues of the current thesis.

PART I:
A COMPUTERIZED BIBLIOGRAPHY OF HUMAN STRENGTH

Content and Source Material of the Bibliography

The bibliography was primarily designed towards the needs of the researcher, task designer, or ergonomist who may wish to research a particular problem on human strength. The content of the data base was constructed with these users in mind. The medical practitioner wishing to find out more about how a particular course of treatment (e.g. drugs or surgery) or medical condition (e.g. myasthenia gravis) influences human strength may find the bibliography of marginal use.

Epidemiological and performance studies associated with manual handling activities are covered comprehensively. In particular much of the recent literature concerning back problems in manual handling has been included. The bibliography also contains selected references related to human strength from the sports science literature. Typical topics covered include training regimens, the influence of drugs (e.g. steroids) and biomechanical analysis of performance.

The source material for the bibliography was derived not only from papers published in journals and books, but also from theses, legislation, government reports and conference proceedings. During collation of the material several large computer and optical disk data bases were searched. These included MEDLINE, NIOSHTIC (National Institute for Occupational Safety and Health (U.S.)), HSELINE (Health and Safety Executive (U.K.)), CISDOC (International Labour Organisation) and SPOR (Data-Star Sport data base). A typical search strategy used to interrogate the MEDLINE data base is outlined in Table 2.1.

Table 2.1:
A search strategy used to interogate the MEDLINE data base for literature on human strength

No.	Records	Request
1:	40	LIFT
2:	11	LIFTS
3:	69	LIFTING
4:	106	LIFT or LIFTS or LIFTING
5:	97	PULL
6:	21	PULLING
7:	55	PUSH
8:	13	PUSHING
9:	157	PULL or PULLING or PUSH or PUSHING
10:	1210	STRENGTH
11:	135	STRENGTHS
12:	1304	STRENGTH or STRENGTHS
13:	368	MANUAL
14:	938	HANDLING
15:	3966	CAPACITY
16:	325	CAPABILITY
17:	4265	CAPACITY or CAPABILITY
18:	3593	WORK
19:	6212	MODEL
20:	7708	MODELS
21:	11510	MODEL or MODELS
22:	1326	MUSCULAR
23:	1028	POSTURE
24:	189	POSTURAL
25:	1103	POSTURE or POSTURAL
26:	803	LOAD
27:	583	LOADING
28:	1317	LOAD or LOADING
29:	781	BIOMECHANICS
30:	135	BIOMECHANICAL
31:	826	BIOMECHANICS or BIOMECHANICAL
32:	142	INTRA-ABDOMINAL
33:	11696	PRESSURE
34:	18	INTRA-ABDOMINAL and PRESSURE
35:	898	FORCE
36:	426	FORCES
37:	1241	FORCE or FORCES
38:	112	PSYCHOPHYSICS
39:	109	PSYCHOPHYSICAL
40:	13	(PSYCHOPHYSICS or PSYCHOPHYSICAL) and (#37 or #18 or #12)
41:	28	#4 and (#12 or #17 or #28 or #18)
42:	9	#9 and (#12 or #17 or #18 or #28)
43:	43	#13 and (#14 or #4 or #12 or #18 or #37)
44:	83	#25 and (#28 or #37 or #18)
45:	62	#22 and (#37 or #12)
46:	50	#31 and #21 and (#25 or #37 or #12)
47:	280	#34 or #40 or #41 or #42 or #43 or #44 or #45 or #46
48:	202896	LA=ENGLISH
49:	236	#47 and LA=ENGLISH
50:	180026	HUMAN
51:	191	#49 and (HUMAN in MESH)

The selection of key words and combinations of key words used in the searches were designed to locate as wide a range of literature on human strength as possible. The search strategy in Table 2.1 was based on combinations of key words found in the titles of relevant papers on human strength reported in the last 25 years of the Ergonomics journal. This particular journal was selected because of the availability of a full complement of back issues and the fact that it was highly likely to contain a large number of relevant papers. In order to ensure that the majority of relevant papers were identified, this latter search was performed manually.

A break down of the number of articles in the data base for each year of publication from 1960 to 1990 is shown in Figure 2.1.

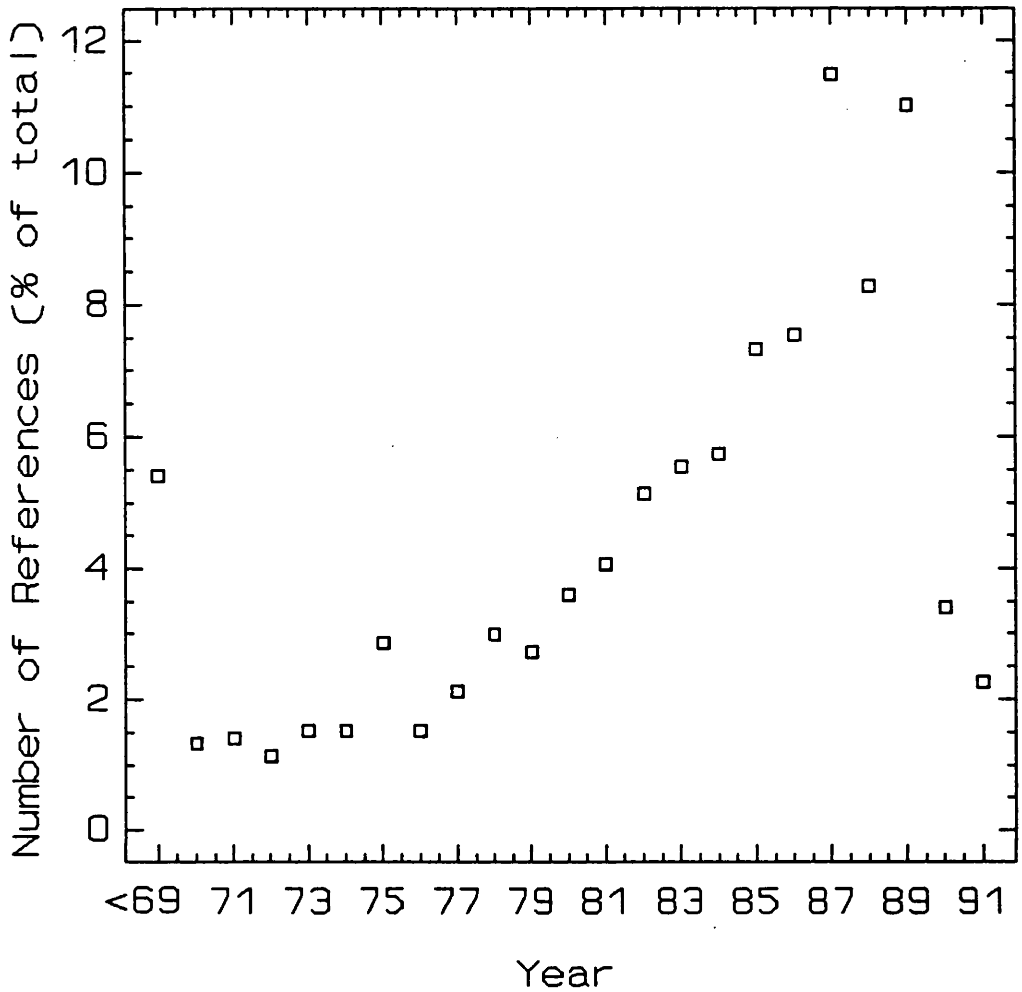

Figure 2.1: Number of articles by year contained in the computerized bibliography on human strength. The data is presented as a % of the total number of references in the data base at the time of writing.

Data Base Structure

In order for the collated material to be accessed quickly and efficiently, all references were entered into a large data base on an IBM PC. Initially a commercial software package called DBASE IV (Ashton Tate Corporation) was used to structure the information and provide an interface to search the data base. For detailed information concerning the operation of this software the reader is referred to the comprehensive set of manuals (Ashton Tate Corporation, 1990).

This particular software enables the user to design and structure the data base according to individual requirements. For the purpose of the bibliography the 12 fields illustrated in Table 2.2 were created. Most fields are self explanatory and refer to the individual elements of information included in standard reference formats. The NUMBER field may be used to associate a given reference with a particular filing code. The ABSTRACT field is a separate but related text file containing an abstract or notes on the particular reference. A description of the contents in the CLASSNO field is provided in a later section.

The field type and field width indicate the size and type of information contained in a particular field. Since it was expected that some references may contain a large number of authors or keywords these fields were allocated the maximum field width of 250 characters. The ABSTRACT field however, is not restricted by this limitation.

The various field sizes were chosen to optimize the balance between; (1) a complete coding of all the information contained in the majority of references and, (2) the amount of computer time and memory that would be required to process and store this information. It should be noted that any subsequent changes to the field width or type once they have been defined may corrupt existing data contained in the data base.

Table 2.2:
The data base structure of the DBASE IV file C:\dbase\mod\strength

Field Name	Field Type	Width	Dec	Index
NUMBER	Numeric	6	0	N
AUTHORS	Character	100		Y
TITLE	Character	250		N
SOURCE	Character	200		N
YEAR	Numeric	4	0	Y
VOLUME	Character	15		N
PAGES	Character	10		N
KEYWORDS	Character	250		N
BOOKEDS	Character	50		Y
PUBLISHER	Character	25		N
CLASSNO	Character	50		N
ABSTRACT	Memo	10		N

Input of Data into the Data Base

Data may be entered into the database manually via the keyboard, or imported directly from other databases via transfer of information on floppy diskette. Before information from other computer data bases can be imported, the incoming data must be in a format compatible with the file structure in Table 2.2.

As a large proportion of the data was derived from the MEDLINE database, a specially designed computer program, written in PASCAL, was used to convert a file created from a MEDLINE search into a format suitable for import into the DBASE IV database. Due to the nature of the Memo field, abstracts could not be imported directly and therefore had to be entered manually.

As considerable time and effort was required to enter the abstracts manually, the data was also incorporated into a commercial software package specifically designed for management of bibliographic material (Reference Manager (version 5), Research Information Systems Inc.). This software permitted downloaded MEDLINE searches, including the abstract field, to be directly imported into a Reference Manager formatted database. Import from other on-line facilities is possible, although some editing of files is necessary before and after importing files from the NIOSHTIC, SPOR and HSELINE databases. Full details on the operation of the Reference Manager software are provided in their manual.

A Customized Classification System for Bibliographic Material on Human Strength

The bibliographic material may be interrogated by author, source (journal/book name), year or by key words in the title, notes or key words field, as well as by using a combination of these fields. If however the objective is to find information relating to a specific practical problem (say for example a given manual handling task), search procedures become lengthy and complicated, and often tend to retrieve irrelevant or miss relevant references. The objective of developing a classification system for bibliographic material on human strength was to simplify and make more efficient searches requiring this latter approach.

Figure 2.2 shows the various categories which were used to classify the content of any given paper. These categories were organised and developed to enable the task designer or ergonomist to customise his search to the problem at hand, by selecting appropriate elements of concern. This is best explained by example.

APPLICATION (A)

- (1) Lifting & Handling (object is freely mobile)
- (2) Controls (e.g. levers pedals)
- (3) Fixtures (e.g. doors)
- (4) Tools

TASK (B)

- (1) Lift
- (2) Lower/ Place
- (3) Push
- (4) Pull
- (5) Carry
- (6) Torque Twist
- (7) Combination of 3 or more tasks

MUSCLE ACTION (C)

- (1) Single static
- (2) Single dynamic
- (3) Repeated static
- (4) Repeated dynamic
- (5) Sustained exertion
- (6) Combination of 3 or more muscle actions

BODY PART & ASSOCIATED MUSCLES (D)

- (1) Whole body
- (2) Lower appendages
  - (.1) Ankle
  - (.2) Knee
  - (.3) Hip
- (3) Torso
  - (.1) Neck
  - (.2) Trunk
- (4) Upper appendages
  - (.1) Shoulder
  - (.2) Elbow
  - (.3) Wrist
  - (.4) Grip
  - (.5) Fingers
- (5) Combination of 3 or more body parts

INDEPENDENT VARIABLES AFFECTING FORCE OUTCOME (E)

- (1) 1 or 2 hands
  - (.1) 1 hand
  - (.2) 2 hands
- (2) Handgrip
- (3) Footing
- (4) Posture
  - (.1) Symmetrical
  - (.2) Asymmetrical
- (5) Spacial constraints
- (6) Injury/ disability
- (7) Combination of 3 or more variables

POPULATION FOR STANDARDS, NORMS AND EXPERIMENTAL DATA (F)

- (1) Military males
- (2) Military females
- (3) Civilian males
- (4) Civilian females
- (5) Age 16-19

TECHNIQUES FOR EXERTION ASSESSMENT (G)

- (1) Force meas't
- (2) IAP IDC
- (3) Psycho/ physical
- (4) Physiological
- (5) Predictive models
- (6) Combination of 3 or more techniques

Figure 2.2: Classification schema for bibliographic material on human strength

Suppose an ergonomist is interested in investigating a task involving the manual handling of ammunition boxes from the floor into the back of a truck. The first step in obtaining relevant references related to this problem is to recognise the key elements in this task which are of primary concern. If the problem is considered as a two-handed whole body dynamic lift of a freely movable object by military personnel, it would be given the classification A1, B1, C2, D1, E1.2, F1, F2.

In a similar manner, various papers entered in the computerized bibliography are classified according to the key elements shown in Figure 2.2. These classification codes (i.e. A1, B1, C2 etc) relating to content of each paper are located in the CLASSNO field of the DBASE IV database, or in the KEY WORDS field of the Reference Manager database. Thus, if a search is performed using the classification codes as in the above example, only papers previously classified with all these elements will be retrieved.

The computer search may be made as specific or general as required by appropriate selection of classification codes. Thus someone concerned with pushing tasks in general may search the data base for any paper containing the classification code B3. Alternatively, relevant papers relating whole body static lifting exertions with intra abdominal pressure (IAP) or intra discal pressure measurements (IDC) may be retrieved by searching with the combination of classification codings C1, D1, G2.

Summary Remarks on the Literature on Human Strength

Summarising the literature in the data base, the many factors shown to influence human strength may be broadly categorized into the six main areas illustrated in Figure 2.3. However, this simple schema belies the true nature of human strength, which only begins to be appreciated when the many individual factors known to affect force exertion are put in perspective.

Figure 2.4 elaborates on the main areas presented in Figure 2.3 to include the direct and indirect influences of only a few of the main factors which have received study in the literature concerning their influence on force exertion. Some of the individual factors shown in Figure 2.4 are themselves affected by a complex array of variables. This is illustrated further by Figure 2.5 in which the dominant physiological/biomechanical factors affecting force exertion are illustrated. The arrangement of Figure 2.5 shows the main mechanical factors which influence force exertion on the left, task and musculoskeletal factors down the centre, and fatigue down the right hand side of the schema. Although the requirements of a given task may be shown to influence one or more of the variables in these catagories, the ultimate effect on force exertion depends on a complex interaction among many of these factors.

Some of the elements in Figure 2.5 are investigated in detail in relation to whole body exertions in the following literature review and experimental work. As the present thesis is directed towards a biomechanical study of human whole body manual strength, it is beyond the scope of the current work to provide all but a brief reference to material peripheral to the main analysis. The bulk of the following literature review thus concentrates mainly on biomechanical determinates of human whole body manual strength. For material on other aspects of human strength the reader is directed to the computerized database.

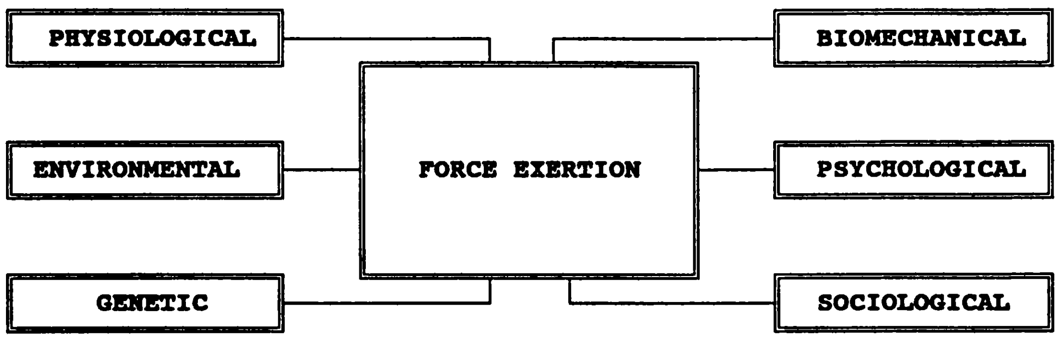

Figure 2.3: The six main areas that combine to influence human strength capabilities and the ability to exert manual forces.

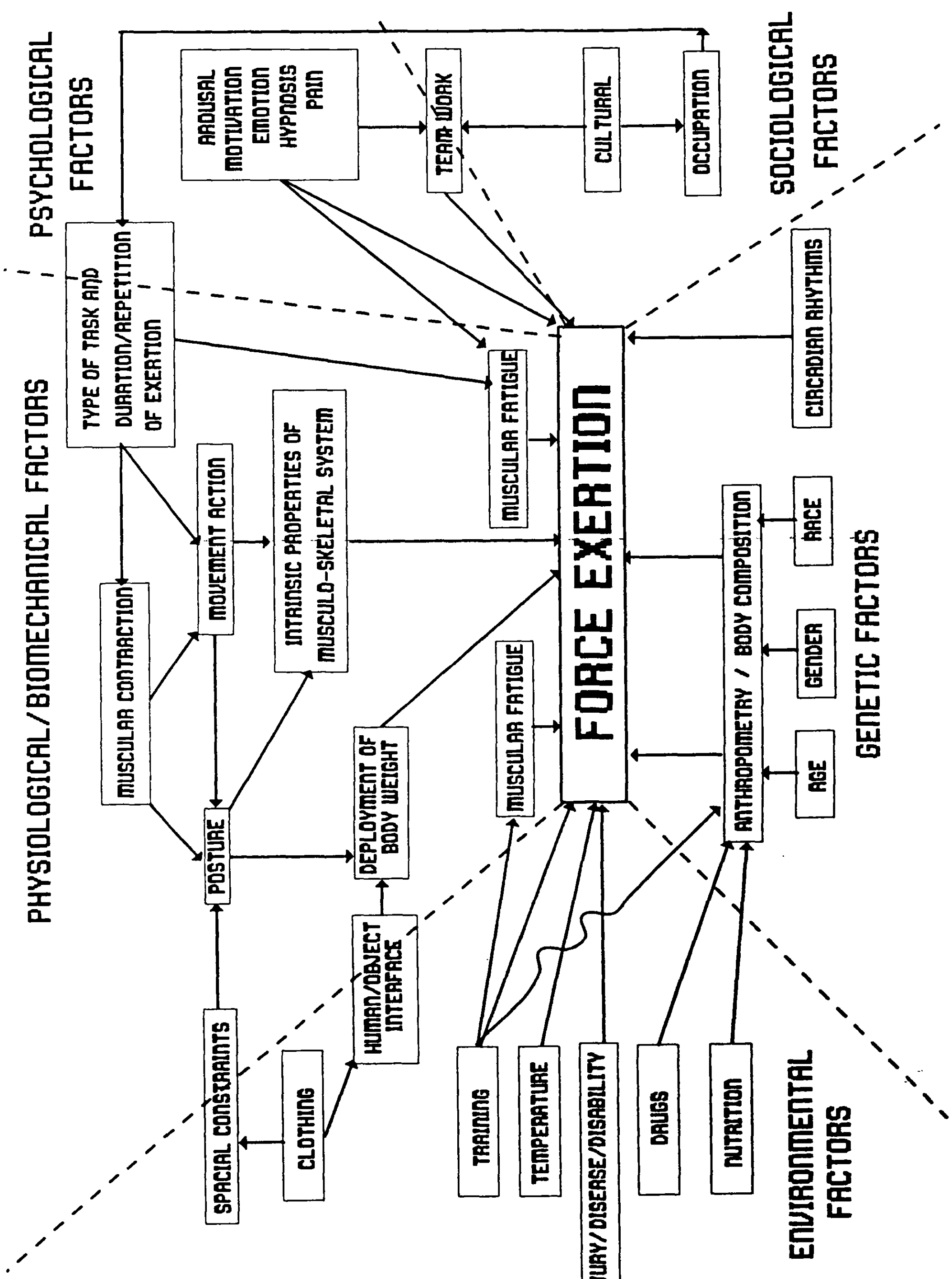

Figure 2.4 : A schema of the main factors influencing force exertion

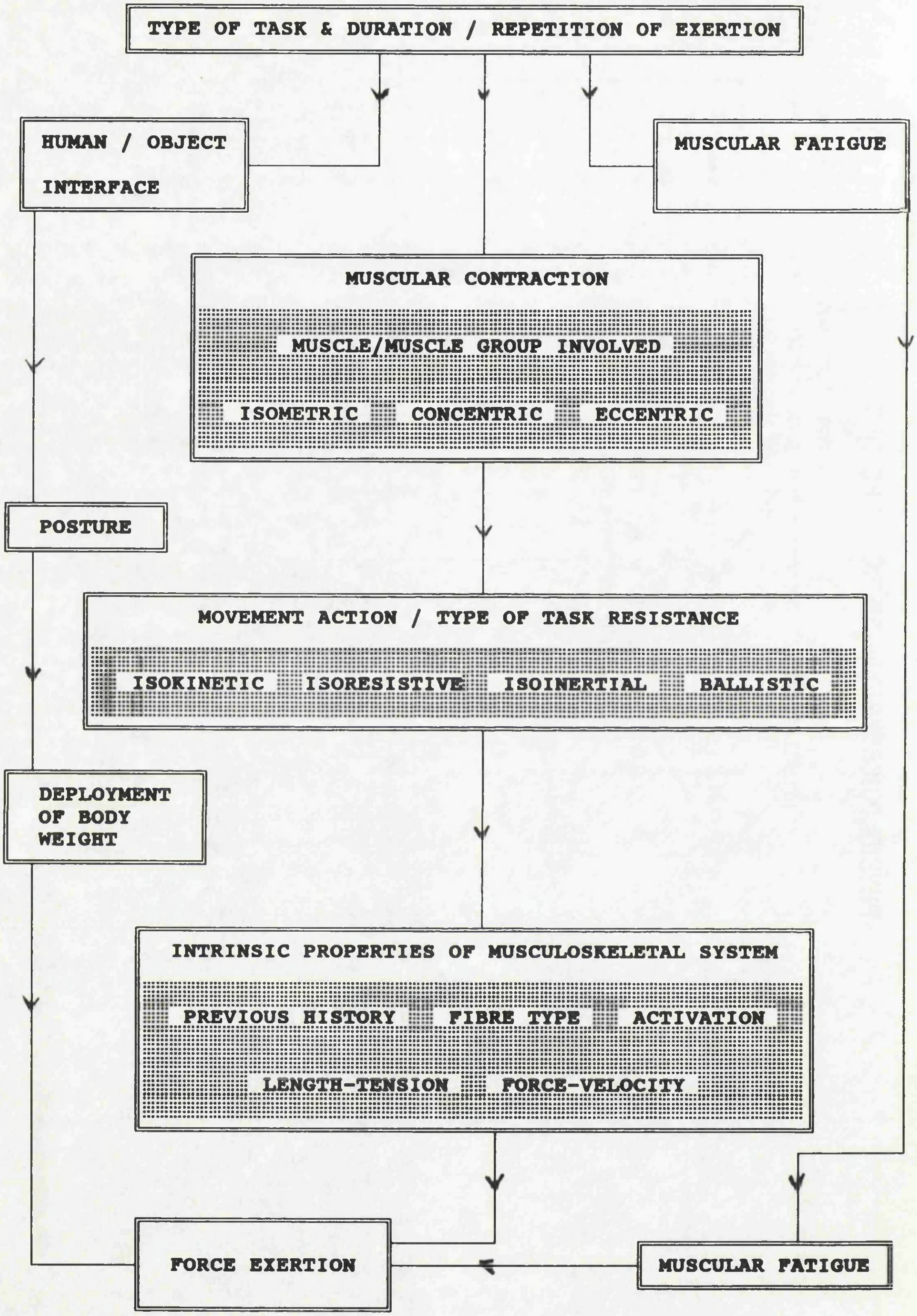

Figure 2.5: Physiological and biomechanical influences on force exertion

PART II

LITERATURE REVIEW

Approaches to Biomechanical Modelling of Whole Body Strength: Whole Body vs the Sum of the Parts

Prediction of Whole Body Strength from the Strength of Individual Joints: Michigan Type Biomechanical Models

It is well known that a muscle's ability to develop force is dependent on:

(1) The activation or stimulation level (Rack & Westbury 1969);

(2) The length, and rate of change in length, of the active muscle fibres (i.e length-tension and force-velocity characteristics) (Pringle 1960; Hill 1970; Gordon *et al.*, 1966; Asmussen *et al.*, 1965)

(3) The muscle's previous history (i.e whether or not the muscle has been prestreched immediately before contraction), (Abbott & Aubert 1952; Hill & Howarth 1959);

(4) The level of fatigue in the muscle induced by a sustained exertion or previous contractions (i.e the strength-endurance relationship) (Monod & Sherrer 1965; Monod 1972);

(5) The physiological cross-sectional area of the muscle[2] (defined as the total area of a set of sections cut perpendicular to the direction of the muscle fibres such that no fibre is included in two sections and no fibre is excluded (Pheasant 1977)) (Morris 1948).

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[2] In order to account for the effects of lengthening or shortening the muscle on the calculation of physiological cross section, as well as problems in identifying the physiological cross section of multipennate muscles, most researchers have adopted the concept of an average cross-sectional area (Crowninshield & Brand 1981). This latter quantity is calculated by dividing a muscle's volume by its length.

(6) The structure and architecture of the muscle (i.e. fibre type and orientation) (Bourne 1972; Dons *et al.*, 1979).

Although the nature of the above relationships are well understood and documented for isolated muscle preparations, the application of this knowledge to the living human remains a problem.

Firstly, most muscles involved in performing external movement act across one or more articulations. The force output is therefore also dependent on: (1) the leverage of the muscle (which is related to the distance of insertion of the muscle relative to the centre of joint rotation) and; (2) the point of application or measurement of the force relative to the centre of joint rotation (i.e. leverage of load).

The leverage of the muscle will vary according to the anatomical nature of the particular muscle/joint unit in question, whereas the leverage of the load will vary according to the posture of the joint. Consequently, the force output is a complex interaction between changes in leverage and the physiological characteristics of the muscle.

Secondly, there are very few human actions performed by a single muscle. The contribution of different muscles each having different leverages therefore add to the complexity of analyzing and predicting the force output, of even single joint actions, based on first principles. In comparison, actual measurements of the external torque output for a given joint action in the living human is elementary.

As a result there are numerous studies which have investigated the torque-angle and torque-velocity relationships of various muscles/muscle groups in the human. Comprehensive reviews of these data, particularly with respect to torque-angle relationships, have been provided by Kulig *et al.*, (1984) and Svensson (1987). The terminology used in many of these studies has subsequently been adopted from those of the early theoretical papers on muscle mechanics and physiology.

Although the torque-angle and torque-velocity relationships for some single joint exertions look remarkably similar to the theoretical relationships derived from isolated muscle preparations, this agreement is likely to be coincidental for the reasons outlined above. Indeed, Kulig *et al.*, (1984) showed that the form of torque-angle curves for single joint exercises varies widely across the different joints of the body.

Even considering a given single joint action, large discrepancies in the form of these relationships exists in the literature. These discrepancies are due to a number of factors related partly to the population studied, partly to psychological factors (i.e. subject motivation, or pain or discomfort associated with the exertion) and partly to the exercise conditions and experimental protocol under which the subjects were tested. The usefulness of these published results is therefore limited by the absence of a standardized experimental protocol.

Despite the above problems, researchers at the University of Michigan, have developed computerized biomechanical models of human strength in which they compare the resultant joint moments at the major articulations of the body, to that capable of being produced by maximum voluntary whole body exertions (Chaffin 1969; Martin & Chaffin 1972; Garg & Chaffin 1975). The input required by these models are: subject anthropometry (sex, height, weight); the direction of force exertion at the hands; and the posture of the subject (i.e. joint angles at the elbow, shoulder, hip, knee, and ankle).

The anthropometric input data is used to predict segment lengths and weights based on the scaling techniques described by Dempster *et al.*, (1964) and Dempster & Graughhran (1967), and to determine a "subject strength coefficient" for each muscle group. This latter variable attempts to account for individual characteristics in maximum voluntary torque production. It is defined as the maximum measured strength of a given muscle group for a selected body position of the particular individual, divided by the predicted mean strength of the same muscle group for the same body position over all subjects considered in the population (Martin & Chaffin 1972).

These data are combined with population data on the static strength torque-angle relationships of the ankle, knee, hip, back, shoulder and elbow, to determine the maximum hand force that the subject will be able to exert for a given posture and direction of exertion. The specific muscle group responsible for limiting these hand forces is also provided.

The most complex of these biomechanical models is that of the Three-Dimensional Strength Prediction Model described by Garg and Chaffin (1975). The authors validated their model using static strength data from 71 male air force personnel who performed seated maximal static exertions in 38 different positions (Thordsen *et al.*, 1972). Most of these exertions were performed one-handed.

The model predictions were compared with the measured forces using a simple linear regression analysis. When all conditions were grouped together the correlation coefficients and the coefficient of variation (ratio of the standard deviation of the residuals to the mean value of the measured hand force strength) for the regression analysis were approximately 0.85 and 0.60 respectively. These values are at odds with those in their abstract in which they quote "error coefficients of variation averaged from 0.27 to 0.49 and correlation coefficients between the measured and predicted hand forces averaged from 0.93 to 0.97" (Garg & Chaffin 1975). It would seem that these latter figures were derived from the mean of the individual analyses performed on each of the 38 positions.

These results are surprisingly good when one considers the model's assumptions and limitations. Firstly, it is assumed that the strength of a particular muscle group is not dependent on the level of loading on adjacent articulations. There is very little evidence however to suggest that this assumption is valid. It is well known that some muscles act about more than one joint and therefore will simultaneously exert torques about two adjacent joints. In these cases the posture adopted and the subsequent loading of one of the joints will influence the torque-angle relationship at the other joint.

Secondly, the model ignores the effects of co-contraction of muscles and their contribution to whole body exertions. Co-contractions (i.e. simultaneous contraction of the agonist and antagonist muscles) act to stabilize joints during whole body exertions so that effective moments can be applied without dislocation or injury to the joints.

Grieve (1987) has investigated muscle activity across the major joints of the body during whole body exertions and has demonstrated the importance of co-contractions during these activities. He concludes that some means of modelling the dual function of muscles, in terms of their role in creating moments and stabilizing joints under the conditions discussed above, would greatly enhance the reliability of the Michigan models.

Thirdly, when one considers the complexity of for example the shoulder joint, which has three rotational degrees of freedom and can exhibit six distinct muscular actions (flexion, extension, adduction, abduction, inward rotation, outward rotation), it is recognized that at least six torque-angle curves are required to accurately predict torque capacity at this particular joint. Kulig *et al.*, (1984) points out that two of these six motions (inward and outward rotation) have not been studied at all from the strength standpoint, and that very few studies have described the torque-angle relationships for the other four motions. One point that is not made clear in the paper by Garg and Chaffin (1975) is the source of data and the number and status of subjects (age, weight, training level etc.) used to derive the torque-angle curves of each individual joint in the model.

Considering the lack of biomechanical strength data on the shoulder it is therefore not surprising that Garg and Chaffin's model was found to under predict or over predict the forces at the hand, dependent on the direction of the force and the height of the handle. In order to account for these errors the authors included an additional, empirically derived, correction factor into the prediction model.

An additional source of error which may have contributed to the magnitude of the coefficients of variation is associated with their calculation of the subject strength coefficient. As specific strength coefficients for the different muscle groups were unavailable for the air force personnel, all strength coefficients were determined on the basis of body weight. This meant that the model was "forced to treat subjects of similar body weight (resulting in similar strengths) and stature (resulting in similar link lengths) as exactly alike, when in reality the measured force data indicates that there is a significant strength variation among these subjects" (Garg & Chaffin 1975). The assumptions involved in predicting the strength of whole body exertions based on body weight is discussed in a later section and explored in detail in Chapter 4.

Because of the above procedures for determining the strength coefficient, Garg and Chaffin (1975) stated that the validation study was "more to determine if the model was consistent for groups of people performing various tasks rather than for testing the inter-subject predictability of the model." In the light of this, their conclusion that "the model can be used to predict human strength on an **individual** and population basis", is unfounded and requires further validation studies. It may also be argued that this model can not be used on a population basis in conditions other than for exertions performed while sitting. This is based on the likelihood that a different set of empirically derived constants may be required to adjust the model predictions to accurately represent forces for standing exertions.

With respect to this latter point, Chaffin *et al.*, (1987) eventually published a report validating the Three-Dimensional Static Strength Prediction Model using the strength data of Warwick *et al.*, (1980) and Rohmert (1966). This study revealed that when used to predict forces at the hands for one-handed sagittal plane exertions and during two-handed asymmetric postures, the model could only account for between 50% and 74% of the variance in the measured strength.

It would seem therefore, that the Three-Dimensional Strength Prediction Model is not a very accurate predictor of whole body strength for exertions performed one-handed or in asymmetrical postures. If the model is used strictly in the sagittal plane for two-handed exertions, much better correlations between actual force values for the strength of a given percentile of the population and that predicted by the model are achieved (r^2 between 0.85 and 0.88) (Chaffin *et al.*, 1987).

In addition to computer models, researchers at the University of Nottingham have developed a biomechanical puppet for simple determination of the loads on the body during symmetrical exertions about the sagittal plane (Tracy & Munro 1989). Although presented in a novel medium, the results obtained from this type of model need to be compared with population data on the maximum voluntary moments about the various joints of interest to provide appropriate assessment of the strength requirements for a given set of conditions. The usefulness of the biomechanical puppet for modelling whole body exertions is therefore dependent on the same underlying assumptions and limitations as the Michigan computerized strength prediction models.

It was felt necessary to provide extensive criticism of the Michigan type of biomechanical models because of; (1) their wide spread use (over 250 different organizations and individuals have purchased Strength Prediction Programs from the University of Michigan (Chaffin 1987)) and, (2) the many reports referring to these models which have appeared in the literature (Martin & Chaffin 1972; Chaffin & Park 1973; Ayoub & McDaniel 1974; Park & Chaffin 1975; Garg & Ayoub 1980; Yates *et al.*, 1980; Chaffin *et al.*, 1983; Pedersen *et al.*, 1989). In addition, the Two-Dimensional Static Strength Prediction Program is a major component of the NIOSH (1981) guidelines for manual handling activities.

Biomechanical Models of Human Strength Based on Whole Body Static Strength Data

An alternative approach to the prediction of whole body strength has been to derive multiple regression models based on anthropometric measures and/or selected strength tests. Using this approach, data on whole body strength is collected in different postures and compared through various statistical models to the task variables of interest usually related to the posture adopted (i.e., position of the hands relative to the feet), the size and nature of the load, the anthropometry of the population tested and/or static strength of key muscle groups involved in the whole body actions.

In order to provide a direct comparison of the above approach with the Michigan models, the following discussion concentrates on those models of whole body strength which were directly determined from static strength measures. A comparison of the dynamic and static methods of whole body strength assessment is provided in a later section.

As the majority of research on whole body strength has concentrated on lifting exertions, most whole body strength prediction models have been concerned with this task. Early work by Poulson (1970) suggested that isometric back strength may be a good predictor of lifting strength. This was based on the assumption that "the weakest link in the structural system that supports the burden in a lift from the floor, is presumably the spine" (Poulson 1970). Although Poulson reported significant correlations between isometric back strength and dynamic lifting from the floor his model only accounted for between 53% and 57% of the variance in the measured lifting strength ($r=0.73$ and 0.76 for men and women respectively). The model was also restricted to the lifting range from 20cm above the floor to knuckle height.

More recently Yates *et al.*, (1980) have derived multiple regression models of whole body lifting strength using maximal isometric tray-lifting strength as the dependent variable and five isometric strength measures (back extension strength, elbow flexion strength, grip strength and shoulder flexion strength at 45° and 135°) as well as anthropometric data as independent variables. A total of 12 different lifting postures were investigated with nine male and nine female college students as subjects. Their results suggested that arm and shoulder strengths were limiting factors in lifting due to their appearance in 19 of the 24 regression equations (12 each for men and women). Isometric back extension strength appeared in ten of the equations. The r^2 values for the regression equations ranged from 0.68 to 0.98.

When this data was compared with lifting strength data derived using the Two-Dimensional Static Strength Prediction model (Martin & Chaffin 1972) considerable differences were found in both the absolute values and the overall relationship. Considering that the gripping surface was stated to be "somewhat limiting" in Yates et al's study, it was surprising to find that in four positions for the men, and all the positions below the waist for the women, the Michigan biomechanical model underestimated isometric lifting strength. In contrast, the biomechanical model tended to overpredict the strength of lifting exertions performed above waist height for both sexes. Some of the discrepancies between the two models were attributed to variations in grasp on the test object, as well as differences in the subject populations.

The data of Yates *et al.*, (1980) lends some support to the above findings of Poulson (1970) of a significant linear relationship between back strength and whole body lifting strength. The correlation coefficients for the linear regression of back muscle strength with lifting ability were however somewhat lower ($r=0.69$ and 0.67 for men and women respectively). Even though the results were compared over the same lifting range as that reported by Poulson (1970), the data of Yates *et al.*, (1980) suggests that arm and shoulder strength play a significant role in lifting exertions performed below waist height. The assumption that the strength of the back is the weak link in these type of exertions may therefore not necessarily be true. It is likely however, that differences in experimental conditions between the two studies may have played a significant role in the amount of loading across the different joints during lifting.

Possibly the most comprehensive computerized prediction model of whole body static lifting strength to date has been developed by Sanchez (1991) and Sanchez and Grieve (1991). Predictive equations for vertical lifting strength were derived for one and two-handed exertions in 96 different postures both symmetric and asymmetric. "The conditions investigated encompassed 6 heights above the ground, 2 horizontal reaches from mid-ankles and 5 vertical planes, 45° apart, from 90° to the left and 90° to the right of the forward facing positions" (Sanchez 1991). For each of the 96 postures linear regression models were derived with vertical isometric lifting strength as the dependent variable and body weight as the independent variable. A total of nine male and nine female medical students or staff of the institute contributed to the subject population for these regression equations. A further 16 subjects contributed anthropometric data for the prediction of maximum reach at the different planes and heights. The strength of lifting exertions at maximum reach were considered to approach zero lift force.

By using computerized linear interpolation procedures these authors were able to predict isometric lifting strength at any height, plane and reach in the work space. A surprising finding from this study was the fact that there was no difference in vertical isometric lifting strength between males and females when strength was expressed relative to body weight and when posture (height and reach of the hands) was expressed as a percentage of stature. Their prediction equations were therefore gender-free.

Validation of this model was performed using another 18 subjects who executed lifting exertions in 60 intermediary postures to those initially used. When the mean predicted strength over the 18 subjects for each of these 60 postures was compared with the observed mean strengths, a remarkably high correlation coefficient was obtained ($r=0.99$). In addition, the standard error of the predicted mean strength was found to be very low (15 N). On examination of this data the results of Sanchez (1991) indicate that the model slightly underpredicts lifting strength in those postures in which the lowest forces were recorded (i.e $<$ 100 N), but overpredicts lifting strength in those postures which high forces were observed (i.e. $>$150 N). Unfortunately no explanation was provided for this phenomenon.

When compared with the Michigan 3D Static Strength Prediction model it would seem that the above approach affords a more accurate prediction of whole body lifting strength, especially for one-handed and asymmetrical postures. This is presumably because the Sanchez model is based on actual measures of whole body lifting strength rather than on a composite measure of whole body strength derived from the torque-angle relationships of the crucial muscles involved in lifting. The whole body modelling approach therefore does not have to rely on the many assumptions inherent in the Michigan models.

The Sanchez model is however limited in a number of ways. Firstly, the prediction equations are only valid for purely vertical static lifting exertions in postures where the feet are maintained in a single standardized position. Secondly, the handle on which exertions were performed was rigidly mounted. As normal lifting exertions require some stabilization of both the load and the body, strength data collected with a rigid handle may be different from that obtained against a test object which has one or more degrees of freedom (e.g., static exertions performed on a handle connected to a force transducer via a chain).

Thirdly, the validation study was carried out on a subject population of almost identical stature, weight, age and of similar social background to the initial subject group. Further validation is therefore required to test this model against other populations with different levels of fitness.

A similar approach to that by Sanchez (1991) was incorporated by Rohmert (1975) for the determination of maximal isometric forces during standing exertions performed within the zone of movement for the arms. The strength data was collected on five male subjects who performed both lifting, pulling and pushing exertions in all six coordinate directions (see figure 1.1). Instead of deriving regression equations from the strength data the mean absolute forces were presented in graphical format as isodynes (lines of equal force) in the zone of movement.

A common limitation of all of the above models is the relatively low number of subjects involved in their development. Strength predictions calculated for a given percentile of the population using these models should therefore be treated with care until larger data sets are available for comparison.

Possibly one of the largest data sets on maximal whole body isometric forces is currently being developed in West Germany (Ruhmann & Schmidtke 1989). Preliminary group results on the measurements of isometric forces for selected kinds of load manipulations commonly found in industry have recently been reported by Ruhmann & Schmidtke (1989). Their data is based on 408 female and 837 male subjects with the ultimate aim of obtaining strength measures on 3,600 subjects. When completed this research will afford a useful data base that could provide standardization of percentiles for maximum forces in a number of selected postures.

Other isometric lifting strength data sets have been reported in the literature (e.g. Chaffin 1974; Davis & Stubbs 1977; Garg & Ayoub 1980) although these have been more concerned with predicting safe lifting loads than of maximum lifting strength.

Chaffin (1974) compared the weights of loads lifted in various industrial tasks to the predicted lifting strength of a large strong male (i.e., the strengths of 97.5 percentile population), to produce a Lifting Strength Rating (LSR) for any given task. The LSR was defined as:

$$LSR = \frac{\text{Load Lifted on Job}}{\text{Predicted Strength in same position}}$$

Predicted lifting strength was obtained from a graph depicting isodynes of lifting force for the sagittal plane. The isodynes were derived from the Two-Dimensional Static Strength Prediction Program of Martin & Chaffin (1972).

The studies by Chaffin (1974) and Chaffin *et al.*, (1977) have been one of the few attempts to link biomechanical stresses resulting from manual materials handling jobs to the risk of musculoskeletal injury. Although high LSR ratios were found to correlate with low-back pain incident rates (Chaffin 1974) it was admitted that the physical stresses of many jobs are not easily described by this simplistic lifting strength rating (Chaffin *et al.*, 1977).

An alternative approach used to provide guidance on acceptable levels of force exertion has been employed by Davis & Stubbs (1977). These authors make use of the relationship which exists between the forces acting on the lower back and the pressures generated in the abdominal cavity (IAP) (Davis 1981). Based on observations on 700 male British subjects, Davis and Stubbs found that workers in occupations where their abdominal pressures were frequently in excess of 100 mmHg had significantly higher incidents of back pain than other workers. The high incidence of back pain in the military forces prompted the British Army to adopt this approach in a study on the human capabilities in the carriage of heavy loads published by the Ministry of Defence in 1975.

Davis and Stubbs (1977) presented their data for strength limits as isodynes of force about the zone of movement of the arms in a similar manner to that described by Rohmert (1975). The isodynes indicate the forces which should result in an IAP of 90 mmHg in a worker whose height and weight coincide with the fifth percentile limits of the British population. It should be noted, however, that the measurement of IAP is a skilled procedure which is fraught with methodological problems (i.e., radio pills for IAP measurement are sensitive to changes in body temperature) and is also dependant on the type of exertion performed (i.e., dynamic or static).

Summary Comments on Static Whole Body Strength Prediction

In summarizing the different approaches to whole body strength prediction, the advantage of the Michigan models is that they may be used to consider any novel posture without requiring human experimentation. In contrast, models based on whole body strength data are limited to the postures in which the models were developed and tested. A way ahead for these latter models has been provided by Sanchez & Grieve (1991). These authors have shown that linear interpolation of both posture and strength, using data collected from a limited number of experiments, can provide an indication of the maximum static strength for vertical lifting actions performed anywhere within the reach envelope.

Regardless of which type of model is used, there are a number of points which need to be considered when applying the results to real life. Firstly, all the models and strength data reviewed so far have been based on static measures of strength. These strength data are therefore only applicable to either static conditions or slow dynamic exertions in which inertial or accelerative effects are negligible.

In order to determine the usefulness of this strength data, static and dynamic measures of whole body strength need to be compared. In addition, more research is needed to discover the forms of relationship which exist between the velocity and force of exertion for maximal whole body actions. Some of these issues are reviewed in a following section of the literature review and investigated for whole body lifting actions in Chapter 6.

Secondly, the above models of human whole body strength recognise only two limitations to force output. These are either musculoskeletal, in which a given element of the body is tested to its limit, or gravitational, in which strength is limited by the weight and mass distribution of the body (Pheasant 1977). A third type of limitation, which is often ignored, occurs when "man's capacity to exert a measurable force is limited by the nature of the interfaces between the outside world and himself" (Pheasant 1977, p.61). These type of limitations have been termed "interface" limitations by Pheasant (1977). The importance of this type of limitation on whole body static pulling strength is investigated for the hand/handle interface in Chapter 3.

Thirdly, when direct strength measures are unavailable or not included in the above biomechanical models, inter-subject differences in whole body strength under a given set of conditions are predicted entirely from an individual's anthropometry. The most common anthropometric measures used for predicting whole body strength have been body weight and stature. Indeed, the predictive regression equations of Sanchez (1991) were derived from exertions performed at heights and reaches which were given percentages of stature, and with individual variances in strength accounted for by body weight.

This latter point raises several questions about the nature of the relationship between body weight and strength.

(1) How good are body weight and stature as predictors of whole body strength?

(2) Is whole body strength linearly related to body weight, as commonly assumed in the above biomechanical models? Or does a different relationship with body weight provide a more accurate prediction of whole body strength?

These issues are discussed in the next section and investigated experimentally in Chapter 4.

Body Weight as a Predictor of Whole Body Strength Capability

Body weight and stature have long been attractive as predictors of strength because of their simplicity and convenience of measurement. Unfortunately, individual variability in strength is, amongst other things, also a function of the state of training, motivation, skill, practice and familiarity with the strength test. Consequently, the published literature has reported a wide range of correlations between body anthropometry and various strength measures (see Table 2.3).

A tentative observation from the studies reported in Table 2.3 suggest that correlations between body weight and strength are greatest for whole body strength measures than for the strengths of individual muscle groups, and for trained subjects compared with untrained subjects. The data of Pheasant (1977) and Kroemer (1971) also indicate that the strength of this relationship for whole body exertions may also depend on the direction of exertion and the quality of the foot floor interface.

As it is well known that height and weight are themselves significantly correlated it is not surprising to find that stature also occasionally shows a significant correlation with strength. However, the correlation between stature and strength is frequently non significant and much lower than that observed between body weight and strength. This difference may be attributed to the large amount of variance in body size and shape which exists in the population when stature is held constant.

Thus correlations between stature and strength are likely to be lowest in studies where there is a large degree of diversity in body shape, size and composition of the subject population tested.

Table 2.3
Zero Order Correlations of Body Weight and Height with Various Strength Measures Reported in the Published literature

SOURCE	STRENGTH MEASURE	CORRELATION WITH BODY WEIGHT	CORRELATION WITH BODY HEIGHT
Tappen (1950)	Isoinertial		
	Bench Press	0.85	
Rasch & Pierson (1963)	Isoinertial		
	Combination of two hands press, two hands curl, supine bench press and two hands reverse curl	0.45	0.11 (NS)
Tornvall (1963)	Isometric		
	Standardized muscle factor[3]	0.56	0.11 (NS)
Laubach & McConville (1969)	Isometric		
	Hip Flexion	0.30	0.17 (NS)
	Hip Extension	0.18 (NS)	0.20 (NS)
	Trunk Flexion	0.34	0.13 (NS)
	Trunk Extension	0.53	0.20 (NS)
	Elbow Flexion	0.50	0.29
	Shoulder Flexion	0.40	0.17 (NS)
	Knee Flexion	0.33	0.13 (NS)

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[3] Derived from the mean *Z* score (calculated using the formula below) of strength tests performed on 22 muscle groups.

$$\text{Standardized muscle factor} = \sum_{n} \frac{(x-X)}{s}$$

Where:

x = a single value of muscle strength for a given muscle group.
X = mean strength value of the same muscle group for the population tested.
s = standard deviation associated with X.
n = number of muscle groups included in the test.

	Knee Extension	0.19 (NS)	0.00 (NS)
	Shoulder Inward Rotation	0.43	0.11 (NS)
	Ankle Plantar Flexion	0.28	0.15 (NS)
	Ankle Dorsi Flexion	0.29	0.26
	Grip	0.41	0.31
	Mean Total Strength	0.49	0.22 (NS)
Poulson (1970)	Isoinertial		
	Lift from floor to knuckle height	males 0.06 (NS) Females 0.28	
Kroemer (1971)	Isometric		
	Forward Push with various coefficients of friction at foot floor interface		
	$\mu = 0.3$	0.70	
	$\mu = 0.6$	0.76	
	$\mu = 1.0$	0.51	
	Footrest	0.34	
	Lateral Push (using the shoulder) with various coefficients of friction at foot floor interface		
	$\mu = 0.3$	0.62	
	$\mu = 0.6$	0.67	
	$\mu = 1.0$	0.43	
	Footrest	0.43	
	Backward Push with various coefficients of friction at the foot floor interface		
	$\mu = 0.3$	0.62	
	$\mu = 0.6$	0.58	
	$\mu = 1.0$	0.49	
	Footrest	0.51	

	Wall	0.57	
Garg & Chaffin (1975)	Isometric		
	Seated single handed exertions in various directions	0.41	
Pheasant (1977)	Isometric		
	Horizontal Pull strength using freestyle postures at a bar height of:		
	1.5 m	0.82	0.79
	1.0 m	0.80	0.76
	0.5 m	0.68	0.68
	Vertical Lifting at a bar height of 0.5 m		
	Mean correlation coefficient over 3 foot placements	0.57	0.62
	Forearm Pronation	0.58	0.61
	Forearm Supination	0.66	0.67
McDaniel *et al.*, (1983)	Isoinertial		
	Weight lifted to 6 ft	males = 0.49 females = 0.36	0.21 0.20
	Weight lifted to elbow height	males = 0.47 females = 0.40	0.19 0.23
Viitasalo *et al.*, (1985)	Isometric		
	Grip	0.23	0.52
	Elbow Flexion	0.43	0.33
	Knee Extension	0.26	0.32
	Trunk Extension	0.34	0.20
	Trunk Flexion	0.47	0.31
Hortobagyi *et al.*, (1989)	Isokinetic supine bench press (0.013 m/s)	0.52	0.30

	Isoinertial supine bench press	0.56	0.18 (NS)
	Slow Isoresistive seated bench press (mean vel. 0.37 m/s)	0.59	0.29
	Fast Isoresistive seated bench press (mean vel. 1.26 m/s)	0.54	0.26 (NS)

Notes:

Unless otherwise indicated all correlations are significant at $\alpha = 0.05$.

In order to minimize the confounding effects of motivation, body type and conditioning which exist in large heterogeneous populations, several studies have concentrated on the relationship between body weight and lifting performance in highly trained athletes (Keeney 1955; Lietzke 1956; O'Carrol 1968; Ross *et al.*, 1984). These studies have analyzed either world or Olympic records of various weight lifting events and body weight classes, in an attempt to match documented performances with theoretically derived relationships between body weight and lifting performance.

These studies have revealed that the strength/weight ratio decreases with increasing body weight, suggesting the relationship between lifting performance and body weight is not one of direct proportionality. This finding may partly explain some of the low correlations reported in Table 2.3 in which body weight and strength were assumed to be directly proportional.

Both Lietzke (1956) and Ross *et al.*, (1984) found that the observed relationship between lifting performance and body weight was very close to that derived from dimensional theory. If body mass can be ascribed the dimension L^3, and strength the dimension L^2, the expected relationship for weight-lifting ability per unit of mass (i.e., L^2/L^3 or $M^{0.667}$) would be described by the allometric equation

$$P = aM^{0.667}$$

where:

P = maximum weight lifted

M = the individuals body weight

a = a constant

In logarithmic form this equation may be expressed as;

$$\log P = 0.667 \log M + \log a$$

Thus by plotting log P versus log M a linear relationship should be obtained which has a slope of approximately 0.667.

By the method of least squares, Lietzke (1956) found that the best equation describing world record weight-lifting total versus body weight class was given by

$$\log P = 0.6748 \log M + 1.458$$

Similarly, an allometric analysis of Olympic weight-lifting records by Ross *et al.*, (1984) revealed slopes for the above equation of between 0.612 and 0.769 with a mean of 0.692. The best fit equations explained between 77% and 99% of the variance in the observed data and seemed to be very close to theoretical expectancy.

Implied in the above analysis are the assumptions that weight lifters show consistency in form and optimal technique, have maximal muscularity, and apart from different body sizes, have similar shape and composition (Lietzke 1956; Ross *et al.*, 1984).

Also implicit in this treatment is that the Newtonian quantities of mass, length and time can be expressed in terms of a single dimensional quantity L. This requires two basic assumptions. Firstly, that mass is proportional to volume L^3, and secondly, that time is proportional to length L.

The rationale for the assumption that mass has the dimension L^3 comes from the acceptance that density is independent of size, resulting in mass and volume having the same dimensions.

If in physiological systems, it can be accepted that the strength of muscles is directly related to their area of cross section, force may be ascribed the dimension L^2. There is some *in vivo* evidence from a study carried out by Ikai and Fuganaga (1968) that the strength per unit of ultrasonic cross-sectional area of biceps brachii in forearm flexion, is approximately constant and independent of sex, age, and level of training.

Hence by substituting the dimensions L^2 and L^3 for force and mass respectively in the Newtonian equation F=ma (where: F=force, m=mass, a=acceleration) it may be seen that the second assumption (i.e., that time is proportional to L^1) is satisfied.

Applying this analysis to other types of whole body exertions (i.e., pulling and pushing) may however produce different results. The theoretical analysis derived above will only be appropriate when the strength of muscle is the primary limitation to force exertion. One would expect the value of the exponent to tend towards 1.0 in directions of exertion where force output is limited by the effective distribution of body weight (i.e., gravitational limitations). Studies investigating the role of musculoskeletal and gravitational factors in whole body exertions are reviewed in the next section.

It is also recognized that the above allometric equation is not the only way to describe or predict strength from anthropometric measures. Complex power functions and polynomials have been employed by several authors (Mital & Manivasagan 1982, 1984; Mital 1984; Mital *et al.*, 1985). Although these functions tend to provide a better fit to the data than simpler lower order regression models, physical meaning of the parameters is lost in the complexity of the equations.

Up until the mid 1950's most studies on whole body strength had been predominantly descriptive in nature and provided purely empirical data. Using a force bar similar to that described in Chapter 3 Gaughran and Dempster (1956), Dempster (1958) and Whitney (1957), were the first investigators to formally elucidate the mechanical factors operating during whole body exertions.

Based on the principles of statics, these authors derived mathematical equations for describing the strength of symmetrical two-handed pulling, pushing and lifting actions in the sagittal plane. Using free body diagrams, the maximum possible horizontal forces in the sagittal plane, capable by a given individual in any known and defined posture, could be determined on theoretical grounds.

The mathematical principles for static exertion derived by Gaughran & Dempster (1956) were confirmed by experimental observations and proved that "the magnitude of the horizontal force is proportional to the moment arm of the vertical couple of a given body weight irrespective of the body posture or the type of muscular action put into the effort." This finding was however confined to the particular conditions studied by Gaughran and Dempster (1956). In their experiments manual forces were performed in a truly horizontal direction and the horizontal distance from the point of effective seat contact to the hands was fairly small in comparison to the vertical distance from the point of seat contact to the hands.

As shown by Pheasant (1977) and discussed below, the above statement by Gaughran and Dempster (1956) does not hold true under the majority of conditions of manual exertion.

A similar observation to that of Gaughran and Dempster (1956) was found for lifting actions by Whitney (1957), who concluded that the maximum steady lifting force which man can exert is largely determined by the magnitude of the counterbalancing couple available during the lifting effort. This he points out, is directly proportional to body weight and to the effective moment arm of the centre of gravity of the body in the posture adopted. However, when the position of the foot pivot approaches coincidence with the axis of the lift, Whitney comments that "the maximum lift force is limited entirely by the muscular capacity for body extension". In this latter case the strength of exertion could not be reliably predicted from theoretical considerations based purely on mechanical principles.

Whitney's observations were later confirmed by Pheasant (1977) who introduced the concepts of a "live" and "dead" axis in the biomechanical theory of whole body exertions. These concepts are best explained by example.

Let us consider the static equilibrium of the man represented in free body diagram form in Figure 2.6. If moments are taken about the centre of foot pressure (F), the Equation of Static Exertion (ESE) may be expressed as:

$$LIFT/W = (h/b).PUSH/W - (a/b) - (TWIST/b.W)$$

The above equation can be presented graphically as a straight line EE' with the slope h/b (see Fig 2.6). This line intercepts the base of the graph in Fig 2.6 (i.e., when LIFT/W = -1) at a distance equal to the horizontal displacement of the centre of gravity expressed as a fraction of handle height. By definition the slope of the line EE' is the same as that of a line connecting the point of action of the force at the hands H, to the centre of foot pressure F.

If the man exerts a maximal force (for example in the direction OP), which is not limited by any physiological or frictional constraints and does not compromise postural stability, the head of the resultant force vector will lie somewhere along the line EE'. The component of the force vector OP resolved in the same direction as the ESE (i.e., vector DP) represents the live axis component. The component vector OD acting perpendicular to the ESE is known as the dead axis component.

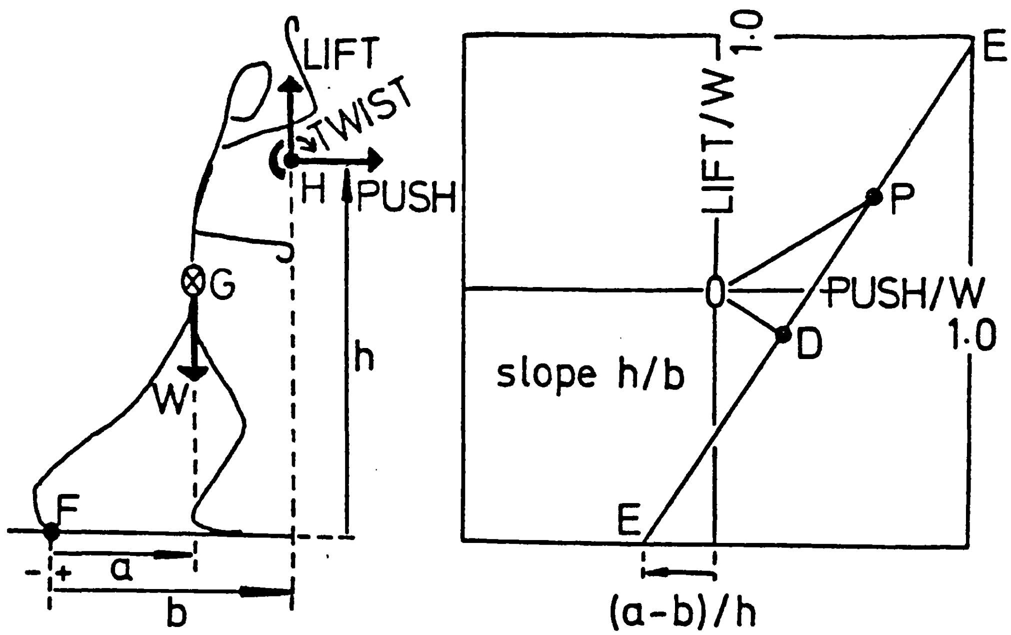

Figure 2.6: Left: A Freebody diagram illustrating the quantities which appear in the Equation of Static Exertion (ESE). Right: The ESE plotted as line EE' on the PSD. The vectors OD and DP depict the components of the resultant force vector OP along the dead axis and live axis respectively. See text for further details. From Grieve & Pheasant (1981a), and reproduced with kind permission of the primary author.

Pheasant (1977) showed that the magnitude and sign of forces acting along the live axis were indeterminate by the application of statics, and wholly dependant on the muscular effort applied by the individual. In comparison, forces acting along the dead axis could be predicted entirely on the basis of statics and were ".... completely specified by the weight and distribution of mass of the body."

These theoretical based statements were subsequently verified from experimental observations on two-handed maximal static lifting and pulling exertions, with various placements of the hands and feet. It was found that on average, 80% of the variance in force was accounted for by the weight and height of the subjects when strength measurements were close to the dead axis (i.e., during horizontal pulling), but only 48% when they were close to the live axis (i.e., during vertical lifting) (Pheasant 1977).

In 1979 Grieve introduced a graphical medium called the Postural Stability Diagram (PSD) for presenting co-planar forces exerted at the hands or the feet during static exertions. The PSD is essentially a plot of the vertical components of static manual forces against the horizontal components. Forces on the PSD may be expressed as fractions of body weight as shown on the scales in Figure 2.7 or in absolute units. The nomenclature referred to in Figure 2.7 correspond to that defined in section 1.4.

The PSD provides a useful means for discussing *'personal statements'* (concerning human strength, body weight and the mobility of the centre of gravity (see Grieve 1979a)) as well as *'environmental statements'* (concerning task demands and the frictional quality of the floor (see Grieve 1979b)) on the static exertion of forces. An example of how personal constraints may be presented on the PSD is shown in Figure 2.6.

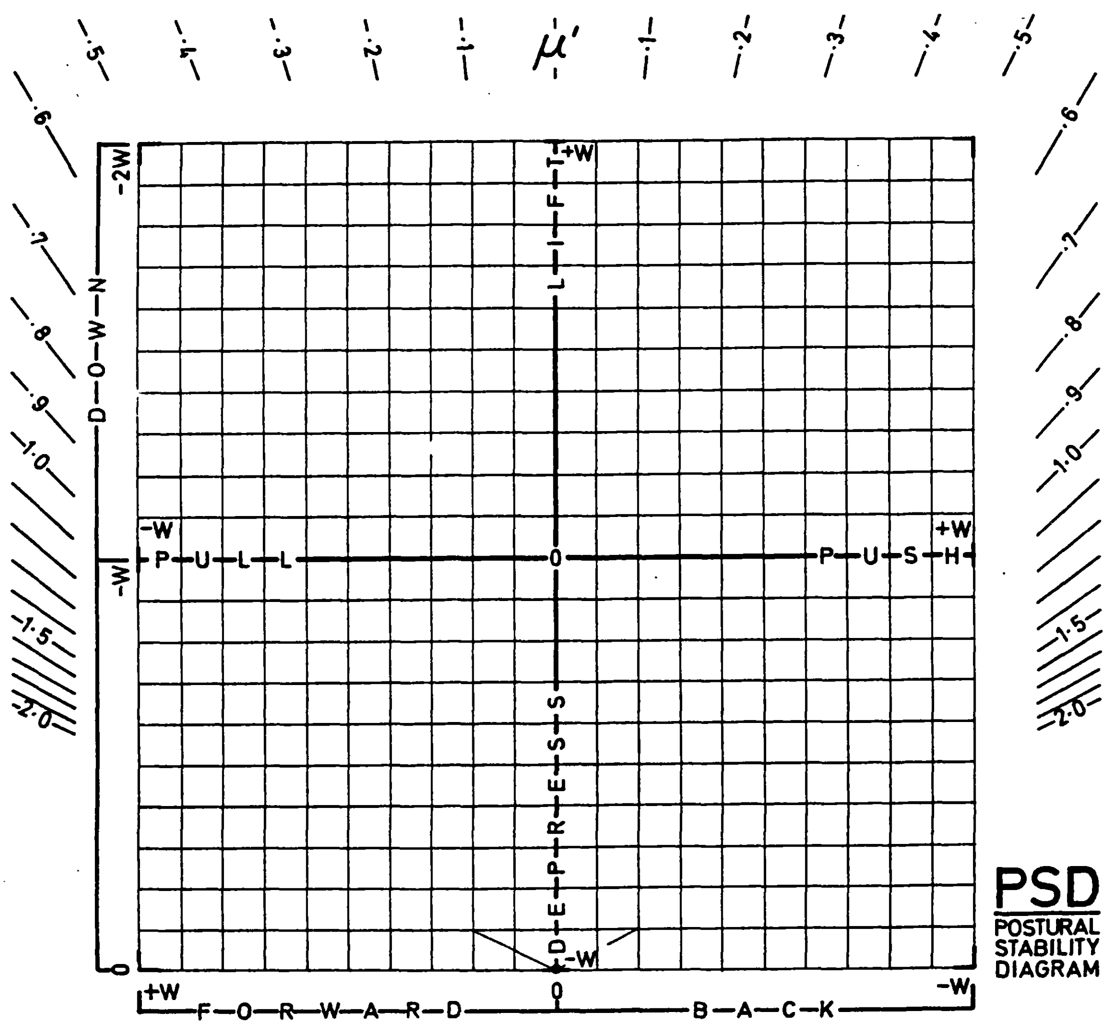

Figure 2.7: The Postural Stability Diagram on which static forces at the hands (zero at the centre) and feet (zero at centre base) are represented. The scale, μ', around the periphery refers to the apparent coefficient of friction (see text for further details). From Grieve 1979b and reproduced with kind permission of the author.

Since forces at the feet are represented on the PSD it is possible to present isodynes of the limiting coefficient of static friction, μ, on the same diagram (see Figure 2.7). In order to avoid slip during static exertions the maximal tangential force at the feet must be less than the product of the normal force and the limiting coefficient of static friction. If this is applied to the PSD we get;

$$\begin{matrix}\mathit{Horzntl\ force\ compnt} \\ \in \mathit{PULL/PUSH\ dirctn}\end{matrix} < \mu . \left(\mathit{Body\ Wght} + \begin{matrix}\mathit{Vertl\ force\ compnt} \\ \in \mathit{LIFT/PUSH\ dirctn}\end{matrix} \right)$$

According to the sign conventions defined in the introduction, lifting exertions will contribute positive vertical force components, and presses negative ones. Normal forces at the foot/floor interface will therefore be greater than body weight for lifting exertions but less than body weight for pressing exertions.

When exertions are performed on a sloping ground both the vertical and horizontal force vectors at the feet will contribute component forces tangential and normal to the surface. Under these conditions an apparent coefficient of friction, μ', may be calculated using the equation

$$\mu' = (\mu - \tan\theta)/(1 + \tan\theta)$$

where

θ = The angle of slope of the ground from the horizontal

The derivation of the above equation is provided in Grieve (1979b) and demonstrates that when pushing exertions are performed on a gradient, the apparent coefficient of friction is dependent on both the angle of slope of the ground as well as the coefficient of static friction. In the case of pulling exertions, the signs of $\tan\theta$ in the above equation are reversed. Thus, in the general case when exertions are performed on sloping ground, the horizontal force component must be less than the product of μ' and the vertical force component in order to prevent slip. If exertions are performed on level ground (i.e $\theta = 0$) the coefficient of limiting static friction, μ, and the apparent coefficient of friction, μ', are by definition equivalent.

The apparent coefficients of friction may be represented as a series of lines on the PSD passing through the centre base. These lines are illustrated by the scale around the periphery of the PSD in Figure 2.7, and provide a useful framework to assess *environmental statements* on the static exertion of forces.

Both *environmental* and *personal statements* on the static exertion of forces have been explored by Grieve and co-workers and reported in a number of publications (Grieve & Pheasant 1981, 1982; Pheasant & Grieve 1981; Pheasant *et al.*, 1982; Grieve 1983). Some of the variables investigated in these studies include the influence of posture (foot and hand placement), confined work spaces, and friction requirements on the ability to exert manual static forces. All these factors along with sex and the direction of exertion have been shown to be important determinates of whole body strength.

Some of the early observations of Gaughran and Dempster (1956), Dempster (1958) and Whitney (1957) were subsequently confirmed by these studies. Pheasant and Grieve (1981) did however, suggest that the contribution of purely mechanical factors to the *personal statement* of whole body strength had, in the past, been assigned undue importance. These authors provided evidence to show that the "centres of foot pressure were rarely located at the posterior limits of a subject's anatomical footbase" during whole body static exertions. This finding indicted that there was only a small number of directions of exertion in which strength was limited by the distribution of body weight and the extent of the foot base.

In most of the above studies foot placement has been formally defined in order to elucidate the underlying mechanisms of whole body exertion. These restrictions are however, artificial when one considers the real life situation in which workers have the freedom to choose their own foot placements. The only available whole body static strength data for freestyle foot placements have been provided by Chaffin *et al.*, (1983) and Pheasant *et al.*, (1982).

The study by Chaffin *et al.*, (1983) was predominantly concerned with describing the postures adopted during maximal horizontal push/pull exertions, and as such only contains strength data from six subjects. The data of Pheasant *et al.*, (1982) is from a slightly larger subject population who performed two-handed maximal static exertions at several hand heights and in all directions in the sagittal plane. This latter data is presented in PSD form in Figure 2.8

The inner envelopes of the PSDs in Fig 2.8 show the mean strength/weight ratios for ten males. The outer envelopes show the advantages of using components of deviated forces. The notion that forces exerted in a deviated direction may be used to achieve an improved result in another direction was recognized and investigated by Grieve and Pheasant (1981). These authors proposed the concept of the maximum advantage of using a component of exertion (MACE). An explanation of MACE is provided in Section 1. Briefly, Grieve and Pheasant define the MACE, in a given direction as "the ratio of the maximum available component compared with the directed resultant in that direction."

This concept was put forward as a means for judging the efficiency of a static exertion. The definition of efficiency was based on that proposed by Ayoub and McDaniel (1974) and was given by (100cosD)%, where D equals the angular deviation of the force vector from the desired direction required to achieve MACE in this direction.

Using these concepts Grieve and Pheasant (1981) observed that the deviated directions of exertion employed by naïve subjects, when attempting to maximize vertical or horizontal forces, were close to those predicted as necessary in order to achieve MACE. It was suggested that the possible existence of these deviated forces should be accounted for when considering tasks which may require heavy exertions.

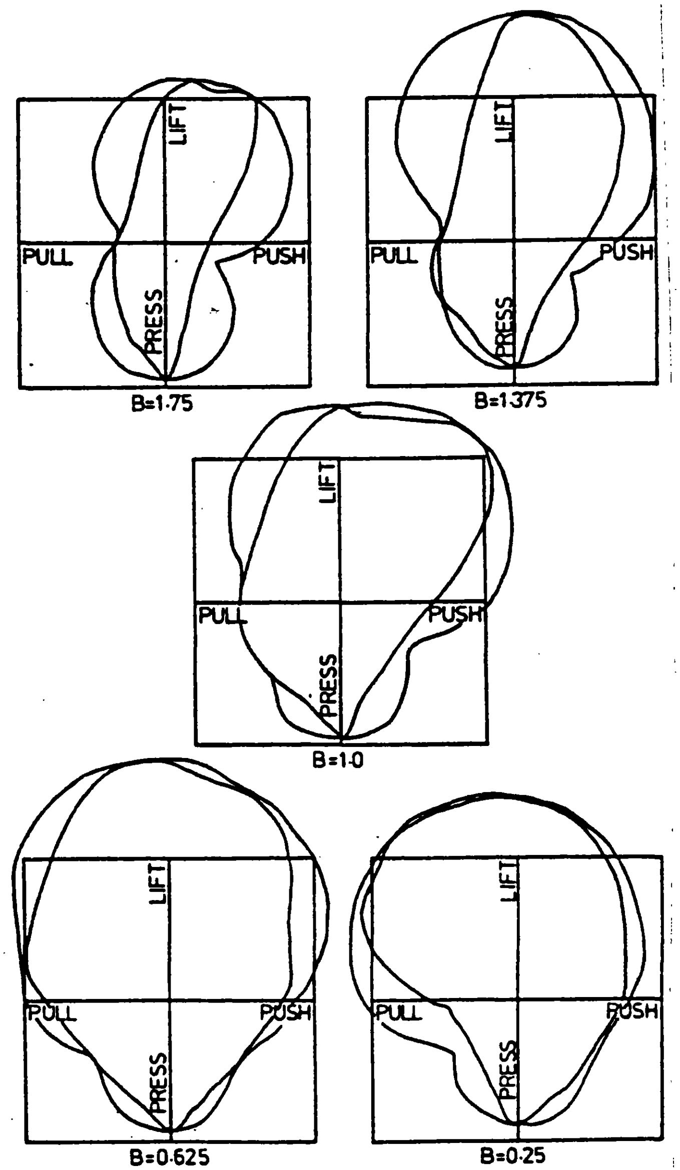

Figure 2.8: PSD data for static exertions performed at five handle heights with freestyle foot placement. The inner envelopes represent mean strength/weight ratios for ten males and the outer envelopes the advantages of using components of deviated forces (see text for further details). From Grieve & Pheasant (1981b) and reproduced with kind permission of the primary author.

A noticeable omission in the literature is the absence of strength data on one-handed exertions suitable for PSD analysis. One of the aims of the current thesis was therefore to rectify this oversight. The importance of considering these type of exertions has been attested to in the introduction. If maximal one-handed strength data is available in PSD format it may provide a starting point for estimating the effects of environmental factors on these type of exertions.

Dynamic Measures of Whole body Strength

Methods and Techniques for Dynamic Strength Assessment

The need for regulations governing safe limits for manual materials handling have incited a plethora of research into human strength capabilities. As discussed above, much of the early research concentrated chiefly on static measures of strength as a means of predicting and assessing human strength for activities in the work place. However, more recent studies have revealed static strength tests to be poor determiners of dynamic performance (Garg *et al.*, 1980; Kamon *et al.*, 1982; Marras 1982; McDaniel *et al.*, 1983; Kroemer 1983; Aghazadeh & Ayoub 1985).

Since most manual materials handling tasks consist of dynamic rather than static efforts, many researchers now believe that strength prediction based on dynamic strength measures may hold a more fruitful future than a static approach (Mital *et al.*, 1986; Aghazadeh & Ayoub 1985). Consequently, in the last 10 years there has been a shift to dynamic strength evaluation, with reports in the literature citing a variety of strength testing devices and methodological techniques. The majority of studies concerned with whole body strength have again predominantly concentrated on lifting activities.

In the United States the 'Mini-Gym' has tended to be the instrument of choice for measuring dynamic lifting strength (Kamon *et al.*, 1982; Pytel & Kamon 1981; Mital & Vinayagamoorhty 1984; Mital *et al.*, 1986; Karwowski & Mital 1986; Karwowski & Pongpatanasuegsa 1988). An adapted version of the CYBEX (Aghazadeh & Ayoub 1985) as well as other commercial devices (e.g. the Ariel Computerized Exercise System Multi-Functional Unit (ACE) (Jacobs & Pope 1986; Jacobs *et al.*, 1988)) have also been used to assess dynamic lifting strength.

Apart from the Mini-Gym, the majority of isokinetic strength testing devices have been expensive and restricted to laboratory use. This has prompted development of an alternative procedure for dynamic strength testing based on an isoinertial technique (Kroemer 1983; Dales *et al.*, 1986; Jacobs *et al.*, 1988; Mayer *et al.*, 1988).

Isoinertial measures of strength usually require the subject to lift a predetermined mass to a given height. If lifted successfully, the amount of this mass is increased in stages to the maximum that the individual can lift. This type of dynamic strength test has been found to be cheap, reliable and easily applied both in a laboratory and an occupational setting (Kroemer 1983; Dales *et al.*, 1986; Jacobs *et al.*, 1988).

A variation of this latter protocol has been used to describe the maximum acceptable strength of whole body actions (e.g. Snook 1978; Ayoub *et al.*, 1979; Jiang & Ayoub 1987). Measures of maximum acceptable strength, however, are based on psychophysical criteria and are more concerned with capacity rather than the strength of whole body exertions.

The capacity of whole body exertions is usually assessed by asking the individual to gauge the maximum load he/she is willing to handle **repetitively** at a given rate over a specified time frame. As this measure digresses from the definition of strength previously described, only those papers which conform to the definitions of strength in Chapter 1 will be reviewed.

Apart from isokinetic and isoinertial measures of strength, a limited number of studies have also assessed dynamic strength using testing apparatus designed to operate at a preset resistance (Ainscough-Potts 1984; Grieve 1984; Grieve & van der Linden 1986; Hortobagyi *et al.*, 1989). As there is no currently accepted terminology to describe the strength measures derived using this type of apparatus, it is proposed that these type of strength measures be termed ISORESISTIVE[4].

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[4] See Chapter 1 for a definition of isoresistive strength.

Isoresistive strength testing devices differ fundamentally from isokinetic dynamometry in that the speed of movement is not controlled but effort dependant. When operated upon, the resistance to motion is usually provided by a viscous fluid which is constrained to pass through an opening of given cross section. Different resistance settings may be obtained by altering the effective cross sectional area through which the viscous fluid must pass. Under very high resistances the velocity of movement capable against these devices may be so constrained as to approach that of isokinetic conditions.

Unlike isoinertial strength measures, which provide only a single value of maximum dynamic strength based on a pass/fail basis, most computerized isoresistive dynamometers provide a profile of both the velocity and force of exertion over the entire movement range.

In addition, isoresistive devices may offer an advantage over isokinetic devices when assessing dynamic strength at high velocities. Although designed to operate at a preset constant velocity the reliability of isokinetic devices during the initial acceleration phase and at high speeds are of question. This has been shown to be particularly the case for the Mini-Gym.

Described in detail by Mital and Vinayagamoorty (1984) the authors skilfully avoid quoting the measurement reliability of this device. In the hands of other authors however, the speed of motion during a dynamic strength test on the Mini-Gym has been shown to vary by as much as 20% from a preset velocity of 0.75 m/s (Pytel & Kamon 1981).

At fast velocities the reliability and accuracy of force measurement from isokinetic devices will depend on the subject being able to reach the preset velocity. Due to the initial acceleration phase the amount of force data for a particular movement profile will diminish as the preset testing velocity is increased. In comparison, isoresistive devices provide an accurate measure of both force and velocity throughout the entire movement profile irrespective of the speed of motion. Other advantages and disadvantages of the various dynamic measures of strength are summarised in Table 2.4.

Table 2.4:
Advantages and Disadvantages of various approaches to dynamic strength assessment.

STRENGTH TEST	ADVANTAGES	DISADVANTAGES
Isokinetic e.g. Biodex, Cybex, Mini Gym	* Can stop in mid test * Relatively safe * Max force obtained over whole range of movement * Good correlations with operational tasks	* Few tasks in real life are isokinetic * Not good for measuring forces of fast velocity movements * Most measuring devices expensive
Isoinertial e.g. Progressive Lifting Test, Maximum Acceptable lift, Inertial Flywheel	* Directly related to real life tasks * Easy to administer * Can be used as a field test * Inexpensive apparatus	* Performance influenced by fatigue, technique and skill * Strength determined on the basis of pass/fail criteria * Could be dangerous if weight dropped
Isoresistive e.g. Hydrodynamometer Omnitron hydrolic Dynamometer	* Can stop in mid test * Relatively safe to conduct * Large range of velocities can be tested reliably * Records both force and velocity over whole range of movement	* Has yet to be validated against other strength tests * Novel type of resistance to motion

Isoresistive Measures of Whole Body Strength

There has been virtually no published literature citing isoresistive strength capabilities of whole body exertions. The only references of which the present author is aware, are by Grieve (1984) and Garg *et al.*, (1988).

In the study by Grieve (1984) a device similar to the one described in Chapter 6 was used to measure the power output of nine male subjects performing braced standing pulls at 1.0 meter above the ground. A mean peak power output of 500 Watts was observed when the hand velocity and force output reached 2.5 m/s and 230 N respectively.

Analysis of the force, speed and power output of seated horizontal pulls in a subsequent study by Grieve and van der Linden (1986) revealed a peak power output of 220 Watts under optimum conditions. Although based on a different subject population to that in the 1984 study, both studies showed that peak power output for these type of dynamic actions was obtained against a resistance of 50 kg m^{-1}.

The study by Garg *et al.*, (1988) measured the isoresistive strength of standing one-handed pulling actions using a Biokinetic ergometer. Unlike the apparatus used by Grieve and van der Linden (1986), the accommodating resistance was provided by an electromagnetic dynamometer operating in a quasi velocity regulated mode (Garg *et al.*, 1988). During operation of the device, velocity changed in proportion to the magnitude of the applied force according to the regulation constant of the generator..

Pulling exertions on the Biokinetic ergometer were performed in various postures and in unspecified directions by 50 male and 49 female subjects. Peak and average isoresisitive strengths were approximately 300 N and 160 N, and 195 N and 100 N for males and females respectively. These values were 55% and 34% of the peak and average static pulling strengths. Average velocities ranged between 1.37 m/s and 1.45 m/s for the males and 1.25 m/s and 1.32 m/s for the females.

Using the peak isoresistive strength and upper range of the average velocity of the males in Garg et al's., study and comparing it with the data of Grieve (1984), we find that the power outputs (435 Watts and 500 Watts) are comparable between the two studies. Both of these studies provided practical applications for their data.

Grieve (1984) illustrates the ergonomic value of his methodology by showing how the results may be used to provide an assessment of the match between the dynamic strength of the user and that required to start outboard motors. In a similar manner Garg *et al.*, (1988) designed their methodology to determine the best match between location of the starter handle for lawn mowers and the dynamic strength of the user.

In comparison to the studies on isoresistive pulling strength the present author is unaware of any published literature describing isoresistive lifting strengths. Although, the direction of force application in the study of Garg *et al.*, (1988) may have significantly deviated from the horizontal in some of the conditions, isoresistive strength data for lifting actions may have a wider application to activities in the work place.

Unpublished work by Ainscough-Potts (1984) has indicated that power outputs of over 1,000 Watts may be achieved during dynamic lifting. In these exertions lifting velocity approached 1.0 m/s and force output 1.5 KN. Force-velocity data collected in the laboratory was compared with that obtained from cine film of industrial workers lifting a box of 15.5 kg. This comparison indicated that the subjects in industry were, at certain stages in the lift, very close to their maximum capacity. Unfortunately the study was limited in that the laboratory experiment utilized only four subjects and had to be discontinued when one of the subjects sustained a back injury during one of the trials.

A study investigating the isoresistive strength of the lifting action in a larger subject population, and including both males and females, may provide valuable data on dynamic strength profiles throughout the lifting range. Furthermore, as the velocity of movement is effort dependent rather than fixed these dynamic strength data may be more applicable to conditions in the working environment than isokinetic strength measures. Consequently, one of the objectives of this thesis was to provide an indication of the isoresistive strength capabilities of a healthy adult population performing maximal lifting exertions at mean velocities commonly observed in the industrial environment.

Relationships Amongst Dynamic and Static Measures of Strength

One of the important issues of strength assessment is whether strength measured under one set of conditions (e.g. static) is significantly related to strength obtained under a different set of conditions (e.g. dynamic). It is commonly assumed that strength is a general physiological capacity and that all strength tests measure a similar phenomenon (Knapik *et al.*, 1983).

If there is such a thing as a general strength component, then individuals who perform well (or poorly) should achieve the same relative level of performance, independent of test mode or type of strength being evaluated (Hortobagyi *et al.*, 1989).

Clearly absolute values of force output for a given muscle/movement action differ dependant on the type of strength measurement involved. Variation in neurophysiological, biomechanical and metabolic factors between dynamic and static exertion will no doubt contribute to these absolute strength differences (Asmussen 1981).

However, evidence for a general strength component would be suggested if strong relationships exist between isometric, isokinetic, isoinertial and isoresistive measures of strength. Given that these various measures of strength are performed on the same muscle groups and the same subject population, intercorrelations that exceed $r = 0.71$ would indicate a greater proportion of generality than specificity between the different strength measures (Clarke & Clarke 1970)

In other words, if the proportion of common variance in force output on two strength tests exceeds 50% (i.e. $r^2 \times 100 = 50\%$) then it can be said that the two methods of strength testing assess a similar component of performance. On the other hand, if $r^2 \times 100 < 50\%$ then the measures of strength obtained are more specific to the type of strength test used.

Evidence of a general strength component between different methods of strength testing has been somewhat equivocal. Some investigators have reported correlations of $r=0.74$ to $r=0.99$ between various measures of strength, thus supporting the concept of generality (Rasch 1957; Rasch & Pierson 1960; Asmussen *et al.*, 1965; Carlson 1970; Otis 1976; Otis *et al.*, 1981; Knapik & Ramos 1980), while others have reported correlations less than $r=0.71$ (Clarke 1960; Clarke & Henry 1961; Henry & Whitley 1960; Smith 1961; Rasch & Pierson 1963; Olson *et al.*, 1972; Osternig *et al.*, 1977) suggesting that performance on the different strength tests show a greater level of specificity than generality.

However, in some of the above studies, which found poor relationships among the different strength tests, correlations were performed between strength and speed of movement rather than maximum voluntary strength. In addition, many of these studies compared strength measures in different postures and through different ranges of motion on the different strength tests.

Using more controlled methodological procedures, Knapik *et al.*, (1983) compared torque measurement at three isokinetic speeds with isometric and isoinertial strengths of knee and elbow extension and flexion at comparable joint angles. Their results showed an average common variance of 72%, 62%, 53% and 48% among (1) the 3 isokinetic modes, (2) the 3 isokinetic and isometric modes, (3) the 3 isokinetic and isoinertial modes, and (4) the isoinertial and isometric modes respectively.

It was also found that as either the isokinetic velocities or joint angles became more widely separated the magnitude of the intercorrelations decreased. The lower correlations observed between strength at the higher isokinetic velocities and performance on the other strength tests may have been the consequence of the subjects not having had time to reach the maximum force possible at high movement velocities.

More recently, Hortobagyi *et al.*, (1989) investigated the interrelationships amongst various measures of bench press strength. In this study comparisons were made between a free weight supine bench press (1 repetition maximum), the peak force during a maximum isokinetic supine bench press (at a test velocity of 0.013 m/s), and the peak torque during a seated bench press performed on an isoresistive hydraulic dynamometer at two test resistances (average linear movement velocity 0.37 m/s (slow) and 1.26 m/s (fast)).

The average correlation between these four bench press tests was $r=0.84$, which was reduced to 0.78 when the influence of body weight was factored out using the technique of partial correlations. These results, along with those of Knapik et al's (1983), provide evidence to suggest that different types of strength test measure a common or general strength component.

The above studies however have only investigated either single joint or two joint actions. The few studies comparing the generality versus specificity of whole body dynamic and static measures have been reported in the occupational physiology and ergonomics literature.

Using the Mini-Gym, Pytel and Kamon (1981) and Kamon *et al.*, (1982) found peak isokinetic lifting strength at a velocity of 0.75 m/s to be a good predictor of the maximum weight that subjects could lift to a shelf height of 1.13 m (r between 0.75 and 0.92). Similarly, Jacobs *et al.*, (1988) reported that the average isokinetic force, performed on the ACE at velocities ranging from 0.024 m/s to 0.110 m/s, correlated highly with the isoinertial progressive lift test (see Kroemer 1983) ($r=0.97$) and an isoinertial operational lifting test (i.e., lifting a tote box from the floor to a 1.3 m high shelf) ($r>0.93$).

From the studies reviewed above, it would seem that there is a high degree of generality between various measures of strength, suggesting an intrinsic similarity of muscular function across the different testing modes (Hortobagyi *et* *al.*, 1989). This is especially noticeable between the different measures of dynamic lifting strength.

However, there is evidence to suggest that the relationship between static and dynamic measures of strength is lower than that between the different dynamic strength measures. This conclusion is somewhat confounded by the fact that some studies have failed to ensure that the isokinetic and isometric strength measures were determined at comparable points in the range of motion or at similar joint angles. Furthermore, the unreliability of some isokinetic devices at high velocities may have contributed to the lower correlations.

In the light of this, there seems to be a clear need to reassess the relationship between dynamic and static measures of strength taking the above points into account. It is particularly important to assess the relationship between whole body dynamic and static exertions, as the data has significant implications for the applicability of static models of human strength to the world involving dynamic exertions. Chapter 6 investigates this issue by comparing isometric with dynamic lifting strength against various resistive loads on an isoresistive strength testing device. The study also serves to fill the gap in the literature concerning the comparison of performance on isoresistive devices with that obtained from other dynamic and static measures of whole body strength.

One of the most prominent factors that will influence the ability of a person to transmit forces to the external environment, is the nature of the interface between the person and the outside world. A brief discussion on the interactions of manual force, body weight and friction at the foot-floor interface is provided above. These interactions were further explored by Grieve (1983) who extended the concepts of the PSD and developed the 'Slip Chart' shown in Figure 2.9.

The dotted lines on the 'Slip Chart' provide an example of how the chart may be used to assess the minimal coefficient of static friction (μ_{min}) required to prevent slip for an individual of given body weight (i.e., a woman of 95th percentile weight (690 N)) exerting a known manual force (300 N) in a particular direction (45° in the PUSH-PRESS sector). In this example $\mu_{min} = 0.47$ is found by comparing the slope of the line which intercepts the Y axis at a value equivalent to the person's body weight, with the slopes of the radiating set of lines in the upper corners of the chart (Grieve 1983). The value for the minimum coefficient of friction shown for these radiating lines is given by the reciprocal of their slopes.

Once μ_{min} for a specific task is known, the risk of slipping may be assessed by comparing this value with frictional conditions expected in the workplace. Specific data on the coefficients of friction for a large variety of floor-shoe combinations have been provided by Kroemer (1974).

The other point of contact between a person and the outside world is usually at the hands. During everyday tasks, both at work and home, an individual may be required to manipulate or carry heavy loads manually. The ability to perform these tasks effectively and safely may often depend on the quality of the interface between the hand and the external object.

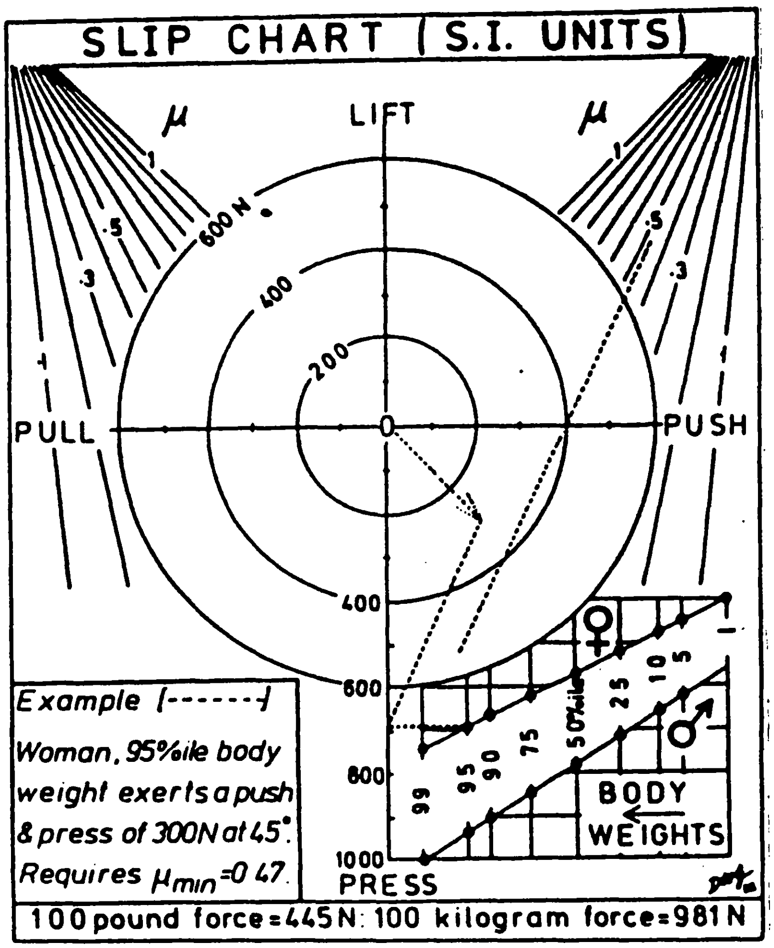


Figure 2.9: The 'Slip Chart' proposed by Grieve (1983) for exploring the interaction between manual forces, body weight and the minimum coefficient of friction required to prevent slip during static exertions. The dashed lines refer to the example described in the text. Reproduced with kind permission of the author.

The importance of the hand/object interface as a major factor in industrial handling accidents, was known by the Ministry of Labour in Great Britain as long ago as 1946. Out of 2,000 reported handling accidents, for the first two weeks in December 1946, over one quarter were due to loads which were dropped or allowed to slip from the hands (Brown 1972). While the nature of the hand/object interface may not have been the principal cause of these accidents, it seems reasonable to argue that the ability of the individual to transmit forces from his (or her) musculoskeletal system to the load, must have been a major contributory factor in many cases.

The conditions at the hand-object interface which will determine the effectiveness of the coupling include:

(1) The type of grip adopted (Pheasant 1977).
(2) The object shape, size and surface texture (Pheasant & O'Neill 1975; Drury 1980; Cochran & Riley 1986).
(3) The presence or absence of gloves (Riley *et al.*, 1985).

The different types of handgripping postures which may be adopted have been classified by several authors (Taylor and Schwartz 1955, Napier 1956, Roebuck *et al.*, 1975). The simplest classification is that described by Napier (1956) in which gripping actions are subdivided into three types:

(1) A **power grip** in which the object is clamped between the partly flexed digits and palm.

(2) A **hook grip** in which the fingers are flexed around the object and the thumb is not used for gripping.

(3) A **precision grip** in which the object is pinched between the flexor aspect of the fingers and opposing thumb.

For ergonomic purposes however, Grieve and Pheasant (1982) found this classification inadequate. These authors have presented an alternative classification in which both hand posture and function is described according to the degree of hand/object contact and the extent to which the hand is used in a closed or open chain configuration.

Often, in manual materials handling, there is a conflict between the design of the handle and the type of grip required to perform a desired function (i.e., whether to move, steady or control the particular object).

Drury (1985) reports that in one survey of manufacturers of handles for luggage and portable equipment, the main factors in handle design considered were visual appearance and cost. Furthermore, Woodson (1981) noted that off the shelf handles tend to be designed as 'decorative appointments' and often have insufficient hand clearance, sharp cutting edges and too small a handle diameter.

For most heavy manual work, handles, handholds and gripping aids on various containers force the worker to adopt a hook or a power grip (Drury 1985). While the power grip permits large gripping forces to be used it may not be the most efficient form of grip for fine control of the container. In addition, force output and manipulation of a load using hook or power grips may be restricted under certain conditions (e.g. when the wrist posture adopted is constrained by the design of the handle or handholds of the container and results in excessive stress on the wrist joint) (Hazelton *et al.*, 1975).

The majority of studies that have investigated hand-handle design, and the maximum torques or forces which may be applied to a handle, have permitted power grips to be employed. Less data is available in the literature comparing the strength of exertions on commercial type handles (that demand gripping actions other than the power grip) with forces capable when the handgrip is optimal. In summarising the data presented by Drury (1985), it is suggested that for tasks requiring maximal pull/push forces a cylindrical handle of between 31 and 44 mm in diameter is about optimum.

Chapter 3 of this thesis investigates the effects of several different handle designs and the corresponding gripping actions on them on the ability to exert horizontal pulling forces. In addition, the experimental work aims to illustrate the interaction of handle placement and handle effectiveness on these type of manual exertions.

Sex Differences in Strength

In the last few decades, the introduction of the Equal Employment Opportunities Act, has meant that more women have been entering vocations traditionally occupied by males. Particularly in North America, physically demanding vocations such as law enforcement, fire fighting and the military have seen an increasing proportion of the workforce occupied by female personnel (Bishop *et al.*, 1987). The ability to perform some of these jobs effectively often requires substantial physical strength. Consequently, there has been considerable interest in the nature and extent of the sex difference in strength.

Table 2.5 summarises the findings of some of the more recent studies that have appeared in the literature concerning sex differences in strength. The differences in strength between males and females in this Table are given as the ratio of the mean female strength over the mean male strength expressed as a percentage. Except where indicated all the ratios were calculated from absolute strength measures. It is seen that the ratio of the means can range from 29% to almost 100%, dependent on the subject populations compared, the muscle groups tested and the type of strength test performed.

Several studies have shown that larger sex differences in strength are observed for the upper body compared to the lower body (Laubach 1976; Pheasant 1983). In addition, whole body strength tests performed up to approximately knuckle height tend to show smaller sex differences in strength than those tests performed beyond knuckle height. This latter finding presumably reflects the predominant action of the upper body musculature during lifting exertions above knuckle height.

Some of the sex differences in strength have been attributed to, (1) genetic differences in muscle mass and/or neuromuscular function (ability to recruit, stimulate, and synchronize motor units), (2) culturally linked behavioral differences in the amount of participation in strength developing activities at work or during recreation, and, (3) experience in producing maximal voluntary efforts or the motivation to perform (Bishop *et al.*, 1987).

The variability in sex differences in strength is however confounded by sampling differences in the male and female subject population compared. Several studies comparing males and females of similar physical activity backgrounds and levels of training have shown that the sex difference in strength can almost entirely be accounted for by the difference in muscle size (Falkel *et al.*, 1985; Bishop *et al.*, 1987). This evidence supports the findings of Ikai & Fukunaga (1968), Davies *et al.*, (1983) and Schantz *et al.*, (1983) who showed that the strength per unit cross-sectional area is not significantly different in males and females, thus suggesting that sex differences in strength can be entirely attributed to differences in muscle cross-sectional area.

Consequently, when male and female strength measures are normalised by dividing by either the muscle cross section, fat-free weight or total body weight, sex differences in strength become much less marked. Wilmore (1974) found that when absolute strength differences between genders were expressed relative to body weight or lean body weight, the women's lower extremity strength was equal to or exceeded that of the men. Sanchez (1991) also found that when vertical lifting strength was expressed as a fraction of body weight and the lifting exertions performed at heights and reaches corresponding to given percentages of stature, there was no significant difference in lifting strength between males and females. In this latter study the mean female/male ratio for normalized strength was 0.93.

Although normalisation of the data shows that men and women of equivalent size, shape and body composition have similar strengths, a certain amount of variability in strength between genders still exists (see Falkel *et al.*, 1985). This variability is likely to reflect differences between the male and female population in the level of training of the specific muscle group tested, and in differences in their skill and motivation when performing the strength tests.

The evidence presented above clearly indicates that the commonly held view that women are two thirds as strong as men is of little practical significance. Task designers who use biomechanical models of human strength, or strength data derived from male populations to predict female strength should therefore be very wary of making simplistic assumptions about sex differences in strength.

Table 2.5:
Sex Differences in Strength Reported in the Literature

SOURCE	STRENGTH MEASURE	MEAN FEMALE/ MALE STRENGTH RATIO (%)	RANGE
Martin & Chaffin (1972) Based on data derived from the 2D Static Strength Prediction Model	Vertical isometric lifting strength at 3 heights above the ground and at 3 foot placements	33	29 - 41
Laubach (1976) Based on data from 9 studies reporting both dynamic and static strength	Strength of Lower Extremities	72	57 - 86
	Strength of Upper Extremities	56	35 - 79
	Trunk Strength	64	37 - 70
	Dynamic Whole Body Strength	69	59 - 84
	Total Body Strength (mean of above measures)	64	35 - 86
Pheasant (1977)	Two-handed static horizontal pulling exertions at 3 grasp heights and 2 foot placements	71	69 -73
	Two-handed static horizontal pulling exertions at 3 grasp heights with freestyle foot placement	67	62 - 70
	Two-handed static vertical lifting exertions at 0.5 m grasp height and 3 foot placements	67	61 - 71
Yates *et al.*, (1980)	Vertical isometric lifting strength at same 3 grasp heights and foot placements as for Martin & Chaffin (1972)	40	30 - 53

Pheasant & Grieve (1981)	Two-handed static exertions performed in all directions in the sagittal plane at 3 bar heights and 2 foot placements		
	Absolute strength	74	60 - 95
	Strength/body weight	86	SD 10
Pytel & Kamon (1981)	Max weight lifted to a 1.13 m shelf	46	
	Peak isokinetic lift force using mini-gym at 0.73 m/s	63	
	As above but with a lifting velocity of 0.97 m/s	65	
Kroemer (1983)	Isoinertial lift test to overhead height	47	
	Isoinertial lift test to knuckle height	79	
McDaniel *et al.*, (1983)	Isoinertial lift test to 6 feet	50	
	Isoinertial lift test to elbow height	52	
Pheasant (1983) Data based on a selection of 112 data sets	Lower limb strength (including action of thrusting on a peddle)	66	50 - 81
	Standing Push/Pull/Lifting exertions	65	38 - 90
	Trunk Strength	62	37 - 68
	Upper limb strength (including grip strength)	58	44 - 86
	Miscellaneous	53	43 - 61
	All tests	61	37 - 90
Falkel *et al.*, (1985)	Mean absolute and normalised (strength /lean body mass (in brackets)) isokinetic torque at 30°/s for:		
	Elbow extension	63 (80)	
	Elbow flexion	56 (77)	
	Knee extension	66 (91)	

	Knee flexion	68 (95)	
Mital & Sanghavi (1986)	Peak isometric torque capability on various hand tools exerted in a variety of postures	66	59 - 97
Jacobs *et al.*, (1988)	Max weight of medical supply box lifted to 1.52 m (Operational Lift Test)	50	
	Isoinertial progressive lift test to a height of 1.52 m	51	
	Mean isokinetic lift force at a lift velocity of 0.024 m/s	59	
	lift velocity 0.073 m/s	55	
	lift velocity 0.110 m/s	54	
Rühmann & Schmidtke (1989)	Isometric lifting strength at various heights above the ground		30 - 80
Stevenson *et al.*, (1990)	Max weight of box lifted to 1.33 m using 3 different lifting techniques	57	52 - 63
	Isoinertial lift test to 1.5 m using 3 different lifting techniques	53	52 - 54
	Isoinertial lift test to 1.8 m using 3 different lifting techniques	49	47 - 51

Summary Comments on the Review of Literature

In summary, the above literature review emphasizes the multi-faceted nature involved in the expression of human strength. It is therefore not surprising that strength measures, even when performed under fairly standardized conditions, show a large degree of variance between individual subjects. The aim of most experimental studies is to minimise the variance associated with those factors not directly relevant to the study, so that the relationships under investigation can be interpreted with confidence. This may be achieved by careful experimental design (e.g. randomization of experimental conditions) and by attempting to control extraneous variables or vary them in a known and systematic manner.

In contrast, although it is recognised that standardized conditions are required to elucidate the theoretical basis of human strength, often the experimental constraints severely restrict the use and applicability of the data to real life conditions. In order for task designers to apply this research to a wide variety of situations, strength data needs to be collected and presented in a way that is less bound by the formal conditions of testing and more relevant to a wider range of circumstances. Throughout the experimental sections of this thesis an holistic approach to data collection and presentation has been attempted in an effort to provide this balance.

Hypotheses

The specific hypotheses which the experimental work aims to investigate are outlined below.

1. Handle placement has a significant influence on horizontal pulling strength when there is a good coupling between the hand and handle, but assumes a reduced importance in the strength of an exertion when there is a poor coupling between the hand and handle.

2. Strength differences between males and females and between one and two-handed exertions vary widely according to direction, height and task resistance under which whole body exertions are performed.

3. There are many directions of exertion in which the static strength of one-handed whole body exertions may benefit by employing components of deviated forces (if the task permits).

4. The proportion of the total variance in one-handed whole body static strength attributable to body mass is not constant, but is a function of; (a) the direction of exertion and, (b) the gravitational, musculoskeletal or interfacial factors which may limit force output under the given test conditions.

5. Through development of appropriate hardware, software and experimental techniques it is possible to accurately measure and analyze the forces at the hands and feet during static exertions performed in any direction in the sphere of exertion.

6. The variation in strength with height above the ground for maximal whole body lifting exertions is similar under dynamic and static conditions. Lifting strength is greatest under isometric conditions and declines with decreasing task resistance and increasing mean lifting velocity.

7. Individuals who perform well (or poorly) achieve the same relative level of performance independent of the test mode (dynamic or static) and velocity under which maximal lifting exertions are evaluated.

Hypothesis 1 is tested exclusively in study I and aims to illustrate the importance of interface limitations on the determination of whole body strength. Study II was designed to test hypotheses 2, 3, and 4 with the general aim of describing personal constraints on freestyle one-handed static exertions in the fore and aft plane. Hypothesis 5 is tested in study III with the objective of developing the PSD concept from two dimensions into three dimensions. Hypotheses 2, 6 and 7 are tested in the final study (study IV) with the purpose of investigating the similarity of performance between dynamic lifting strength (as performed under different resistive loads on a hydrodynamometer) and static lifting strength.

As the latter two studies required extensive instrumentation (involving development of novel methods and techniques for measurement of human strength) it was felt necessary to provide a full description and analysis of the strength testing devices. This analysis provided the necessary background information for the interpretation of the strength measurements collected using these devices.

CHAPTER 3

STUDY I

THE INFLUENCE OF SOME HANDLE DESIGNS AND HANDLE HEIGHT ON THE STRENGTH OF THE HORIZONTAL PULLING ACTION

Introduction

Although handle placement or height and handle design have been investigated independently with respect to manual exertion (see literature review) less is known about their interactions and the conditions in which one of these particular variables becomes the limiting factor during manual exertions. The present study investigated the interaction between these two variables during one-handed maximum pulling exertions.

Methods

Subjects

Sixteen female and 14 male volunteer staff or students of this institute participated in the study. Their physical characteristics are described in Table 3.1. Twenty seven subjects were right-hand dominant and three were left-hand dominant.

Table 3.1:
Physical Characteristics of Subject Population
Values are mean plus or minus SD

	Male (n=14)		Female (n=16)		Total (n=30)
	Mean (SD)	%ile[5]	Mean (SD)	%ile	
Age (yrs)	30.4 (9.9)		29.7 (6.6)		30.0 (8.2)
Weight (kg)	71.3 (8.2)	39	64.2 (9.4)	56	67.5 (9.4)
Height (cm)	177.9 (6.4)	71	163.8 (6.7)	67	170.4 (9.6)
Grip Strength (N)	465 (88)		330 (44)		393 (96)

[5] Percentile values for height and weight were derived from the data of Pheasant (1986) and show how the current subject population compare with anthropometric estimates of British adults aged 19-65 years.

Apparatus

The apparatus for measurement of maximum pulling strength consisted of a modification of the force bar described by Whitney (1957) and Pheasant and Grieve (1981). Three handles/knobs, of contrasting design (see Figure 3.1) were mounted on a square piece of wood and secured firmly to the horizontal force bar. The force bar itself was used as a fourth 'handle' for comparison with the other three. Output from foil strain gauges, mounted on vertical and horizontal cantilevers at the ends of the bar, were first amplified by Medelec AD6 amplifiers before being passed to the A/D converter of a 64k BBC microcomputer (Acorn Computers Limited).

Custom designed software, written in BASIC language, sampled and then plotted both an analogue and digital display of the force/time data permitting peak horizontal pull forces and mean horizontal pull forces to be determined.

Grip strength was measured using an adjustable handgrip dynamometer (Takei and Company Ltd). The dynamometer was adjusted to the subject's own comfort.

The floor on which the subjects stood was covered with a coarse emery paper to prevent slipping. Subjects wore their normal everyday footwear in which they entered the laboratory. The majority wore rubber soled shoes or trainers. The coefficient of limiting friction between the above surface and rubber-soled shoes has been previously reported as 0.99 (Pheasant and Grieve 1981). None of the subjects exhibited problems with slippage throughout the experiment, irrespective of footwear worn or the extreme postures adopted during exertion.

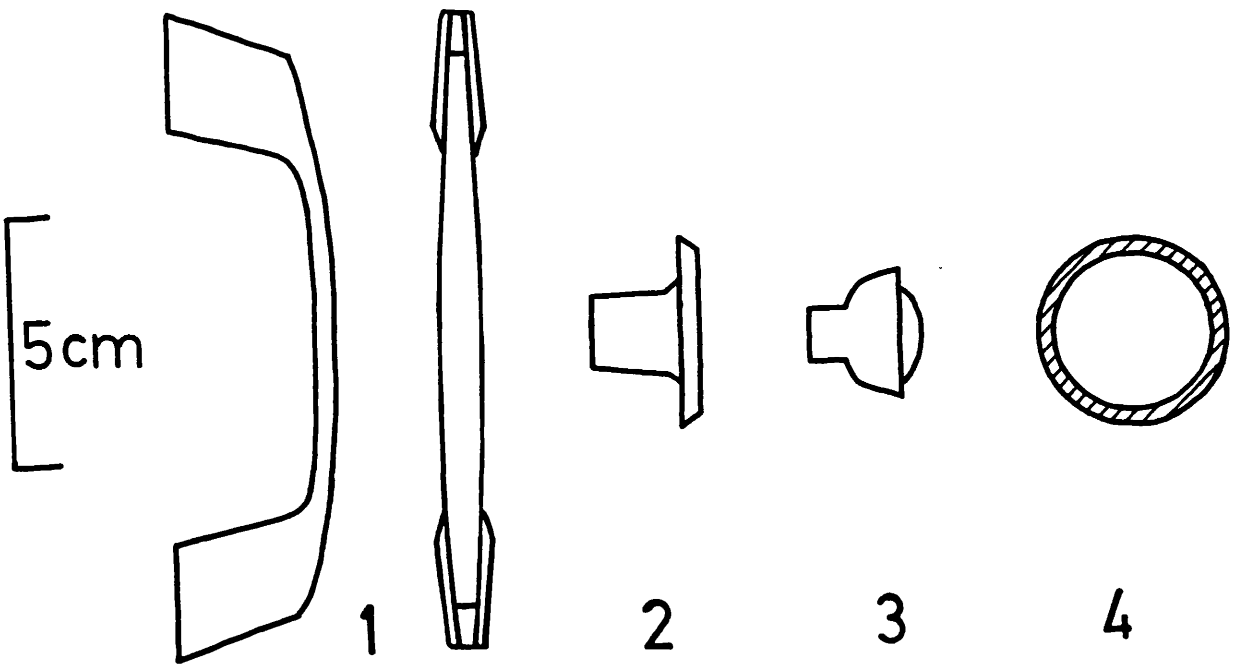


Figure 3.1: Side views of the four handles used in the study (the front view for handle 1 is also shown). Handles 1 and 2 were cast alloy, handle 3 was made of bakelite and handle 4 was a mild steel bar.

Procedure

On entering the laboratory, the subjects' grip strength, unshod weight and stature were measured. Grip strength was determined from the best of two efforts with the dominant hand. Peak and mean maximum horizontal pull strengths were then collected for the three handle types plus the bar, with the force bar set at a height of 1.0 and 1.75m above the ground. Half the subjects completed exertions at the 1.0m bar height first, while the other half completed the 1.75m condition first. The order of presentation of the different handle types plus the bar was randomized for both bar heights. Successive exertions were performed following a minimum rest period of one minute.

Subjects were instructed to exert a steady maximal pull on each handle for five seconds, in a direction as close to the horizontal plane as possible. Trials in which the subject clearly 'jerked' on the handle were repeated.

The type of grip on each handle and the posture adopted during the exertion were freely chosen, provided that, (1) only the dominant hand was used on the handle/bar, (2) only the feet made contact with the floor and, (3) the leading foot was not placed in front of the handle.

Peak horizontal pull forces were determined from the maximal horizontal force vector of the force/time data during exertions on each handle. Steady maximal pull strengths were calculated from a 3 second average of the horizontal force vector time trace in accordance with the suggestions of Caldwell *et al.*, (1974) for the measurement of static strength. The reliability of the test procedures was checked by retesting seven male and 11 female subjects two weeks following the initial experiment.

Analysis

The effects of handle type and bar height on maximum horizontal pulling strength were determined according to a two-way repeated measures ANOVA design. Subsequent post hoc analysis was conducted using Tukeys HSD test. All correlation coefficients were calculated according to the Pearson product-moment method.

Results

The peak and steady maximum pull forces observed on each handle at the two placement heights are summarized in Table 3.2. Test-retest reliability of the measurement of peak and steady maximum horizontal pulling forces were found to be satisfactory (see Table 3.3). The test-retest statistics shown in Table 3.3 were calculated from average strength values for each subject for all test conditions combined.

Differences in strength values between the first experiment and the retest were not significant ($p > 0.05$). As steady maximal pulling strength gave a slightly higher test-retest correlation coefficient than peak pulling strength, this former measure was used in all subsequent analysis and discussion.

The ratio of female strengths per kg of body weight to male strength per kg of body weight (normalized f/m strength ratio), combined over all experimental conditions, was 0.80. When expressed in absolute terms the f/m strength ratio decreased to 0.72, a value which was almost identical to that found for the f/m grip strength ratio (0.71). However, when the normalized f/m strength ratio was determined for the various handles individually, the normalized f/m strength ratio for handle 3 was found to differ from those on the other handles. Handles 1, 2 and 4 produced identical normalized f/m strength ratios (0.78), whereas, handle 3 exhibited an f/m strength ratio of 0.90.

Since both male and female data demonstrated the same overall pattern of results, the two data sets were combined for the final analysis. Pulling strength was significantly affected by both handle type ($F=105$, $df=3,87$, $p<0.01$) and handle position above the ground ($F=147$, $df=1,29$, $p<0.01$). On average pulling strength was reduced by 37% when the handle height was raised from 1.0m to 1.75m. Analysis of variance, however, detected a significant interaction between the two independent variables ($F=48$, $df=3,87$, $p<0.01$), indicating that pulling strength on the different handles was not equally affected across all handles by the change in bar height.

At the bar height of 1.75m, pulling strength was most affected using handles 1 and 4. Least affected was handle 3 which demonstrated very little change in horizontal pulling strength at the different bar heights. Performance on handles 1, 2, 3 and 4 at 1.75m was 45%, 66%, 95% and 47% of the respective performances at 1.0m. Table 3.4 shows summary statistics for pairwise comparisons of steady maximal pulling strengths across the different handle types at both bar heights.

The largest pulling forces were recorded on handles 1 and 4, with the lowest generated using handle 3. Post hoc analysis showed that pulling strengths using handle 3 were significantly lower than for handles 1, 2 and 4 at the 1.0m bar height ($p<0.05$), but only significantly different from handles 1 and 4 at the 1.75m bar height ($p<0.05$).

Figure 3.2 shows the 1.75m bar height pulling strength/1.0m bar height pulling strength ratio (1.75/1.0 m strength ratio) as a function of the average force data over the two bar heights, for each handle. The data presented in this Figure reveals that pulling strength tended to be most affected by handle placement when using handles which permitted the largest pulling forces to be exerted.

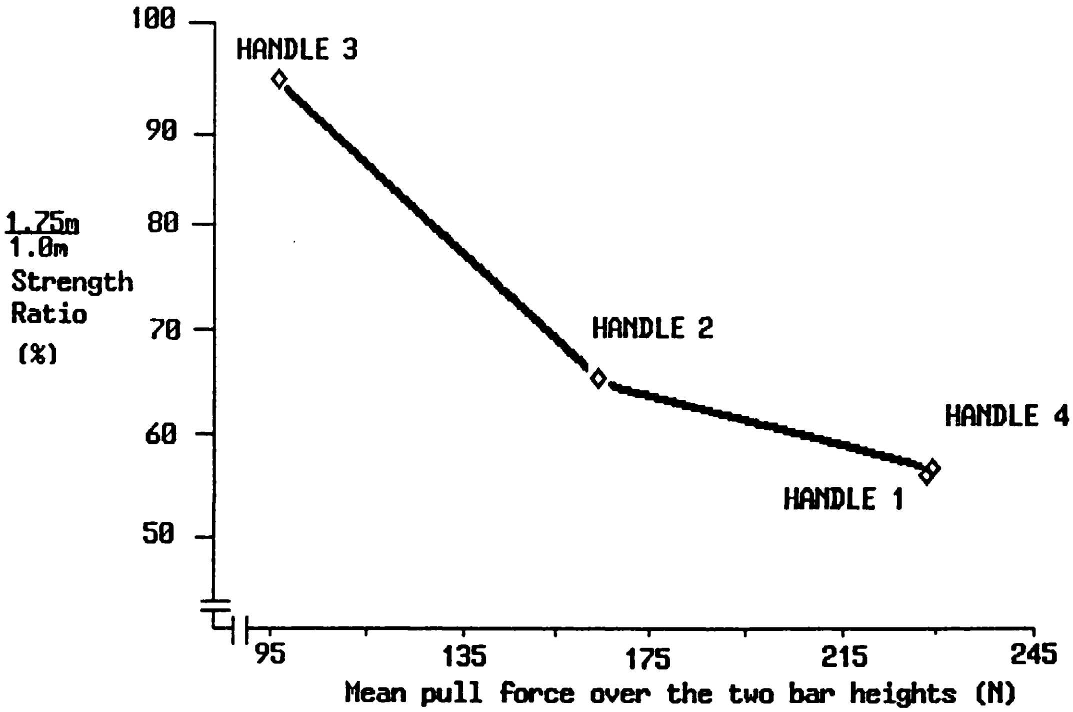


Figure 3.2: 1.75m/1.0m pulling strength ratios for each handle, as a function of their respective average values of pulling strength over the two conditions of handle placement (1.0m and 1.75m).

Table 3.2:
Peak and steady maximal horizontal pulling strengths on 4 different handle designs at 2 different heights from the ground (values are means ±SD)

	Bar Height 1m				Bar Height 1.75m			
Handle Type*	1	2	3	4	1	2	3	4
Peak pulling strength (N)								
Male Data (n=14)	400(125)	256(86)	127(27)	403(114)	232(58)	191(46)	121(28)	241(61)
Female Data (n=16)	276(58)	186(36)	112(18)	282(76)	164(30)	122(20)	100(16)	178(40)
TOTAL (n=30)	334(113)	219(72)	119(23)	338(112)	196(56)	154(49)	110(24)	207(59)
Steady Maximal Pulling Strength (N)								
Male Data (n=14)	364(125)	225(87)	105(22)	361(109)	197(50	168(44)	104(31)	201(53)
Female Data (n=16)	247(51)	171(45)	90(21)	244(62)	139(28)	101(21)	82(17)	144(25)
TOTAL (n=30)	302(109)	197(72)	97(23)	299(104)	166(49)	133(47)	93(26)	171(49)

* See Figure 3.1 for the different handle designs

Table 3.3:
Test-retest reliability of peak and steady maximal strength values for horizontal pulling on a variety of handle types placed at two different levels from the floor.

	Peak Pulling Strength	Steady Maximal Strength
n	18	18
Test Mean (SD) (N)	199 (45)	170 (39)
Retest Mean (SD) (N)	202 (47)	178 (45)
t	0.52 (NS)	1.72
(NS)		
r	0.88	0.91

p = significance level
NS = Not Significant ($p>0.05$)
n = number of subjects
t = Student's t-test value
r = Pearsons product-moment correlation coefficient

Table 3.4:
Summary statistics for Tukeys HSD post-hoc analysis of steady maximum pulling strength on 4 different handle types placed 1.0m and 1.75m from the floor

		Bar Height 1m				Bar Height			
					Handle Number*				
		1	2	3	4	1	2	3	
Bar Height 1m	Handle 1	-	0.05	0.05	NS				
	Handle 2		-	0.05	0.05				
	Handle 3			-	0.05				
	Handle 4				-				
Bar Height 1.75m	Handle 1	0.05			-				
	Handle 2		0.05			NS	-		
	Handle 3			NS		0.05	NS	-	
	Handle 4				0.05	NS	NS	0.05	-

NS = Not significant
0.05 = $p<0.05$
* The handle numbers correspond to the handle types shown in Figure 3.1.

Discussion

The four handles investigated in this study were chosen to illustrate how the coupling at the hand influences the ability of a person to exert maximal horizontal pulling forces in different postures.

The contrasting dimensions and designs of the handles clearly dictated the type of grip which could be employed and the subsequent effectiveness of pulling exertions on them.

The most common grips employed on the different handles by subjects with different hand sizes[6] are shown with each handle in Figure 3.3. In virtually all cases the bar (handle 4) encouraged an overarm power grip. This particular grip produced the greatest degree of hand/handle contact over all other grips observed, and was considered optimum for pulling exertions.

A similar grip to that shown for the bar, tended to be employed on handle 1. However, due to the limited knuckle clearance this type of grip was less closed chained than for the power grip, and approximated a hook grip, with the thumb, in some cases, pressed against the upper anterior aspect of the handle. Hand/handle contact was much less than on the bar, leading to a certain amount of discomfort during exertions. Despite contrasting grips and handle designs, there was no significant difference ($p > 0.05$) for maximal pulling forces between the bar and handle 1 at the two bar heights.

Handles 2 and 3 evoked various forms of precision grip in which the handle was pinched between the side and/or flexor aspects of the fingers and opposing thumb. Pulling strengths using this type of grip on the above handles were lower than those recorded for the power grip or hook grips employed on the

[6] Hand size was determined from seventeen hand dimensions each converted to percentiles using the data of Pheasant (1986). Mean hand size was estimated from the average percentile value of these 17 dimensions.

bar and handle 1. The differences in maximum pulling strengths between handle 2 and 3 were most likely due to the fact that handle 2 allowed for a better grip purchase by providing an edge on which to hook the distal aspects of the phalanges. In comparison, the small spherical surface of handle 3 made gripping extremely difficult, resulting in much lower pulling strengths. The hand/handle contact area for handle 3 was also less than that for handle 2 especially when a pinch grip (see Figure 3.3) was used.

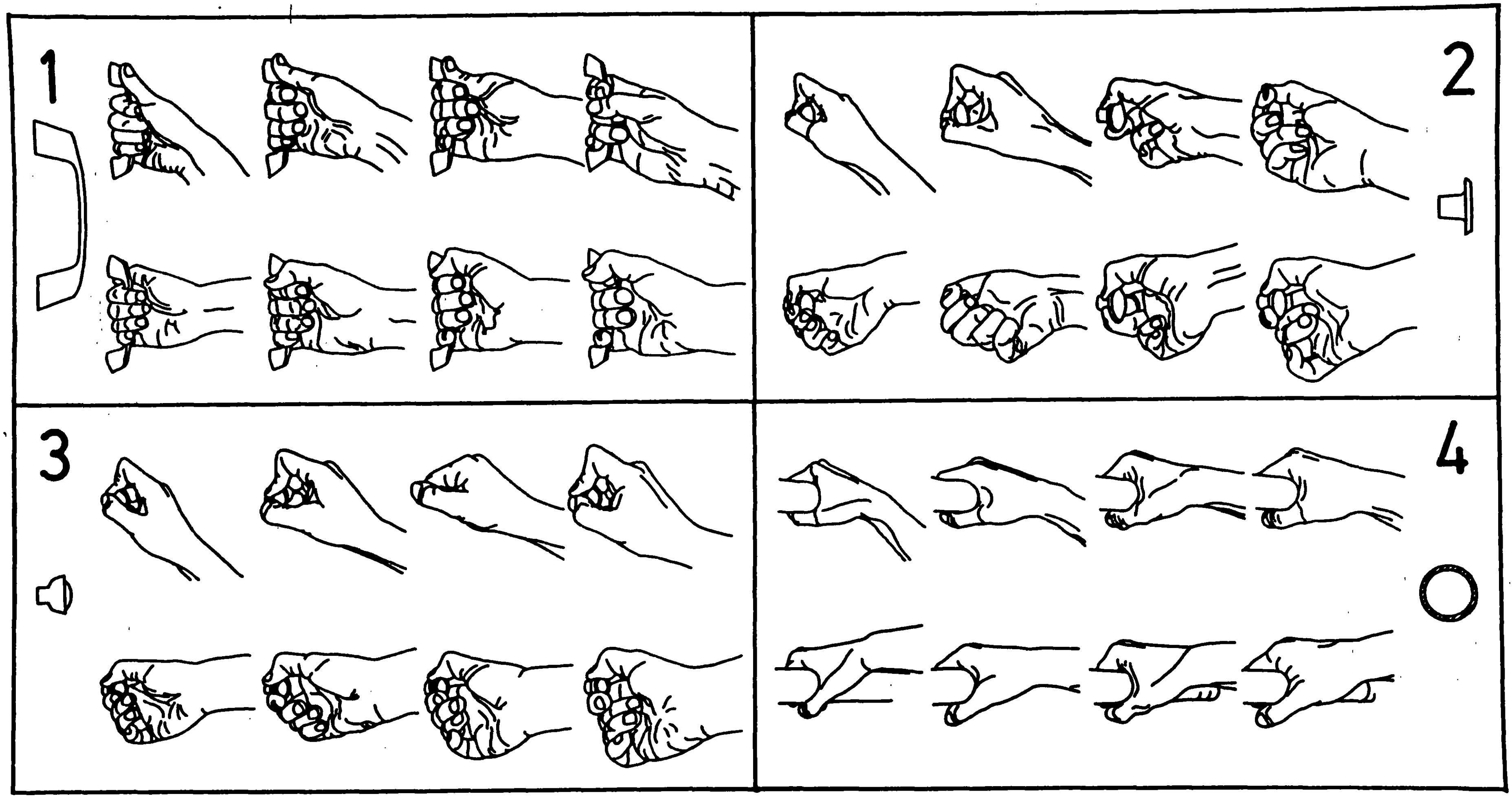


Figure 3.3: Typical grips employed on the four different handles by four subjects with mean hand dimensions corresponding to a 50 percentile female and 40, 50 and 90 percentile male (from left to right respectively). For each handle the upper figures are for pulling exertions at 1.75m and the lower ones for exertions at 1.0m.

Figure 3.3 also shows that orientation of the hand on handles 2 and 3 changed between exertions performed at 1.0 and 1.75m. Perhaps this reflected an attempt on behalf of the subjects to avoid excessive ulnar deviation and reduce stress on the wrist during exertions at the higher bar height. In comparison, the design of handle 1 did not permit such changes in posture, thereby resulting in a large degree of ulnar deviation at the 1.75m bar height.

Although the results indicated no significant difference in pulling strength between handles 1 and 4 at 1.75m, it is likely that exertions on the former handle resulted in much larger stresses on the wrist. In other studies on manual handling, excessive wrist deviation has been found to significantly reduce force capability and be related to well known pathologies and worker complaints (Drury 1985).

Design parameters of handles for manual materials handling have been reviewed by Drury (1980). Both handle size and handle diameter have been shown to affect pull force (Bobbert 1960, Ayoub and LoPresti 1971, HEDGE 1974).

Other features of handle design known to affect force capability are surface texture and the presence of sharp edges (Pheasant and O'Neill 1975). Prominent corners or ridges on the handles create high pressure point loadings on the hand during exertion, leading to pain and discomfort. This was a common complaint following exertions using handles 1 and 2. In contrast the frictional properties and smooth shape of handle 3 provided a poor grip purchase.

An example of how handle design and hand anthropometry can interact in an unexpected way is demonstrated by the small difference in normalized pulling strength between males and females on handle 3. Only the smallest fingers could fully occupy the space at the rear of handle 3. Under these conditions, the pulling force depends more upon compression of the finger against the handle rather than upon friction at the interface. Subjects with large finger and thumb dimensions were forced to adopt a pinch grip nearer the outside edge of the handle where a tangent on the curved edge approaches horizontal. In this case frictional limitations become more critical when exerting a pulling force. Consequently, for a given coefficient of friction and horizontal pulling strength, the pinch force required to prevent slip on the handle for a women of 5th percentile finger dimensions was considerably less than for a male with 95th percentile finger dimensions.

Differences in pulling strength capabilities at the two handle placements depend, in part, on the way in which body weight may be deployed in the different postures. 'Weak links' in force transmission between regions of force production within the human body and the point of force application on the external object will also limit maximum strength capabilities. These weak links may occur at or across an articulation of the musculoskeletal system, or at the hand/handle interface. Factors determining where the weak link will reside in the overall system, for a given condition, will include handle placement and design and those variables dependent on these elements.

Figure 3.2 showed that the poorer the handle design, the less effect its location had upon the force which could be exerted. In other words, in the case of handle 3, the limiting factor, or weak link in force transmission, was at the hand/handle interface; whereas for well designed handles the force was more strongly dependent on posture and the weak link must therefore have been elsewhere.

Evidence from the current study indicated that horizontal pulling strength may be reduced by as much as 65% when performing exertions against a poor hand/object interface. In contrast, current manual handling guidelines (NIOSH, 1981) and biomechanical models (e.g. Martin & Chaffin, 1972) assume that the hand/object interface is close to optimal and does not limit the strength of exertion. There seems to be a clear need to classify couplings between hand and object as "strong" or "weak links" in these models to enable a better prediction for safe manual handling.

Conclusions

Maximum pulling strength was influenced by both the hand/handle interface and by handle position. Factors which distinguished a good hand/handle interface from a poor one, for maximal pulling exertions, included the handle design (size and shape) and the type of grip encouraged by the particular handle.

Handle placement had a significant effect on whole body pulling strength when exertions were performed using a good handle, but showed little effect on the strength of exertions with poorly designed handles. It was inferred that in the latter condition the hand/handle interface was the 'weak link' in force transmission between the human and external object.

CHAPTER 4

STUDY II

HUMAN STRENGTH CAPABILITIES DURING ONE-HANDED MAXIMUM VOLUNTARY EXERTIONS IN THE FORE AND AFT PLANE.

Introduction

The main objective of this study was to describe human strength capabilities during one-handed maximal voluntary exertions in the fore and aft plane in freestyle postures. In order for the strength data to be potentially useful as an aid in task design and in the recognition of hazards during manual exertion, forces are presented in vector form as a Postural Stability Diagram (see literature review).

Further objectives of the present study were to investigate the influence and interactions of sex, body weight, handle height and direction of exertion on one-handed strength; and to compare the strength of one and two-handed exertions.

Methods

Subjects

The 22 subjects (18 right handed, 4 left handed) were unpaid volunteer staff or students of this institute. Their physical characteristics are summarized in Table 4.1.

Table 4.1
Physical Characteristics of Subjects (Values are means (±SD)

	Male	Female	Group
n	12	10	22
Age (yrs)	32.9 (10.7)	28.0 (5.5)	30.7 (8.9)
Weight (kg)	76.3 (13.6)	62.2 (5.3)	69.9 (12.7)
Height (cm)	178.4 (8.6)	167.4 (7.0)	173.3 (9.5)
Grip (N)	493 (71)	348 (53)	427 (97)

Apparatus

The same force bar described in Chapter 3 was used to measure vertical and horizontal components of static exertions. Using a 64k BBC microcomputer, customized software was designed to sample and then plot the maximal horizontal and vertical components of the force vectors applied to the bar in all possible directions in the fore and aft plane. A plot of these force vectors on a VDU screen presented the strength data in the form of a Postural Stability Diagram (PSD) (see Grieve 1979a, b).

A combination of emery cloth floor and rubber soled shoes provided a unity coefficient of limiting friction (Pheasant and Grieve 1981). Despite some of the extreme postures adopted during exertions, slippage did not occur.

Grip strengths were measured with a handgrip dynamometer (Takei and Company Ltd) where grip size was adjusted to the preference of the subjects.

Procedure

The subjects' unshod weight and stature were measured. Grip strength was determined from the best of two efforts with the dominant hand. Free style manual strengths, with the dominant hand, were measured on the force bar while standing. The only limitation placed on the subject's posture was that the leading foot should not be placed anterior to the handle. Subjects performed steady maximal exertions in all possible directions in the fore and aft plane with the force bar set at 1.0 or 1.75 m above the ground,. No 'jerking' or 'swinging' on the force bar was allowed. The procedure for obtaining a Postural Stability Diagram (PSD) has been described previously (Pheasant and Grieve 1981). At least one day separated tests at the two heights. Half the subjects started with the 1.0 m bar height, the remainder started at 1.75 m. One month later, twelve subjects who had completed the one-handed exertions followed the same procedures and protocol using two hands.

Analysis

Strength data were stored on disc as sets of 36 force vectors 10° apart. Group mean strengths and standard deviations in each condition were calculated. Prior to plotting all charts, the data were fitted with a cubic spline function as described by Pheasant and Grieve (1981).

The Maximum Advantage of using a Component of Exertion (MACE) was also calculated from the PSD data for each subject at each bar height and in all directions in the fore and aft plane (Grieve and Pheasant 1981).

The proportion of variance in strength that could be accounted for by the variance in body weight alone, or body height and weight in combination, was calculated for each direction at both bar heights using 3 different regression models. Two were simple linear regression models in which the strength of exertion was regressed against (a) body weight (WReg) and (b) body weight and height in combination (WHReg), and the third was a multiplicative regression model of the form $Y=aX^b$ (W^bReg) (see literature review). A two-way repeated measures ANOVA followed by a Tukeys HSD test *post hoc* test for all pairwise comparisons was performed on the variances obtained from these three models to ascertain which of the models explained the greatest amount of variance in strength over the two bar heights.

Results

Sex Differences in the Strength of One-Handed Exertions

PSD plots for one-handed exertions at the two bar heights (1.0 m and 1.75 m) are shown in Figure 4.1. The data are presented as strength/weight ratios and show the group means ± one standard deviation.

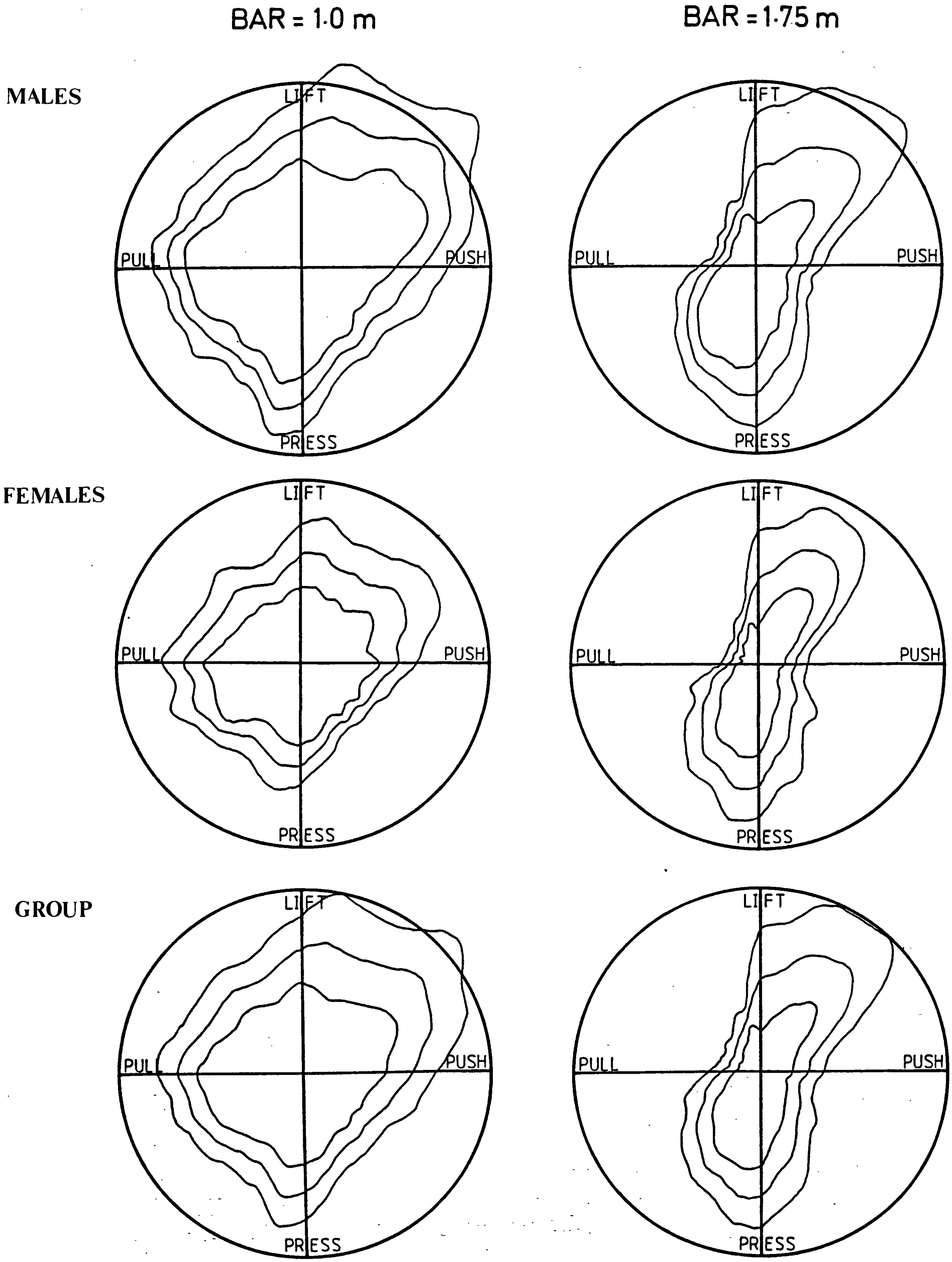
A comparison of the PSD's in Figure 4.1, between male and female subjects, show almost identical shapes for the vector diagrams with only small differences in their normalized strengths for exertion at the two bar heights. When the female/male (f/m) strength ratios were calculated, for the normalized data in each of the 36 directions at the two bar heights, a mean value of 0.79 (SD = 0.09) was obtained (n=72). This f/m strength ratio decreased to 0.65 (SD = 0.08) when absolute strength values were considered.

Female/male strength ratios (calculated from the normalized strength data) for all 36 force vectors at the two bar heights are presented in Figure 4.2. Although the mean f/m strength ratio at the two bar heights were very similar, (Bar=1.0 m, ratio=0.78 (SD=0.08); Bar=1.75 m, ratio=0.80 (SD=0.11); n=36) Figure 4.2 clearly shows that the magnitude of this ratio varies according to direction of exertion and bar height.

At the 1.0 m bar height males were significantly stronger ($p<0.05$) than females in most directions, except for exertions performed in the Pull/Press quadrant. In this latter quadrant the normalized f/m strength ratio averaged 0.86 (SD=0.07, n=9) with a peak ratio of 0.93 occurring between 120 and 130 degrees. Over a large area of this quadrant there was no significant difference in strength ($p>0.05$) between males and females when forces were normalized against body weight.

At the 1.75 m bar height, normalized female strength approached that of the males in many more directions. Figure 4.2 indicates large areas in the fore and aft plane where there were no significant differences ($p > 0.05$) in normalized strength between males and females. Large strength differences between males and females were observed in the directions of horizontal Pulling/Pushing and most of the Pull/Lift quadrant.

Figure 4.1: Postural Stability Diagrams (PSD's) for one-handed exertions, in the fore and aft plane, at handle placements of 1.0m and 1.75 m above the floor. The data are average maximal strengths ($\pm$ one standard deviation) as a percentage of body weight. The centre of each diagram represents zero manual exertion and the edges represent forces equal in magnitude to body weight. The posture adopted was freestyle.



BAR = 1·0 m
BAR = 1·75 m
MALES
FEMALES
GROUP
LIFT
PULL
PUSH
PRESS

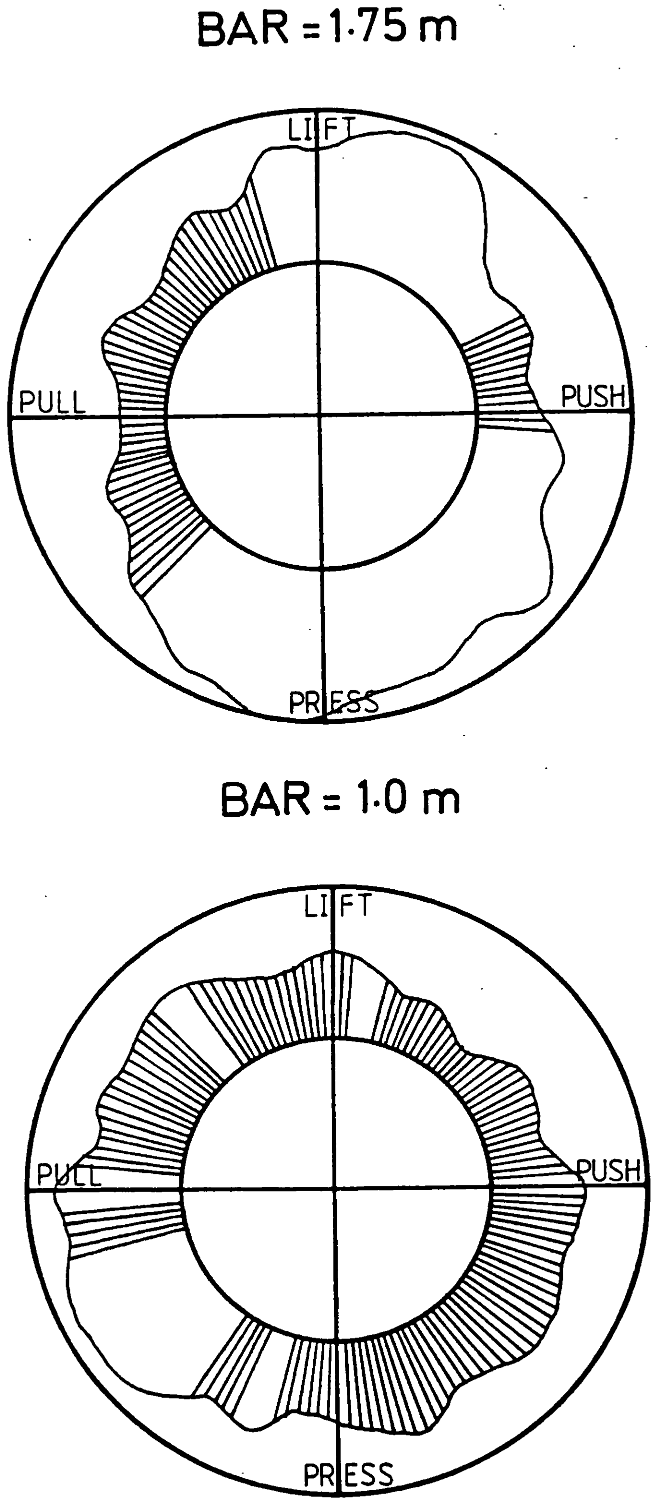


Figure 4.2: Female/male strength ratios in all directions in the fore and aft plane, for one-handed maximal exertions, under two conditions of handle placement (1.0 m and 1.75 m). The centre of each plot represents a f/m strength ratio of zero, the inner circle an f/m strength ratio of 0.5 and the outer circle an f/m strength ratio equal to unity. The hatched areas represent directions in the fore and aft plane where males were significantly stronger than females ($p < 0.05$). All data calculated from strengths expressed as a percentage of body weight.

The Maximum Advantage of Using a Component of Exertion (MACE) for One-Handed Exertions.

Using individual PSD data, advantages of using components of deviated forces were calculated for all directions in the fore and aft plane, at both bar heights. An example of the plot obtained for one subject is shown in the upper diagrams of Figure 4.3. In these two diagrams the advantage of using the components of deviated forces (outer envelope) is superimposed on the raw PSD data (inner envelope). A plot of the average maximal forces (as well as standard deviations), which may be obtained by employing components of deviated forces, for the subject population (n=22) at the two bar heights is shown in the lower two diagrams of Figure 4.3.

Figure 4.4 presents the average MACE values for the group (n=22) for all directions in the fore and aft plane. The centre of the plot in Figure 4.4 corresponds to a MACE value of 1.0 and is the point where the actual resultant force observed is equivalent to the maximum available component. The inner and outer circles represent MACE values of 1.5 and 2.0 respectively. MACE data at the 1.75 m and 1.0 m bar heights are shown by the solid and dashed lines respectively.

At the 1.75 m bar height Figure 4.4 indicates that forces exerted in certain directions (i.e. the upper LIFT/PULL and the lower LIFT/PUSH quadrants) may be more than doubled if a person chooses and is able to, take advantage of deviated forces. In contrast, there are other directions of exertion at both bar heights, (i.e. vertical pressing and the upper LIFT/PUSH quadrant) which gain no benefit from deviated force components. These latter directions of exertion naturally correspond to areas on the PSD's where the largest manual forces were observed.

The average MACE value over the 36 directions of exertion for the 1.75 m bar height was 1.63 and was significantly greater ($t=6.73$, $df=35$, $p<0.001$) than the average MACE value at the 1.0 m bar height ($MACE_{1.0m}=1.18$).

For the purpose of discussion, Table 4.2 presents the MACE values for the 90°,180°,270° and 360° force vectors at both bar heights, along with their angular deviations from the maximum horizontal or vertical force vectors.

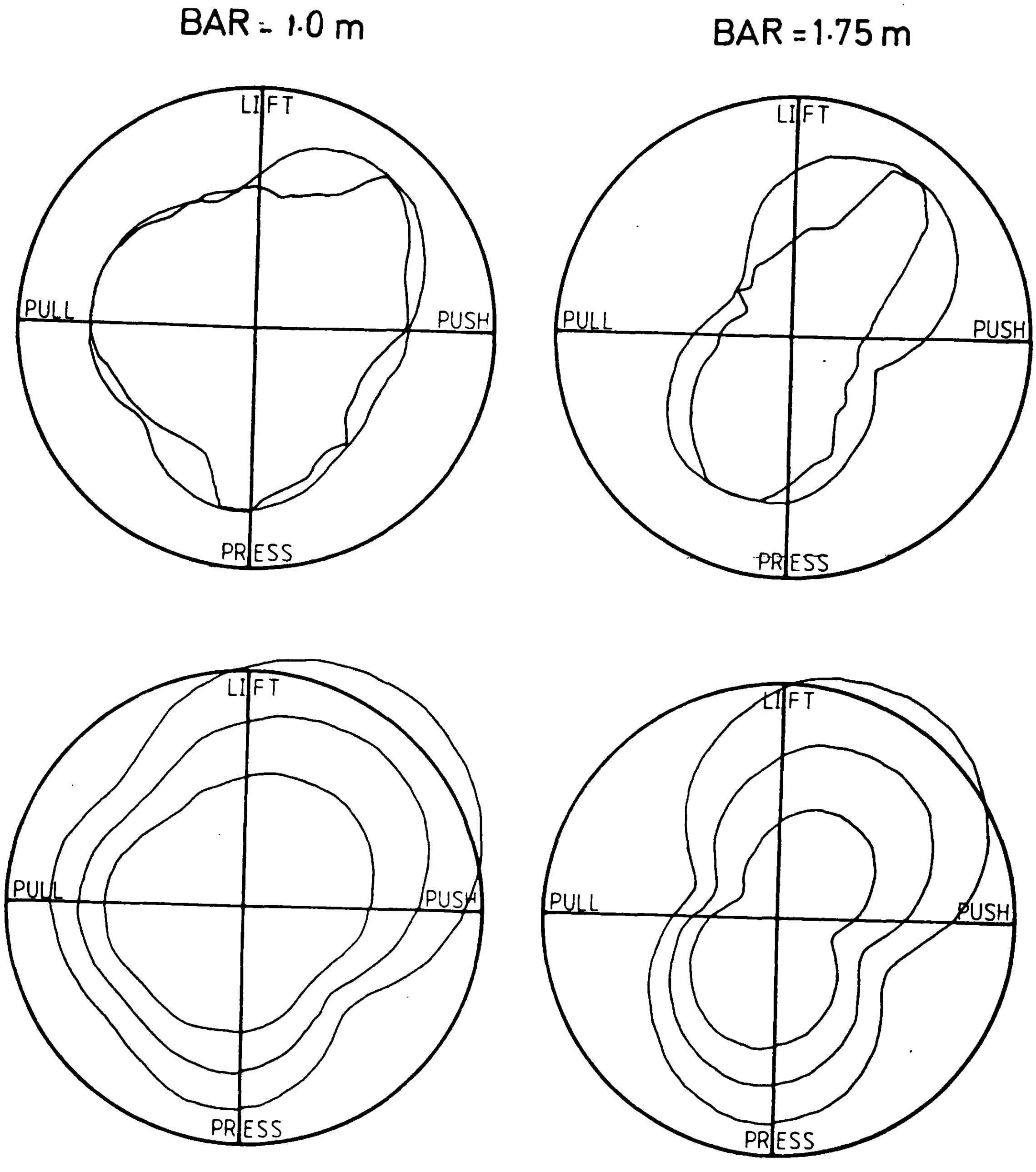


Figure 4.3: Upper diagrams: PSD plots of subject DS for one-handed maximal exertions in the fore and aft plane at bar heights of 1.0 and 1.75 m above the ground (inner envelopes). The advantages of using components of deviated forces are shown by the outer envelopes. Lower diagrams: PSD plots illustrating the average maximal forces ($\pm$ one standard deviation) which may be obtained by using components of deviated forces at the two bar heights (n=22). Presentation of data is as described in Figure 4.1.

Table 4.2:

MACE values for Pulls (90°), Presses (180°), Pushes (270°) and Lifts (360°) and the angular deviations, D, of the force vectors from the vertical or horizontal which give a greater component than forces generated exactly in those directions. Positive and negative values refer to anticlockwise and clockwise deviations respectively.

Bar Height		LIFT	PULL	PRESS	PUSH
1.75 m	MACE	1.42	1.76	1.03	2.12
	D(°)	-20	+40	-10	+40
1.0 m	MACE	1.16	1.03	1.06	1.26
	D(°)	-10	0	-10	+20

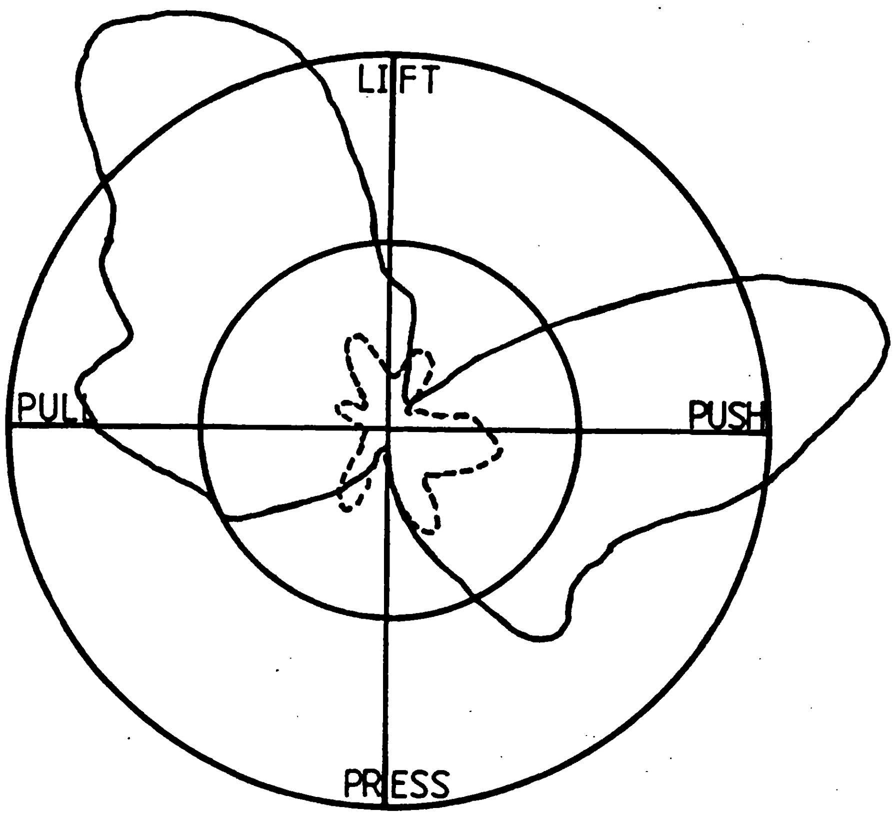


Figure 4.4: MACE values for one-handed freestyle static exertions performed at bar heights of 1.75 m (solid line) and 1.0 m (dashed line). The origin corresponds to a MACE value of 1.0, and the inner and outer circles to MACE values of 1.5 and 2.0 respectively.

One-Handed Versus Two-Handed Exertions

PSD plots showing the average maximal strength ($\pm$1.0 SD) of twelve subjects who performed two-handed exertions at the 1.0 and 1.75 m bar height are shown in the upper portion of Figure 4.5 The PSDs are displayed relative to body weight. These data were compared with their one-handed exertions to produce one-handed/two-handed strength ratios for all 36 directions at each bar height. The resulting mean one-hand/two-hand strength ratios are presented in the lower portion of Figure 4.5 in the same format as that described for the f/m strength ratios in Figure 4.2.

At the 1.0 m bar height one-handed exertions were significantly weaker ($p<0.05$) than two-handed exertions over most directions in the fore and aft plane. Exertions performed in the lower half of the Pull/Lift quadrant were however the exception. For force vectors between 30° and 100° one-handed and two-handed exertions were virtually equivalent, with one-handed/two-handed strength ratios approaching and actually exceeding unity.

Fewer significant differences between one and two-handed exertions were found at 1.75 m. The main strength differences (Fig. 4.5, lower right) resided in the Lift/Push quadrant and the lower portions of the Pull/Press-Push/Press quadrants. Outside of these regions strength differences between one and two-handed exertions were largely insignificant ($p>0.05$).

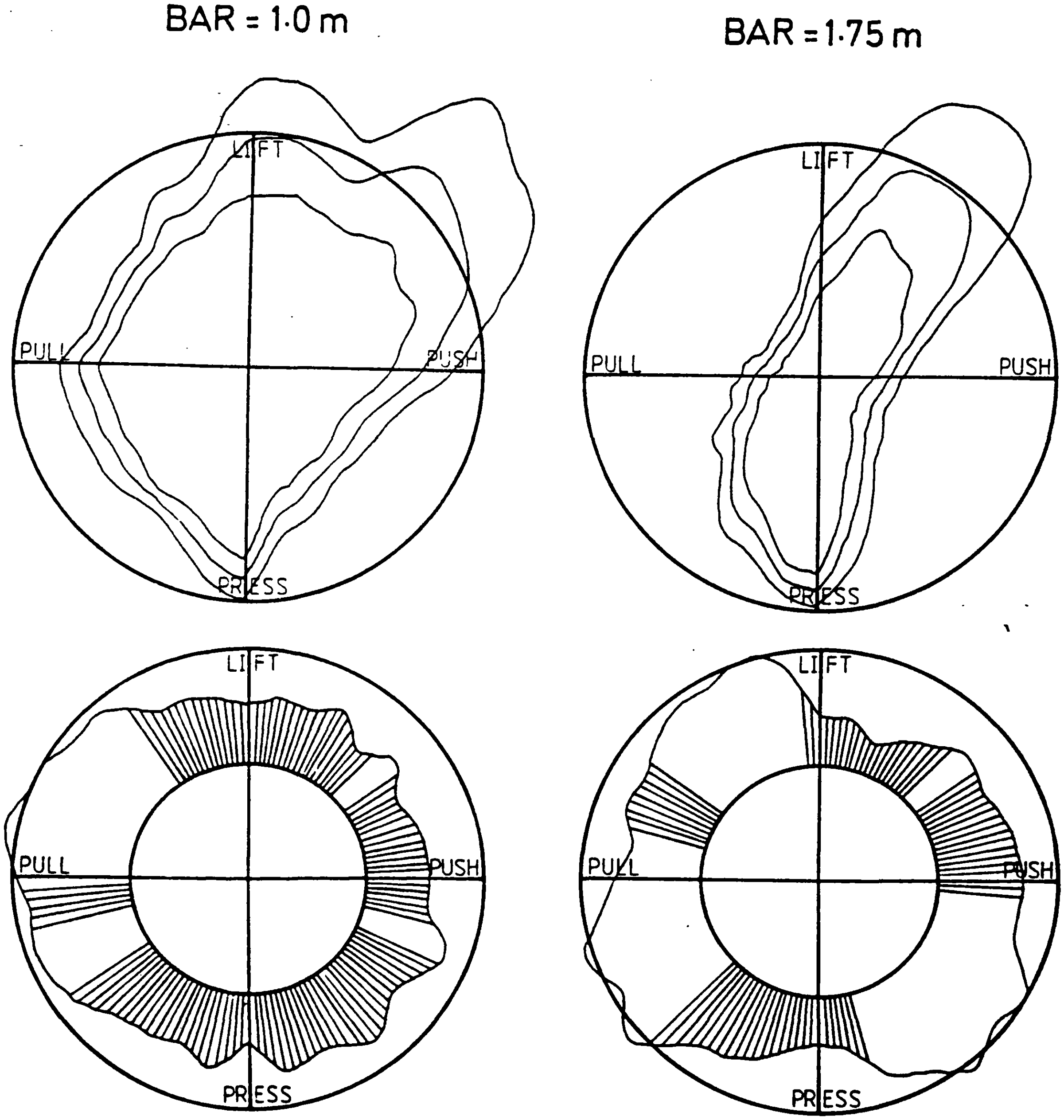


Figure 4.5: Upper diagrams: PSD plots of two-handed maximal exertions in the fore and aft plane with the force bar placed at 1.0 m and 1.75 m above the floor (n=12). Presentation of the data is as described for Figure 4.1. Lower diagrams: Plots showing the mean 1 handed/mean 2 handed strength ratios for all directions in the fore and aft plane at the 1.0 m and 1.75 m bar heights. Scaling of the strength ratios is the same as that described in Figure 4.2. The hatch areas represent directions in the fore and aft plane where two-handed exertions are significantly stronger than one-handed exertions ($p<0.05$).

Relationships between Body Weight, Strength and the Direction and Height of Exertion

Figure 4.6 shows the proportion of total variance in strength which may be accounted for by the variance in body weight or body weight and height combined for all directions of exertion in the fore and aft plane at the 1.0 m and 1.75 m bar heights. The centre of this plot represents an r^2 of zero and the inner and outer circles an r^2 of 50% and 100% respectively. The proportion of the total variance in strength explained by the three regression models WReg, WHReg and W^bReg are shown by the dashed, solid and dotted lines respectively. The results of the two-way ANOVA are presented in Table 4.3 and show that the proportion of total variance in strength explained by these regression models changes significantly according to the direction of exertion ($p<0.001$), but differs little in their mean r^2 values between the two bar heights ($p>0.05$).

A significant F ratio was also found for the regression model type ($p<0.001$). This indicated that there were significant differences in the overall proportion of the total variance in strength accounted for by the different models. A *post hoc* comparison of the three regression models using the Tukey's HSD test for significance revealed that the WHReg model (mean r^2=63%, SD=18%), explained a significantly greater proportion of the total variance in strength than either the WReg or W^bReg models ($p<0.05$). There was no significant difference in the mean r^2 values observed between the WReg (mean r^2=57%, SD=17%) and W^bReg models (mean r^2=55%, SD=16%) ($p>0.05$).

Table 4.3

Analysis of variance summary statistics for the main effects handle height, direction of exertion and type of regression model on the proportion of the total variance in strength accounted for solely by the variance in body weight or body weight and height combined.

FACTOR	SOS	DF	MS	F	p
Bar Height (A)	2327	1	2327	3.95	$p>0.05$ (NS)
Error A S	20642	35	590		
Regression Model (B)	2886	2	1443	134.04	$p<0.001$
Error B S	754	70	11		
Interaction A B	43	2	21	1.51	$p>0.05$ (NS)
Error A B S	996	70	14		
Angle (S)	37853	35	1082	76.02	$p<0.001$
Total	65501	215			

Notes:

SOS = Sums of squares
DF = Degrees of freedom
MS = Mean square
NS = Not significant

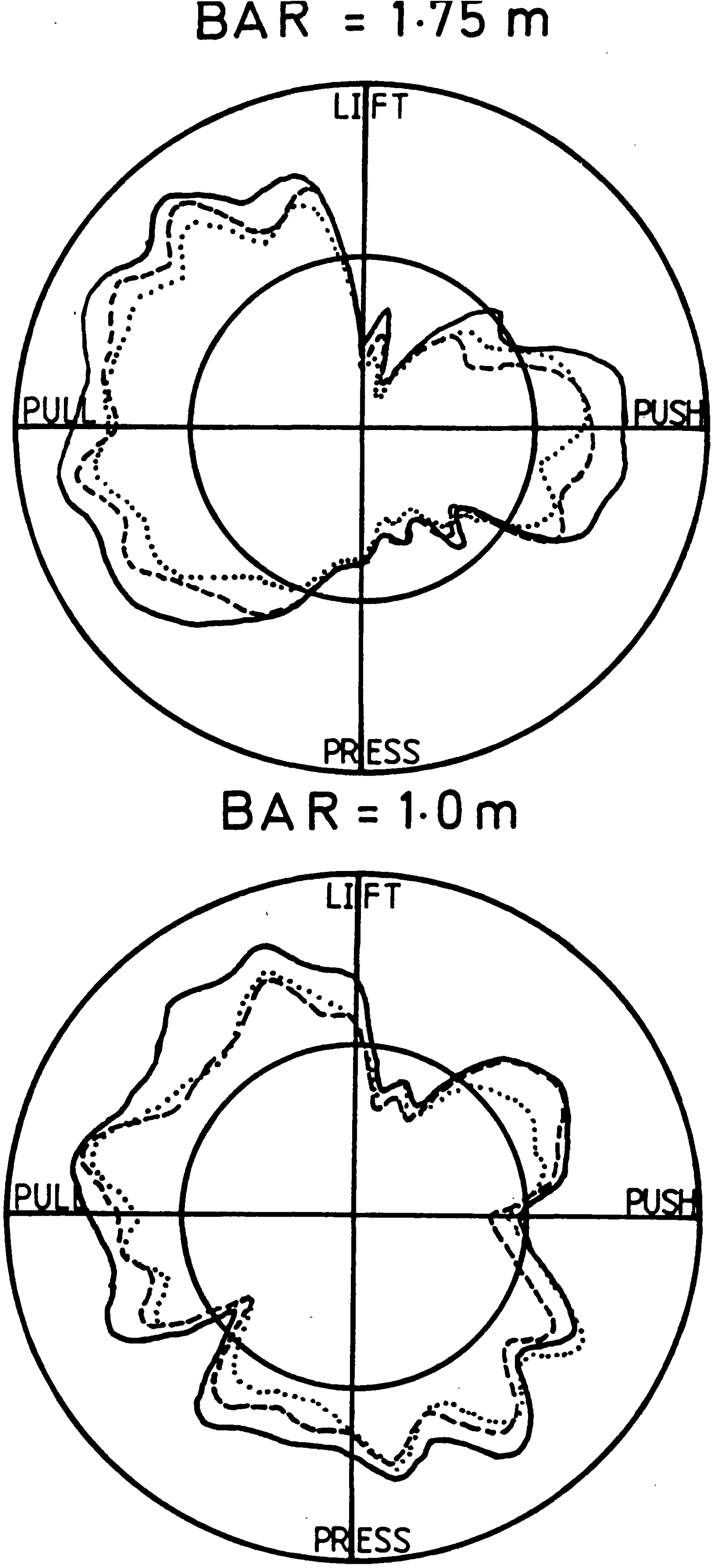


Figure 4.6: The proportion of the total variance in one-handed static strength explained by the regression models WHReg (solid line), WReg (dashed line) and W^bReg (dotted line) at the 1.0 m and 1.75 m bar heights.

Discussion

Sex Differences in the Strength of One-Handed Exertions.

Part of the variation in f/m strength ratios (shown in Fig. 4.2) is likely to reflect differences in stature between the male and female subject population. In addition, sex differences in the strength of the principal muscle groups involved during exertions in different postures are likely to add to this variance.

In those regions where sex differences were small it may be assumed that the physical strength of the individual played only a minor role in the force of exertion. Under these circumstances the deployment of body weight may therefore be the predominant factor dictating force output.

The above argument does not explain the similarity of forces produced by males and females in the Lift/Push quadrant at the 1.75 m bar height. It was in this region of the PSD that the largest forces were recorded by both sexes. As described by Pheasant and Grieve (1981) these peak forces arise from postural configurations in which muscular torque required about the major articulations is minimized. This occurs when the trunk, upper and lower limbs approximate a straight line and the whole body is brought as close as possible to the line of thrust. One reason for the similarity of strengths between the sexes under the above conditions may be that the postures adopted employed muscle groups with minimal sex differences in strength.

Based on 112 data sets Pheasant (1983) noted that the ratio of female/male average strengths can vary from 0.37 to 0.90 depending on a number of factors including the direction of exertion and muscle group tested. Upper and lower extremity strength of women were reported to be on average 58 and 66% of men's respectively (Pheasant 1983). In view of this fact it may be hypothesised that sex differences in whole body strength will be greatest in directions of exertion that require mainly upper body strength. Alternatively, sex differences in whole body strength will be minimized where the force produced is limited predominantly by leg strength.

As discussed in the literature review some of the variability in strength between the sexes are likely to be due to differences in their skill and motivation when performing the strength tests. As the current experiment permitted freestyle postures to be adopted, it would be reasonable to assume that these conditions would entail a greater element of skill to produce maximal exertions than would be required if formal foot placements were investigated. Unfortunately it is difficult to isolate and quantify skill level. Nevertheless, the freedom of choice of posture, and the subjects ability to adopt the optimum or most efficient posture for force exertion in a given direction, will no doubt have played a significant contribution to the sex differences in strength, and indeed to the overall variability in strength.

In general, the present data illustrate the large variability in strength between the sexes under different conditions. The findings also depict the complex interactions between angle of exertion and handle height (implying changes in posture and the use of different muscle groups) as well as body weight in the determination of strength.

It is interesting to note that the mean f/m strength ratio (based on absolute strength data) over all conditions investigated was close to the commonly quoted rule of thumb that in general, women are two thirds as strong as men.

Although this absolute strength difference between the sexes provides a strong argument for separate load limits for men and women in the field of manual handling; the current results indicate that it would be inappropriate to use a single mean ratio to predict female strength from male data.

Advantages of Using a Component of Exertion

The closer the MACE values are to unity, the smaller the benefit that can be obtained by using the component of a deviated force vector. Consequently, the data in Figure 4.4 clearly indicate that substantial advantages may be gained by employing deviated force components at the 1.75 m bar height, but little benefit may be gained by employing them at the 1.0 m bar height. The amount of benefit which may theoretically be derived from these deviated forces does however depend on the intended direction of exertion.

If only the truly horizontal or vertical directions are considered as shown in Table 4.2, it is seen that there is little to be gained by using a deviated component in horizontal pulling, vertical lifting or vertical pressing actions at 1.0 m. The MACE value shown for horizontal pushing, however, shows that if a subject exerts a maximal one-handed push at this height it is likely that a small vertical lifting component of force will also be exhibited (providing the subject chooses to take advantage of the deviated resultant force).

At 1.75 m, aside from vertical pressing, the MACE values indicated that a substantial advantage may be gained by utilizing a deviated resultant force during exertions. For example, if the objective is to produce a maximal horizontal push at this particular height it is best to direct the resultant force at approximately 40° above the horizontal rather than directly along the horizontal plane. Similarly, if the goal is to produce maximal horizontal pulling at 1.75 m, the resultant force should be directed approximately 40° below the horizontal plane of the handle.

In practice the individual will only benefit from the above resultant forces in tasks where the vertical component of the force is unimportant. Similarly, for deviated forces to be useful in lifting tasks their horizontal components must not compromise any frictional or task limitations. The possible use of deviated resultants should therefore be accounted for when designing equipment or considering tasks which may require heavy exertions.

Data provided by Grieve and Pheasant (1981) have shown (at least for two-handed exertions with defined foot placement) that adult males instinctively know that force exerted in a deviated direction may be used to achieve an improved result in another. This knowledge has important implications for predictive biomechanical models of human strength. Often many of these models assume that lifting or pushing and pulling exertions are performed in truly vertical or horizontal directions. In comparison the data of Pheasant and Grieve (1981) and that of the current study, would suggest that these type of biomechanical models may grossly underpredict the force available to an individual under these circumstances.

One-handed Versus Two-handed Exertions

In many directions of exertion, the difference in strength between one-handed and two-handed maximal efforts was surprisingly small.

In theory, strength differences between one and two-handed exertions should be minimized when: (1) deployment of body weight relative to the centre of foot pressure is the limiting factor in the strength of the exertions, or (2) the weak link limiting the amount of force produced and/or transmitted by the musculoskeletal system lies in a part of the body other than the upper limbs.

The implications of weak links, either at the hand/handle interface or within the musculo-skeletal system were investigated in Study I (see Chapter 3). Based on this work it was assumed that the coupling between the hand and bar in the present study was an effective one and unlikely to be the weakest link determining force outcome.

The current data show regions in the fore and aft plane at both bar heights where one-handed exertions actually exceeded the strength of two-handed exertions. Under these circumstances the greater freedom of postures available under the one-handed condition permitted the subject a more advantageous use of the body's centre of gravity. For example, in the case of exertions directed in the Pull/Press quadrant at 1.75 m, releasing one hand from the bar permits the subject to rotate about an axis connecting the leading foot and the hand grasping the bar. If the body is rotated about this axis until perpendicular to the bar, and the free leg and arm splayed out as far as possible from the axis in the direction of the exerted force, (as shown in Fig. 4.7) displacement of the body's centre of gravity away from the bar will be maximized. Thus for a given force vector the moment arms about which the horizontal and vertical components of the body weight act will be optimal. Consequently, in exertions where deployment of body weight is the predominant factor limiting force production, postures possible under one-handed conditions may permit greater forces to be applied than when performed using two hands.

As one-handed exertions performed in certain directions can approach the strength of two-handed exertions, the stress on the load bearing shoulder and arm may reach close to double that found during two-handed efforts. Due to the anatomical nature of the shoulder joint and the inherent instability of the articulation as a consequence of its degrees of freedom, the high stresses possible during one-handed efforts may lead to an increased risk of injury. Further epidemiological studies on upper limb injuries incurred during heavy manual exertion may provide evidence to support this hypothesis.

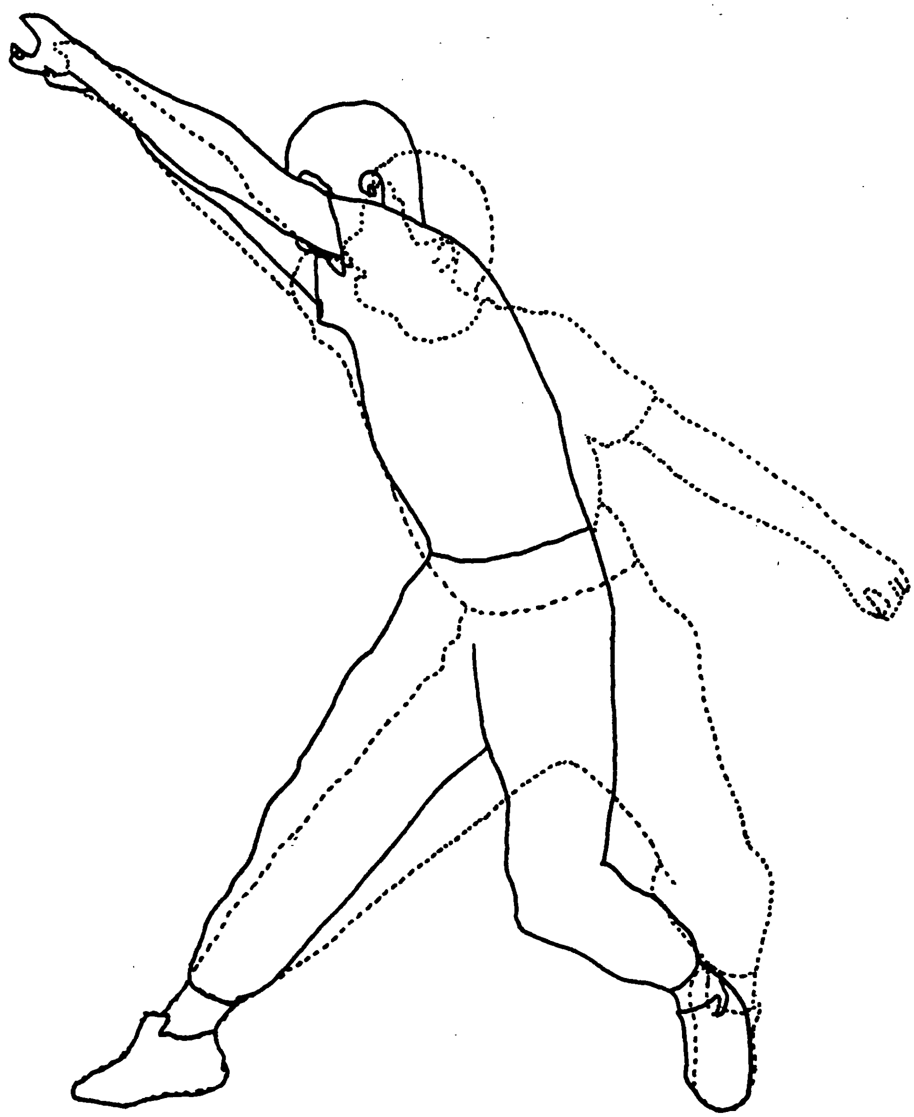


Figure 4.7: Tracings from photographic records of one subject showing the change in freestyle posture permitted by releasing one hand from the bar during a maximal exertion directed in the Pull/Press quadrant of the PSD. Bar height = 1.75 m. (See text for further details).

Relationships Between Body Weight, Strength and the Direction and Height of Exertion

The three regression models WHReg, WReg and W^bReg were chosen for comparison because of their common use in the literature. The regression model W^bReg (of the form $Y=aX^b$) was used by Lietzke (1956) and Ross *et al.*, (1984) in their analyses of the relationship between weight lifting performance and body weight. Their rational for using this type of regression model was based on dimensional theory and is explored in detail in the literature review.

The present results illustrate that the W^bReg model was no better at predicting one-handed freestyle whole body strength from body weight than a simple linear regression model (i.e. WReg). The value of the exponent, b, for the W^bReg models, averaged over the 36 directions and combined over both bar heights, was 1.67 (SD=0.43). This was greater than the 0.667 derived from theoretical expectancy and is likely to reflect the predominating influence of body weight rather than muscular strength *per se* in the determination of whole body strength when the data is averaged over all directions in the fore and aft plane.

In directions where the strength of exertion is limited solely by the weight and mass distribution of the body (i.e. gravitational limitations) it would be expected that strength would be linearly related body weight. In these cases the value of b in the regression model of the form $Y=aX^b$ would be 1.0 and not 0.667. However, it was found that the b value for many directions of exertion was greater than 1.0 and that, apart for a few individual directions, rarely approached the value of 0.667. This observation is likely to reflect the freestyle nature of the experiment and the diversity of the subject population.

Compared to the world class weight lifters in the studies of Lietzke (1956) and Ross *et al.*, (1984), it is reasonable to assume that the current subject population was far less homogeneous in their technique, ability, and body type. In addition, the current experimental design relied upon the intrinsic motivation of the subjects to produce maximum exertions, and for individuals to choose their own "optimum" or best posture for the different directions of exertion. This is far removed from the well trained skills and high motivation required of elite weight lifters for optimum performance in world class competition. It is therefore not surprising that the current subject population displayed somewhat different results than would have been predicted from theoretical expectancy.

The proportion of the total variance in strength accounted for by the WHReg model has been termed by Pheasant (1977) as the dead weight factor (D-W.F.). Pheasant (1977) defines the D-W.F. as the sum of the squares of the zero order correlation of strength against weight and the first order partial correlation of strength against stature with weight held constant. The same quantity is found from the r^2 value obtained for a simple linear regression analysis performed using strength as the dependent variable and height and weight as the independent variables.

Because of the freestyle nature of the conditions and the fact that only a few photographic records of the postures were taken, it is not possible to describe the exact orientation of the live and dead axes in the fore and aft plane at the two bar heights (see literature review). It may be anticipated however, that the extensive postures, and foot placements available under the current conditions would permit the orientation of the live axis (and hence dead axis) to vary over a wide range of angles. The extent of this range will be dependent on both the bar height and the location of the centre of foot pressure while performing exertions in the different directions. Clearly one limit is set by experimental constraints and will occur when the centre of foot pressure is directly beneath the bar. In this case the live axis is exactly vertical. The other limit will depend on the subjects choice of foot placement and optimum use of his or her body weight.

Despite the above problems in determining the orientation of the live axis, exertions at both bar heights demonstrated distinct regions where the D-W.F dramatically dipped below an r^2 of 50%. It is of note that these low D-W.F.

occurred predominantly in the upper portion of the LIFT/PUSH quadrant where the direction of exertion would be expected to be close to the live axis (i.e when exertions are directed along the line connecting the centre of foot pressure to the position of the hand). In these directions of exertion it may be deduced that factors other than body weight, such as muscular limitations, skill and motivation, play the main role in determining force outcome.

In contrast, body weight and stature explained a large proportion of the total variance in strength over the majority of directions of exertion at both bar heights. Under the present set of experimental conditions these data would suggest that on average, two thirds of the total variance in strength of freestyle one-handed whole body exertions performed in the fore and aft plane may be explained by individual variation in body weight and stature. Although the proportion of total variance in strength accounted for by the D-W.F. does not change with bar height (when averaged over all directions of exertion), the relationship between strength and body weight does change significantly with the direction of exertion.

The above findings again have important implications for biomechanical models of whole body strength. As discussed in the literature review many biomechanical models use body weight to predict individual variation in strength. In addition, some biomechanical models also assume that muscular factors (i.e. torque-angle relationships) are the main limitations for whole body exertions (e.g. Garg & Chaffin 1975). The current findings suggest that in certain directions these models may be unreliable unless they account for the changing contribution of body weight over the different directions of exertion.

Summary and Conclusions

The current data give some indication of whole body strength capabilities of one-handed exertions in the fore and aft plane. These data may be more applicable to the working environment than previous research as exertions were performed using freestyle rather than experimentally defined postures.
The main conclusions emerging from the study were:

(1) Sex differences in static one-handed maximum voluntary strength varied substantially according to the direction of exertion and bar height. This served to illustrate the complex interactions occurring between the underlying variables (e.g. body weight, posture and the sex differences in strength of the muscle groups involved).

(2) Considerable strength advantages (in a given direction) may be gained by employing components of deviated forces during one-handed exertions at 1.75 m. Relatively little benefit may be obtained by using these deviated forces at 1.0 m.

(3) It was more common to find two-handed strengths exceeding one-handed strengths at the 1.0 m bar height. There were, however, a number of directions of exertion at both 1.0 and 1.75 m bar heights where one-handed strengths approached and even exceeded two-handed strengths.

(4) On average almost two thirds of the total variance in the strength of one-handed static exertions may be explained by individual variation in body weight and stature (i.e the dead weight factor). The amount of the total variance in one-handed static strength accounted for by the dead weight factor did not on average change with bar height, but did change significantly with the direction of exertion.

(5) A comparison of the three different regression models WReg, WHReg and W^bReg revealed the best overall predictor for one-handed static strength was the

WHReg model (i.e. a linear regression model using body weight and stature as predictors of static strength).

When considering the current strength data, it should be kept in mind that the values given are for ideal conditions. This assumes posture is unrestricted by work space and force output is essentially unaffected by conditions at the foot and hand interfaces. While such conditions are unrealistic for a typical working environment, the data provide a starting point for estimating the effects of environmental factors on one-handed exertions.

Finally, due to the widely differing postures available, use of the strength data in biomechanical models of strength (e.g. Garg and Chaffin 1975) is problematic unless detailed anthropometric and postural analysis is performed. Nevertheless, data from the present experiment may enhance the reliability of such models in areas of interpolation where there have previously been few data.

CHAPTER 5

STUDY III

WHOLE BODY STATIC STRENGTH MEASUREMENT IN THREE DIMENSIONS

Introduction

In the area of manual materials handling most studies of human whole body strength have been limited to exertions performed in either a purely vertical or horizontal direction. In reality, however, the human interacts with the environment unhindered by these experimental constraints. Our knowledge of human whole body strength capabilities is therefore somewhat limited, with strength measurements in many directions of exertion yet to be explored.

In Chapters 2 and 4 the Postural Stability Diagram (PSD) was presented as a method for analyzing whole body static strength in a single plane. This approach required a two dimensional analysis and was suitable for the simultaneous evaluation of multiple factors on the static exertion of force. In keeping with this holistic approach to task evaluation, the current chapter extends the analysis of human strength into three dimensions.

Extending the concept of the PSD into three dimensions introduces a new set of problems relating to equipment design, experimental protocol, data processing and presentation of experimental results. This chapter addresses these problems with the aim of providing a reliable and effective means for measuring and presenting the forces at the hands and feet during static exertions performed in any direction in the sphere of exertion.

The first problem to be solved was to design a suitable dynamometer to accurately and reliably measure single handed manual forces in three dimensions.

Dynamometer Design

The dynamometer was constructed around a handle that was free to rotate about the three perpendicular axes (X, Y and Z). This ensured that manual forces could only be applied to the dynamometer when the resultant force was directed exactly through the handle's centre. By fixing the force vector through this known point the direction and magnitude of a force on the handle could be measured without the confounding influence of torques. This greatly simplified data collection by minimizing the number of transducers required to decode forces in three dimensional space. The completed dynamometer and its component parts are shown in Figures 5.1a and b.

The dynamometer consisted of a 127 mm long cylindrical handle of 36 mm diameter which was free to rotate about its long central axis. The ends of the central axis of the handle were mounted within an annulus consisting of a ring bearing with an inside diameter of 132 mm. This ring bearing permitted free rotation about the horizontal axis perpendicular to the long axis of the handle. The outer casing of the annulus was connected to a rigid metal framework through self centring bearing mounts that allowed the annulus free rotation about a vertical axis directed through the centre of the handle.

Between the top and bottom bearing mounts and the outer metal framework were three ring transducers. One ring transducer was located beneath a "shimmying" bearing directly under the annulus on the vertical axis (i.e. Z axis). The other two transducers were located perpendicular to each other in the horizontal plane. The first of these was positioned between the top of the annulus and the outer framework along the X axis. The second was placed between the bottom edge of the annulus and the metal frame work along the Y axis.

Universal joints were used to connect the X and Y ring transducers and their perpendicular horizontal supports to the outer framework. These universal joints along with the "shimmying" bearing were introduced to ensure component forces were directed exactly along the central axis of each ring transducer. Forces transmitted to each transducer were therefore proportional to the magnitude of the respective component forces acting at the centre of the handle and directed along the appropriate axes.

Figure 5.1a and b: A photograph of the dynamometer (Figure 5.1a) and its component parts (Figure 5.1b). A = Connector box for ring transducer output. B = ring transducers and strain gauges. C = the handle enclosed within the ring bearing. D = Horizontal supports containing self centring bearings and universal joints. E = Rotational bearing. F = Universal joints.

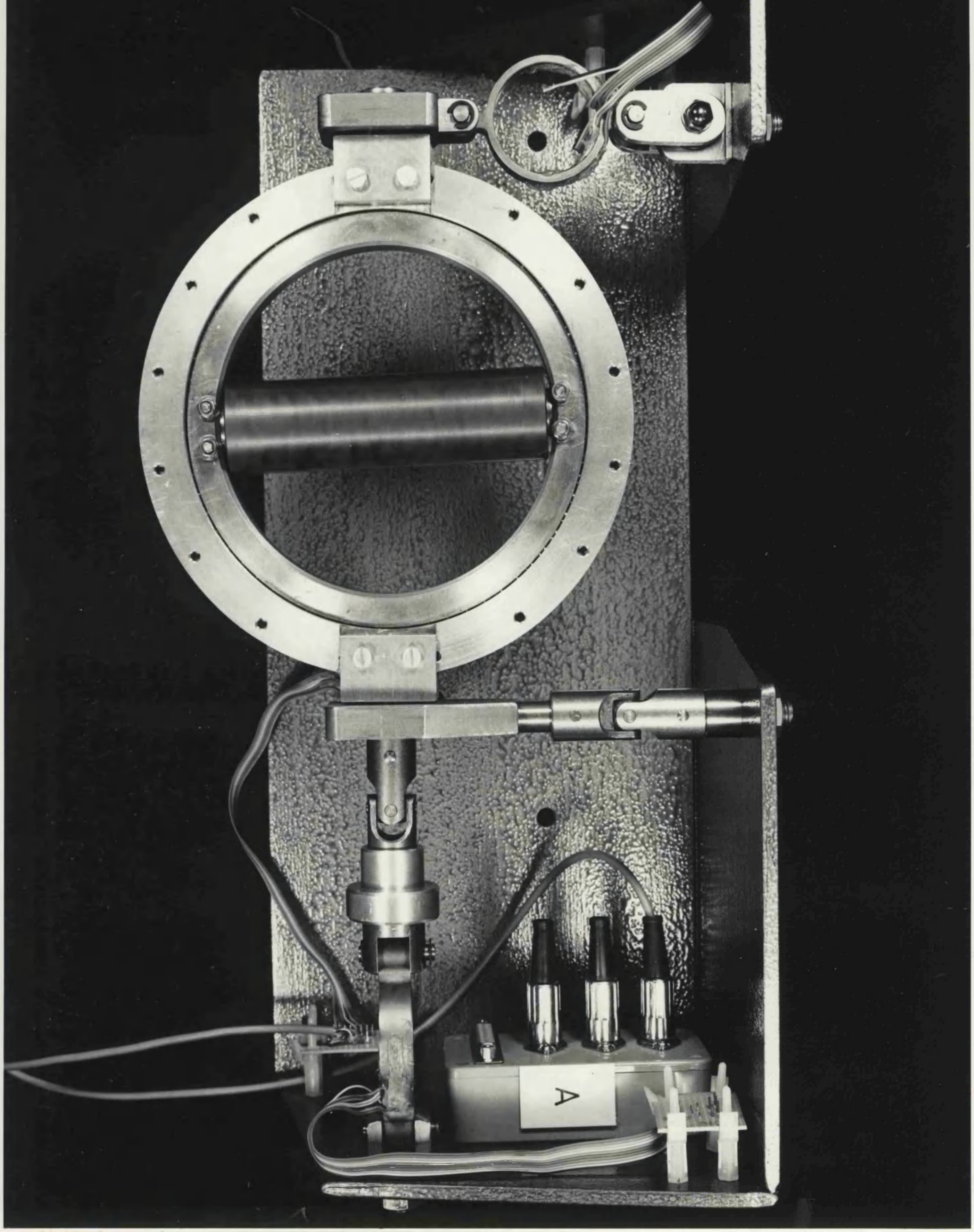


Figure 5.1a:

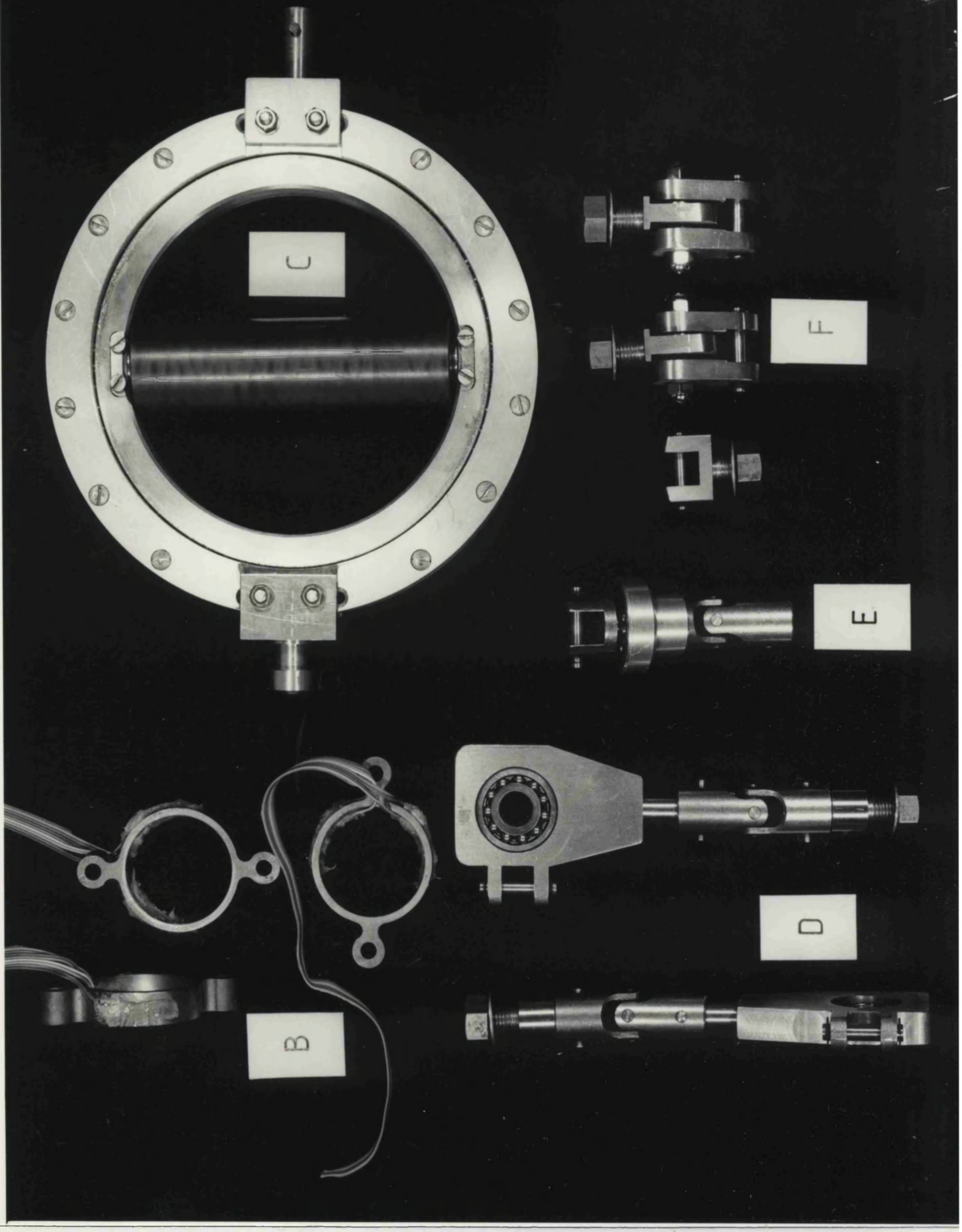


Figure 5.1b:

Force Measurement and Computer Interface

Compressive and tensile forces transmitted to each ring were measured by foil strain gauges bonded to the inner and outer surface of the ring transducers in Wheatstone Bridge configurations. Forces tending to compress the transducers were given a negative sign and tensile forces a positive sign. These sign conventions are summarized for the three dimensions in Figure 1.1.

Output from the strain gauges was amplified by operational amplifier circuits (RS Components, strain gauge amplifier 308-815 and PCB 435-692) before being passed to the analogue inputs of a CED 1401 Intelligent Interface (Cambridge Electronic Design Ltd).

The CED 1401 converted the analogue voltage signals from the ring transducer into 12 bit digital format. Each transducer was sampled at 500 Hz over successive 100 ms time intervals. The average digital value over each time interval was calculated for each channel and passed to a host computer (BBC B computer with a 6502 second processor, Acorn Ltd) for further processing and display. Processing this data and updating the display took 280 ms thereby giving an overall sampling frequency of 3.6 Hz.

Dynamomometer Calibration

Each ring transducer was calibrated independently before being incorporated into the framework of the dynamometer. The transducers were hung vertically and loaded in tension by attaching known masses on the free end. Regression lines, of the analogue to digital conversion of the transducers voltage output (ADVAL) on force, were found to be linear with r^2 values of 100% and standard errors of the slopes less than 0.003 ADVALS/Newton. Ring transducers showing hysteresis changes greater than 0.5% between loading and unloading conditions were reinstrumented with new strain gauges.

Once each ring transducer was considered satisfactory the dynamometer was assembled and mounted on a rigid scaffolding frame. Calibration constants for the X, Y and Z ring transducers in the completed dynamometer were determined using the equation below. This equation assumed that each force transducer was independent and was unaffected by forces acting perpendicular to its measuring axis.

$$R^2 = (V_x a)^2 + (V_y b)^2 + (V_z c)^2 \qquad (5.1)$$

where;

R = resultant force in Newtons

V_x = ADVAL value measured on the X force transducer/ X cal. deflection

V_y = ADVAL value measured on the Y force transducer/ Y cal. deflection

V_z = ADVAL value measured on the Z force transducer/ Z cal. deflection

a = calibration constant for X force transducer

b = calibration constant for Y force transducer

c = calibration constant for Z force transducer

Calibration deflections for the CED were obtained by activating a calibration resistor located in parallel with the Wheatstone Bridge circuit of each transducer. Base-line values were recorded and used to adjust these calibration deflections and the ADVAL values of the component forces for each channel.

The calibration constants a, b and c were determined by solving a set of three simultaneous equations. Data for these equations were obtained by loading the dynamometer in three different directions. This was achieved by hanging known masses on the handle with the dynamometer orientated at different angles on the scaffolding rig. A total of eight loads between 0 and 80 kg were applied in each orientation. Data collected from a fourth orientation was then used to test the reliability of these calibration constants.

Although the dynamometer gave linear output when loaded in a given direction, the derived calibration constants did not provide an accurate measure of the forces recorded in other directions. Forces calculated for the fourth orientation gave errors of 7%, 16%, 12%, and 4% for the resultant force and the X, Y, and Z components respectively.

In order to obtain the best estimate of the calibration constants, data collected from a total of eight different orientations were subjected to a multiple regression analysis. Figure 5.2 shows the results of this analysis in which a linear regression of the form presented in equation 5.1 has been fitted to the applied resultant forces. It is clear from Figure 5.2 that for a given resultant force applied to the handle there was at least one direction in which the actual forces fell outside the 95% confidence intervals for the model.

The root mean square (RMS) error of the predicted resultant force was 15 N indicating the measurement accuracy of the system using these calibration constants was $\pm$ 7.5 N.

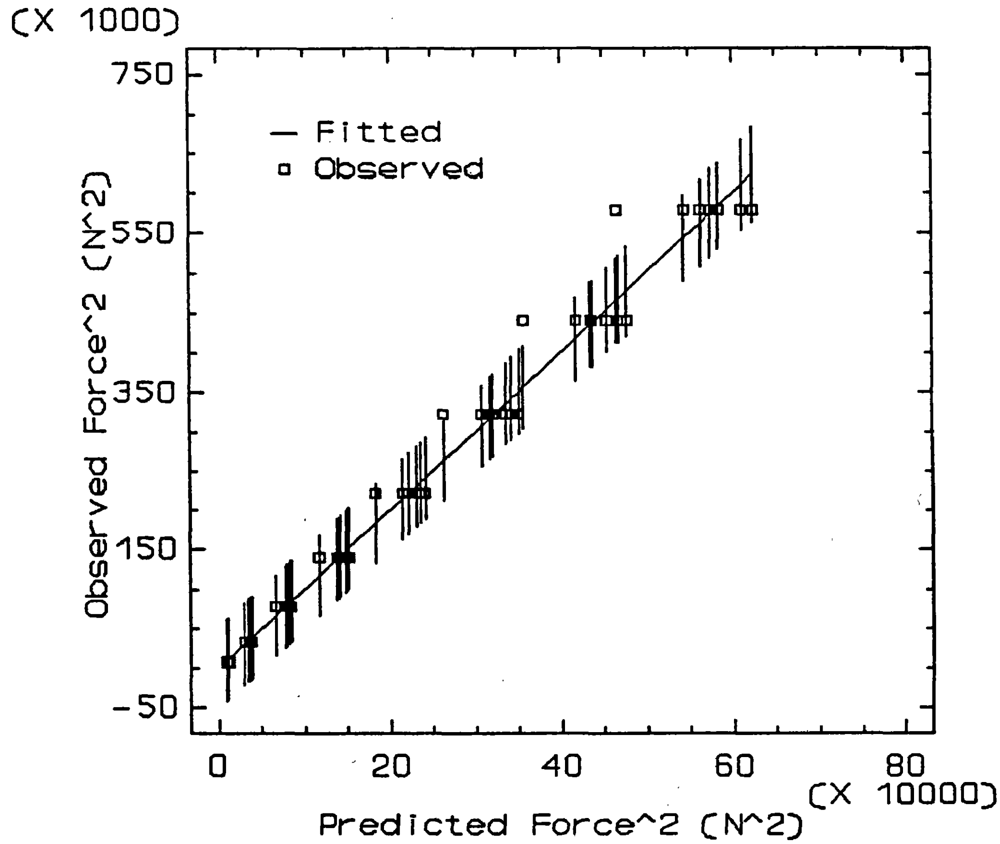


Figure 5.2: Predicted and observed resultant forces (with 95% confidence intervals for predictions) following regression analysis of the calibration data for the right handle (see text for details).

The initial calibration results suggested the assumption of independence of the three force transducers was incorrect. A second set of calibration equations was therefore constructed to account for the possibility of cross talk between the transducers.

The assumptions were made that each of the force components would produce outputs in each of the three transducers, and each of the components would be equal to the sum of the outputs multiplied by appropriate constants. This was expressed by the following set of simultaneous equations.

$$F_X = V_x a + V_y b + V_z c \qquad (5.2)$$

$$F_Y = V_x d + V_y e + V_z f \qquad (5.3)$$

$$F_Z = V_x g + V_y h + V_z i \qquad (5.4)$$

where;

F_X = Force component along the X axis

F_Y = Force component along the Y axis

F_Z = Force component along the Z axis

V_x = ADVAL value measured on the X force transducer/ X cal. deflection

V_y = ADVAL value measured on the Y force transducer/ Y cal. deflection

V_z = ADVAL value measured on the Z force transducer/ Z cal. deflection

a, b, c = calibration constants for X force transducer

d, e, f = calibration constants for Y force transducer

g, h, i = calibration constants for Z force transducer

The nine calibration constants in the above equations were again obtained by solving a set of three simultaneous equations for each force component. Data for these equations were collected by loading the handle in three different directions using the apparatus and procedures outlined below. The reliability of these calibration constants was tested using data collected from loading the dynamometer in a fourth direction.

The apparatus used to measure the magnitude and direction of applied force is shown in Figure 5.3. This consisted of:

(1) A precalibrated ring transducer connected in series between the dynamometer handle and the applied load;

(2) Two plumb lines to determine the angle of applied force in the vertical and horizontal planes;

(3) A stable scaffolding rig to enable the handle to be loaded in any desired direction.

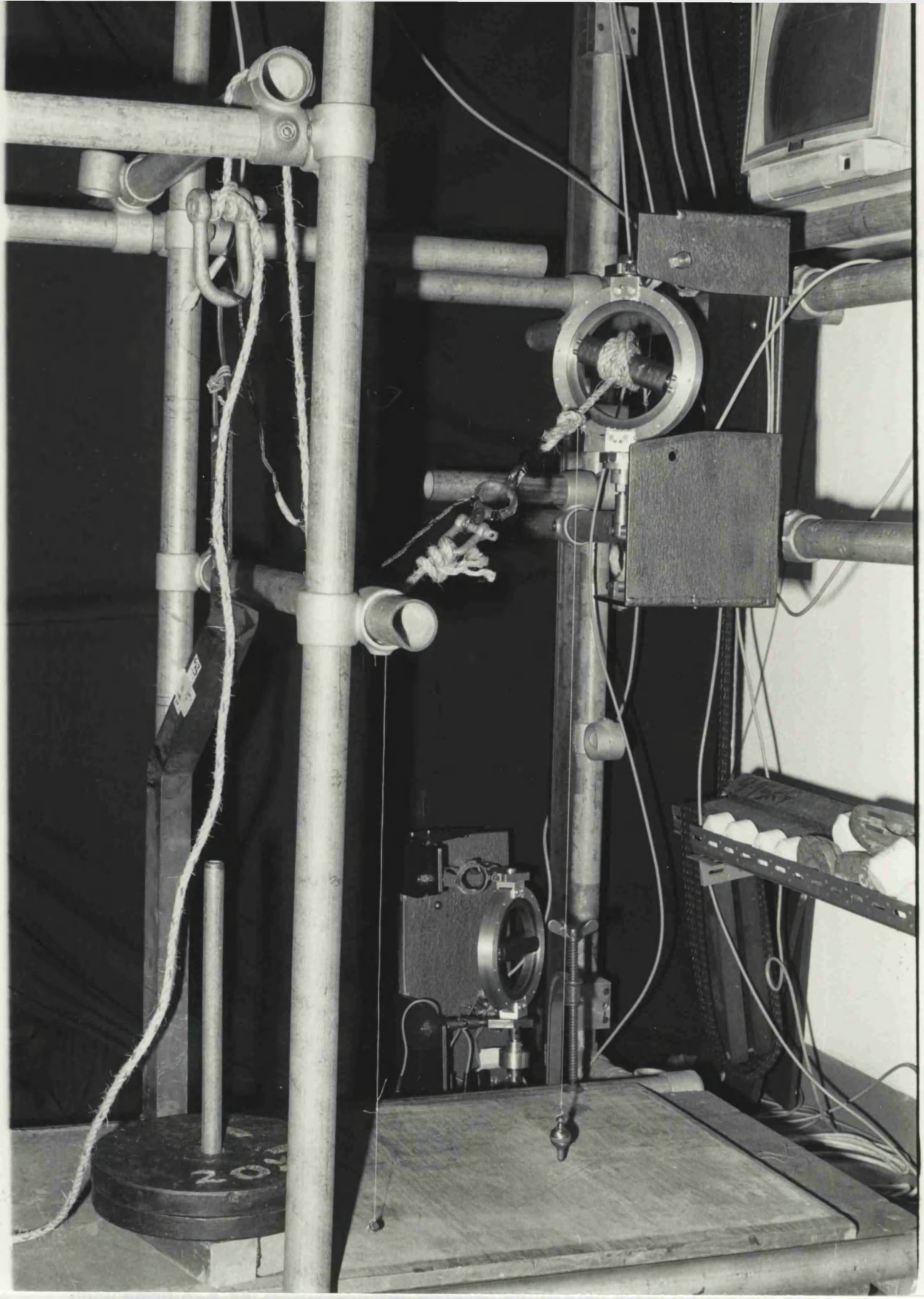


Figure 5.3: The experimental set up used to calibrate the 3D dynamometer strength testing device.

Weights applied to the free end of the rope (connecting the ring transducer to the centre of the handle) were hung over the scaffolding rig at a fixed angle to the vertical and horizontal reference axes of the handle. The resultant force on the dynamometer was given by the instantaneous tension in the rope as measured by the ring transducer. The angle subtended by the resultant force to the vertical and horizontal planes was measured from the plumb lines using a protractor.

To ensure simultaneous measurement between the four channels, the additional ring transducer was interfaced to the CED 1401 and sampled by the computer in exactly the same manner as the dynamometer ring transducers.

The component forces F_X, F_Y and F_Z were derived from the magnitude and direction of the resultant force vector applied to the handle using the equations below.

$$F_Y = \sqrt{\frac{R^2}{\left(\frac{\cos^2\Phi}{\sin^2\Phi\,\cos^2\Theta}+1\right)}} \tag{5.5}$$

$$F_Z = \frac{F_Y}{\tan\Phi} \tag{5.6}$$

$$F_X = F_Z\tan\Theta \tag{5.7}$$

Where:

Φ = the angle from the Z axis to the resultant force vector in the Y-Z plane.

Θ = the angle from the Z axis to the resultant force vector in the X-Z plane.

The results of these calibration trials did not however provide a satisfactory improvement over the previous calibration attempts. Errors between the measured and predicted forces were as large as 4% (12 N), 26% (17 N), 47% (49 N) and 2% 10 N) for the resultant force and the X, Y and Z components respectively. Maximum errors calculated between the measured and predicted angles *theta* and *phi* were in the order of 7 degrees.

It was thought that these errors were due to the unpredictable way in which forces were transmitted to the framework as a result of the complex nature of the system of universal joints and supporting links. This hypothesis was tested by loading the dynamometer in the Z-Y plane with the ring transducer and supporting arm in the X axis removed.

Calibration of the dynamometer under these conditions resulted in much lower errors of 1% (8 N), 1% (8 N) and 3% (5 N) between measured and predicted values for the resultant force and Y and Z force components respectively. The angle of force application in the vertical plane was predicted to within 1 degree. The remaining errors were attributed to measurement errors in the angle and resultant force, and errors introduced by the self-centring and shimmy bearings.

In view of these results it was decided to simplify the system of links in the dynamometer so that forces applied to the handle could only be transmitted to the outer framework via the three ring transducers.

The Redesigned Dynamometer

The dynamometer's structure was simplified by removal of the shimmy bearing, universal joints and the two horizontal supporting links, and then rigidly mounting the X, Y and Z ring transducers between the outer framework and annulus. In addition, the self-centring bearings were replaced by thrust bearings to ensure an entirely rigid and statically determinate structure. The redesigned dynamometer thus consisted of the original annulus suspended via three rigid perpendicular arms linking the X, Y and Z ring transducers to thrust bearings and the outer framework. Both the X-axis and Y-axis ring transducers were connected to the top thrust bearing while the Z-axis ring transducer retained its original position between the bottom thrust bearing and the framework. The redesigned dynamometer is shown complete in Figure 5.4.

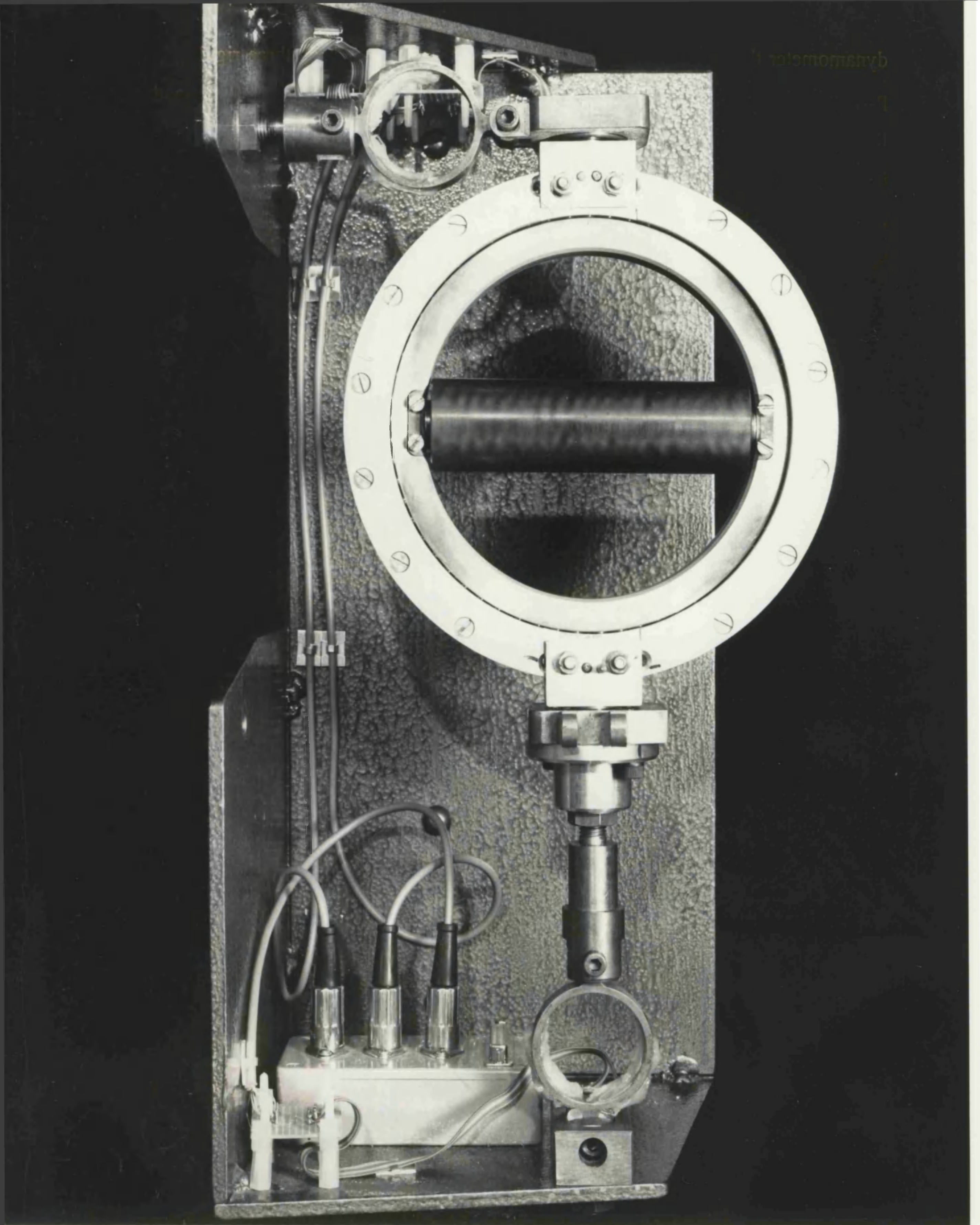


Figure 5.4: The redesigned dynamometer.

The newly designed dynamometer was calibrated using the same apparatus as shown in Figure 5.3. Multiple regression analysis was employed to derive the calibration constants in equations 5.2, 5.3 and 5.4. Data for this analysis was collected with the handle loaded in the eight different sectors of the sphere of exertion (i.e. TOP-FRONT-LEFT, TOP-FRONT-RIGHT, BOTTOM-FRONT-LEFT, BOTTOM-FRONT-RIGHT, TOP-BACK-RIGHT, TOP-BACK-LEFT, BOTTOM-BACK-RIGHT, BOTTOM-BACK-LEFT). In each of these eight directions four loads between 0 N and 770 N were applied to the handle.

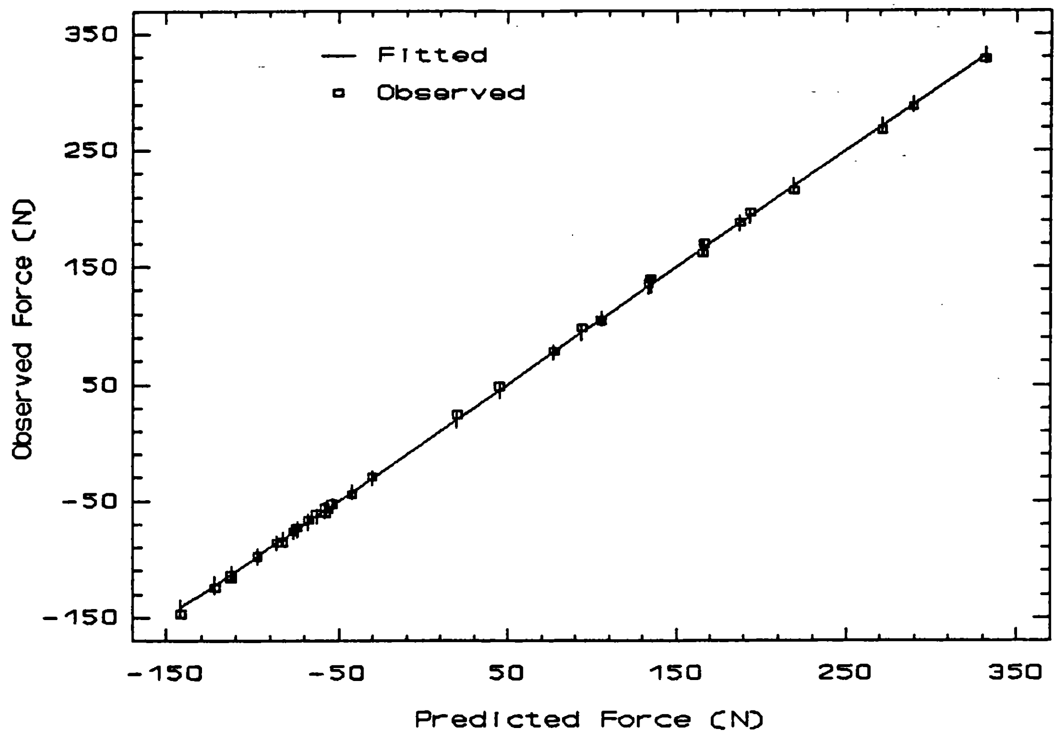
Table 5.1 summarises the results of the multiple regression analysis; the corresponding linear regression lines are plotted along with the actual forces in Figures 5.5 and 5.6.

When the calibration loads (observed force) for the eight directions were calculated using the regression equations in Table 5.1, the RMS error between observed and predicted forces for the resultant and X, Y and Z force components were 5 N, 3 N, 4 N and 8 N respectively. The direction of exertion was found to be predicted to within $\pm$ 1°.

It was concluded that these results provided an acceptable level of measurement error and therefore the calibration constants in Table 5.1 were incorporated into the sampling program to convert digital values from the CED into a force in Newtons.

Table 5.1
Summary of Multiple Regression Analysis for determination of the X, Y and Z force components following calibration of the redesigned left-handed dynamometer. Units = Newtons.

Force Component	Calibration Constant	Value of Calibration Constant	Standard Error	R^2 For fit of Model Results
F_x	a	-1763.99	6.99	1.00
	b	-27.91	2.46	
	c	-97.31	3.46	
	constant	-2.74	3.46	
F_y	d	580.88	9.06	1.00
	e	1249.67	3.19	
	f	151.88	4.48	
	constant	-8.13	0.77	
F_z	g	-250.45	19.99	1.00
	h	-139.02	7.05	
	i	1187.58	9.89	
	constant	-10.09	1.69	



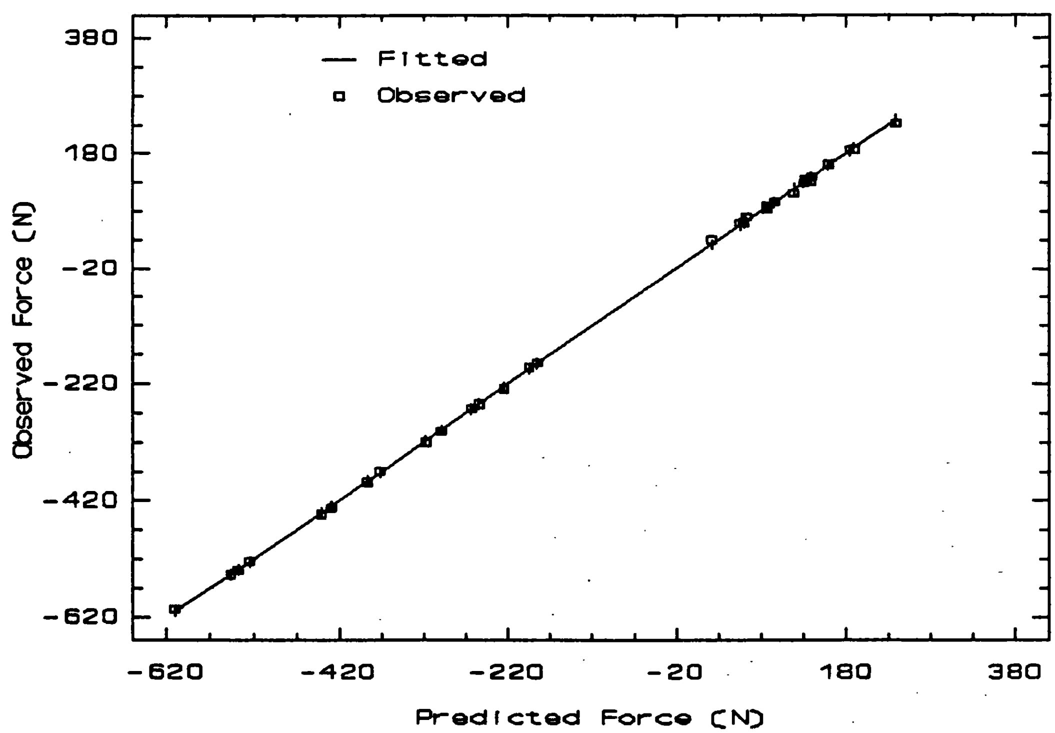


Figure 5.5: Predicted and observed forces (with 95% confidence intervals for predictions) for the X and Y component forces (top and bottom figure respectively) from calibration data on the left-handed dynamometer.

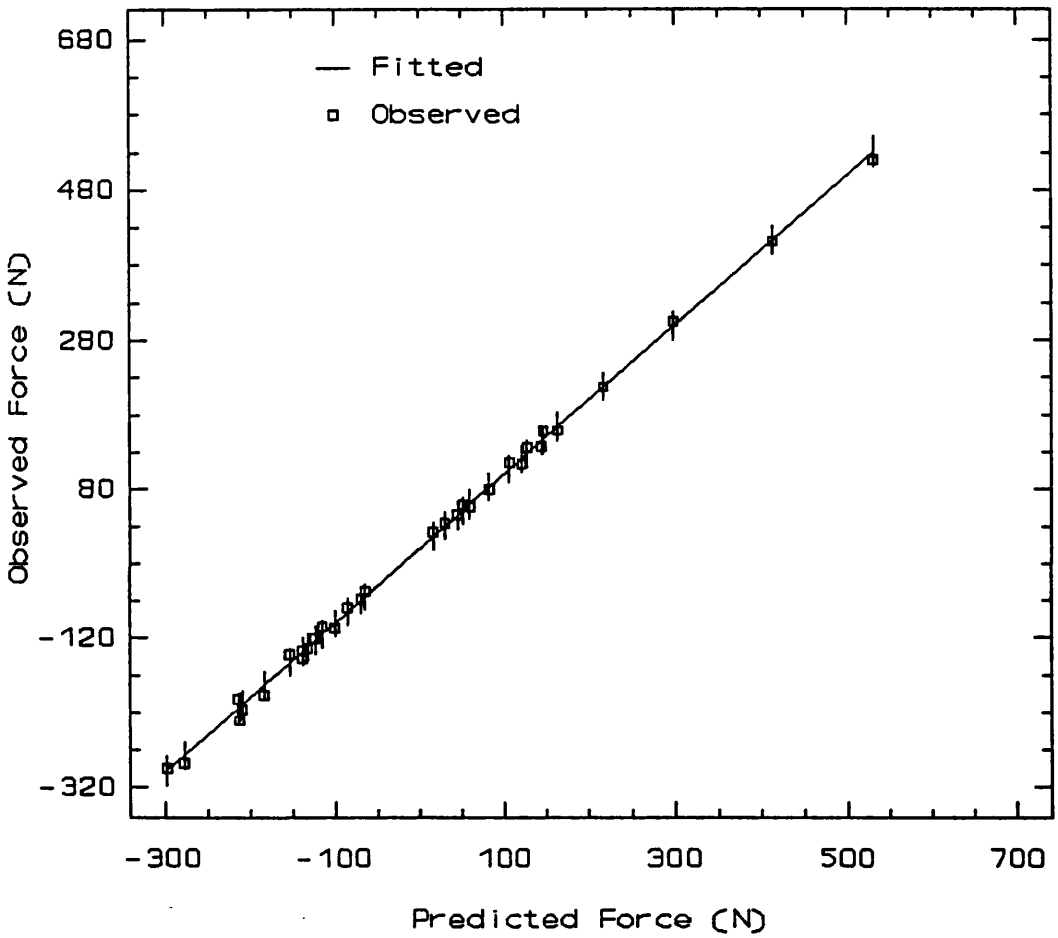


Figure 5.6: Predicted and observed forces (with 95% intervals for predictions) for the Z component forces during calibration of the redesigned handle.

Early Approaches to Data Collection and Presentation of Forces in Three Dimensions

In addition to developement of the hardware it was necessery to design appropriate software to provide an effective and efficient means for collecting, storing and displaying the three dimensional force data.

Presentation of an individual's static strength in three dimensions was constructed from a series of vertical slices or planes about a central vertical axis, where each vertical plane was comprised of a single PSD containing 36 force vectors 10° apart. With the original PSD (see Chapter 4), as the vertical plane directly in line with the Y axis as 0°, the complete sphere of exertion (i.e. a 3D PSD) was described by 18 successive PSD's at 10° intervals about the Z axis.

Data collection procedures required the subject to explore one of the 18 vertical planes at a time. If the subject produced resultant forces which deviated by more than 5° either side of the chosen vertical plane then the computer provided feedback via a beeping sound.

Visual feedback of the direction and magnitude of the resultant force was also presented to the subject on a VDU screen. Angular deviations of the resultant force in the XY plane were displayed on a circle indicating which of the 18 planes of exertion was being explored.

The procedure for collecting and displaying forces exerted in the chosen vertical plane followed the same methodology as that described for the PSD in Chapter 4. Once the subject had completed the chosen plane, the force data was stored on floppy disc for later analysis. An option was then provided to continue data collection in another vertical plane or to cease testing. This allowed data collection on an individual subject to be spread over different testing sessions.

Initial trials revealed that the above approach to data collection was inefficient and time consuming. Forces directed outside the limits of the chosen plane were not recorded, and directing exertions only in the chosen plane was found to be difficult. This resulted in a substantial "wastage of effort" by the subject which inevitably contributed to fatigue and increased the time required for rest pauses during data collection.

Based on the time required to produce a single PSD it was estimated that the complete sphere of exertion may take over 6 hours to complete. Although data collection could be spread over several sessions to minimise fatigue effects, a more efficient approach to data collection was clearly required.

Software Redesign

On-line Data Presentation

On-line presentation and collection of data was modified so that forces were sampled and recorded irrespective of their direction of exertion. An example of the on-line screen display is shown in Figure 5.7. In this figure the sphere of exertion is divided into 10° sectors in "latitude" and "longitude" and presented onto a 36 by 19 rectangular matrix in a similar manner to that of a Mercator's projection. The darkness of the character printed at each location on this matrix indicates the intensity of the maximum force exerted in each sector.

A total of 32 user defined characters were designed and used to represent the intensity forces as a percentage of body weight from 0% to 100%. The full character set and their corresponding force levels are shown in Figure 5.8.

As the subject explores different directions of exertion the display becomes gradually filled with these characters. The direction of a resultant force at any instant is indicated by projecting the displayed character in the appropriate sector in a contrasting colour. If the subject reenters a sector in which a force has been previously recorded the displayed character is only updated if the new resultant force is greater than the previous.

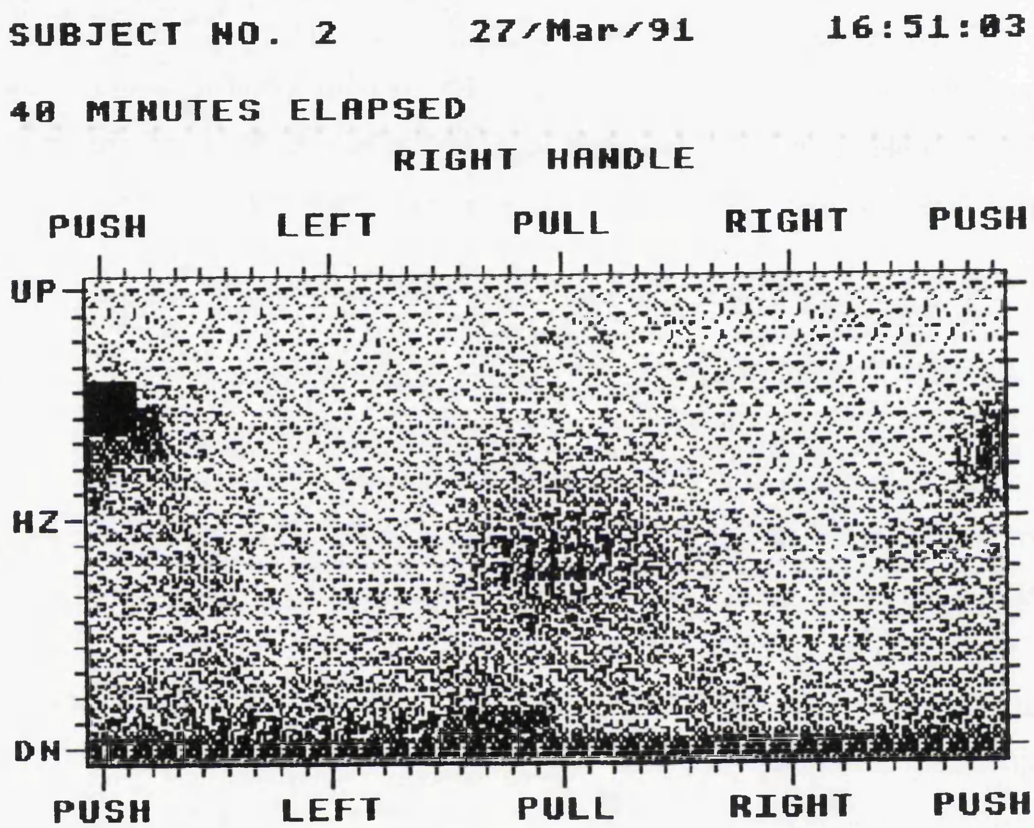


Figure 5.7: The on-line screen display for presentation of the direction and intensity of static manual forces measured by the three dimensional strength testing dynamometer.

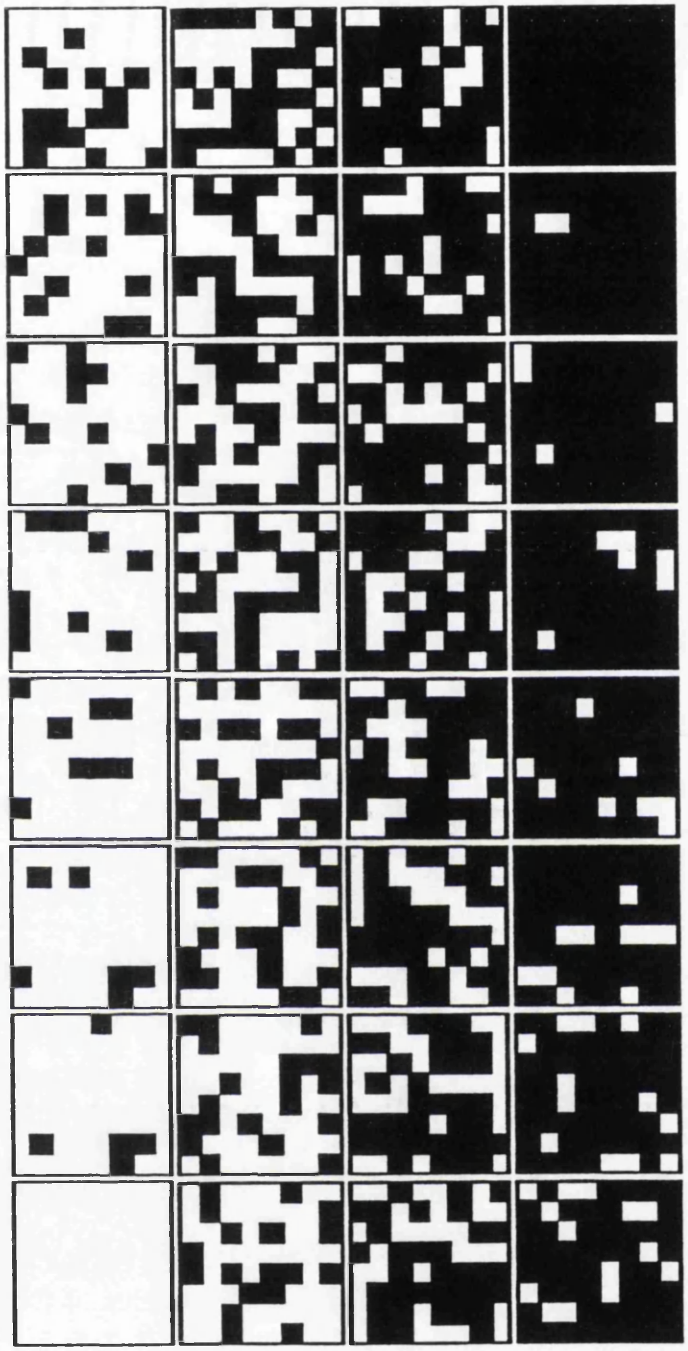


Figure 5.8: The user defined character set used for indicating force intensity in the on-line display. Forces equal to 0% and 100 % of body weight are represented by the solid white and solid black characters respectively. The 30 other characters, ranging from the lightest to the darkest, represent increasing levels of force in steps of approximately 3% of body weight.

After every 2 minutes of exertion, data collection ceases and the computer provides an audible cue for the subject to take a rest pause. During the rest pause an update procedure identifies those sectors in which no force had been exerted. If these sectors are bordered by 4 sectors containing forces then the average value of the forces in the bordering sectors is used to determine the character to fill the middle sector. In addition, the top and bottom rows of the display (which represent a vertical lift and vertical press respectively) are filled in with characters representing the highest resultant force recorded at each pole. It was assumed that this update procedure would reduce the time and effort required to complete the sphere of exertion on the basis that these isolated empty sectors would be difficult to target.

At the end of an experiment the subject data (i.e height and weight) as well as the unsmoothed resultant forces and their X, Y and Z components for each sector may be saved to disc. This data can then be retrieved and added to at a later date or be transferred to an Archimedes microcomputer for off-line data analysis.

Off-line Data Presentation

Individual or group mean data are smoothed in a similar manner as described above. The off-line smoothing algorithm is based on the premise that peak forces in an individual sector were unlikely to be lower than peak forces in the four immediately adjacent sectors. During one smoothing operation a forward and backward pass is made on the force data locating those 10° sectors which are immediately bordered by sectors containing larger forces. During each pass these "troughs" are smoothed by being replaced with the mean value of the forces in the four adjacent sectors. Although multiple passes may be performed the smoothing process is self limiting. As soon as a smoothed sector becomes equal to, or greater than one of the surrounding sectors, that sector will no longer smooth.

Smoothed or raw force data can be presented as a set of 18 PSD's or as a contour map. The former format presents the data in the same manner as that described in section 5.4. An additional nineteenth PSD is also presented to show the pattern of forces exerted in the horizontal (XY) plane when the vertical (Z) force component was zero.

An example of the output for one vertical plane of exertion is shown in Figure 5.9. The plane of exertion is for the -70° PSD and is indicated by the arrows on the smaller circle. The arrows also show the side from which the plane of exertion is viewed. The data represent average one-handed maximal static strengths ($\pm$ one standard deviation), as a fraction of body weight, for four male subjects. Exertions were performed with a horizontal foot placement of 0.5 m from the handle, and at a handle height of 1.75 m. A cubic spline function was fitted through the data points as described in Chapter 4.

An overall representation of the sphere of exertion was obtained from a contour map of the strength data. The presentation is similar to that of the on-line display except that intensity of exertion is represented by different coloured contour regions. Various shades of blue, green, yellow and brown indicate regions of increasing force from 0% to 100% body weight in 5% body weight intervals. A key showing the 20 different colours used and their corresponding levels of force is shown below the contour map. (See the results section for examples of the off-line screen display showing contour maps of static strength for the sphere of exertion).

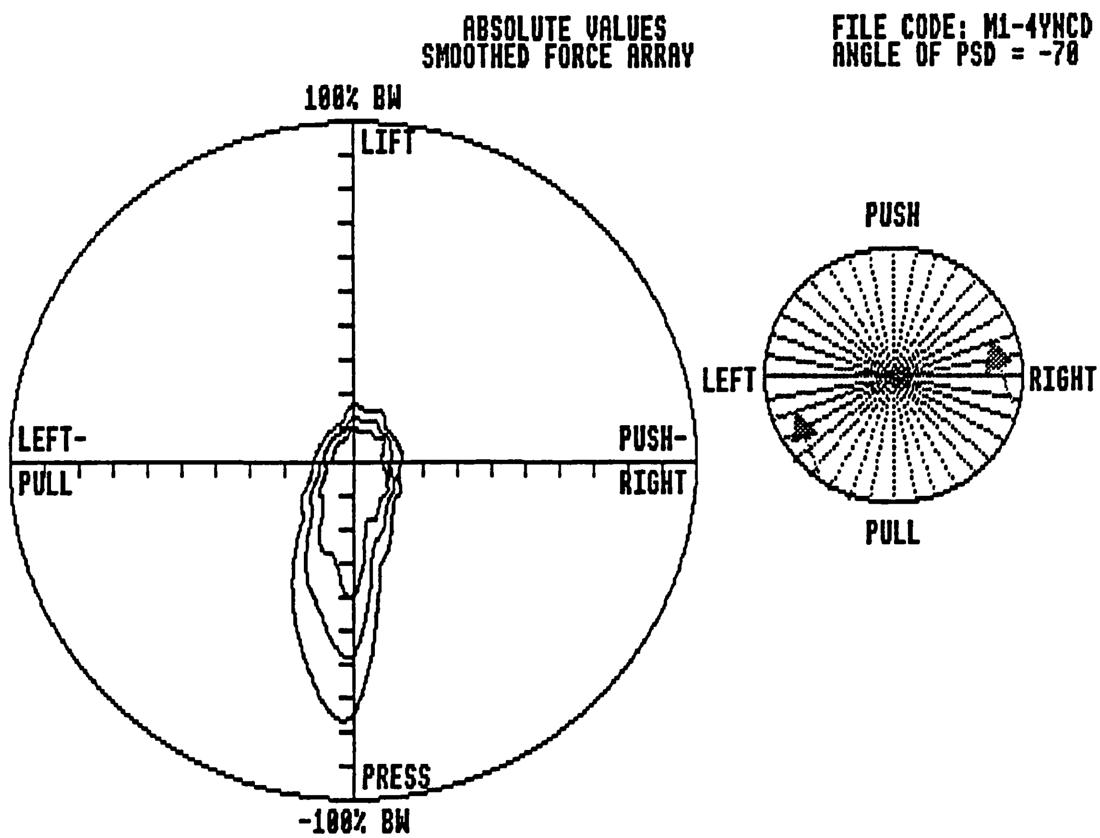


Figure 5.9: Graphical output showing an example of how the forces exerted in a given vertical plane may represented in PSD format. The arrows of the smaller circle indicate the vertical plane or 'slice' through the sphere of exertion presented on the Postural Stability Diagram.

In order to produce the relatively smooth contour lines for the contour plot, linear interpolation was used to calculate resultant forces for every 1° sector in "latitude" and "longitude". This effectively resolved the sphere of exertion into 64,442 individual resultant force vectors.

Using the same form of display it was also possible to generate a map of the minimum coefficient of friction, μ, required to prevent slip for all directions in the sphere of exertion. This was calculated from the horizontal and vertical force vectors (F_x, F_y and F_z) using the formula below.

$$\mu = \frac{\sqrt{F_x^2 + F_y^2}}{F_z + Body\ Weight} \qquad 5.8$$

The same colour scale as that used for presentation of forces was used to denote increasing values of coefficients of friction from 0.0 to 1.0 in steps of 0.05.

Experimental Work

Objectives

The experimental work aimed to address the final problem of development, namely that of designing a suitable protocol for data collection. The main objectives were to:

(1) Devise a testing protocol which would enable an individuals one-handed whole body static strength capabilities to be assessed in all directions in three dimensional space with the minimum influence of fatigue;

(2) Given the conditions in (1), to determine the minimum time required for an individual subject to produce a completed sphere of exertion;

(3) Assess the reproducibility of the strength data under given experimental conditions;

(4) Test the validity of the proposed testing protocol under different postural constraints.

Methods

Subjects

Four male volunteers took part in the experiments. Two were considered knowledgeable in that they were involved in the development of this research. The other two subjects had not taken part in any previous experiments in this laboratory and thus were considered as naive of the current experimental set up. Half the subjects were left hand dominant and the other half right hand dominant. Their physical characteristics are summarised in Table 5.2.

Table 5.2
Anthropometric characteristics of the subjects

Subject		1	2	3	4	MEAN	SD
Age (Yrs)		28	27	25	24	26	1.8
Weight (Kg)		78.9	78.1	72.1	68.7	74.5	4.9
Grip Strength (N)	Right	402	544	520	432	475	68
	Left	432	540	559	392	481	81
Stature (mm)		1758	1854	1830	1767	1802	47
Shoulder height (mm)		1429	1518	1510	1440	1474	46
Elbow height (mm)		1088	1113	1149	1105	1114	26
Hip height (mm)		868	871	933	948	905	41
Knuckle height (mm)		727	780	770	736	753	26
Knee height (mm)		500	503	539	452	499	36

Apparatus

Early experiments were carried out using the initial right-handed version of the dynamometer while the left-handed version was reconstructed according to the new design. It was assumed that there was no cross-talk between the transducers and mid-range values (derived from the initial calibration trials) were used for the calibration constants. The accuracy of the dynamometer under these conditions is given in section 5.3.

Experiments performed at the 1.75 m handle height were conducted using the redesigned left-handed dynamometer in which cross-talk between the transducers was assumed to be present. The calibration constants and accuracy of the dynamometer for this design are given in section 5.4.

The outer frame of the dynamometer was mounted securely to a wall via a scaffolding structure so that the centre of the handle was 1.0 metre above the ground. Slippage was prevented using the same shoe/floor combination as described in previous chapters.

Grip strength of the hand to be used in the exertion was measured with a hand grip dynamometer (Takei and Company Ltd) with grip size adjusted to the preference of the subjects.

Procedure

Subjects' unshod weight and stature were measured and entered into the computer. Before starting each experiment grip strength was determined from the best of two efforts. The subjects were then positioned in front of the dynamometer so that the centre of the handle was aligned with the mid-line of the body at a horizontal distance of 0.5 metres from the toes.

Experimental conditions were the same as those employed for the PSD in Chapter 4. The only additional constraints were; (1) that toe-heel alignment was parallel to the Y axis and no wider than shoulder width apart and (2) that the toes remained on the floor and 0.5 metres from the handle at all times.

Instructions to subjects required them to perform steady maximum exertions on the dynamometer handle in all possible directions in three dimensional space. The initial direction of exertion was chosen at random by the subject. As the experiment progressed the subject was encouraged to explore other directions of exertion and to take frequent rest pauses. A compulsory rest pause was however introduced after every two minutes of sampling. The duration of this rest pause was dictated by the individual subjects and was recorded using a stop watch.

During each compulsory rest period the subject was asked to report any discomfort and to indicate their present level of fatigue on a 100 mm line. The extreme left-hand of the line was labelled as "no fatigue" and the extreme right-hand as "absolute exhaustion". Their level of fatigue was scored as the distance in millimetres from the left-hand extreme. The left-hand extreme was considered as a base line for the level of fatigue at the start of the experiment. Successive reports of fatigue were recorded on separate 100 mm lines with previous responses hidden from view.

In order to avoid excessive fatigue, experiments were limited to one session involving 10 minutes of data collection during any one day. A direct measure of fatigue was made by comparing grip strength at the start of the experiment with that obtained immediately after the fifth two minute period of data collection.

Successive experiments were performed a minimum of one day apart. In subsequent trials, the subject was presented with the force data obtained from the previous session and instructed to complete the sphere of exertion, or attempt to better the forces already recorded.

The full sphere of exertion was considered complete when; (1) all sectors contained some level of force (whether actual data or interpolated data) and, (2) the mean difference in force added between successive sessions (over the whole sphere of exertion) was less than 1% of body weight. This criterion was chosen as a compromise between (1) providing an accurate and reliable measure of an individuals static strength in all directions and (2), the amount of time that could be reasonably expected for the subject to complete a full experiment.

Statistical criteria for determining the end point of the experiment were investigated and discarded. Due to the nature of data collection, the difference between absolute forces recorded in successive experiments is never negative. Thus when each resultant force vector is subtracted from its corresponding force vector recorded on a subsequent occasion, the distribution curve observed for the force differences is not normal but forms an extremely skewed J-distribution. Under these conditions using statistical analysis as a criterion for completion of the sphere of exertion would be inappropriate.

Reproducibility of the data, collected using the right-handed dynamometer, was investigated by retesting the subjects under the same conditions three weeks after completion of the initial sphere of exertion. Validation of the methodology was performed under different postural constraints by testing the same four subjects one month after the repeat trials at a bar height of 1.75 m. The latter experiments followed the same instructions and protocol as for the 1.0 m bar height except that exertions were performed with the left hand.

Data Analysis

A comparison of fatigue responses, duration of rest pauses and changes in grip strength within testing sessions, between testing sessions and between handle heights were analyzed using a three way repeated measures analysis of variance (ANOVA). The test-retest reliability coefficient[7] was used as a measure of the repeatability of the force data over the sphere of exertion (Ferguson 1976).

Analysis of the strength data between the 1.0 m and 1.75 m conditions was limited to simple descriptive statistics due to the small number of subjects. Individual subjects' strength data were smoothed before combining the data to produce group mean plots for the contour maps and the PSD slices.

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[7] The reliability coefficient is determined from the formula

$$r_{xx} = \frac{\sum (X_{i1} - \mu)\ (X_{i2} - \mu)}{N_p \sigma_1 \sigma_2}$$

where

r_{xx} = the reliability coefficient
X_{i1} = the ith force value on the initial trail
X_{i2} = the ith force value on the repeat trial
N_p = the total number of data pairs
σ_1 = the standard deviation of strength measurements for the initial trial.
σ_2 = the standard deviation of strength measurements for the repeat trial.
μ = the grand mean of the force measurements over the initial and repeat trials.

Results

Three Dimensional Static Strength Measurements at the 1.0 metre Handle Height

During the initial trials at the 1.0 m bar height all four subjects completed five 10 minute sessions of data collection. The two experienced subjects managed to satisfy the criterion for successful completion of the sphere of exertion after four 10 minute sessions. In comparison the two naive subjects showed an average increase in force of 1.6% and 2.9% of body weight over the sphere of exertion between the fourth and fifth 10 minute sessions.

During the repeat trials four 10 minute sessions were completed by each subject. The number of 10 minute sessions required to satisfy the criterion for successful completion of the sphere of exertion was reduced to three for the two experienced subjects and four for one of the naive subjects. The remaining naive subject produced an average increase in force of 2.6% of body weight over the sphere of exertion between the third and fourth 10 minute sessions.

Figure 5.10 shows the mean increase in force (as a percentage of body weight), averaged over the four subjects, that was added to the sphere of exertion following each successive experiment during the initial trials at the 1.0 m bar height. After the first experiment, the mean force added over the sphere of exertion was approximately 18% of body weight. During subsequent experiments the amount of force added to the sphere of exertion declined exponentially. By the time the subjects had completed the fifth experiment, the mean increase in force between successive experiments had reached the 1% of body weight criterion for completion of the sphere of exertion.

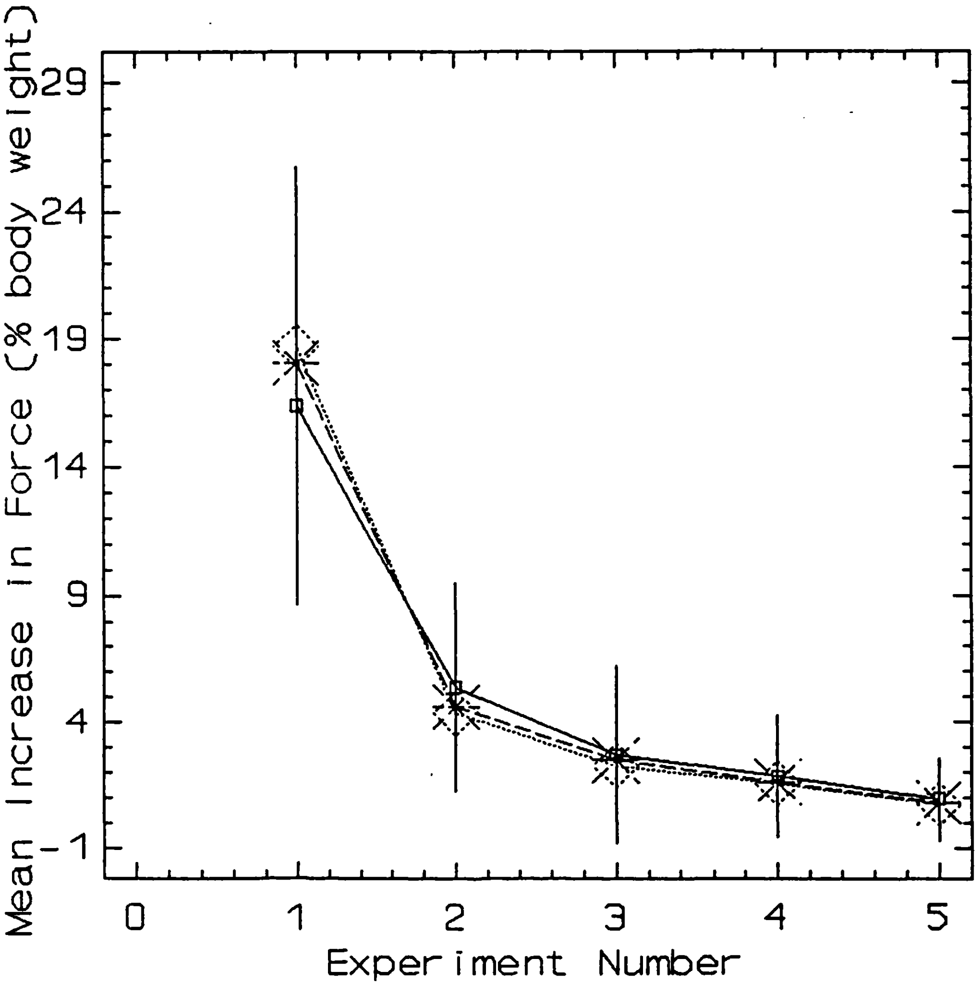


Figure 5.10: Mean increase in force added to the sphere of exertion following successive experiments at the 1.0 m bar height. Solid line = raw force data, dashed line = force data after 1 smoothing pass, dotted line = force data after 10 smoothing passes. Bars represent standard deviations.

Also shown in Figure 5.10 are the effects of the smoothing algorithm on the mean force data. The largest change in the mean force was observed after 1 smoothing pass (i.e. one forward and one backward pass) with very little change in the mean force occurring with subsequent passes. A more obvious effect of the smoothing algorithm is observed when the unsmoothed and smoothed contour plots are compared. In Figure 5.11 several sectors on the unsmoothed contour plot are clearly visible due to the fact that they contain considerably lower levels of force than their immediately surrounding sectors. In comparison these sectors are less distinguishable in the smoothed contour plot.

Figure 5.12 shows a contour map of the forces (as a percentage of body weight), averaged over the four subjects, following 5 experiments at the 1.0 m bar height. The repeat data at this height is shown in Figure 5.13. Mean forces over the sphere of exertion (averaged over the four subjects) were found to be almost identical for the initial and repeat trials (see Table 5.3). Although there are slight differences between Figures 5.12 and 5.13, on the whole, the general pattern of the contour lines and their force intensities are very similar. This observation was confirmed statistically by the high reliability coefficient (0.96) calculated from the test-retest forces taken over the entire sphere of exertion. The above reliability coefficient indicates that less than 4% of the variation in strength shown over the sphere of exertion in Figures 5.12 and 5.13 was attributable to error or test-retest unreliability.

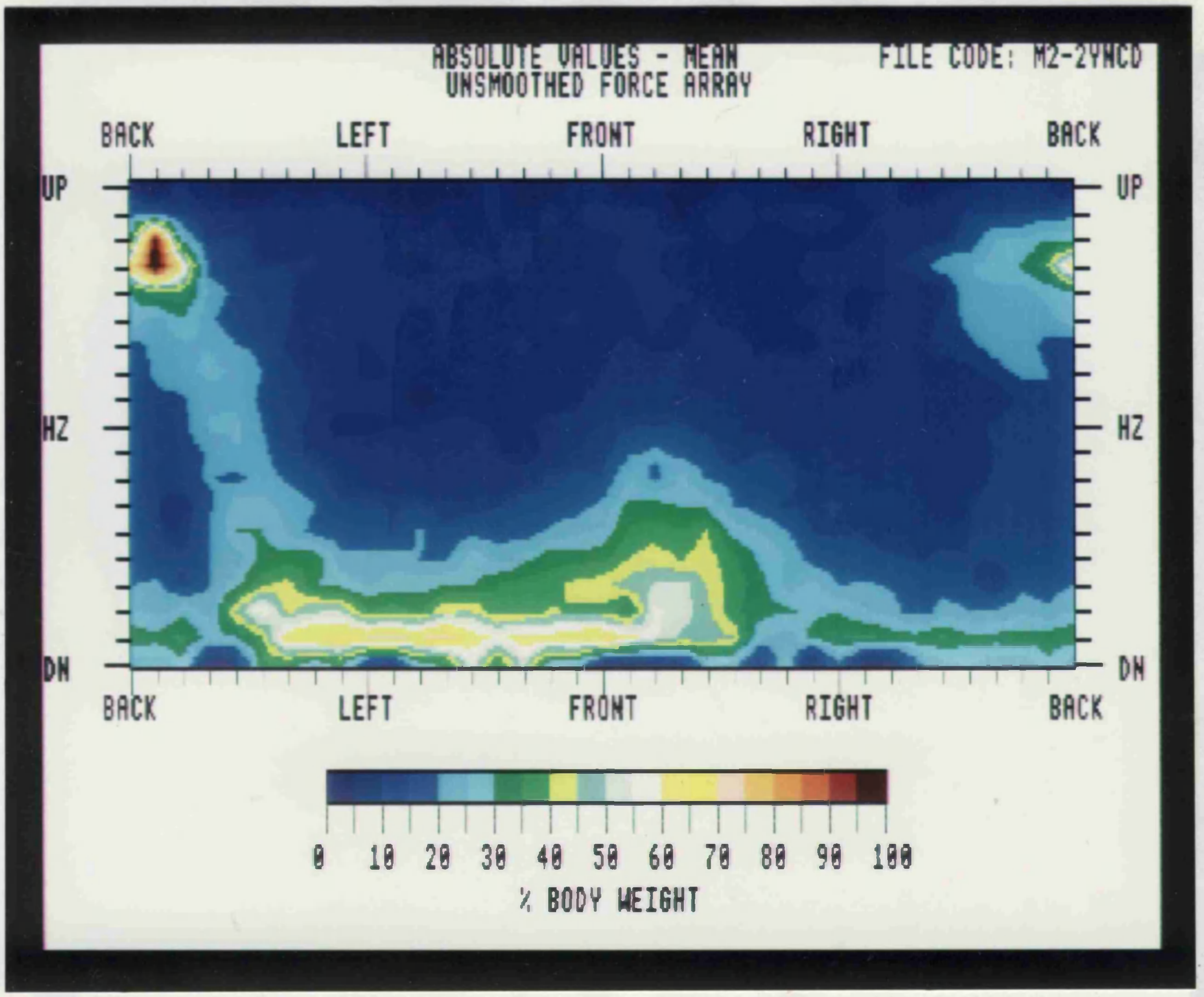


Figure 5.11a and b: Contour maps showing the unsmoothed (this page) and smoothed forces (next page) over the sphere of exertion for subject 2 after 4 experiments at the 1.75 m handle height.

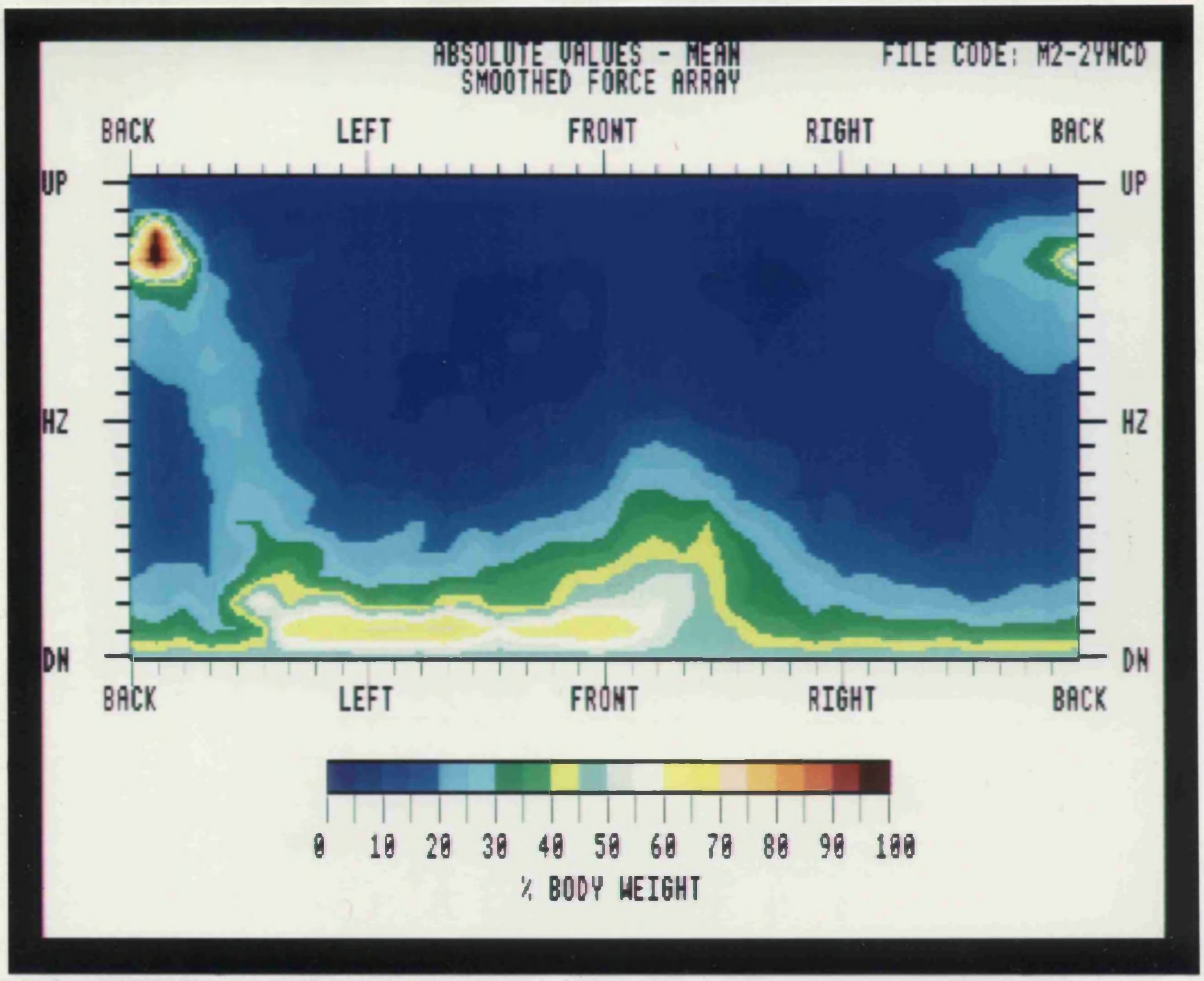


Figure 5.11b: A contour map of the smoothed forces over the sphere of exertion for subject 2 after 4 experiments at the 1.75 m handle height.

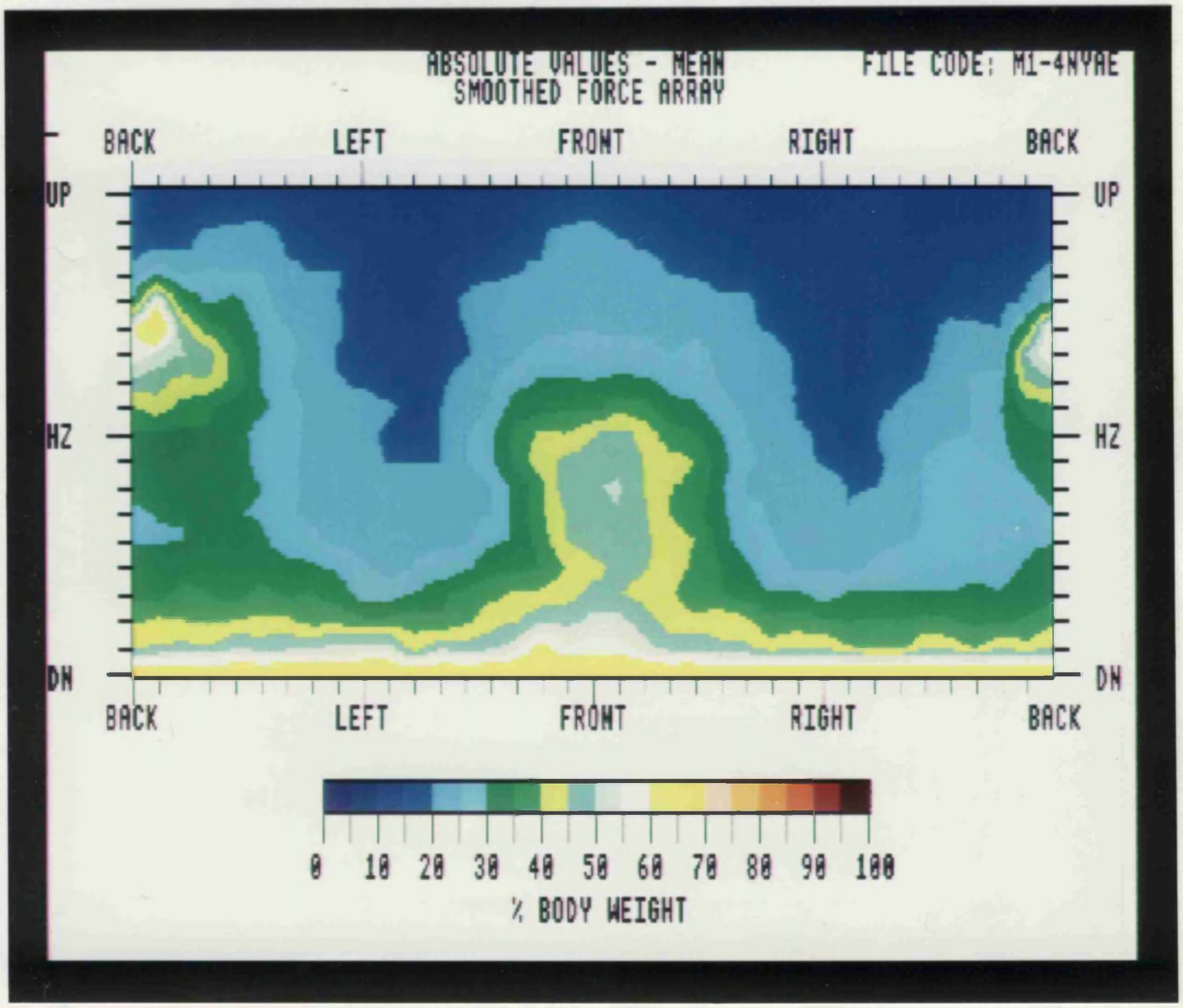


Figure 5.12: A contour map representing the mean static strength of 4 subjects over the sphere of exertion for right-handed exertions performed at the 1.0 m handle height. The data was collected over 5 experiments and is presented as a percentage of body weight.

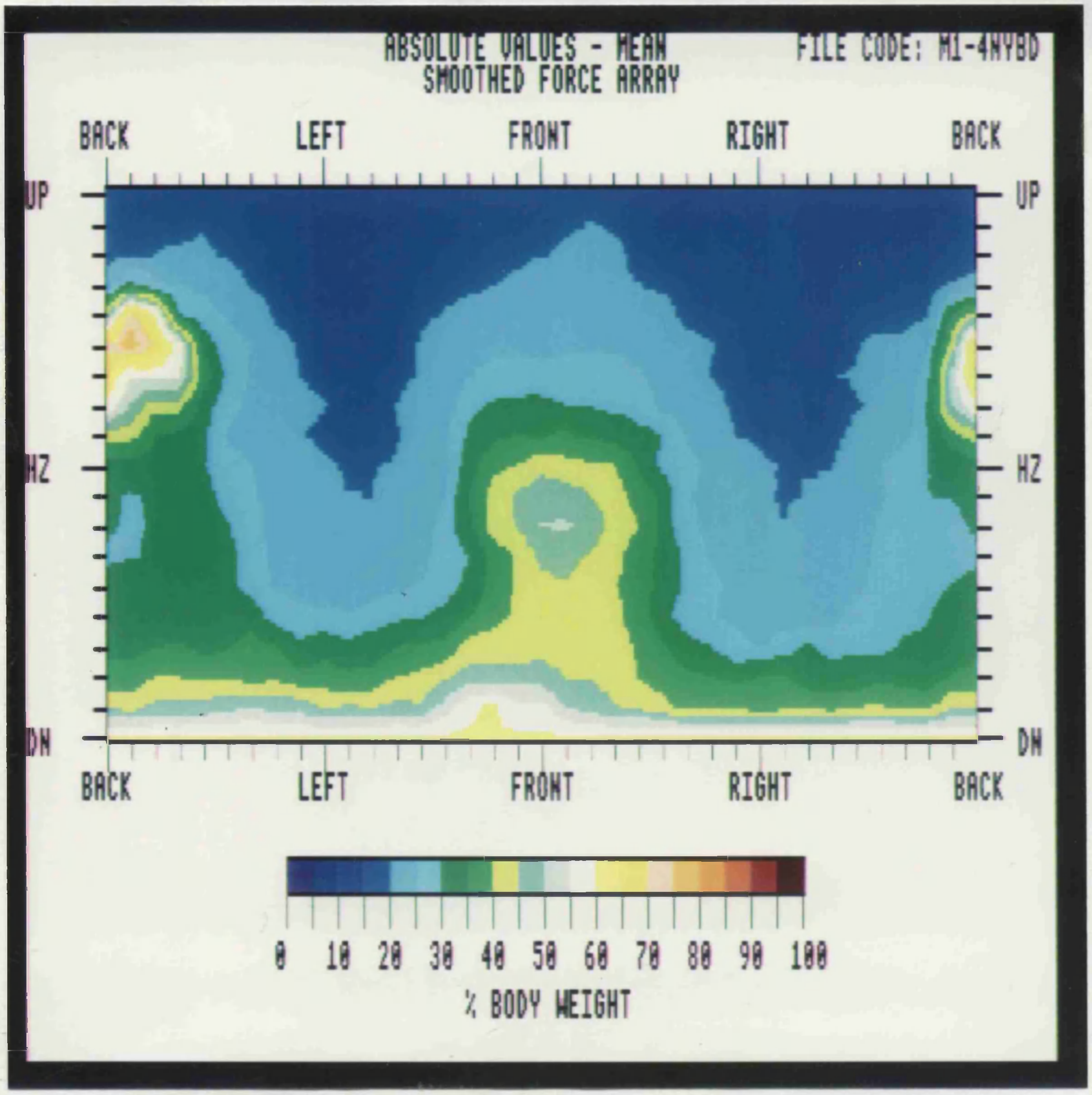


Figure 5.13: A contour map representing the mean static strength of 4 subjects over the sphere of exertion for the repeat experiments at the 1.0 m handle height. The data was collected over 4 experiments and is presented as a percentage of body weight.

Table 5.3
Mean forces over the sphere of exertion (n = 614 force vectors per subject), averaged over the 4 subjects, for static one-handed exertions with the handle set at 1.0 m and 1.75 m above the ground.

	1.0 m after 5 Experiments		Repeat 1.0 m after 4 Experiments		1.75 m after 4 Experiments	
	Mean	SD	Mean	SD	Mean	SD
Mean Force (N)	209	75	209	79	135	80
Mean Force (% body weight)	29	10	29	11	19	11

The contour maps in Figures 5.12 and 5.13 indicate that the highest intensity forces (between 60 and 70% of body weight) are found for vertical pressing and for pushing exertions 20° either side of the 0° vertical plane at approximately 40° above the horizontal. High forces are also shown for pulling exertions about the 0° vertical plane in the pull-press quadrant. Outside of these areas the force intensity gradually diminishes. The large expanse of blue in the contour maps illustrates that the intensity of forces exerted in lateral and upward directions ranges between 15% and 20% of body weight.

Static Strength in Three Dimensions at the 1.75 metre Handle Height

At the 1.75 m handle height all subjects completed four 10 minute sessions of data collection. Mean increases in force over the whole sphere of exertion between successive experiments are shown in Figure 5.14. For comparison, the repeat data at the 1.0 m handle height is also shown in this Figure. Apart from the higher mean forces observed for exertions at 1.0 m (see Table 5.3), the two curves show a similar decline in the average amount of force added to the sphere of exertion between successive experiments. After the fourth experiment the 1% of body weight criterion for the increase in force between successive experiments had been reached and the sphere of exertion was considered complete.

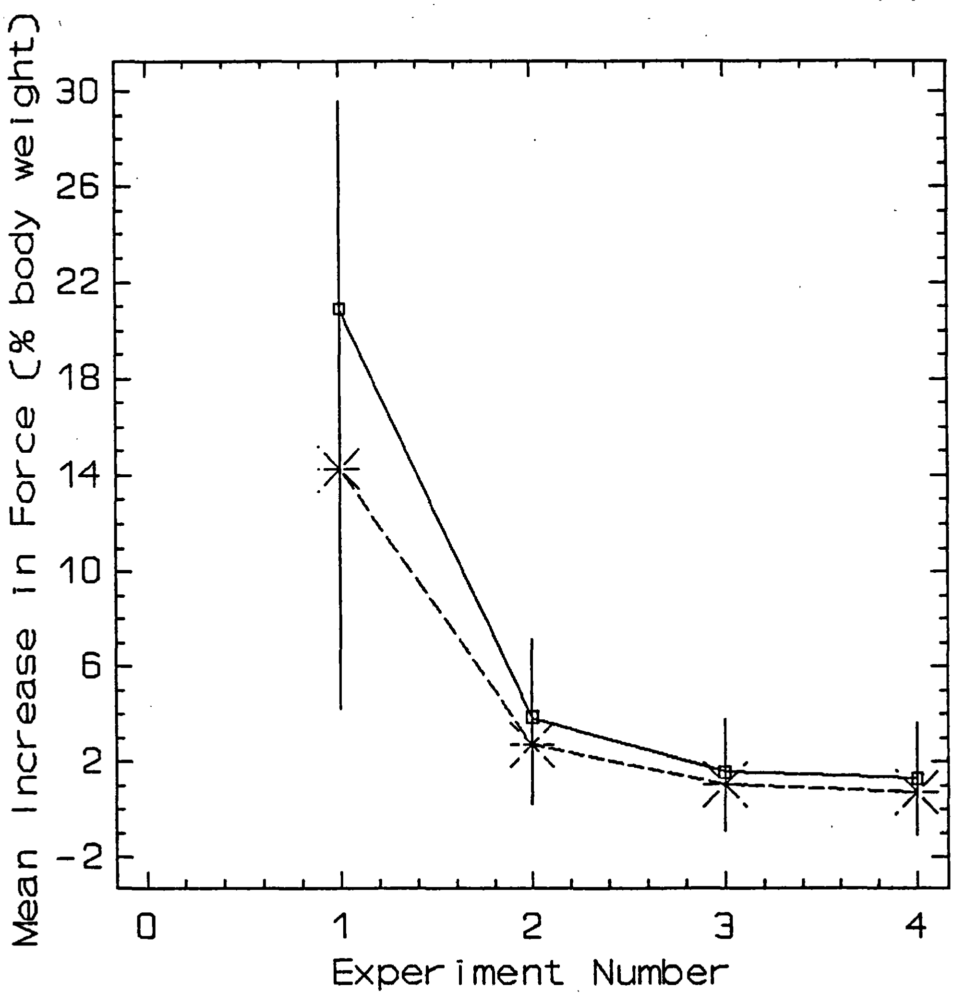


Figure 5.14: Mean (and standard deviations) of the increases in force between successive experiments at the 1.0 m bar height (repeat experiment), (□ data points) and the 1.75 m bar height (star data points).

A contour map of the forces exhibited over the sphere of exertion at the 1.75 m handle height, averaged over the four subjects, is presented in Figure 5.15. The highest forces were observed for vertical pressing and for pushing exertions directed within 10° of the fore and aft plane (i.e. 0° vertical plane) at approximately 60° above the horizontal. In comparison with forces at the 1.0 m handle height, the sphere of exertion at the 1.75 m handle height featured a large number of directions in which forces ranged between 5% to 15% of body weight.

In appendix C the data in Figures 5.13 and 5.15 are presented in the form of PSDs to afford a more detailed comparison of the mean and standard deviations of the forces over the sphere of exertion at the two handle heights.

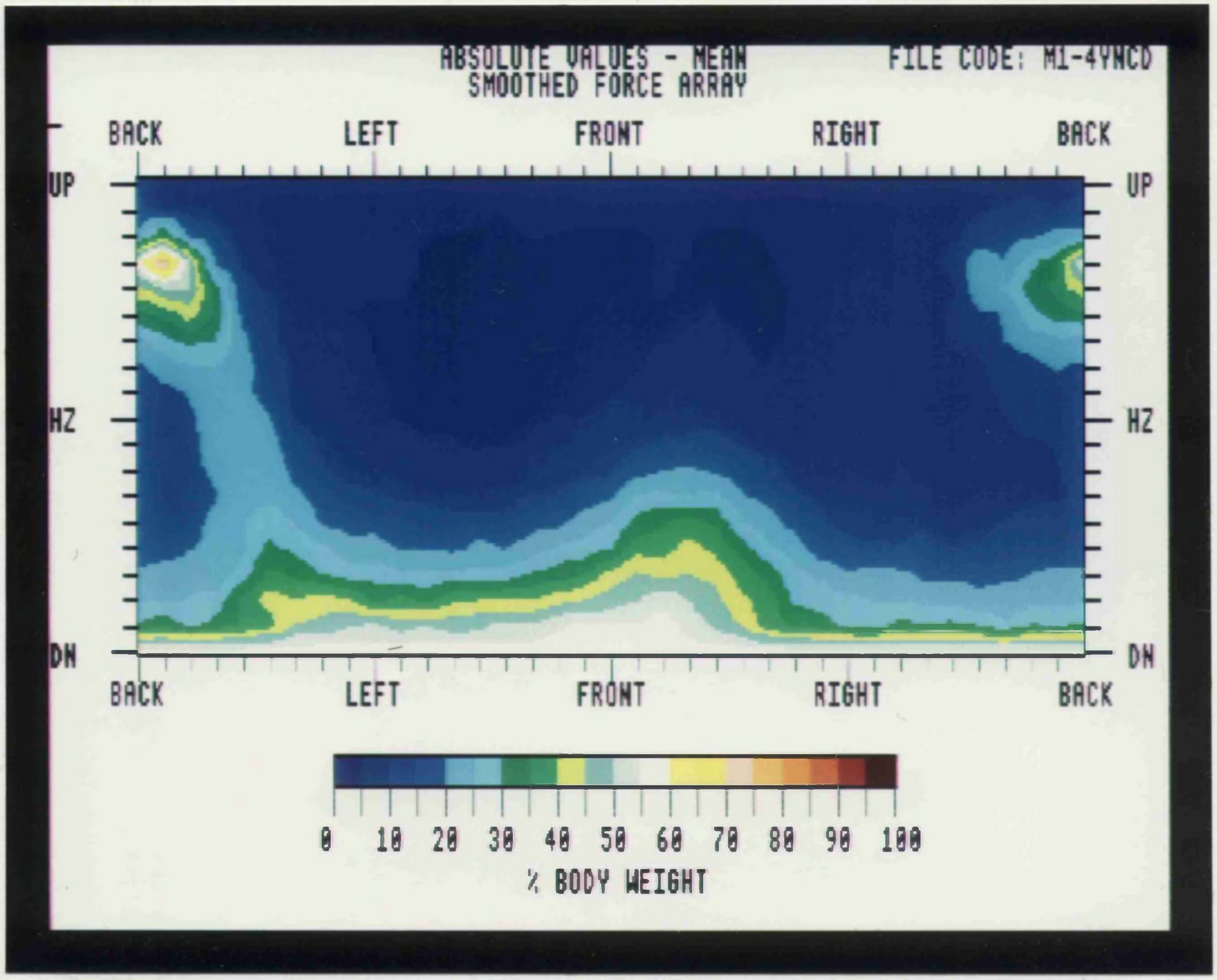


Figure 5.15: A contour map representing the mean static strength of 4 subjects in three dimensional space for left-handed exertions performed at the 1.75 m handle height (data collected over 4 experiments).

Subjective Responses, Fatigue and Grip Strength

Reports by the subjects following each two minute data collection period revealed that the main area of discomfort was localised to the lower part of the upper limb involved in the exertion. During trials at both bar heights subjects consistently reported discomfort in the forearm, wrist and hand or grip. The other main area of discomfort was the deltoid region of the active shoulder.

The visual analogue scale of fatigue was intended to provide a more objective evaluation of general fatigue experienced by the subjects following each two minute data collection period. An analysis of variance of this data (see Table 5.4) indicated that there was no significant difference in the subjects reported levels of fatigue for exertions performed on different days ($p > 0.05$), or at the different handle heights ($p > 0.05$). There was however, a significant change ($p < 0.001$) in the reported level of fatigue between each two minute data collection period.

Table 5.4
Analysis of variance summary statistics for the fatigue ratings taken after each successive two minutes of data collection (variable C) during the four trials (variable B) at the 1.0 m and 1.75 m handle heights (variable A).

SOURCE OF VARIANCE	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (HANDLE)	102.40	1	102.40	2.029	NS
B (DAY)	333.23	3	111.08	0.682	NS
C (TIME)	21272.46	4	5318.12	11.471	P<0.001
S	2291.28	3	763.76	13.724	P<0.0001
AB	699.65	3	233.22	0.937	NS
AC	958.41	4	239.60	3.885	P<0.05
BC	278.34	12	23.20	0.487	NS
ABC	396.29	12	33.02	0.593	NS
ERROR AS	151.40	3	50.47		
ERROR BS	1464.88	9	162.76		
ERROR CS	5563.29	12	463.61		
ERROR ABS	2239.35	9	248.82		
ERROR ACS	740.04	12	61.67		
ERROR BCS	1715.31	36	47.65		
ERROR ABCS	2003.46	36	55.65		
TOTAL	40209.78	159			

Figure 5.16 shows that over the course of an experiment the subjects reported level of general fatigue increased gradually after each two minute session in almost a linear fashion. By the end of the final two minutes of data collection of each experiment, the subjects on average felt they were approximately mid way between the conditions of "No Fatigue" and "Absolute Exhaustion".

Similar results to the above analysis on the general fatigue were found following an analysis of variance on the changes in grip strength (see Table 5.5). There were no significant changes in grip strength between experiments performed on different days or at the different handle heights ($p > 0.05$). Grip strength did however drop significantly ($p < 0.0001$), by an average of 18%, between pre-trial measurements and measurements taken immediately after the fifth two minute data collection period of each experiment.

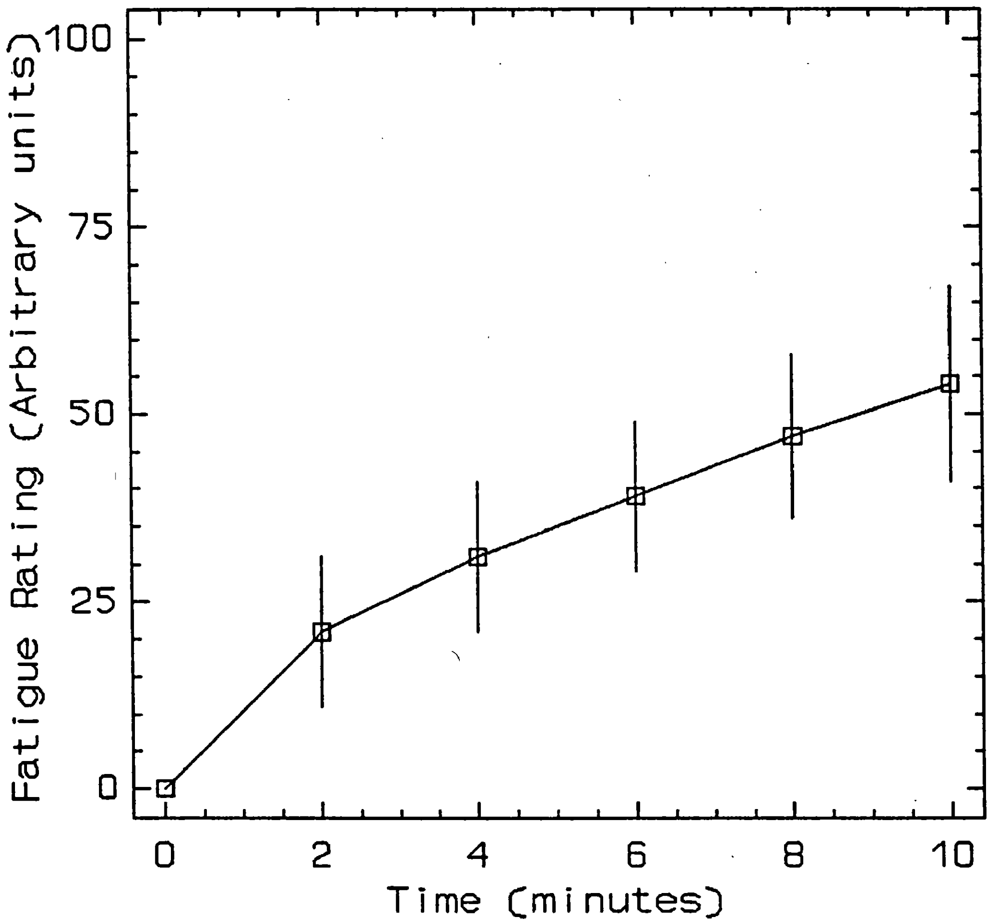


Figure 5.16: Mean and standard deviations of fatigue ratings reported after each two minutes of data collection (data combined over the two handle heights). Zero fatigue rating = no fatigue, 100 = absolute exhaustion.

Table 5.5
Summary statistics following analysis of variance on the grip strength data measured before and after (variable C) each of the four trials (variable B) at the 1.0 m and 1.75 m handle heights (variable A).

SOURCE OF VARIANCE	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (HANDLE)	65.00	1	65.00	0.677	NS
B (DAY)	19.51	3	6.50	0.844	NS
C (GRIP)	1309.54	1	1309.53	70.930	P<0.0001
S	992.98	3	330.99	70.086	P<0.0001
AB	31.70	3	10.57	1.723	NS
AC	4.25	1	4.25	0.878	NS
BC	23.48	3	7.82	1.404	NS
ABC	16.76	3	5.59	1.183	NS
ERROR AS	287.92	3	95.97		
ERROR BS	69.38	9	7.71		
ERROR CS	55.39	3	18.46		
ERROR ABS	55.19	9	6.13		
ERROR ACS	14.54	3	4.85		
ERROR BCS	50.16	9	5.60		
ERROR ABCS	42.50	9	4.72		
TOTAL	3038.31	63			

Table 5.6 shows the results of the analysis of variance on the rest pause duration taken by the subjects during each experiment. The analysis revealed no significant change in the total amount of time spent recovering within the different experimental sessions ($p>0.05$) at either handle height ($p>0.05$). Despite the increasing perception of general fatigue over the course of an experiment, there was no significant change in the amount of time taken for rest pauses between each of the two minute data collection periods ($p>0.05$).

The mean rest pause time (in seconds) taken by the 4 subjects between each two minutes of data collection (collapsed across both handle heights) was 225 (SD= 109), 257 (SD= 132), 262 (SD= 105), and 255 (SD= 98) for rest pauses 1, 2, 3 and 4 respectively. Based on this data, on average, approximately 1 hour and 47 minutes of experimental time, spread over four separate days, is required for a subject to complete the full sphere of exertion.

Table 5.6

Summary statistics following analysis of variance on the amount of time taken for rest pauses between successive two minutes of data collection (variable C) during experiments (variable B) at the 1.0 m and 1.75 m handle heights (variable A).

SOURCE OF VARIANCE	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (HANDLE)	79601	1	79601	3.022	NS
B (DAY)	29976	3	9992	0.361	NS
C (PAUSE)	27238	3	9079	0.865	NS
S	33849	3	11283	0.881	NS
AB	13207	3	4402	0.386	NS
AC	38297	3	12766	2.201	NS
BC	89259	9	9918	0.764	NS
ABC	42831	9	4759	0.372	NS
ERROR AS	79011	3	26337		
ERROR BS	249406	9	27712		
ERROR CS	94470	9	10497		
ERROR ABS	102774	9	11419		
ERROR ACS	52207	9	5801		
ERROR BCS	350309	27	12974		
ERROR ABCS	345721	27	12804		
TOTAL	1628156	127			

Coefficient of Friction Requirements

Contour plots showing the minimum coefficients of friction required to prevent slip for exertions at the 1.0 and 1.75 m handle heights are shown in Figures 5.17 and 5.18. For each contour plot the coefficients of friction were calculated from the mean smoothed component forces of the four subjects for each of the 614 force vectors over the sphere of exertion. The same linear interpolation procedures, as used for the force data, enabled the coefficients of friction to be determined for every 1° sector in "latitude" and "longitude". The data in Figures 5.18 and 5.17 are also presented in PSD format in Appendix C.

The highest coefficients of friction were required for horizontal pulling exertions and pushing exertions directed 20° above and below the horizontal in the fore and aft plane at the 1.0 m handle height. In these directions μ values of between 0.4 and 0.6 were required to prevent slip. In comparison, the lesser horizontal forces applied at the 1.75 m handle height resulted in much lower requirements for the minimum coefficient of friction over the majority of directions of exertion.

The mean value for the coefficient of friction over the 614 directions of exertion was 0.21 (SD = 0.11) and 0.13 (SD = 0.07) at the 1.0 and 1.75 m handle heights respectively.

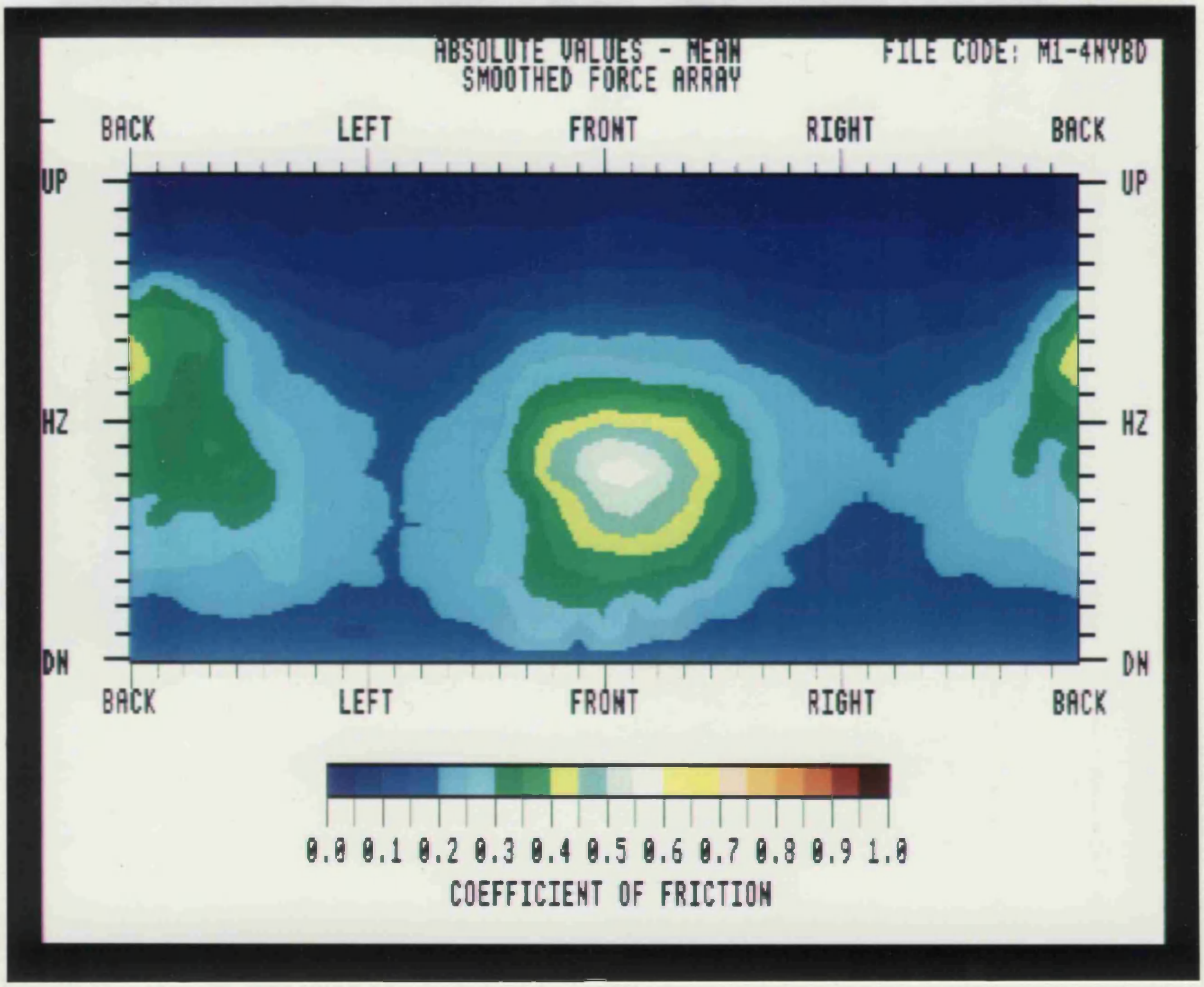


Figure 5.17: A contour map showing the minimum value for the coefficient of friction required to prevent slip for exertions performed at the 1.0 m bar height. The coefficients of friction were calculated from smoothed force data averaged over the four subjects.

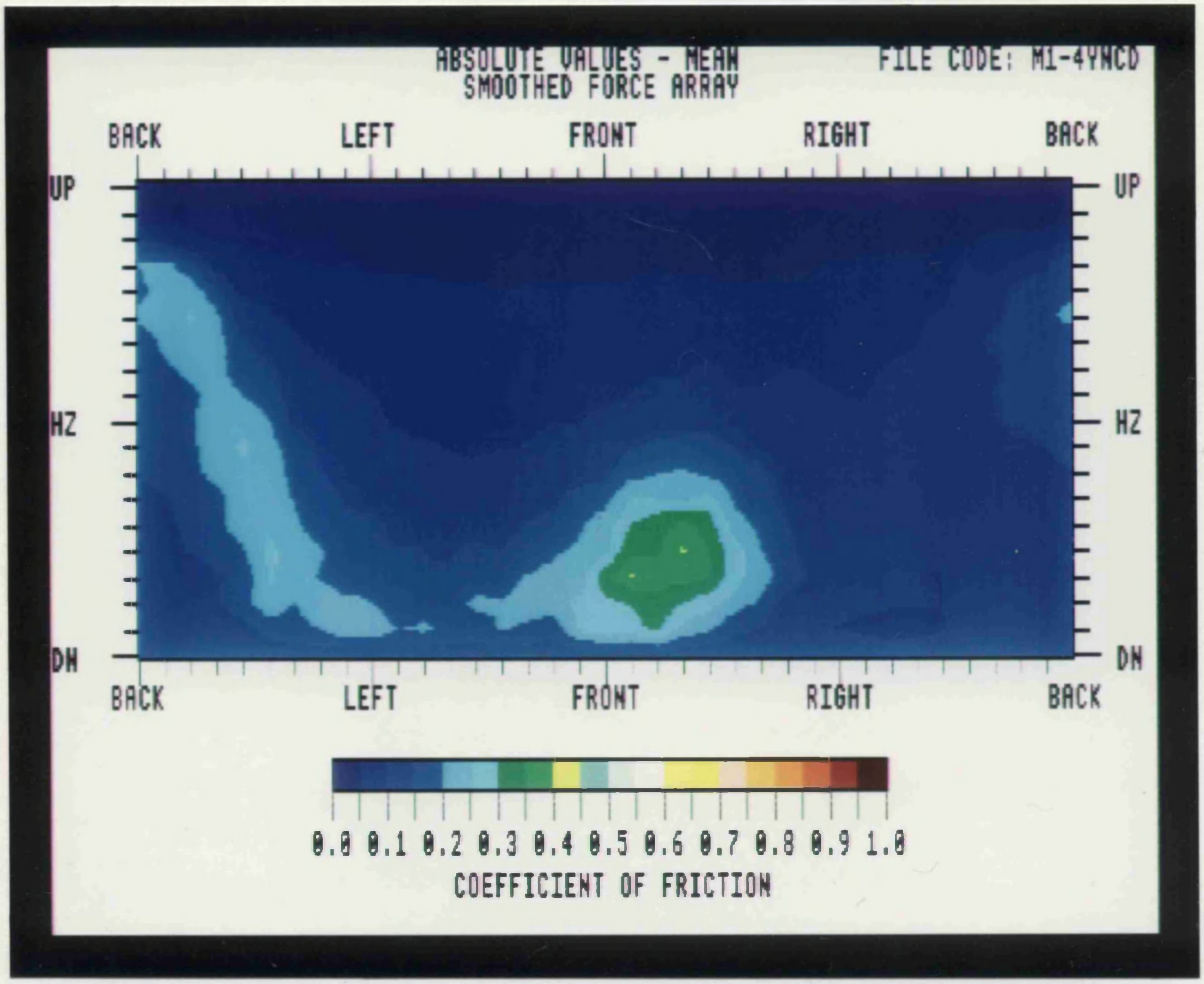


Figure 5.18: A contour map showing the minimum value for the coefficient of friction required to prevent slip for exertions performed at the 1.75 m bar height. The coefficients of friction were calculated from smoothed force data averaged over the four subjects.

Discussion

The results illustrate that the dynamometer and current protocol provide an accurate and reliable way of assessing an individual's one-handed whole body static strength in all directions in three dimensional space. Frequent rest pauses during data collection, as well as additional experiments performed on different days, are required to ensure that fatigue has minimal influence on the strength of exertions.

Although the design of the handle made it inherently unstable, subjects found little difficulty in applying maximal forces in the desired directions. Indeed, the freedom to rotate the handle about the three perpendicular axes allowed subjects to position their hand in a preferred orientation for any direction of force exertion. This ensured that stresses on the wrist joint were minimised and that maximum forces were not constrained by the posture of the wrist.

Subjective reports did however indicate that the grip, wrist joint and hand suffered most discomfort during the single handed exertions. As the hand is the sole area of contact between the body and the dynamometer it has to transmit considerable forces during the exertions. Consequently, it is hardly surprising to find that, by the end of an experiment grip strength declined significantly indicating signs of fatigue in the forearm musculature. In some cases fatigue in the grip may have limited the strength of exertion in directions where the strength of the grip was important in the effective transmission of particularly large forces.

Since the strength of exertions in all directions depends on an effective coupling between the hand and handle, any fatigue in the grip has important implications in the safe handling of heavy objects in the work place. In the current experiments the handle was considered optimal for heavy exertions. Unfortunately, as discussed in Chapters 2 and 3, hand/object interfaces commonly found in the workplace are likely to be less than ideal, increasing the likelihood of the object slipping from the hands, and preventing full use of the strength available.

One interesting finding was that the subject's level of general fatigue, as measured by self report on the visual analogue scale, increased almost linearly throughout the course of an experiment. This observation is similar to that found in a study by Vecchiet *et al.*, (1983) who observed a similar linear relationship between the duration of hold of an isometric contraction and muscular pain. It would seem that individuals perceive general fatigue and localised pain induced through forceful isometric contractions in a similar manner. This suggests that in the context of the current experiment the concepts of pain and fatigue may be closely related. Alternatively, it may have been that the subjects in the current study were basing their perceptions of general fatigue on somatic sensations of pain.

Extrapolation of the fatigue responses suggests that continuing exertions beyond the fifth 2 minute collection period would result in substantial levels of fatigue. Since it is expected that subjects would add very little additional force over the sphere of exertion when fatigued, it is suggested that future experiments should not continue beyond a total of 10 minutes of data collection during any one testing session.

It was clear from the experimental trials that there was a learning effect as the subjects gained experience in using the handle and recognised the most effective postural configurations for the different directions of exertion. This presumably reflected an initial unfamiliarity in matching the direction of force exertion with the visual feedback of the on-line display, as well as, inexperience in selecting the most appropriate posture for a given direction of exertion.

With appropriate instruction the subjects learned quickly and by the fourth experiment were able to direct forces into given 10° sectors of the on-line display. The repeat experiments at the 1.0 m handle height showed that the subjects were able to reproduce their performance successfully on a different occasion. The experimental protocol used for data collection at the 1.0 m handle height was also found to be satisfactory for data collection at the higher handle height of 1.75 m.

The on- and off-line displays were designed to be an effective way of presenting the three dimensional measures of strength over the whole sphere of exertion at once. Because of memory, screen resolution and colour mode limitations of the BBC microcomputer, the on-line display was limited to using a four colour mode to portray the direction and intensity of forces. However, once the data was transferred to the Archimedes the additional processing power and range of colour modes available permitted extensive use of colour in the development of the off-line presentations.

Careful consideration was given to the choice of colours to represent the intensity of forces in the off-line display. The colours chosen were modelled on those used in cartography to represent elevation on maps of the world. Thus shades of blue were used to represent low forces, and yellows and browns to represent the higher levels of force.

As shown in Figures 5.13 and 5.15 the contour maps illustrate quite clearly the unique pattern and intensities of the forces exerted over the sphere of exertion at the two handle heights. If finer detail is required the data in these contour plots may be presented in PSD format for any desired vertical plane and for the horizontal plane in which the vertical force is zero (see appendix C).

Similar shapes in the PSDs (for the fore and aft plane) were found between the current results and those observed by Grieve and Pheasant (1981). The strength data reported by Grieve and Pheasant (1981) was for 10 male subjects performing two-handed exertions under the same postural constraints as in the current experiment. The similarity in the data serves to illustrate the importance of postural constraints on human strength capabilities regardless of whether exertions are performed one or two-handed.

In order for the three dimensional strength data to have as wide an application to real life as possible it is necessary to measure strength under less restrictive conditions than those involved in the current experiments. However, if freestyle conditions of foot placement are allowed, the direction of exertion relative to the body should still have meaning. Thus adoption of complete freestyle postures would convey little correspondence with the directions of exertion defined in Chapter 1 unless certain constraints on foot placement were maintained.

Three dimensional static strength in *pseudo* freestyle postures may be investigated in conditions where the feet are required to be placed parallel to, and equidistant either side of, a line on the floor representing a projection of the Y axis passing beneath the centroid of the handle. With these provisos it would be possible to collect three dimensional strength data under *pseudo* free style conditions of posture and yet retain the same conventions for directions of exertion as described in Chapter 1.

Experiments performed under *pseudo* freestyle conditions are currently in progress. Figures 5.19, 5.20 and 5.21 illustrate provisional results collected on 11 male subjects of mean age, height and weight of 26.7 yrs (SD = 3.5 yrs), 1752 mm (SD = 66 mm) and 75.1 kg (SD = 10.1 kg) respectively. The handle heights investigated were 0.5 m, 1.0 m and 1.5 m above the ground and the data was collected over four experiments at each handle height (Pinder & Wilkinson, unpublished results).

If the 1.0 m bar heights are compared with the present results it can be seen that the freestyle exertions exhibit substantially greater forces in many directions. This presumably reflects the fact that subjects were able to adopt more favourable postures enabling them to either make greater use of their muscular capacity, or deploy their body weight to better effect.

The contour maps of the forces presented in Figures 5.19, 5.20 and 5.21 show directions of exertion common to all three heights in which high force values were recorded. These areas of high forces occurred most notably in the vertical lift (UP) and vertical press directions (DN) and for push exertions (BACK) 10° to the right of the fore and aft plane at approximately 40° above the horizontal. Although results of the postural data taken during this study have yet to be analyzed, it is hypothesized that these large forces occur when exertions are directed along the line of the live axis.

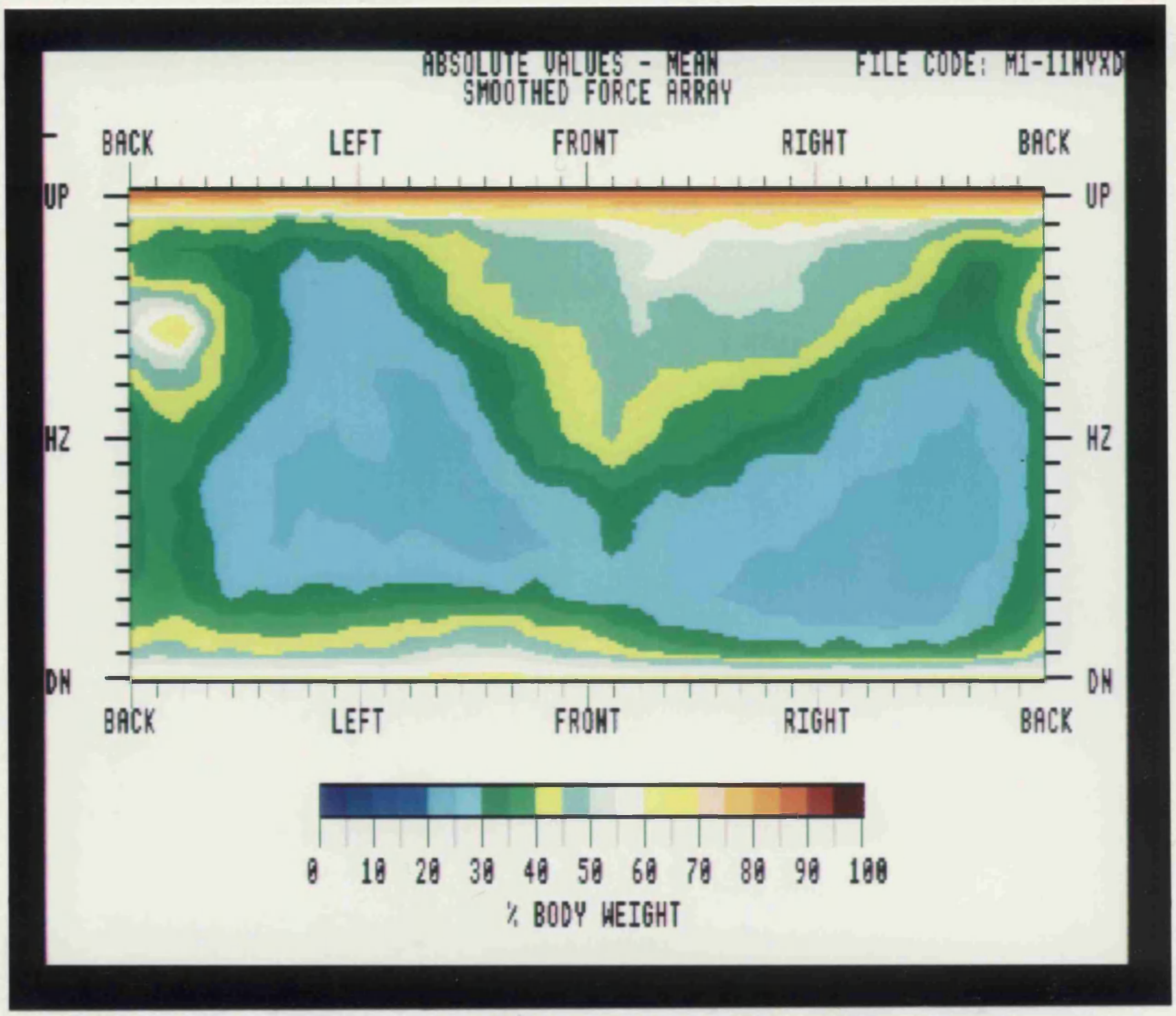


Figure 5.19: A contour map of the static one-handed forces generated over the sphere of exertion at a handle height of 0.5 m. The strength data represents the mean of 11 male subjects performing exertions in *pseudo* freestyle postures (see text for explanation).

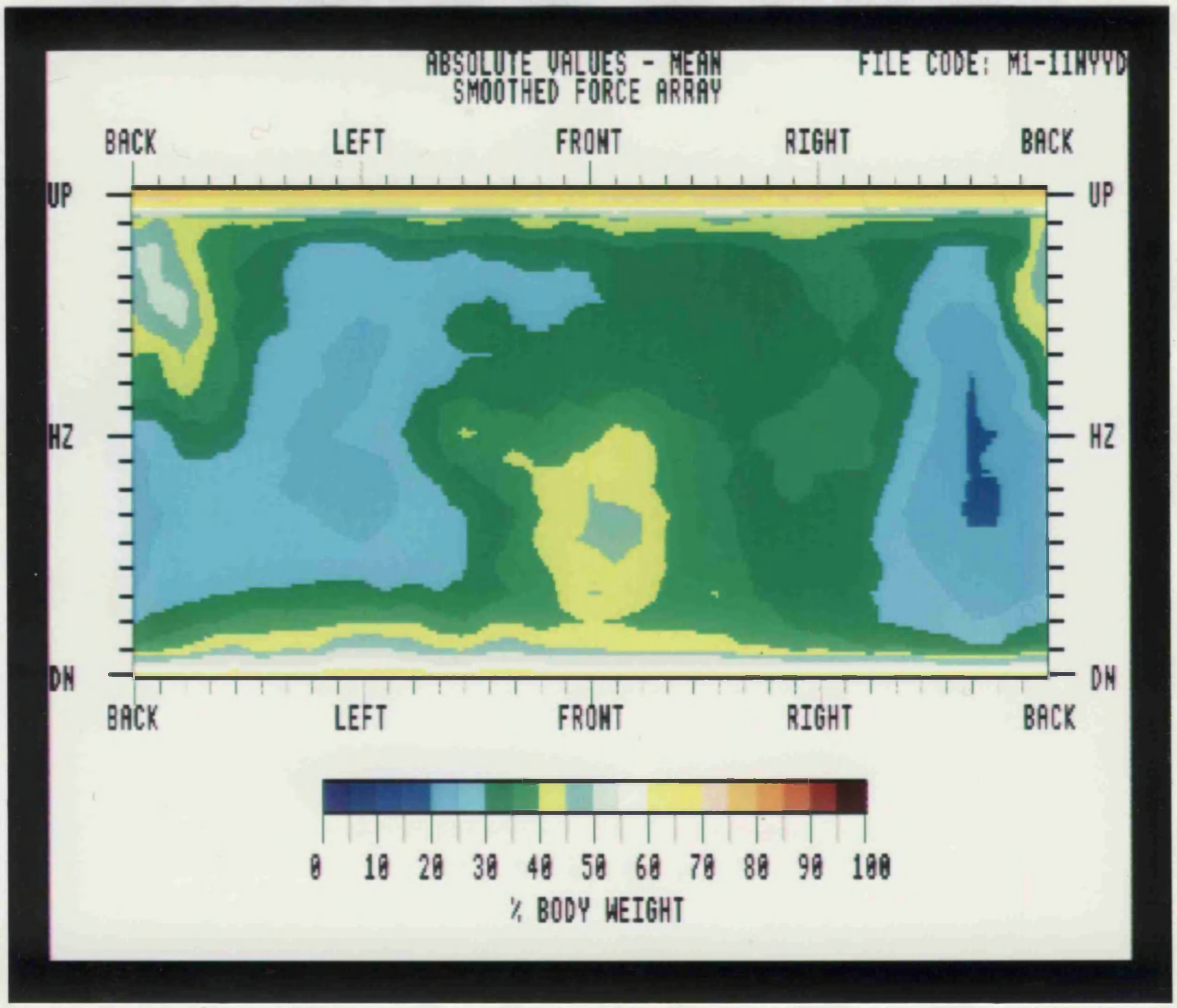


Figure 5.20: A contour map of the static one-handed forces generated over the sphere of exertion at a handle height of 1.0 m. The data represents the mean strength of the same 11 male subjects as in Figure 5.19. The posture adopted was *pseudo* freestyle (see text for explanation).

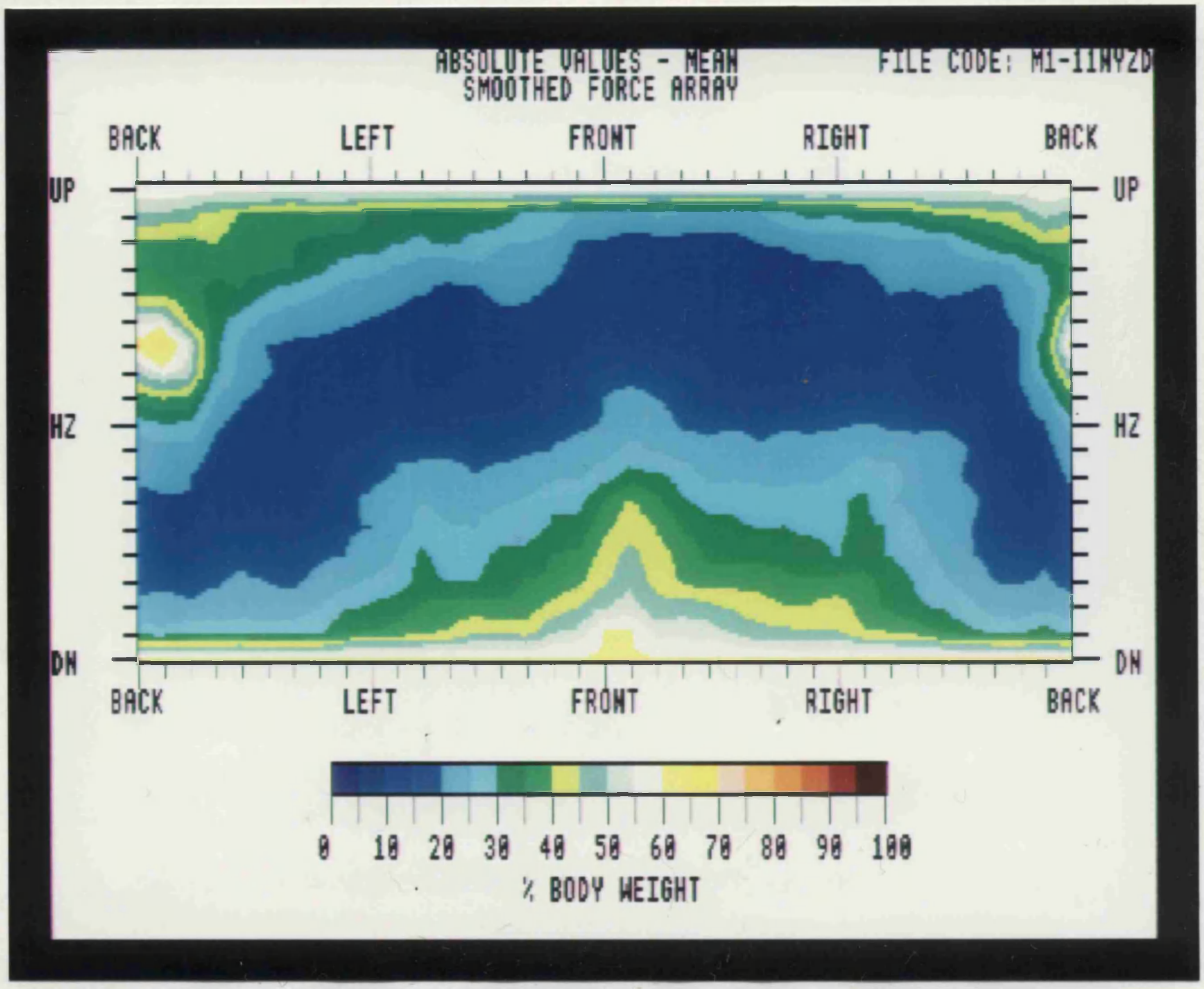


Figure 5.21: A contour map of the static one-handed forces generated over the sphere of exertion at a handle height of 1.5 m. The data represents the mean strength of the same 11 male subjects as in Figure 5.19. The posture adopted was *pseudo* freestyle (see text for explanation).

Coefficient of Friction

Apart from assessing human strength capabilities in three dimensions the strength data may also be used to calculate the minimum coefficient of friction required to prevent slip for maximal exertions performed in any direction. The contour maps of friction shown in Figures 5.17 an 5.18 illustrate clearly those directions at both bar heights in which maximal exertions are most likely to result in slip of the feet if there is a poor foot/floor interface.

The coefficients of limiting friction apply to a single point on the floor representing the centre of foot pressure. As most exertions are performed with both feet on the ground the horizontal and vertical reaction forces will be divided between the two feet. In many cases it is likely that the reaction forces are unevenly divided between the feet, leading to the possibility that one foot may slip. Although it is not possible to generate torques at the hand/handle interface during one-handed exertions, it is possible for the individual to generate a torque at the feet in the horizontal plane.

In order to separate out the individual component forces acting at each foot it would be necessary to measure three dimensional forces at one of the feet. Forces at the other foot may then be calculated by subtraction of these component vectors from those measured at the hand. Once the forces at each foot are known it would then be possible to determine which of the feet are likely to slip during exertions performed in a given direction and posture.

Future Development of the Hardware and Software

Most of the improvements which may be made to the current experimental setup involve the host computer.

The BBC B microcomputer, which runs the sampling and data collection programs and controls the CED 1401, is currently required to operate at the limit of its memory and processing capacity. Virtually all the available RAM is used by the sampling program and any further extension of this program would require extra memory boards to be added to the BBC. In addition if the sampling rate is to be increased, the BASIC program needs to be either compiled or a different computer used as host for the CED 1401.

Ideally the Archimedes would act as the host computer. As the Archimedes has an improved version of BBC BASIC, very few programming changes in the sampling program would be required. The additional RAM of the Archimedes would provide the necessary memory requirements while the superior central processing unit and operating system would considerably increase the sampling rate and reduce processing time.

The fact that data may be stored directly onto hard disk in the Archimedes would also reduce the need for transfer of the data for off-line analysis. Indeed, if the Archimedes were used for data collection the sampling program could be altered to incorporate or call up the off-line analysis program at any point during an experiment.

Other changes which may improve the current experimental set up include designing a wall mounting for the handle so that it can be easily moved and fixed at any height above the ground. The wall mounting would need to be secure enough to ensure that the transducers retain their positions in the vertical or horizontal planes at all times.

Future Research

One possible avenue for future research would be in the development of a three dimensional static strength prediction program. Unlike currently available strength prediction programs (e.g. Garg and Chaffin 1975), strength predictions would be generated from actual observations of whole body strength rather than from strengths calculated from individual joint torque-angle relationships.

Such a model would however require postural data to be collected in addition to the strength measurements. As photographic or video methods for recording postures in three dimensions would be very labour intensive, alternative procedures would be required to develop the necessary posture library.

One feasible approach to postural data collection would be to use electrogoniometers to measure the angles across the major joints. *Penny and Giles Biometrics* currently market twin axial electrogoniometers for measuring joint angles in two planes and are about to introduce a tri-axial version for three dimensional angle measurements. Goniometers of this type permit postural information to be directly coded and stored in computer memory in 'real' time. In comparison, postural data obtained through processing of film or digitization of video images are likely to be prone to more measurement error (e.g. parallax and digitization errors) and to take substantially more time to process.

If both strength and postural data are sampled under the control of a computer program a large library of postures could be built up very quickly. This posture library would represent the most common postures adopted during maximal exertions in all of the 614 directions in three dimensional space at a given handle height. A simple flow chart showing the basic structure of the sampling routine for a computer program to collect this data is shown in Figure 5.22

In order to describe a posture in three dimensions, the minimum number of electrogoniometers needed for input of joint angles would be 4 single axis goniometers for the elbow and knee joints, 4 tri-axial goniometers for the hip and shoulder joints and 1 tri-axial goniometer for the L5/S1 joint of the lower back. Data from these electrogoniometers may then be input via A/D ports directly into a computer and used to create a simple 9 segmental model for computerized representation of the posture.

As the magnitude, direction and point of force application in three dimensions is known from the output of the 3D dynamometer, and the posture is known from the electrogoniometer output, it would be possible to determine the moments in three dimensions about the individual joints, and the back. Link lengths, their weights, and locations of centre of gravity, would of course need to be scaled relative to stature and body weight for a given individual or percentile of the population.

One disadvantage of creating a 9 segmental model based only on electrogoniometer output is that complex changes in the shape of the trunk as well as movements of the shoulder girdle are not indicated. While the model may be sufficient to compute the demands on the low back, detailed analysis of the upper torso would require additional data on the relative positions of landmarks such as the acromion, the seventh cervical and eleventh thoracic vertebrae of the spine.

This returns the problem of postural analysis back to either film analysis, or to one of the more sophisticated optoelectronic computerised motion analysis systems such as CODA (Charnwood Dynamics Ltd., Loughborough, UK) or VICON (Oxford Metrics Ltd., Oxford, UK). Which ever method is used the basic technique for posture analysis in three dimensions is the same. This includes placing markers on the subject so that the X, Y and Z co-ordinates of various landmarks may be determined.

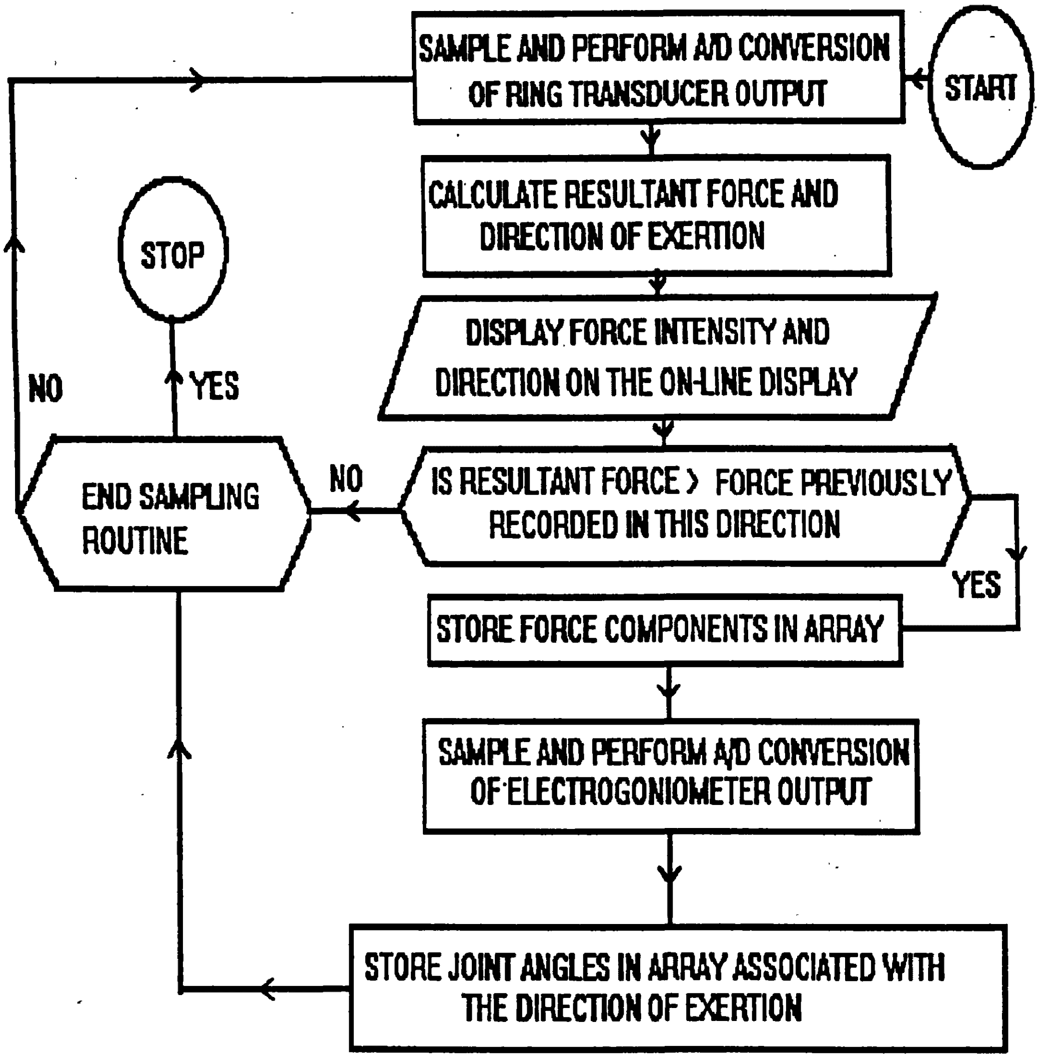


Figure 5.22: A flow chart showing the basic structure of a sampling routine for collection of strength and postural data using input from the 3D dynamometer and electrogoniometers.

With film analysis the markers need to be visible in at least two perpendicular views to define the X, Y and Z coordinates. This necessitates the use of either dual cameras or a mirror system. A detailed account of the methodology and techniques used in stereophotogrammetry is provided in Grieve and Pheasant (1982). Although relatively cheap, stereophotogrammetry requires a considerable amount of time to process, especially if manual digitization of the film images is performed.

The advantages of more expensive computerized optoelectronic systems like CODA and VICON is that sampling, processing and display of the coordinate data is done by computer in real time. In addition, some systems (e.g. Orthotrak, Motion Analysis Corporation, Santa Rosa, CA, USA) also permit force or EMG data to be measured and presented simultaneously with the postural data. Accuracy of the posture data will however be dependent on the sensors being able to locate the position of the markers in space. With some postures it is highly likely that one or more of the markers will be hidden from the camera or sensors of the motion analysis system.

Thus in order to provide a comprehensive and accurate description of any adopted posture in three dimensions in combination with three dimensional strength measurement, it may be necessary to combine electrogoniometer data with postural data collected from either film or one of the optoelectronic motion analysis systems.

Strength and postural data collected in such a way may afford a useful comparison with the Three Dimensional Static Strength Prediction Program marketed by the Regents of the University of Michigan, Centre for Ergonomics. In light of the assumptions of the above model (see Chapter 2), such a comparison would provide a worthwhile validation of the Three Dimensional Static Strength Prediction Program in many more directions of exertion than has previously been studied.

If however, three dimensional postural and strength data is collected over a larger number of subjects and over a range of handle heights, it may be possible to develop a comprehensive three dimensional static strength prediction program based on actual observations of whole body strength in real postures. Strength data would have to be collected at handle heights relative to stature, and the postures adopted must allow the directions of exertion to be described accurately by the conventions in Chapter 1.

Linear regression equations of strength on body weight could then be created for each of the 614 directions of exertion for each handle height. These equations along with their associated postural data would be incorporated into a computer prediction program. Using the linear interpolation procedures described by Sanchez (1991) to predict both posture and strength between the nodes of data collection (i.e. different handle heights) for the different directions of exertion, it may then be possible to predict static strength for any direction and at any height in the work space.

Such a model would have significant relevance to industrial safety and work place design. Appropriate use of the strength data would enable the Ergonomist to make better judgements on whether task-demands are within a workers' physical ability. The posture library would also be useful in determining the space requirements for manual handling tasks.

The measurement of static strength in three dimensions also opens up possibilities for testing the Equations of Static Exertion (ESE) and exploring the MACE concept in three dimensions. The ESE for exertions performed in the fore and aft plane (YZ plane) is derived in Chapter 2. By the same principle, if the free body diagram is extended into three dimensions and moments are taken about the centre of foot pressure, it is possible to describe the ESE for the other two planes (i.e. the XY and XZ planes). Future experiments measuring posture and static strength in three dimensions may be devised to explore these personal constraints on static exertion beyond the fore and aft plane.

Similarly, the concept of MACE may also be extended into three dimensions. Consider a single force vector of magnitude, X Newtons, representing a maximal, static, manual exertion in a given direction. This force vector has components in other directions in three dimensions which lie on the surface of a sphere whose diameter is X Newtons. If the maximal resultant vectors are known for all possible directions, and the spheres representing the components of each vector in the other directions are drawn, they would generate a new outer envelope of forces covering the sphere of exertion. This outer envelope represents the maximum components in each direction that are possible by employing resultant forces in other directions. Using the same definition of MACE as in Chapter 1 the maximum advantage of using a component of exertion may be calculated for any chosen direction in the sphere of exertion.

As two versions of the dynamometer have been constructed (one for the left and one for the right hand) it is possible to investigate two-handed static exertions in three dimensions. The fact that forces at the hand are measured independently permits the investigator to break into the closed loop system of two-handed manual exertions. Analysis of these forces may be useful in determining weaknesses in, or the favouring of, one side of the body or arm during two-handed exertions.

Use of both handles for two-handed exertions would also make it possible to measure an individual's capacity to exert whole body torques at the hands in any plane. The ability to produce whole body torques has relevance to turning large knobs or handles (e.g. wheel type control valves) and to any exertion that requires active force to be exerted with one arm while the other acts as a brace. Some of the questions which may be posed in future studies include:

- Is there an optimal handle separation for development of maximal whole body torque?
- What effect does handle placement have on the strength of whole body torques?
- In which plane of exertion are the largest whole body torques observed?

Summary and Conclusions

To the author's knowledge, a comprehensive description of whole body strength beyond two dimensions has not been previously attempted. This study therefore set out to develop appropriate hardware, software and experimental techniques for measuring static forces in three dimensions. A dynamometer permitting forces but not torques to be applied to a handle was designed and constructed for the measurement of forces in three dimensions. The dynamometer was calibrated and found to give an accuracy of $\pm$ 4 N for the resultant force and $\pm$ 1° for the direction of exertion.

Both on and off-line computer displays were developed to present the direction and intensity of the forces over the whole sphere of exertion. The component forces at the hands were also used to calculate the minimum value of the coefficient of friction required to prevent slip at the feet for any direction of exertion.

Experimental trials were carried out on four male subjects with the handle of the dynamometer placed at 1.0 and 1.75 m above the ground and with foot placements at a horizontal distance of 0.5 m from the handle. After an initial learning period most of the subjects completed the sphere of exertion after 4 experiments performed on separate days. Each experiment consisted of 5 two minute sessions of data collection interspersed with rest periods of the subject's own duration. The strength testing protocol adopted was found to be suitable for both handle heights and subjects were able to repeat their performance satisfactorily at the 1.0 m handle height.

In conclusion the apparatus and methodology proved to be accurate and reliable for measuring static strength over the entire sphere of exertion. The current work thus provides the basis on which to develop future studies investigating human strength capabilities in all or any chosen direction in three dimensions.

Possibilities for future research are discussed and include investigation of both environmental and personal constraints on the static exertion of forces in three dimensions. The combination of both postural and three dimensional strength data also has a potential application in the development of a comprehensive biomechanical model for prediction of static strength in three dimensions. Unlike previous biomechanical models the new model would be based on observation rather than on measures of whole body strength derived from the torque-angle relationships across the major joints.

CHAPTER 6

STUDY IV

THE CHARACTERISTICS OF MAXIMAL DYNAMIC LIFTING EXERTIONS ON AN ISORESISTIVE HYDRODYNAMOMETER

Introduction

The objective of this study was to describe the dynamic characteristics of maximal lifting exertions under conditions in which the velocity of lift is effort-dependant. This objective was aided by the instrumentation of a novel strength testing device called a hydrodynamometer.

The resistance to motion during a lift on the hydrodynamometer is determined by the rate at which a piston with holes in is drawn through a water-filled tube. Since the resistance (i.e force at the hands / velocity^x) is constant, when exertions are performed against a piston of given cross sectional area moving through a fluid of given viscosity, these type of exertions were termed isoresistive (see definition in Chapter 1).

By using pistons with different numbers of holes (and hence different cross sectional areas), in addition to isometric lifting strengths, it was proposed to measure the strength of lifting exertions performed at velocities ranging from 0 to 2.0 m/s. To the author's knowledge, this is the first attempt to describe the characteristics of lifting over such a wide range of velocities.

A further objective of the study was to compare performances on the hydrodynamometer with isometric lifting strength in comparable postures throughout the lifting range. It was expected that individuals who perform well (or poorly) would achieve the same relative performance independent of the test mode (dynamic or static), posture, or velocity under which maximal lifting exertions are evaluated.

Methods

Apparatus

A photograph of the hydrodynamometer and the experimental set up is shown in Figure 6.1. The main body of the hydrodynamometer consisted of a flat cylindrical piston of 20 cm diameter, located in a water-filled tube. The piston was connected to a handle over a series of pulleys by inextensible wire cable. Resistance to motion was provided by the viscous drag on the piston. This has been previously calculated to vary in proportion to approximately the square of the velocity (Grieve 1991). Large changes in the magnitude of the viscous resistance offered by the hydrodynamometer could be altered by opening one or more of 48 individual 1.7 cm diameter holes in the cylindrical piston. The five resistances used were labelled as very heavy (0 holes), heavy (12 holes), medium (20 holes), light (28 holes) and very light (48 holes). These piston resistances were chosen to cover the extreme conditions expected for dynamic lifting.

The moving parts of the hydrodynamometer had an equivalent inertial mass of 6.8 kg.

A force transducer (Ether Ltd, Dynamometer type UF2) determined the force of the lift by measuring the instantaneous tension in the cable connecting the handle to the piston. Rotational motion of the hydrodynamometer pulley system was transmitted via a gearing mechanism to additional pulleys connected to a velocity and a displacement transducer (JLT Group, Displacement transducer type PD).

The force transducer was calibrated by clamping the wire cable at the piston end and then hanging weights of known mass on the handle end. A calibration curve for the displacement transducer was determined from output recorded at 16 handle positions between 390 mm and 1855 mm from the floor. Both transducers gave linear signals over their full range to an accuracy of 1 N and 1 mm for force and displacement respectively.

The velocity transducer operated on the principle of magnetic induction and consisted of a closely wound wire coil located in a strong magnetic field. The rate at which this coil was drawn through the magnetic field induced a voltage in the coil which was proportional to the velocity of lift. During a calibration lift, output from the velocity transducer was integrated and then compared with the displacement output. The regression of integrated velocity on displacement was linear ($r^2 = 0.99$) and provided calibration constants with a coefficient of variation of 0.67% over sampling frequencies ranging from 30 to 300 Hz.

Output from the various transducers were amplified using a four channel amplifier (Racal Instruments Ltd) before being digitized to 12-bit resolution by the analogue to digital converter (ADC) ports of a CED 1401 intelligent interface (Cambridge Electronic Design Ltd). Each transducer channel was sampled at 30 Hz under the very heavy condition, 150 Hz under the heavy, medium and light conditions and 300 Hz under the very light condition. Operation of the CED 1401 was under the control of a BBC B microcomputer (Acorn Ltd.) which was connected via the 1 MHz bus interface to the CED 1401. Specifically designed software written in BASIC language was used to perform the calibration and sampling procedures and present time derivative data (i.e. force-time, velocity-time and displacement-time plots) on a VDU.

Isometric strength was measured using a handle which was connected via a metal chain to a strain gauge transducer (Model 1269F, Takei KiKi Kogyo Co., Ltd) secured firmly to the floor.

Recordings of experimental trials on the hydrodynamometer were filmed with a 16 mm cine camera (Bolex H 16). The horizontal optical axis was aligned 1.0 m from the floor at a distance of 9.07 m from the sagittal plane of the subject. Filming speed was set at 32 frames/sec for all lifts except for the very heavy resistance (12 frames/sec).

Figure 6.1: A photograph of the hydrodynamometer and the experimental set up.

Subjects

Nine males and nine females at the Royal Free Hospital School of Medicine volunteered to perform one and two-handed dynamic exertions against the light, medium and heavy resistances as well as isometric exertions at several heights above the ground. Most of the subjects were either staff or students with no specific background or training in strength related sports or activities.

Detailed analysis of two-handed dynamic lifting (which included exertions against the very heavy and very light resistances) was carried out on one male (DF) and one female subject (CB). All subjects received information packages describing the purpose of the experiments and signed informed consent releases. The physical characteristics of the subjects are shown in Table 6.1.

One particular feature of note is the fact that the male and female groups were matched very closely for age.

Table 6.1
The physical characteristics of the subjects

	Subj DF	Subj CB	Males (n=9) Mean	SD	Females (n=9) Mean	SD	Group (n=18) Mean	SD
Age (Yrs)	26	24	29.1	11.7	29.1	7.4	29.1	9.5
Weight (kg)	78.1	62.6	74.4	8.7	58.4	5.3	66.4	10.8
Grip (N)	540	353	492	96	301	66	397	127
Stature (mm)	1854	1668	1785	98	1669	55	1727	97
Shoulder height (% stature)	81.9	81.8	82.3	1.0	81.4	1.4	81.9	1.3
Elbow height (% stature)	60.0	63.2	62.1	1.3	62.8	1.8	62.5	1.6
Hip height (% stature)	47.0	51.9	50.6	1.9	50.2	1.7	50.4	1.8
Knuckle Height (% stature)	42.1	43.5	41.9	1.0	43.0	1.4	42.5	1.3
Knee height (% stature)	27.1	26.4	29.1	1.4	27.9	1.5	28.5	1.6

Protocol

On entering the laboratory, the subject's anthropometry and grip strength were measured. The hydrodynamometer was then calibrated and the subjects performed maximal one and two-handed exertions against the high, medium and low piston resistances. Half the subjects completed the one-handed exertions first and the other half the two-handed exertions first. The order of presentation of the piston resistances was fully randomised for both the one and two-handed exertions. Lifting technique was free style, with foot placement parallel to and directly beneath the hydrodynamometer handle. The instructions required the subject to lift as forcefully and as fast as possible from the starting position (390 mm from the floor) to just above head height. Exertions were performed at intervals not less than 5 minutes apart. An over arm grip was employed on the dynamometer handle at the start of each lift.

One and two-handed isometric lifting strength at knee, knuckle, hip, elbow, shoulder and head height was assessed on a separate day. The protocol followed that described by Caldwell *et al.*, (1974) in which strength measurements were determined from the average force recorded over the final three seconds of a five second maximal exertion. Foot placement with respect to handle position and type of grip on the handle was the same as for the dynamic experiments. The order of presentation of the one and two-handed exertions at the different heights was randomized in a similar manner to that described above.

For detailed analysis of dynamic lifting, subjects DF and CB wore bathing costumes so that markers could be placed on the skin to indicate the ankle, knee, hip (head of femur), wrist, elbow, and shoulder joints and C7, T11 and L5 positions of the spine. With the Bolex camera set up as described above, each subject was filmed performing two-handed exertions against the light, medium, heavy, very light, and very heavy piston resistances.

Reliability of the hydrodynamometer data were tested by comparing the performance of subjects CB and DF against the heavy, medium and light resistances with repeated trials performed against the same piston resistances one month later.

Data Analysis

The time derivative data (i.e., force, velocity and power) collected on subjects DF and CB were smoothed using an unweighted 11 point moving average before presentation. The force, velocity and power data for each subject was converted from time derivative data into distributions corresponding with 0.25% intervals of stature before being combined for group analysis.

The influences and interactions of sex, handle height, number of hands and piston resistance on force and power output and on the position of maximum force were analyzed using split plot repeated measures analysis of variance. The same form of statistical analysis was performed on the isometric lifting strength data.

Pearson product-moment correlations were used to examine the relationships between dynamic and static tests of lifting strength. The partial correlation technique was used to determine the net relationship between measures of strength without the confounding effect of body mass. Intercorrelations that exceeded $r = 0.71$ (i.e. $r^2 \times 100 = 50\%$) were judged to indicate a greater proportion of generality than specificity between the different strength tests (dynamic or static) and different task resistances. In order to remove the effects of error variance, the correction for attenuation was applied to the intercorrelations using estimates of the reliability coefficients for the various strength measures (Ferguson 1976). The relation between the correlation of true and obtained scores is given by

$$r_{T_xT_y} = \frac{r_{xy}}{\sqrt{r_{xx}\, r_{yy}}}$$

where $r_{T_xT_y}$ = correlation between true scores
r_{xx} = reliability of X
r_{yy} = reliability of Y

RESULTS

Repeatability

Force-displacement traces for the test-retest exertions against the heavy, medium and light piston resistances are shown for both subjects in Figure 6.2. Repeatability of the exertions were assessed by calculating the root mean squares of the differences (RMSD) in the force trace for the first and second trials against the mean for each piston resistance. The overall mean RMSD for all conditions and both subjects combined was 15 N for forces recorded between 21% and 99% of stature.

The largest absolute force differences between trials were recorded against the heavy piston resistance for both subjects and the light piston resistance in the case of subject CB. The main force differences between trials for these lifts occurred between the start of the lift and knuckle height with the remainder of the lift, above knuckle height, showing no significant difference between trial 1 and trial 2 ($p > 0.05$). In the remaining exertions there was no significant difference ($p > 0.05$) between trials throughout the entire lifting range.

Reliability coefficients calculated from the test-retest data of both subjects for one and two-handed lifting against the three resistances are presented in Table 6.2. All reliability coefficients were greater than 0.92 indicating that less than 8% of the variation in dynamic strength over the entire lifting range was attributable to error or differences in performance between the test and retest exertions.

Table 6.2
Test-retest reliability coefficients for subjects DF and CB for one and two-handed dynamic lifting exertions against the heavy, medium and light resistances.

	RESISTANCE	SUBJECT DF	SUBJECT CB
ONE-HANDED	HEAVY	0.99	0.95
	MEDIUM	0.97	0.94
	LIGHT	0.98	0.97
TWO-HANDED	HEAVY	0.98	0.97
	MEDIUM	0.99	0.92
	LIGHT	0.98	0.96

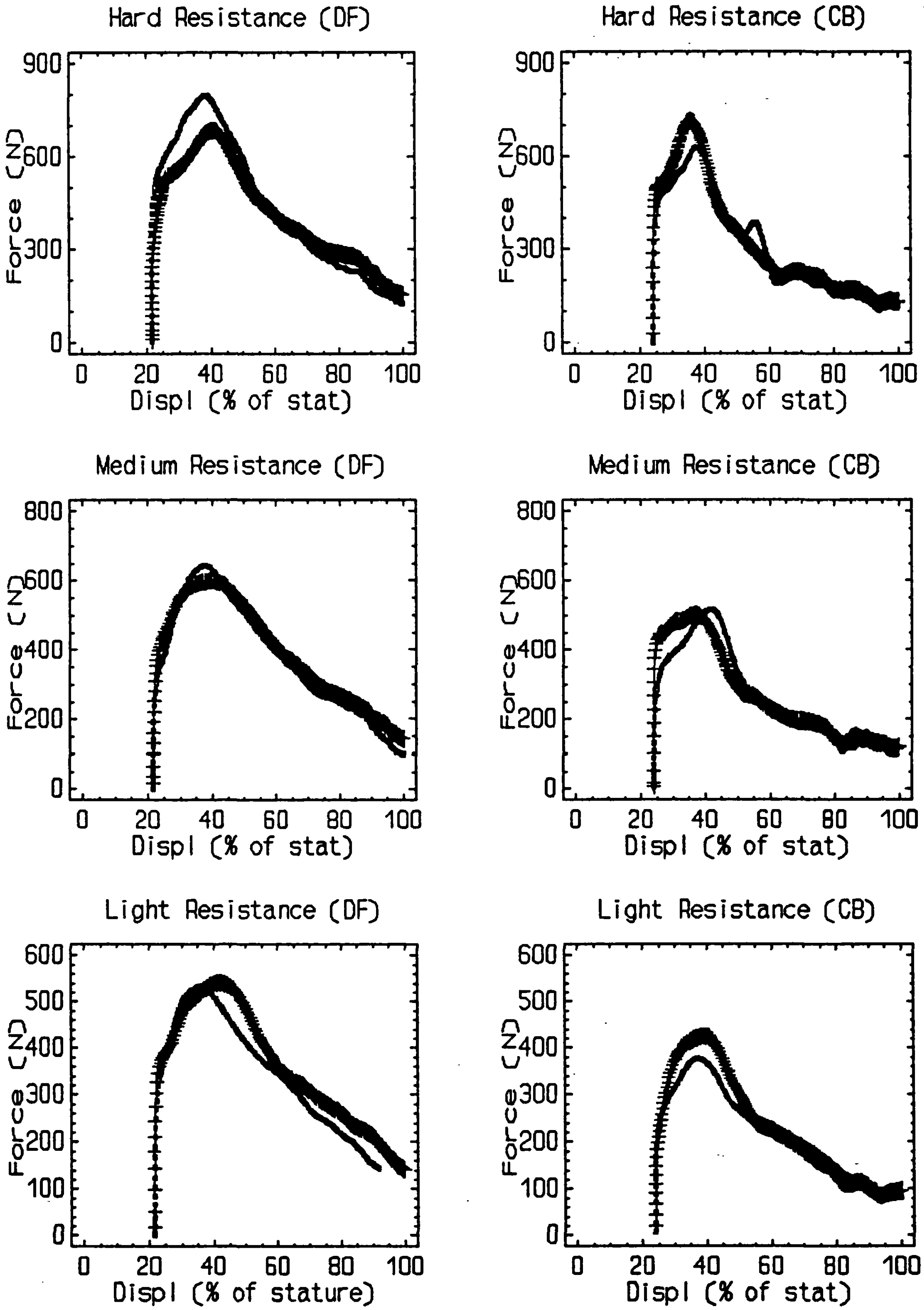


Figure 6.2: Force versus hand height above the ground for the initial and repeat trials of maximal lifting exertions against the hard, medium and light piston resistances for subjects DF and CB.

Physical Characteristics of the Hydrodynamometer

When the force due to the weight and the acceleration of the hydrodynamometer's moving parts are subtracted from the force measured at the hands, the resultant force-velocity curve describes the viscous force characteristics of the particular piston. Figure 6.3 gives an example of both the measured and viscous force-velocity characteristics for subject DF against the very light piston resistance.

After 50 ms into the lift, the total force reaches a peak of approximately 380 N. Ten milliseconds after this initial impulse the force-velocity curve of the viscous force begins to follow a particular resistance characteristic. At this point in time, the proportion of the total force at the hands due to the weight and acceleration of the system's inertial mass is approximately equal to the viscous force. After 110 ms the force observed at the hands is used almost entirely to overcome the viscous resistance. The total time course of the lift from just below knee height to head height took 900 ms.

The viscous characteristics of each piston resistance is more clearly illustrated by plotting the viscous force and velocity on logarithmic axes as shown in Figure 6.4. Linear regression analysis of these log transformations for the 5 piston resistances revealed mean slopes of 1.56 Ns/mm (SD=$\pm$0.16) and 1.50 Ns/mm (SD=$\pm$0.06) for subjects CB and DF respectively. R^2 values for the regression lines were all 0.99 except for the very heavy piston resistance (R^2 = 0.90 and 0.94 for subjects CB and DF respectively).

Using a slope value of 1.55 (derived from the log-log graphs of force and velocity for lifting exertions of CB and DF against the heavy, medium and light piston resistances) it was possible to test the isoresistive nature of the hydrodynamometer. For each resistance and for every 0.25% of stature above the ground the force data (averaged over the one and two-handed conditions for the 18 subjects) was divided by the corresponding velocity raised to the power 1.55. The resulting values expressed in units of $Ns^{1.55}/m^{1.55}$ are plotted against displacement in Figure 6.5.

Apart from at the very start of the lift, resistance over the operating range of the hydrodynamometer was relatively constant against a given piston. Mean lift resistance (in units of $Ns^{1.55}/m^{1.55}$) for the heavy, medium and light piston conditions was 1180 (SE = 2.0), 535 (SE = 1.0) and 306 (SE = 0.9) respectively.

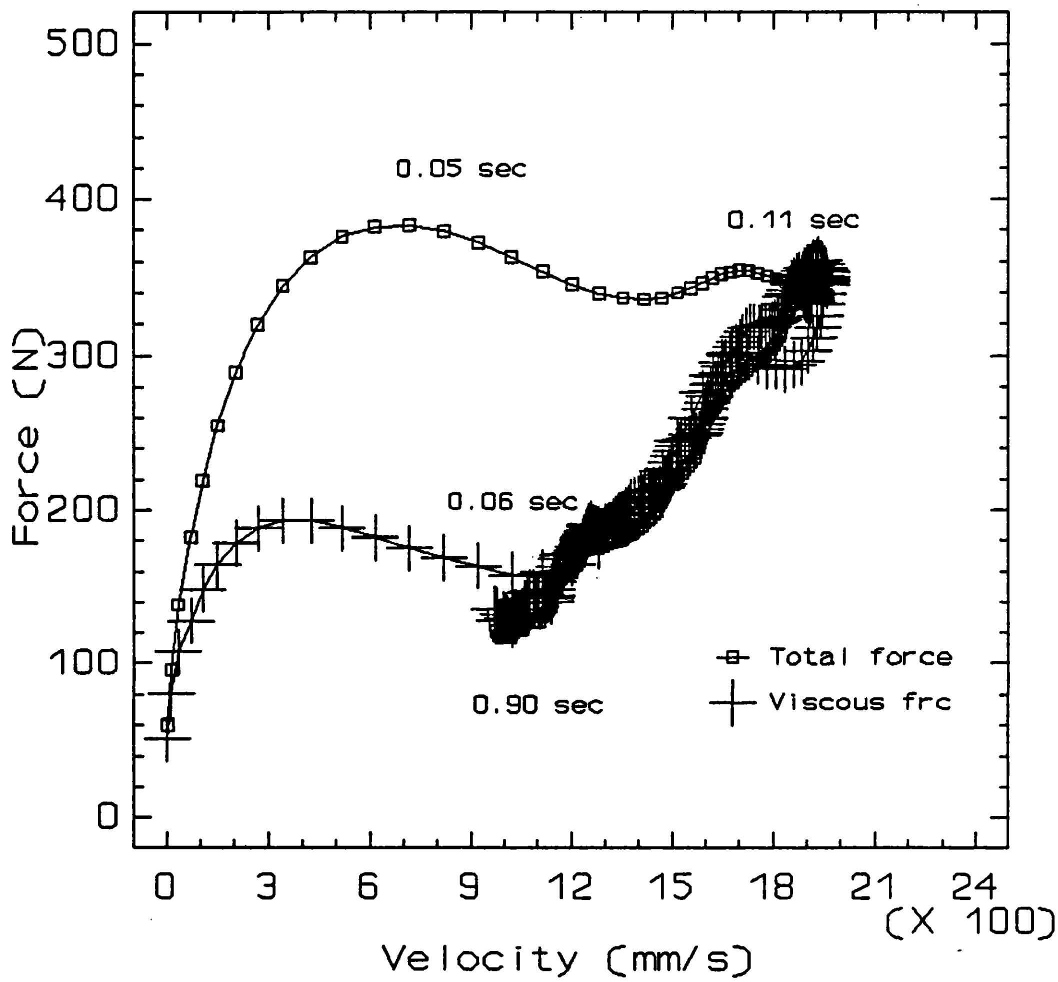


Figure 6.3: Force-velocity characteristics of subject DF lifting against the very light resistance. The contribution of the viscous force to the total force measured at the hands is also illustrated. The numbers presented at various points on the force-velocity curve represent different stages in the time course of the lift (see text for further explanation).

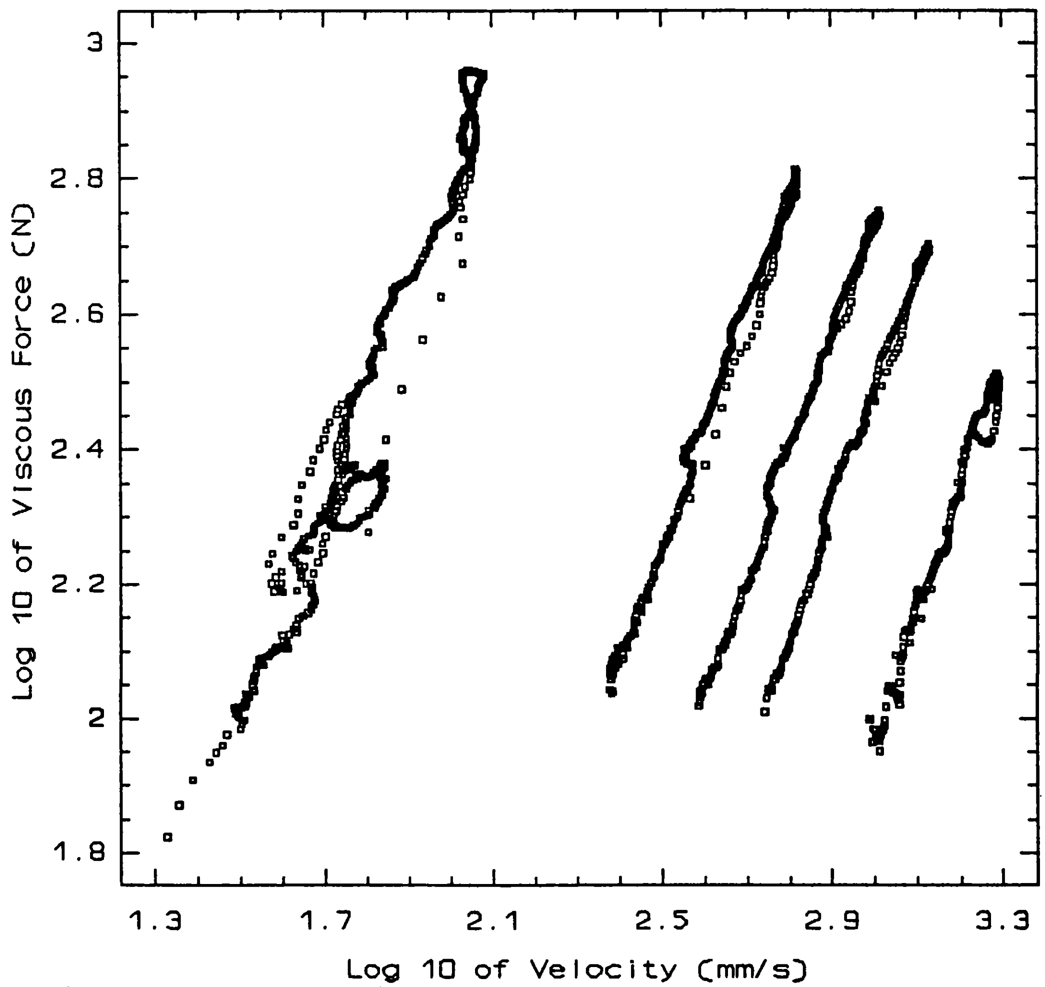


Figure 6.4: A logarithmic plot showing the relationship between the viscous force and velocity of lift for exertions on the hydrodynamometer against the very heavy, heavy, medium, light and very light resistances (from the extreme left hand curve to the extreme right hand curve respectively). The mean value of the slopes was 1.5 Ns/mm. The curves were derived using the data from subject DF.

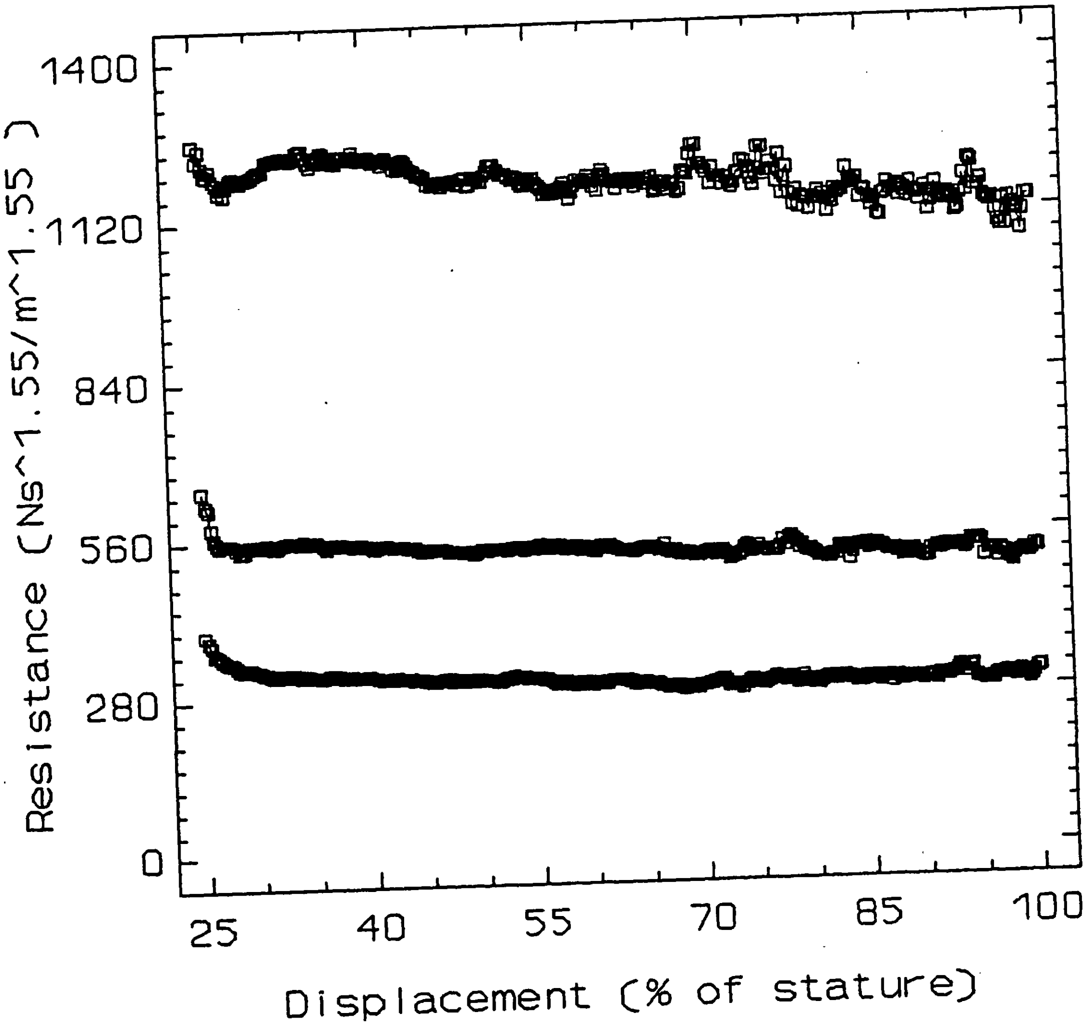


Figure 6.5: Resistance-displacement characteristics for the heavy, medium and light resistances (top, middle and lower curves respectively) on the hydrodynamometer. The resistance at a given hand height 'd' was calculated from the mean force and velocity data averaged over the one and two-handed exertions for the 18 subjects using the formula resistance$_d$ = Viscous Force$_d$/velocity$^{1.55}{}_d$.

Force-displacement characteristics under the extreme conditions (very light and very heavy piston resistances) are shown along with the isometric strength at various fractions of stature in Figure 6.6. Large differences in the magnitude of the force are observed between the curves in the initial stages of the lift. Differences in the strength of lift between isometric exertions and the dynamic resistances tended to decrease in magnitude as the lift progressed towards head height.

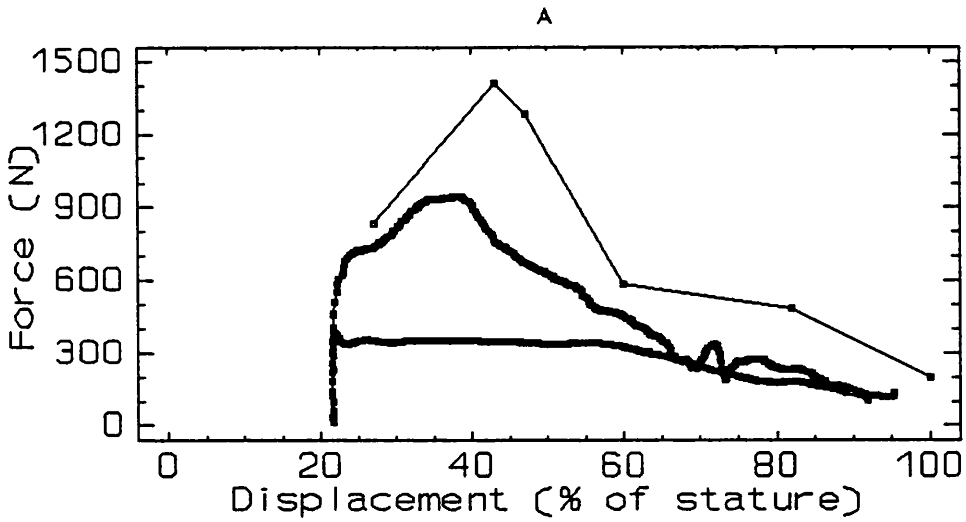
Isometric strength was found to be on average 58% (SD=$\pm$37%) greater than dynamic strength recorded against the very heavy piston resistance and 206% (SD=$\pm$80%) greater than the strength recorded with the very light piston resistance.

Velocity and power-displacement curves against the different piston resistances are shown in Figures 6.7 and 6.8. The general form for these curves and the force-displacement curves (Figure 6.2) show a sharp rise during the initial stages of the lift to a peak, in most cases, at around knuckle height. From this point the curves declined with a gradient which became less marked as the lift progressed towards head height. The time course of the lifts from the start position (400 mm above the ground) to 90% of stature ranged from 80 ms for the very light resistance to 18 seconds for the very heavy resistance (see Figure 6.9).

Although peak power against the light resistance was larger than against the very light resistance for subject DF, overall mean power output was greatest against the very light resistance and decreased with increasing piston resistance for both subjects.

Lifting against the very heavy piston resistance was notably more erratic than any of the other exertions with both subjects demonstrating large perturbations in the force trace between 65% and 75% of stature (see Figure 6.6).

These perturbations were investigated further by analyzing the cine film of the lifting exertions.



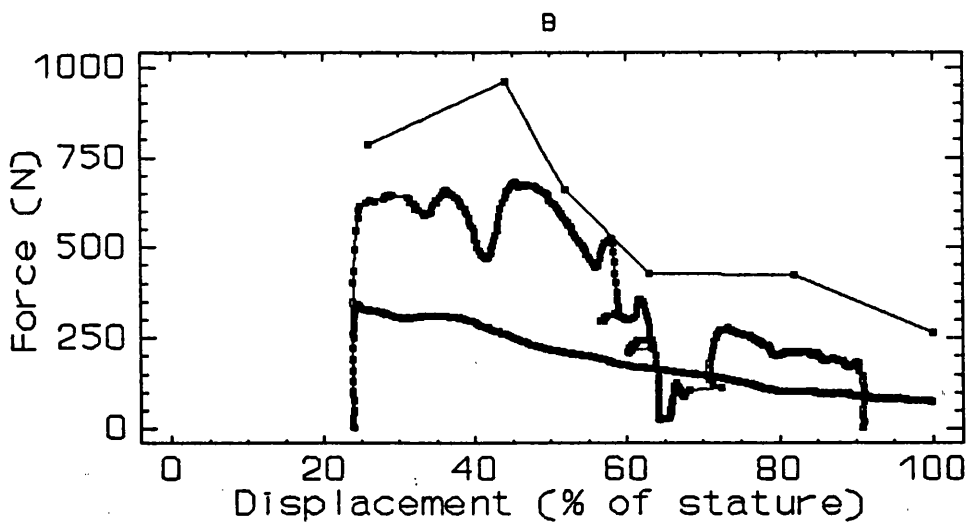
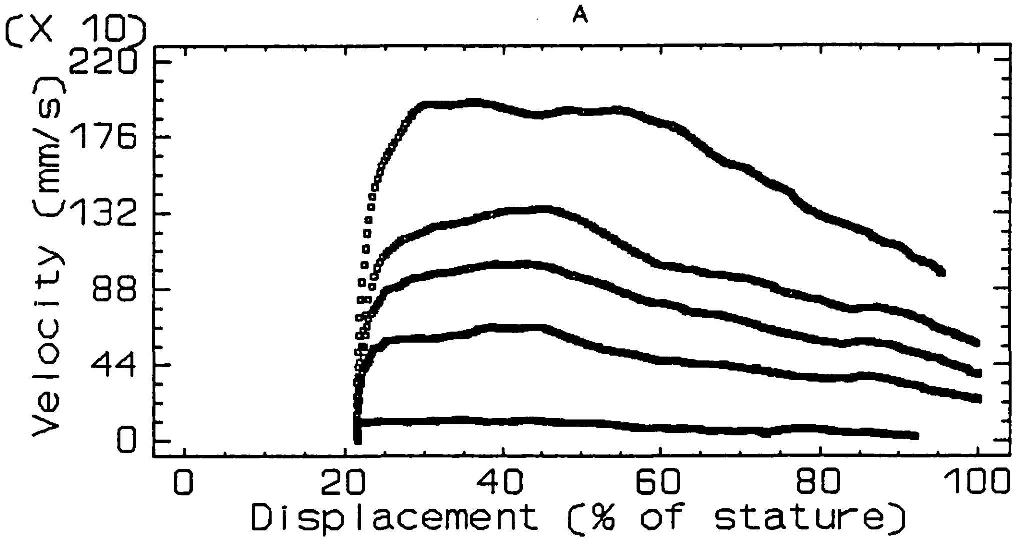


Figure 6.6: Force versus hand height for lifting exertions against the very heavy and very light piston resistances by subjects DF (Figure A) and CB (Figure B). Note the erratic nature of the force-displacement curve against the very heavy resistance. For comparison isometric lifting forces measured at knee, knuckle, hip, elbow, shoulder and head height are shown by the upper curve in each figure.



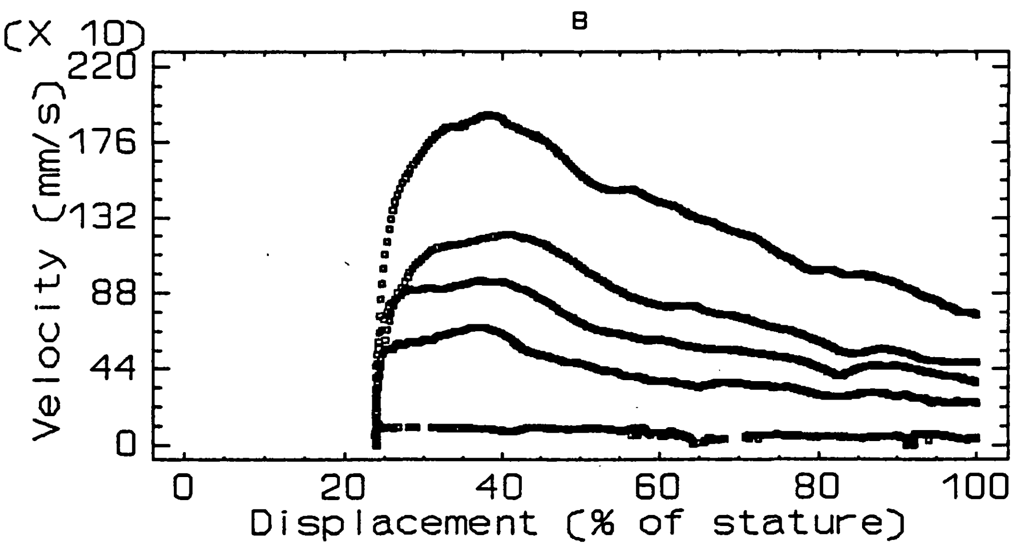


Figure 6.7: Velocity versus hand height for lifting exertions against the five different piston resistances by subjects DF (Figure A) and CB (Figure B). The largest velocities are observed against the very light resistance and the lowest against the very heavy resistance.

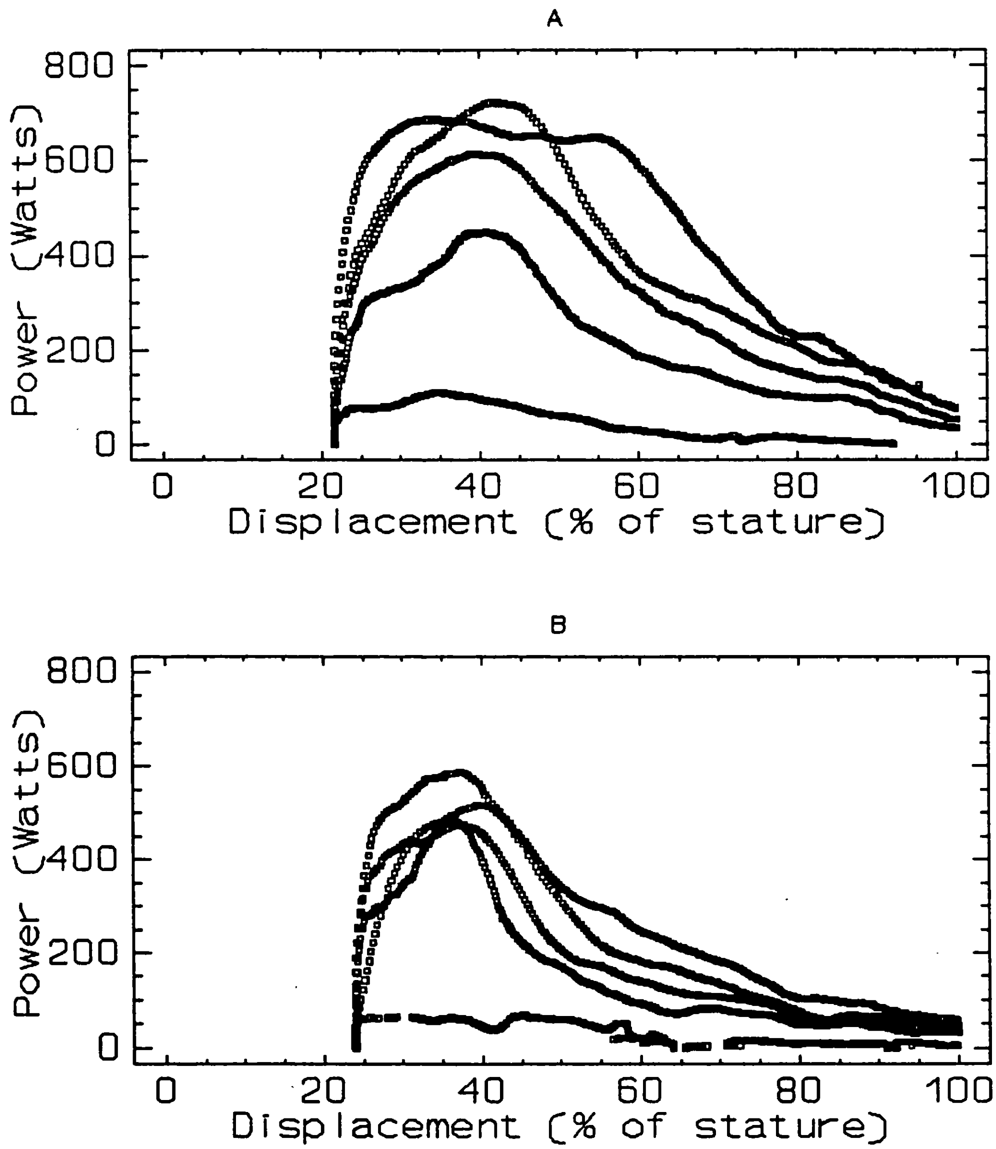


Figure 6.8: Power versus hand height for lifting exertions against the five different piston resistances by subjects DF (Figure A) and CB (Figure B). Taken over the entire lifting range the largest mean power is observed against the very light resistance and is shown to decrease as the piston resistance increases.

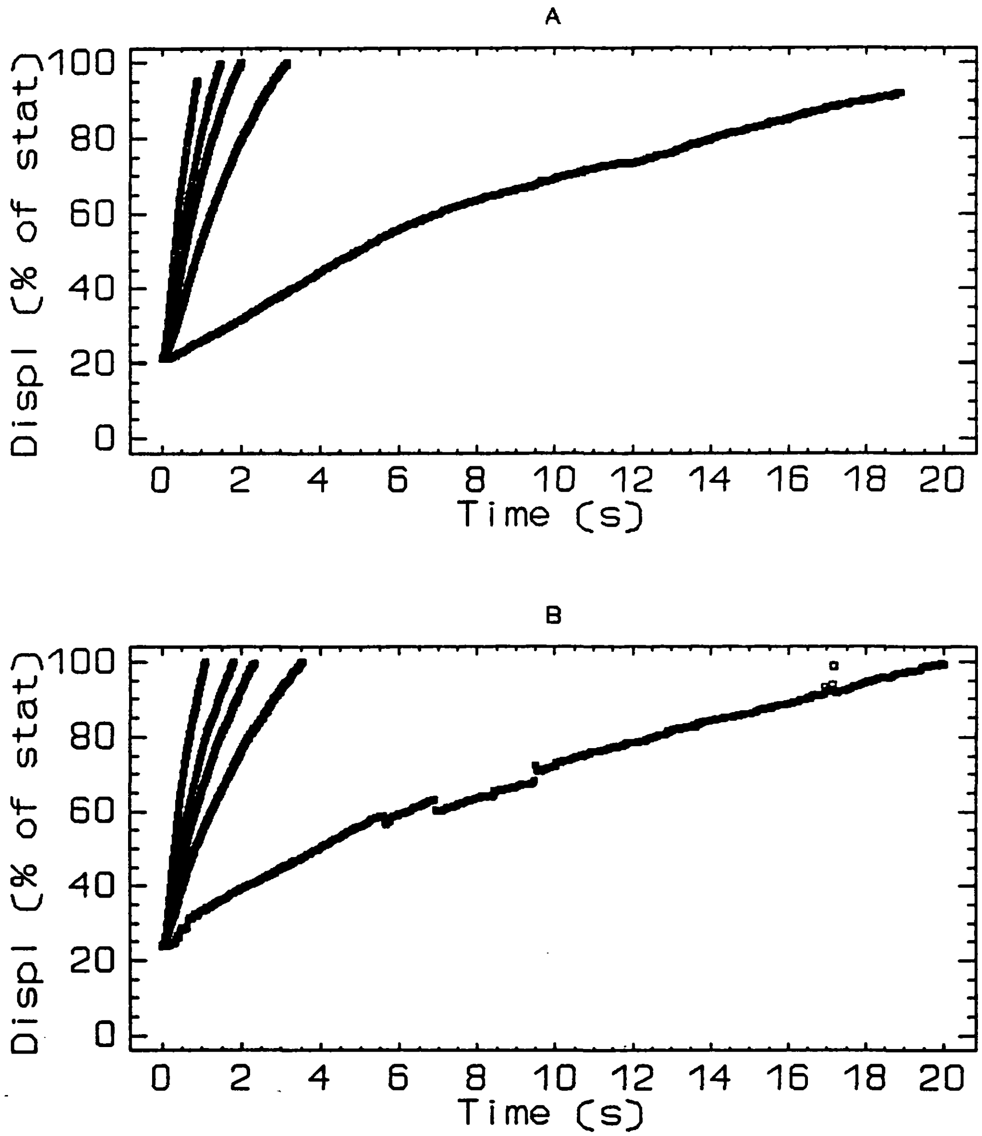


Figure 6.9: Displacement-time curves for lifting exertions against the five different piston resistances by subjects DF (Figure A) and CB (Figure B). The time course of lift from 21% of stature to head height increases as the piston resistance increases and ranges from less than 1 second for the very light resistance to almost 20 seconds for the very heavy resistance.

Figure 6.10 shows tracings of the postures adopted by subject DF during lifting exertions against the five resistances. Also marked on these tracings are the locations of the hip and C7. The tracings illustrate very similar lifting techniques against all but the very heavy resistance. A similar phenomenon was also observed with subject CB.

Differences in the movement pattern against the various resistances is shown quite clearly when the distance between the hand and C7 is plotted as a function of the hand height above the ground as shown in Figure 6.11. In this Figure the data obtained from analysis of the postures adopted against the very light to the heavy resistance are bounded by the envelopes. The dotted traces indicate the substantial difference in lifting technique adopted by both subjects when lifting against the very heavy resistance. The arrows show the point at which the slope of the curve becomes 1. In other words, after this point the trunk is fully erect and any further lifting action is performed entirely by the displacement of the upper limbs.

Similar observations are noted when the height of the hip and C7 and the difference between C7 and the hip is plotted against hand height (see Figures 6.12 and 6.13). Again the arrows indicate that extension of the hip and torso are completed by the time the hands have reached hip height.

When lifting against the very heavy resistance both subjects demonstrated a marked drop in the hips as the hands were brought towards shoulder height. The drop in the hips was a result of the subject flexing the knees in an attempt to bring the body underneath the handle and continue the lift with a thrust upwards. This required a change in grip from an over arm to an under arm posture. In the case of subject CB several attempts were made throughout the lift against the very heavy resistance to change from an overarm lift to an upward thrust. These sudden changes in posture resulted in the erratic nature of the force-displacement trace seen for the very heavy resistance in Figure 6.6.

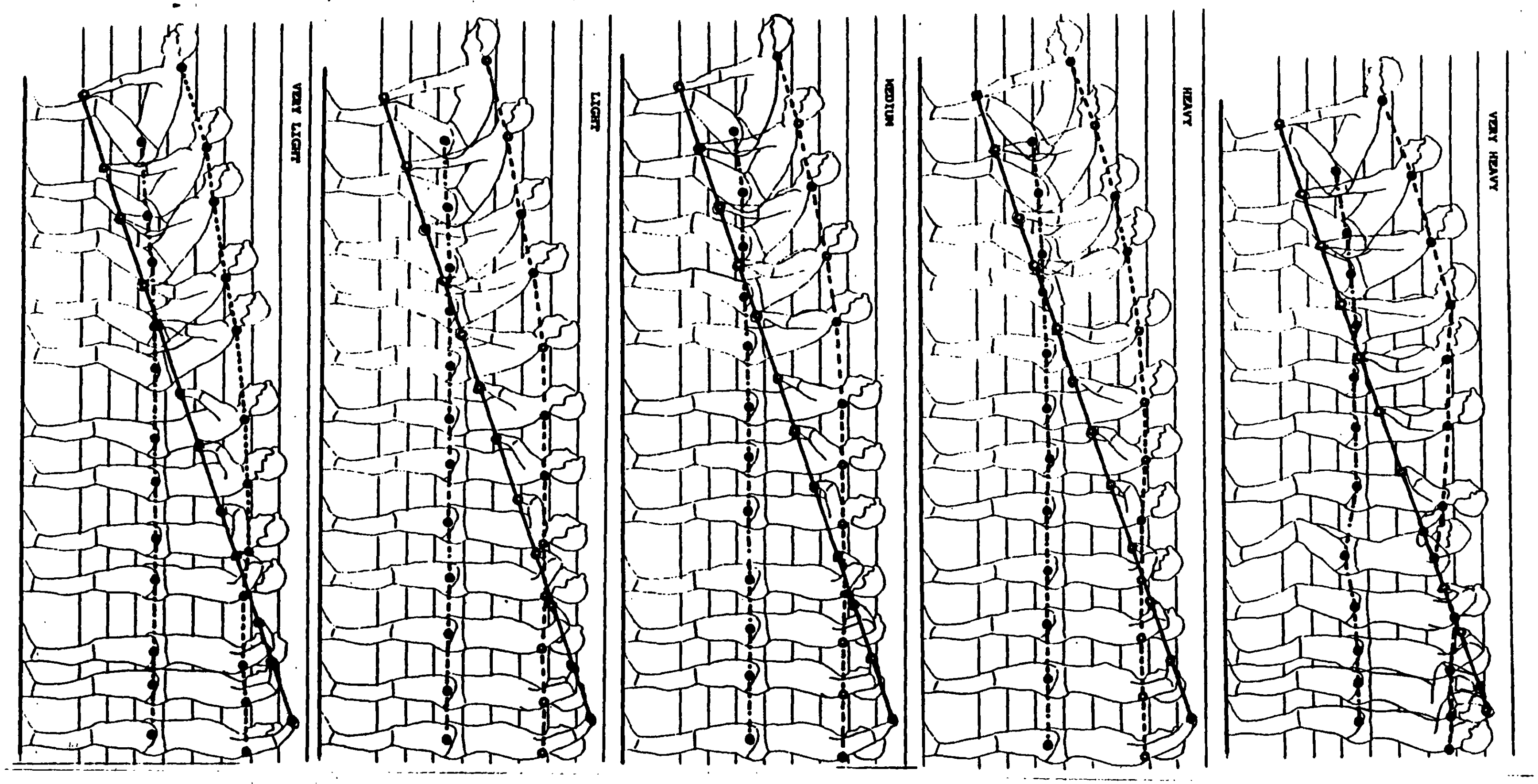


Figure 6.10: Tracings from 16 mm cine film of subject DF performing lifting exertions on the hydrodynamometer against five different resistances ranging from very light to very heavy.

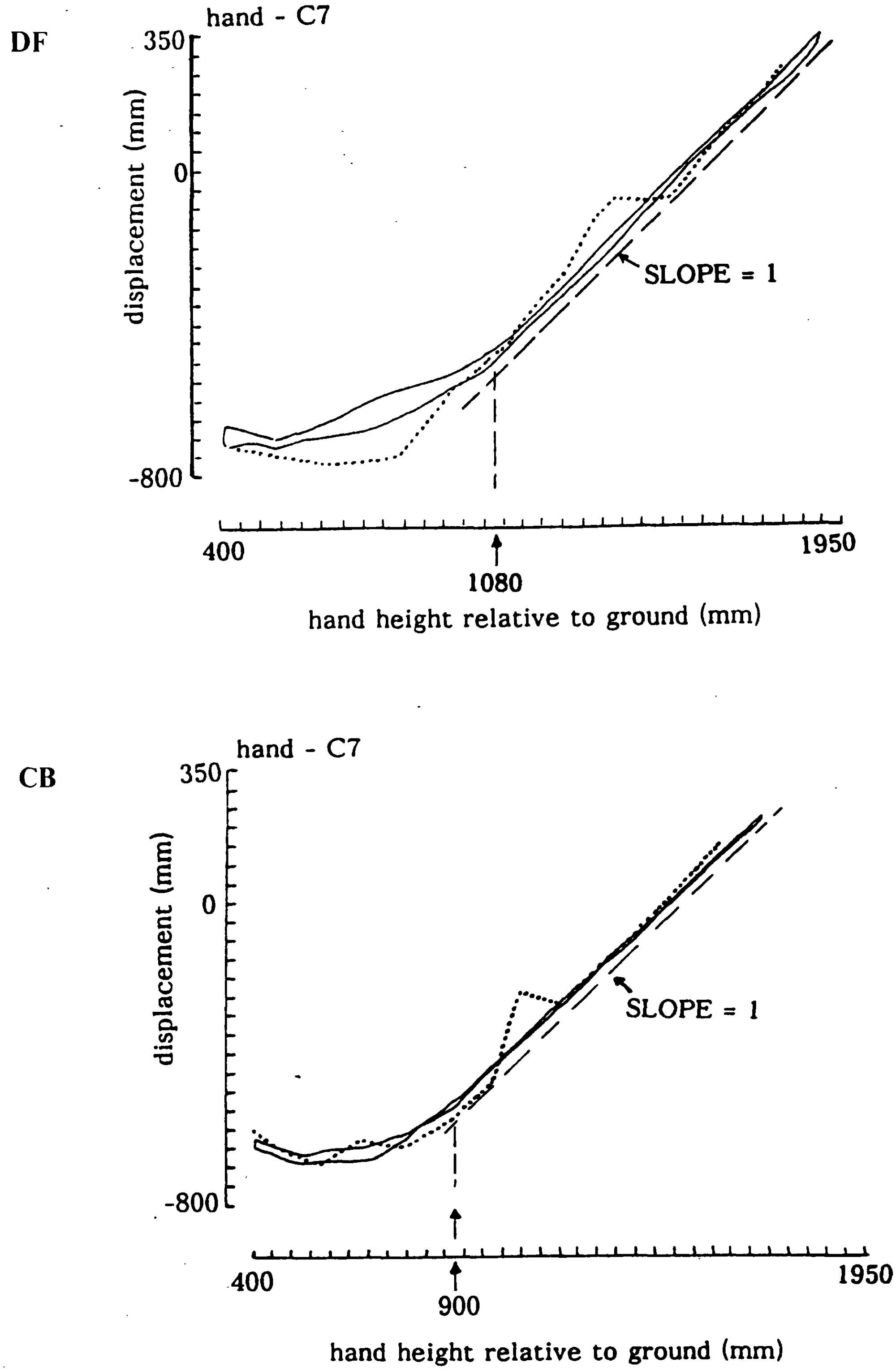


Figure 6.11: Displacement traces of the hand with respect to the floor and the position of the C7 spine during two-handed lifts against the five different resistances by subjects DF and CB. The envelopes encompass the data points for exertions against the very light, light, medium and heavy resistances. The dotted trace shows the data for the very heavy resistance.

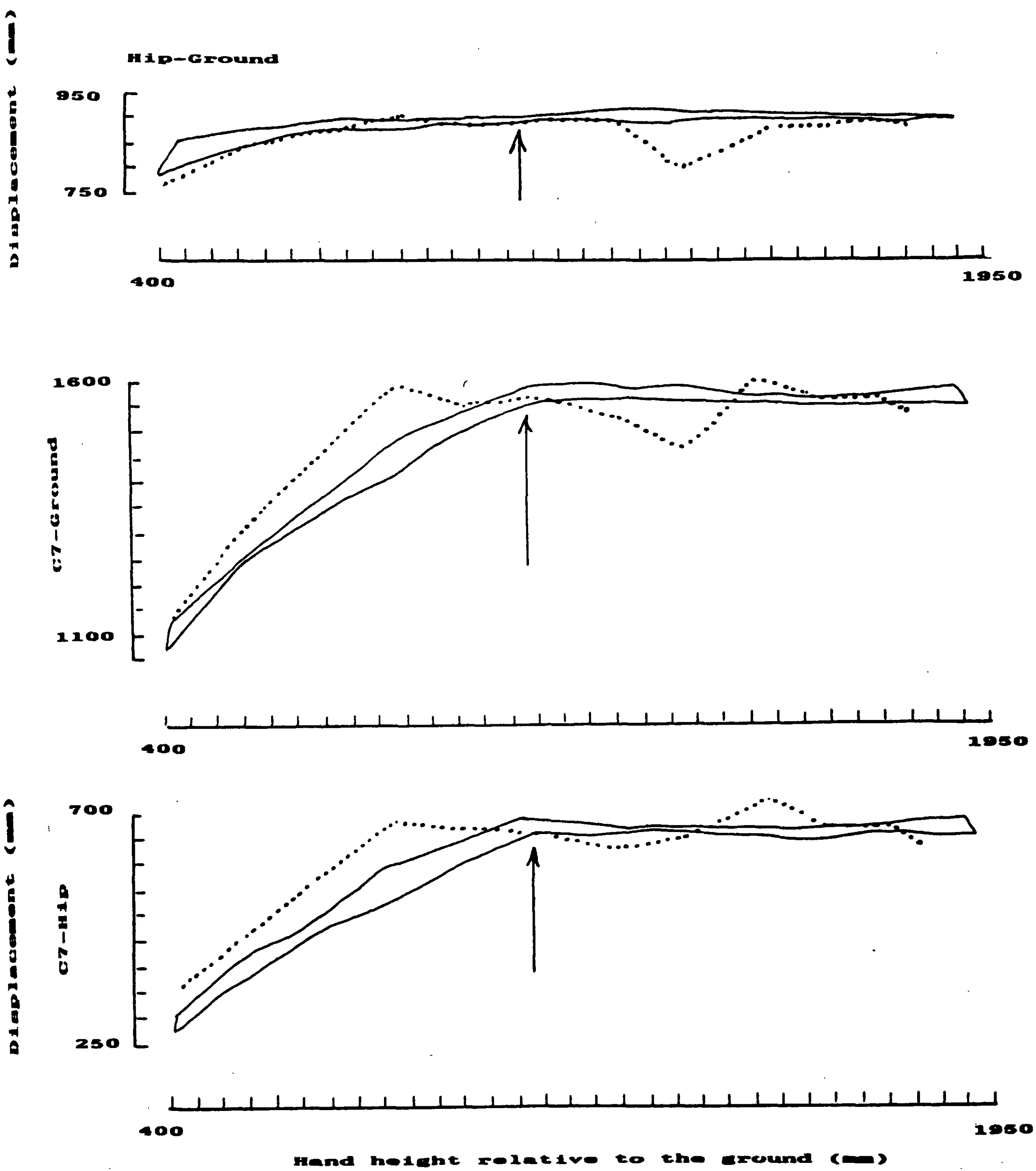


Figure 6.12: Displacement traces of the hip and C7 with respect to the ground and of the hip with respect to C7 during two-handed lifts by subject DF against the five different resistances.

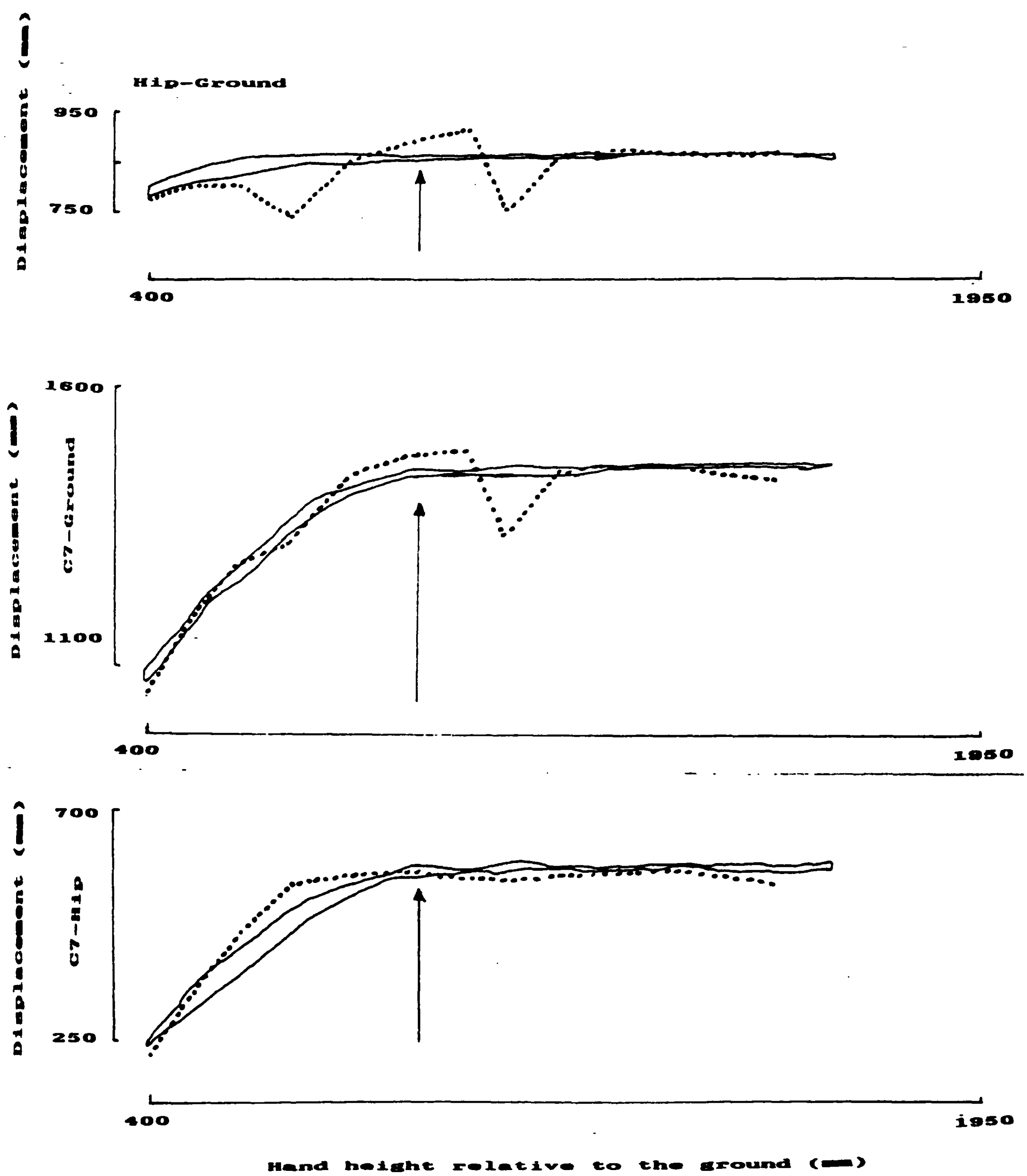


Figure 6.13: Displacement traces of the hip and C7 with respect to the ground and of the hip with respect to C7 during two-handed lifts by subject CB against the five different resistances.

Group Data for Maximal One and Two-Handed Dynamic and Static Lifts

During lifting exertions on the hydrodynamometer the position of the feet were raised by 8 cm for the one-handed lifts to ensure the same relative starting position when using the one- and two-handed handle attachments. In the case of several taller male subjects this resulted in the displacement transducer reaching the end of its measuring range by the time the one-handed lifts had reached head height. In addition, as the starting height of the handle was fixed at 39 cm from the floor for all subjects, the starting height expressed as a percentage of stature was different for each subject. The following data analysis and presentation of results were only performed with data sets comprising of a full complement of data points (i.e. n=18). Consequently, data for the first 2 or 3 % of stature from the start of the lift, and those data at hand heights in excess of 95% of stature have been omitted.

Dynamic Lifting

The dynamic characteristics for one and two-handed lifting exertions against the heavy, medium and light resistances on the hydrodynamometer are illustrated in Figures 6.14 to 6.16. The data presented are mean values of force and velocity at 0.25 % intervals of stature for the 18 subjects. Standard errors have been omitted from these Figures for clarity. Despite differences in the magnitudes of the forces and velocities between the different resistances the general shape of the curves over the lifting range are very similar.

The highest lift forces were recorded for two-handed exertions against the heavy resistance and the lowest for one-handed exertions against the light resistance. The smaller changes in lift velocity against the heavy resistance when compared with the light resistance are reflected by the flatter velocity-displacement curves of the former.

An analysis of variance of the dynamic lifts revealed that peak force occurred at the same height above the ground irrespective of the lift resistance and of the sex of the subjects (see Table 6.3). There was however a significant difference ($p<0.005$) in the position of peak force between one and two-handed lifts. The position of peak force was slightly lower for one-handed lifts (mean value over the three resistances = 35.9% of stature) than that observed for two-handed lifts (mean value over the three resistances = 38.4% of stature).

An analysis of variance of the normalized force data collected at knee, knuckle, hip, elbow and shoulder height, with sex, resistance, number of hands, and hand height as independent variables is presented in Table 6.4. This analysis revealed that dynamic lifting strength differs significantly between, (a) males and females, (b) the number of hands used (i.e. one or two-handed exertions), (c) the task resistance, and (d) the height of the hands above the ground. A full complement of Figures illustrating force, velocity and power output over the entire lifting range for one and two-handed lifting and for males and females is presented in Appendix D.

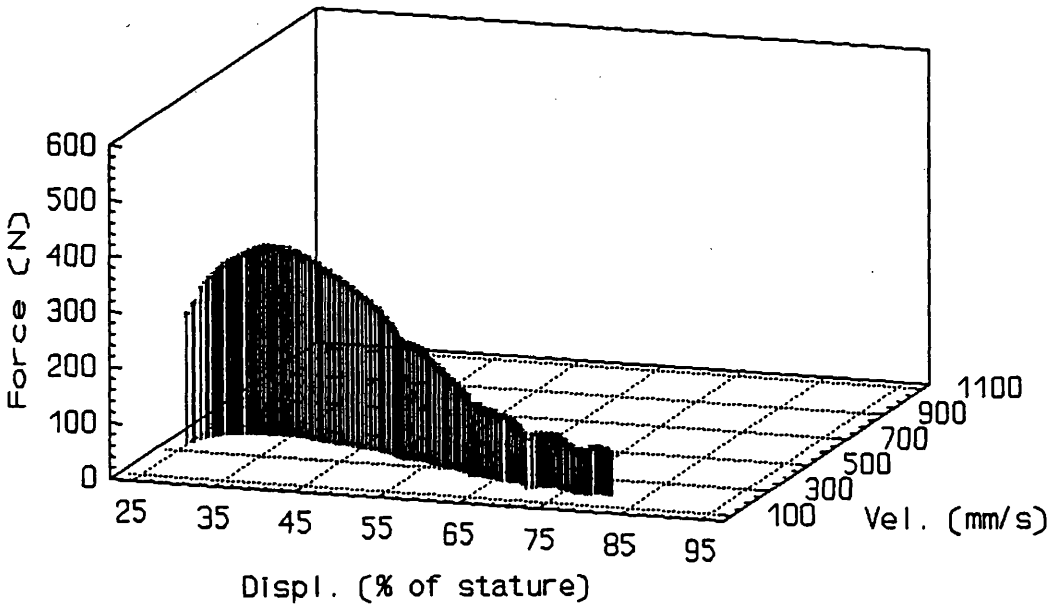
Averaged over the three resistances, two hand conditions and five heights, the female/male normalized dynamic lifting strength ratio was 0.68. When dynamic lifting strength was expressed in absolute units of force this ratio decreased to 0.53. Figure 6.17 shows the female/male strength ratios calculated for every 0.25% of stature over the lifting range. Although some changes in the female/male strength ratio with displacement are evident in this Figure, the interaction between sex and hand height above the ground was insignificant ($p>0.05$).

The significant interaction between sex and hand condition (1 or 2 handed) in Table 6.4 revealed that strength differences between one and two-handed lifts were different for males and females. The mean one/two-handed strength ratio for the males and females were 0.63 and 0.67 respectively. Thus males showed a greater difference in dynamic lifting strength between one and two-handed exertions than the females.

Figure 6.18 shows one/two-handed strength ratios for the males and females over the entire lifting range. The insignificant three-way interaction between sex, number of hands and hand height ($p > 0.05$) indicate that the two curves shown in Figure 6.18 follow a similar rate of decline.

The mean female/male normalized strength ratio for one and two-handed exertions was 0.70, and 0.65 respectively. Analysis of variance indicated the differences in normalized dynamic strength between males and females were significantly greater for two-handed exertions than for one-handed lifting exertions ($p < 0.001$).

Averaged over the 18 subjects, 5 heights and 3 resistances, two-handed exertions were found to be 36% stronger than one-handed exertions ($p < 0.0001$). However, the difference between one and two-handed exertions changed significantly according to the height above the ground ($p < 0.0001$) and the task resistance ($p < 0.005$). As shown in Figure 6.19 one/two-handed strength ratios tended to decrease against all resistances as hand height (displacement) increased. A slight increase in the one-handed/two-handed strength ratios was however observed against all resistances when the hands approached shoulder height. The interaction between hands and resistance is reflected in Figure 6.19 by the larger differences in the one/two-handed strength ratios observed at the lower hand heights between the medium and light and the heavy resistance in comparison to their smaller differences at the higher hand heights. Thus as hand height above the ground increases the difference in strength against the three task resistances tends to become less.



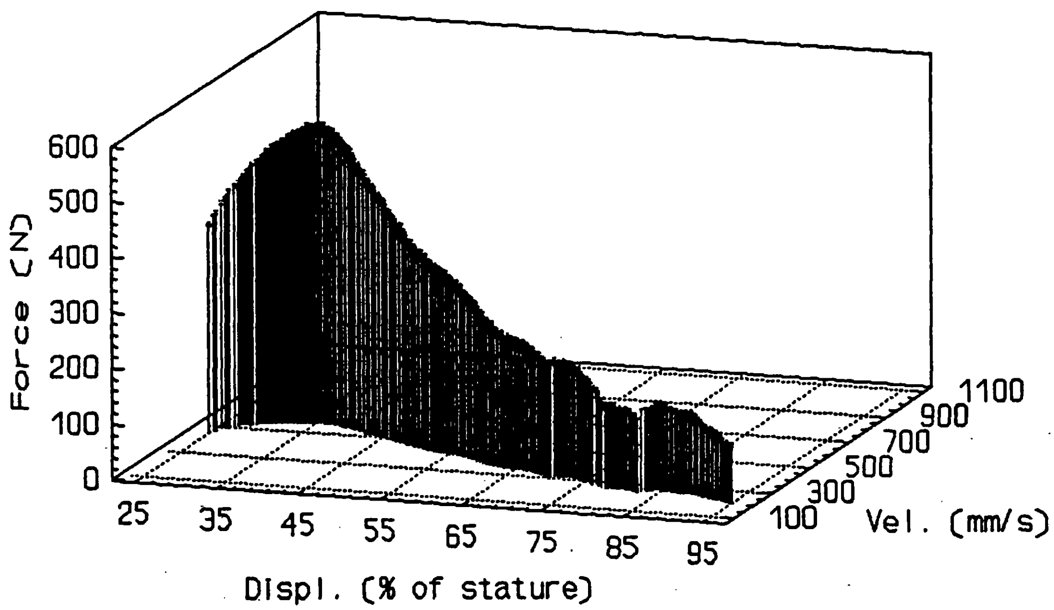


Figure 6.14: Dynamic characteristics for one-handed (top figure) and two-handed (lower figure) lifting against the heavy resistance. The data are mean values for the 18 subjects. SEM have been omitted for clarity.

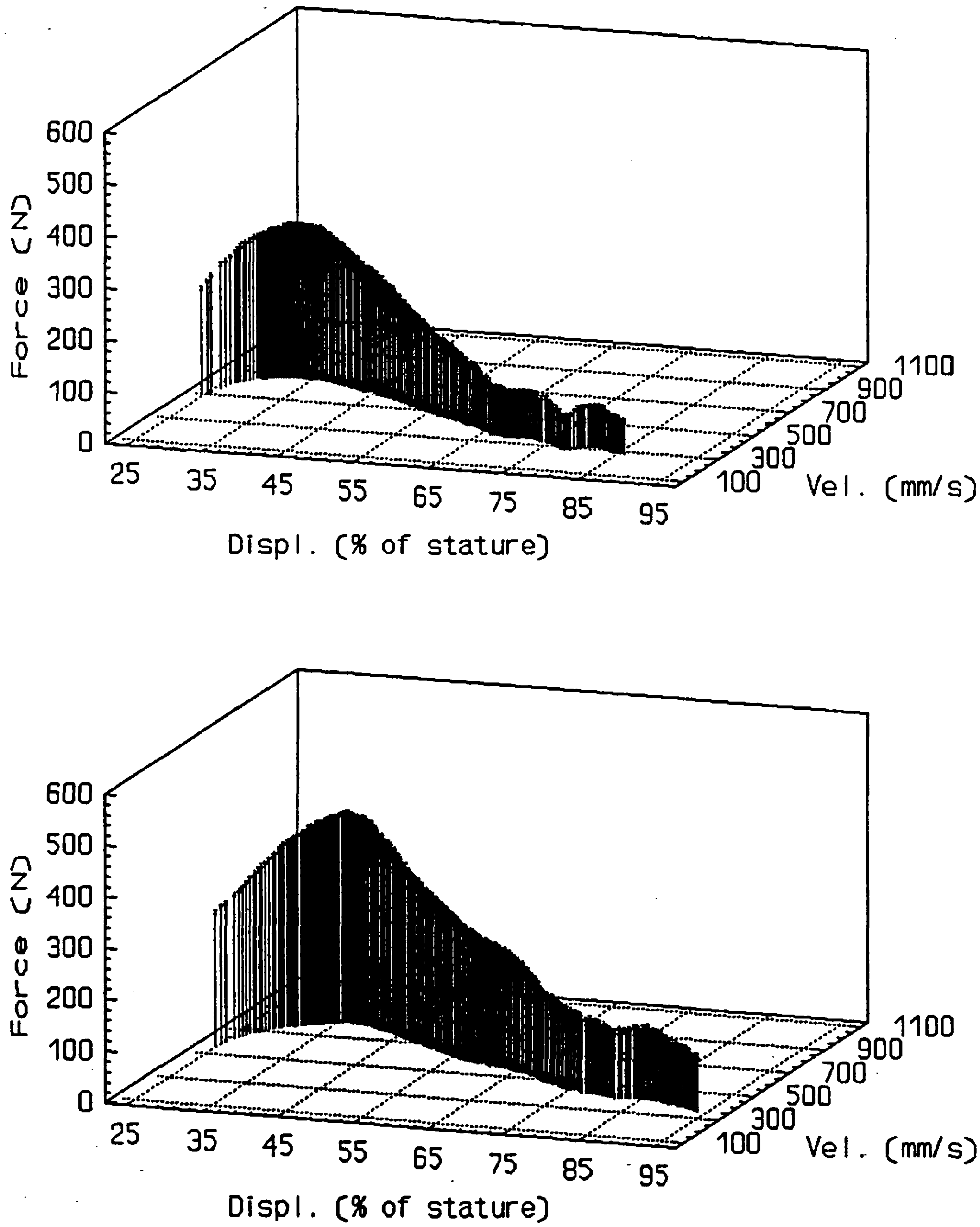


Figure 6.15: Dynamic characteristics for one-handed (top figure) and two-handed (lower figure) lifting against the medium resistance. The data are mean values for the 18 subjects. SEM have been omitted for clarity.

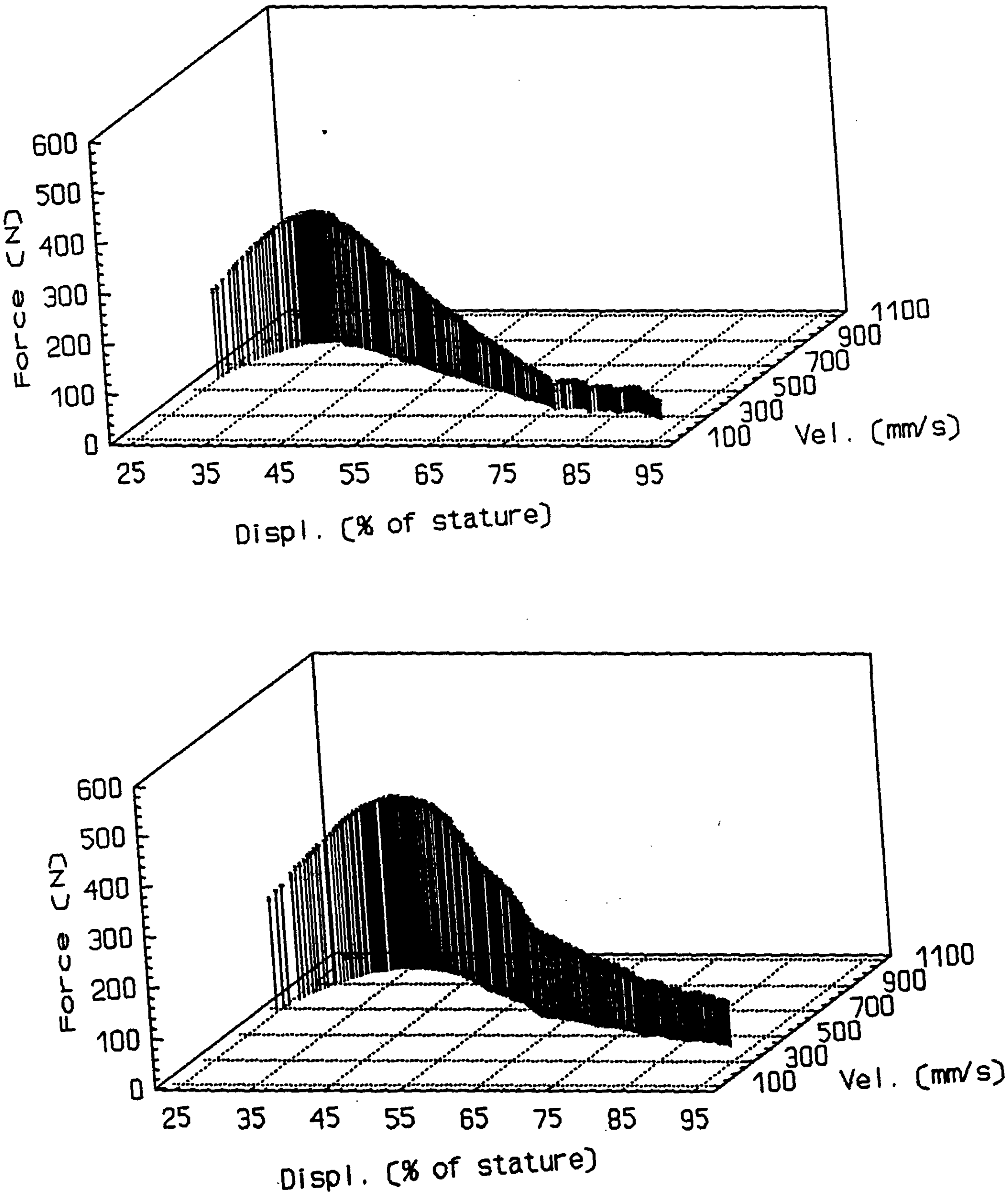


Figure 6.16: Dynamic characteristics for one-handed (top figure) and two-handed (lower figure) lifting against the light resistance. The data are mean values for the 18 subjects. SEM have been omitted for clarity.

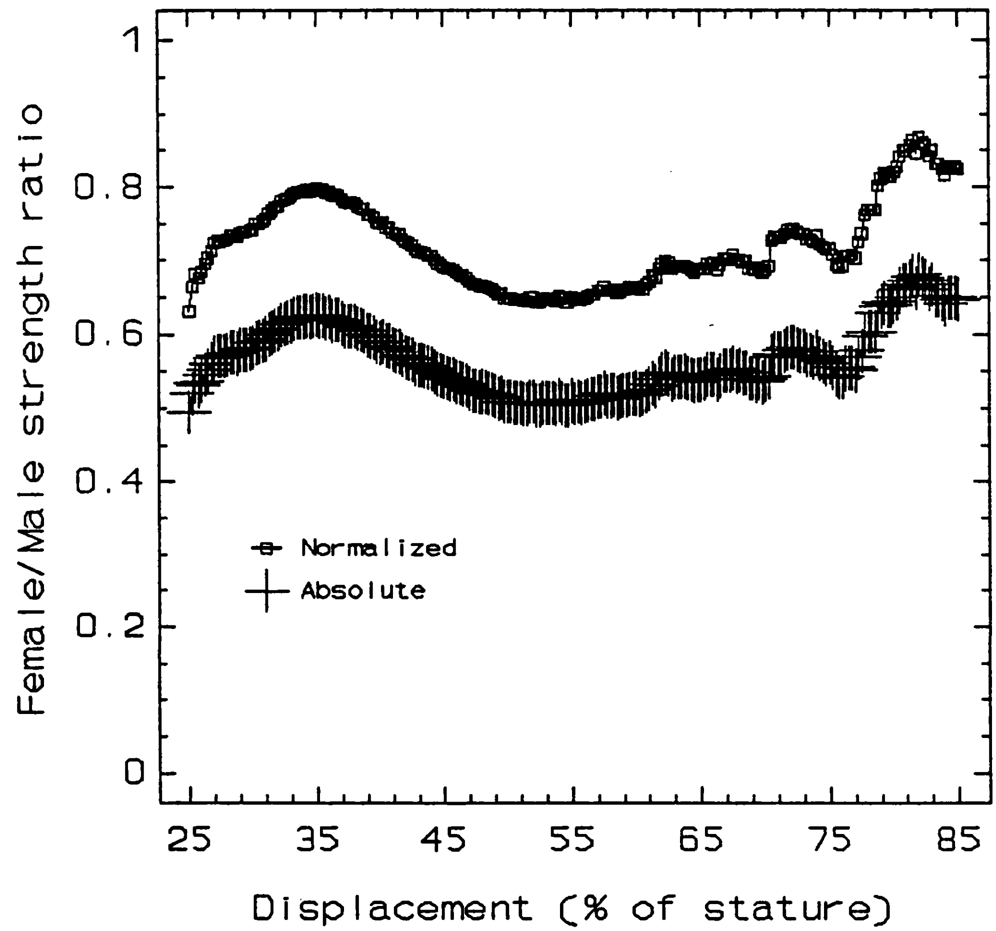


Figure 6.17: Absolute and normalized female/male strength ratios over the dynamic lifting range. The ratios were derived from force data averaged over the three resistances and the one and two-handed exertions for the 9 male and 9 female subjects.

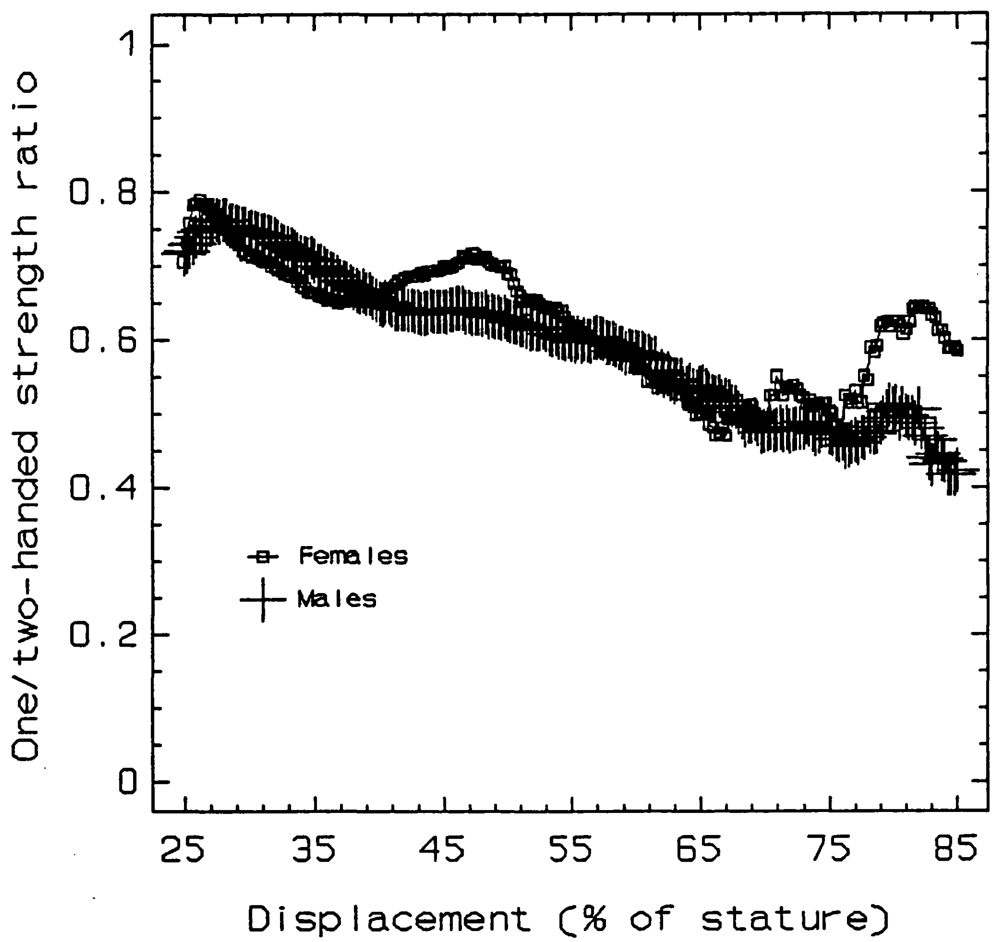


Figure 6.18: Male and female one/two-handed strength ratios over the dynamic lifting range. The ratios were derived from force data averaged over the three resistances for the 9 male and 9 female subjects.

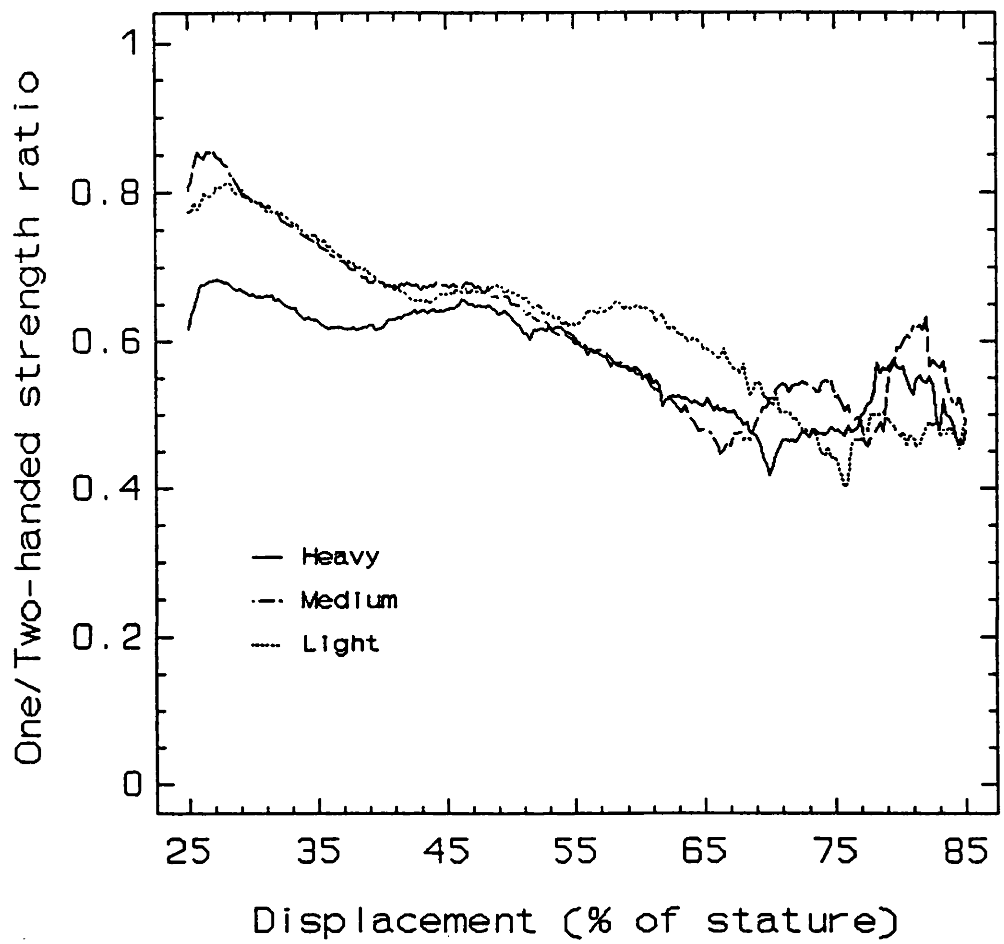


Figure 6.19: One/two-handed strength ratios over the dynamic lifting range for the heavy, medium and light resistances. The ratios were derived from force data averaged over the 18 subjects.

Table 6.3
Analysis of variance results on the position of maximum forces during dynamic lifts on the hydrodynamometer

SOURCE OF VARIANCE	NO OF CONDS	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (SEX)	2	0.025	1	0.025	1.166	NS
AS		0.348	16	0.022		
B (HANDS)	2	0.016	1	0.016	11.234	P<0.005
AB		0.000	1	0.000	0.184	NS
ABS		0.023	16	0.001		
C (RESIST)	3	0.017	2	0.008	2.747	NS
AC		0.001	2	0.001	0.165	NS
ACS		0.097	32	0.003		
BC		0.002	2	0.001	0.428	NS
ABC		0.000	2	0.000	0.000	NS
ABCS		0.059	32	0.002		
TOTAL		0.588	107			

Table 6.4
Analysis of variance summary statistics for normalised lifting forces on the hydrodynamometer

SOURCE OF VARIANCE	NO OF CONDS	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (SEX)	2	2.576	1	2.576	9.045	P<0.01
AS		4.556	16	0.285		
B (HANDS)	2	3.224	1	3.224	253.318	P<0.0001
AB		0.227	1	0.227	17.834	P<0.001
ABS		0.204	16	0.013		
C (RESIST)	3	1.049	2	0.525	61.682	P<0.0001
AC		0.022	2	0.011	1.282	NS
ACS		0.272	32	0.009		
E (HEIGHT)	5	8.731	4	2.183	49.770	P<0.0001
AE		0.369	4	0.092	2.105	NS
AES		2.807	64	0.044		
BC		0.075	2	0.037	7.542	P<0.005
ABC		0.015	2	0.008	1.523	NS
ABCS		0.159	32	0.005		
BE		0.174	4	0.044	9.712	P<0.0001
ABE		0.016	4	0.004	0.882	NS
ABES		0.287	64	0.004		
CE		0.388	8	0.049	11.856	P<0.0001
ACE		0.027	8	0.003	0.820	NS
ACES		0.524	128	0.004		
BCE		0.080	8	0.010	3.700	P<0.001
ABCE		0.019	8	0.002	0.896	NS
ABCES		0.348	128	0.003		
TOTAL		26.151	539			

Power of Dynamic Lifting

The way in which the power of lift changes with hand height above the ground is shown for one and two-handed exertions against the three resistances in Figure 6.20. At the start of the lift power rises quickly to a peak at around knuckle height and then diminishes in an exponential manner as the lift progresses beyond this point. The curves show a similar characteristic pattern to those of the force and velocity-displacement traces.

Analysis of variance revealed that the position of peak power differed significantly between one and two-handed lifts ($F = 5.88$; $df = 1,16$; $p < 0.05$), but was independent of the sex of the subjects ($F = 1.06$; $df = 1,16$; $p > 0.05$). The position of peak power for one and two-handed lifts occurred at the same point as peak force. Peak power was greatest for two-handed exertions against the light resistance and least for one-handed exertions against the heavy resistance. Mean (and standard errors) of the absolute values of power at the five landmark heights (knee, knuckle, hip, elbow and shoulder height) and peak power for one and two-handed lifts against the three resistances are provided in Tables D11 - D15 and D19 in Appendix D.

An analysis of variance of normalized power (i.e. power/body weight) on data collected at the five landmark heights revealed similar results to that obtained from the normalized force data. As summarized in Table 6.5 normalized power output was found to change significantly between (a) males and females, (b) the number of hands used (i.e. one or two-handed exertions), (c) the task resistance, and (d) the height of the hands above the ground.

Averaged over all conditions the female/male power ratio was 0.39, which increased to 0.51 when power was normalized to body weight. The average one/two-handed power ratio over the three resistances and five heights was 0.54.

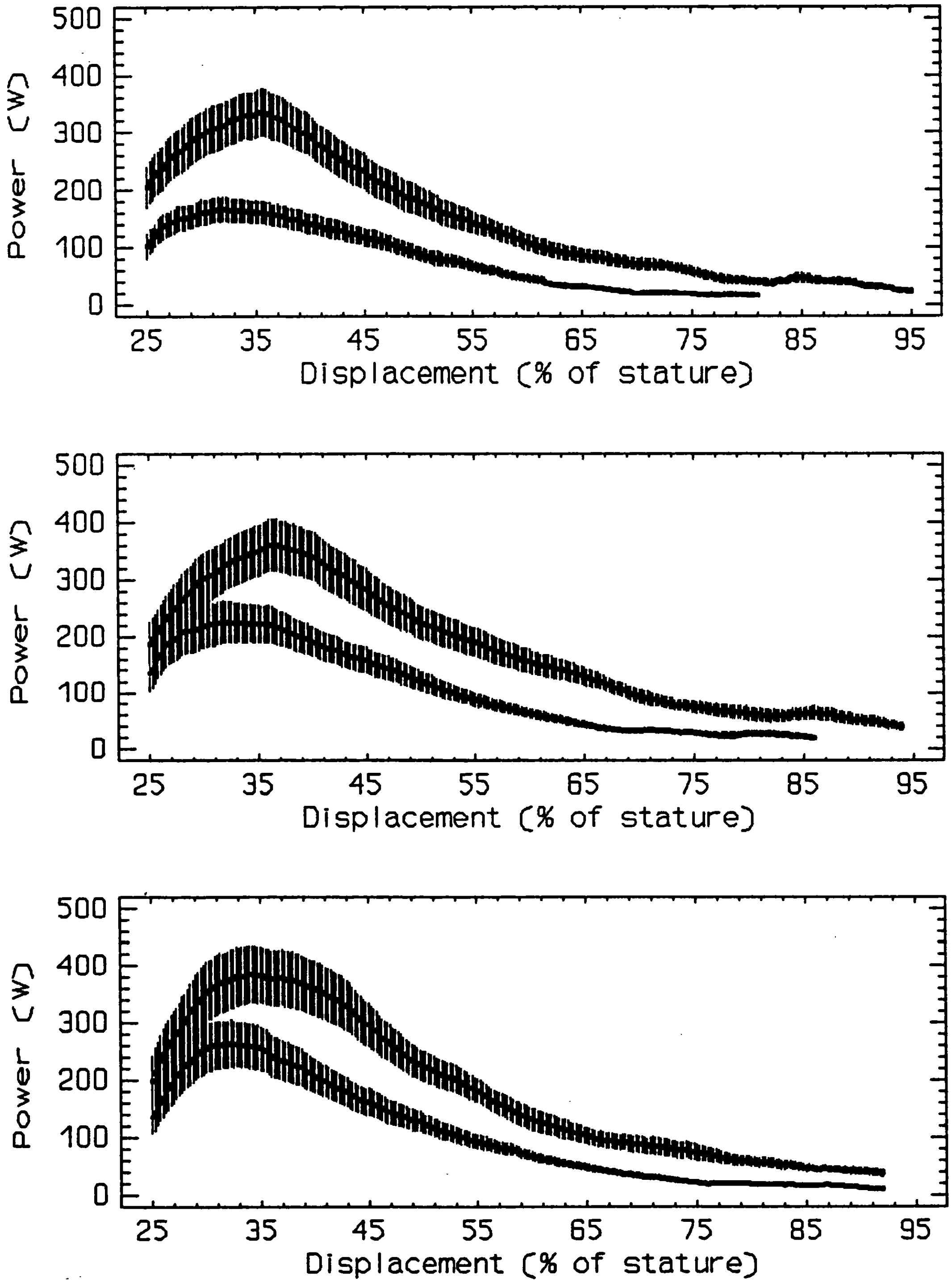


Figure 6.20: Power versus hand height for dynamic lifts against the heavy, medium and light resistances (top middle and lower figures respectively). The data are mean values for the 18 subjects (±SEM). In each figure the top curve is for two-handed lifting and the lower curve for one-handed lifting.

Table 6.5
Analysis of variance summary statistics of normalised power for dynamic lifts on the hydrodynamometer

SOURCE OF VARIANCE	NO OF CONDS	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (SEX)	2	302.311	1	302.311	14.777	P<0.005
AS		327.342	16	20.459		
B (HANDS)	2	260.103	1	260.103	194.000	P<0.0001
AB		38.659	1	38.659	28.835	P<0.0001
ABS		21.452	16	1.341		
C (BUNGS)	3	64.315	2	32.157	24.437	P<0.0001
AC		13.175	2	6.587	5.006	P<0.025
ACS		42.110	32	1.316		
E (HEIGHT)	5	697.164	4	174.291	36.705	P<0.0001
AE		63.044	4	15.761	3.319	P<0.05
AES		303.897	64	4.748		
BC		3.738	2	1.869	2.378	NS
ABC		1.035	2	0.518	0.659	NS
ABCS		25.154	32	0.786		
BE		36.121	4	9.030	21.975	P<0.0001
ABE		4.844	4	1.211	2.947	P<0.05
ABES		26.299	64	0.411		
CE		9.273	8	1.159	2.228	P<0.05
ACE		2.698	8	0.337	0.648	NS
ACES		66.584	128	0.520		
BCE		6.833	8	0.854	2.282	P<0.05
ABCE		1.733	8	0.217	0.579	NS
ABCES		47.907	128	0.374		
TOTAL		2365.790	539			

The way in which dynamic one and two-handed lifting strength varies with hand height above the ground is shown in Figure 6.21. During the initial part of the lift the force rises rapidly to a peak at a point just before the hands reach knuckle height. As the lift progresses beyond this point the force drops quickly at first but then begins to level off as the hands approach shoulder height.

An analysis of variance of the normalized isometric lifting forces is presented in Table 6.6. This Table reveals similar results to that found following analysis of the normalized dynamic forces. Isometric lifting strength changed significantly according to the number of hands used ($p < 0.0001$) and hand height above the ground ($p < 0.0001$). In addition, significant two-way interactions were found between sex and hands ($p < 0.05$) and between hands and hand height ($p < 0.05$). One major difference between the analysis of normalized dynamic and static forces is the insignificant effect of sex on normalized static lifting strength.

The female/male normalized static strength ratio averaged over the six heights and two hand conditions was 0.76, which decreased to 0.60 when calculated from absolute values of force. The same values for the above ratios are obtained when lifting strength at head height was omitted from the calculations. When compared with the f/m ratios obtained with the dynamic strength data the differences in strength between males and females were found to be less marked for static exertions than for dynamic exertions.

The mean one/two-handed strength ratio over the six heights was 0.52. As indicated by the significant two-way interaction between hands and height this latter ratio was found to vary with hand height above the ground. A comparison of the dynamic and isometric one/two-handed strength ratios over the five hand heights above the ground is shown in Table 6.7. Apart from lifting exertions at elbow height the difference between the strength of one and two-handed exertions tends to be greater for static lifting than dynamic lifting.

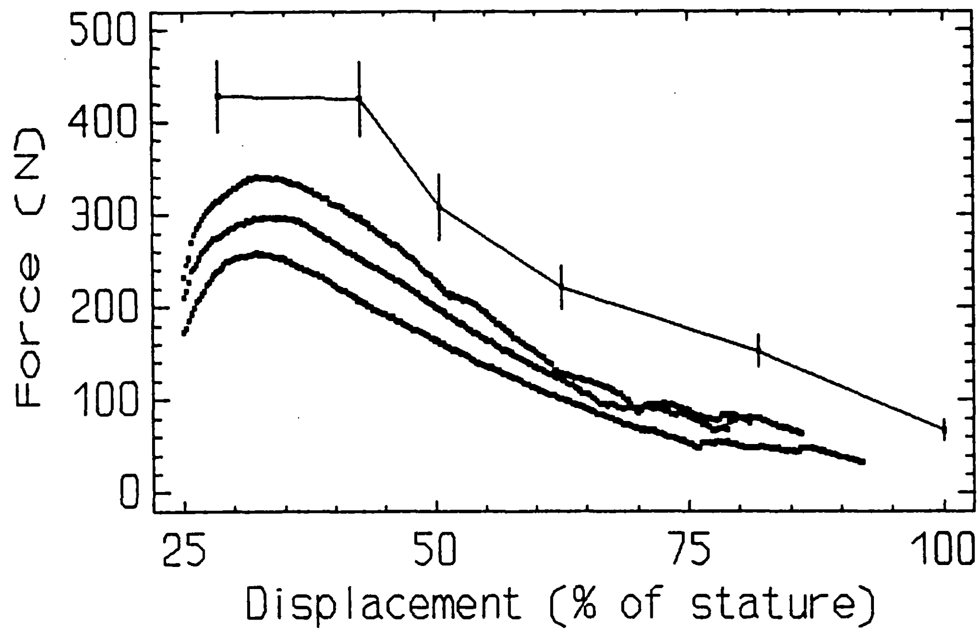
When dynamic and static lifting strength were correlated with body weight fairly low correlations were obtained (see Table 6.8). Insignificant correlations ($p > 0.05$) between body weight and lifting strength were observed at shoulder height. Although the correlations at the other heights were significant ($p < 0.05$) body weight accounted for less than 50% of the variance in dynamic and static lifting strength over most of the lifting range. A power curve regression (of the same form as described in Chapter 4) was also performed to determine if a multiplicative model would provide a better fit to the data. This analysis did not produce a better fit to the data than a simple linear regression and in some cases demonstrated correlation coefficients lower than those in Table 6.8.

Generality versus Specificity between Dynamic and Static Measures of Lifting Strength

In order to determine the degree of generality versus specificity between dynamic and static measures of lifting strength first order partial correlation coefficients (with body weight held constant) were calculated between the different strength measures (see Table 6.9). The partial correlation coefficients shown in Table 6.9 were derived using mean lifting strength values for each subject combined over knee, knuckle, hip, elbow and shoulder heights. These intercorrelations were then corrected for attenuation to account for any unreliability in the strength measures due to error variance (Ferguson 1976). This latter procedure utilized estimates of the reliability coefficients for dynamic lifting based on the test-retest data of subject CB shown in Table 6.2.

Estimates of the reliability coefficient for static lifting were based on the data of Asmussen *et al.*, (1959) and the test-retest measures for one-handed static pulling exertions at 1.0 m described in Chapter 3. The strength testing protocol used in Chapter 3 was very similar to that employed for the static lifting exertions and revealed a reliability coefficient of 0.83 for freestyle static pulling exertions against the bar at 1.0 m. It was however expected that the freestyle nature of the experiments in Chapter 3 would have contributed to a greater amount of error variance than would have been present with the more formal foot placements required for the current static lifting exertions. In comparison, Asmussen *et al.*, (1959) describes reliability coefficients of 0.92 and 0.91 for isometric trunk and knee extension respectively. Consequently, a value of 0.90 was chosen as a best guestimate for the reliability coefficient of static lifting strength.

Using the aforementioned reliability coefficients the intercorrelations in Table 6.9 were adjusted to provide a true measure of the generality versus specificity of the dynamic and static strength measures. The proportion of generality between the different strength measures are given in Table 6.10. The values in Table 6.10 are expressed as r^2 x 100 for generality. Alternatively, the degree of specificity between the strength measures is given by $(1 - r^2)$ x 100.



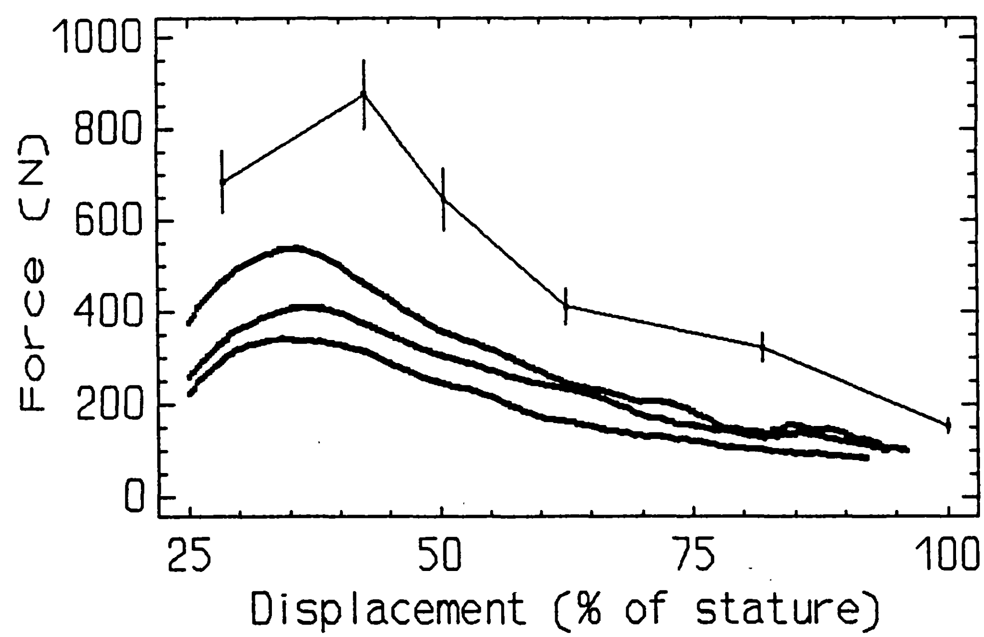


Figure 6.21: Force versus height above the ground for one-handed and two-handed lifting (top and bottom figures respectively) against the heavy, medium and light resistances. The data are mean forces for the 18 subjects (SEM have been omitted for clarity). The top curve in each figure represents the mean (±SEM) of isometric lifting strength measured at knee, knuckle, hip, elbow, shoulder and head height.

Table 6.6
Analysis of variance summary statistics for normalised isometric lifting strength

SOURCE OF VARIANCE	NO OF CONDS	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARES	F-RATIO	PROB
A (SEX)	2	1.430	1	1.430	3.420	NS
AS		6.691	16	0.418		
B (HANDS)	2	7.632	1	7.632	189.889	P<0.0001
AB		0.198	1	0.198	4.919	P<0.05
ABS		0.643	16	0.040		
C (HEIGHT)	6	17.417	5	3.483	104.793	P<0.0001
AC		0.358	5	0.072	2.154	NS
ACS		2.659	80	0.033		
BC		1.707	5	0.341	38.031	P<0.0001
ABC		0.116	5	0.023	2.585	P<0.05
ABCS		0.718	80	0.009		
TOTAL		39.570	215			

Table 6.7
One/two-handed strength ratios for maximal static and dynamic lifting exertions. The ratios for the dynamic exertions were derived from the pooled results for exertions against the low, medium and heavy resistances.

Position of hands above the ground	Dynamic 1/2 handed strength ratio	Static 1/2 handed strength ratio
Knee height	0.75	0.62
Knuckle height	0.65	0.49
Hip height	0.64	0.48
Elbow height	0.53	0.54
Shoulder height	0.53	0.47
Head height		0.44

Table 6.8
Correlations of static and dynamic lifting strength with body weight at different heights above the ground (n=18)

Hand Height	Static Lifting			Dynamic Lifting					
	1 Hand	2 Hand		1 Handed			2 Handed		
				Lght	Med	Hvy	Lght	Med	Hvy
Knee	0.59	0.51		0.53	0.57	0.56	0.71	0.58	0.60
Knuckle	0.53	0.67		0.55	0.56	**0.46**	0.56	0.68	0.65
Hip	**0.41**	0.58		0.59	0.59	0.58	0.63	0.74	0.71
Elbow	0.49	0.62		0.65	0.60	0.61	0.72	0.71	0.70
Shoulder	**0.41**	**0.44**		**0.43**	**0.16**	**0.26**	0.53	**0.39**	0.69
Head	**0.12**	**0.40**							

Notes:

Correlations marked in bold type are not significant (i.e. p>0.05).

Table 6.9
Partial correlation coefficients (with body weight held constant) between dynamic lifting strength against the three resistances and static lifting strength (n=18) for one and two-handed exertions

			Isometric		Dynamic (Dyn)					
					Low (L)		Med (M)		Heavy (H)	
			1	2	1	2	1	2	1	2
Dyn	L	1	0.74		1.0					
		2		0.78		1.0				
	M	1	0.85		0.92		1.0			
		2		0.84		0.84		1.0		
	H	1	0.78		0.93		0.91		1.0	
		2		0.87		0.87		0.91		1.0

Table 6.10
Proportion of generality between dynamic and static measures of one and two-handed lifting strength

			Isometric		Dynamic (Dyn)					
					Low (L)		Medium (M)		Heavy (H)	
			1	2	1	2	1	2	1	2
Dyn	L	1	63							
		2		70						
	M	1	85		93					
		2		85		80				
	H	1	70		94		93			
		2		87		81		93		

Discussion

Physical Characteristics of the Hydrodynamometer

The current results provide an insight into the physical characteristics of the hydrodynamometer. The predominant relationship between force and velocity over the majority of the instruments measuring range is dictated by the viscous characteristics of a particular piston resistance. Empirical observations using maximal lifting exertions of two subjects against the five piston resistances revealed that the force recorded at the hands was directly proportional to viscous force raised to the power 1.55.

The exact nature of the relationship between velocity and the viscous force will however depend on the viscosity of the water in the hydrodynamometer. Since changes in water temperature affect the water's density and thus viscosity the above power function may change slightly in hot and cold environments. Despite this fact, when the resistance of lift was calculated for a given piston condition using the above empirically derived power function, it was found to be constant over the majority of the instruments range. This finding thus confirms the isoresistive nature of the hydrodynamometer.

The hydrodynamometer does however contain a significant inertial component and thus a certain amount of force is also required to accelerate the moving parts of the hydrodynamometer. The clearest example showing the contribution of the force attributable to acceleration of the systems inertial mass to the total force measured at the hands was revealed for exertions against the very light resistance. Under these conditions substantial changes in velocity occurred at the start of the lift which resulted in a large proportion of the total force at the hands comprising of forces required to accelerate the inertial mass. It was only when these large accelerations subsided (at approximately 60 ms after the start of the lift) that the hydrodynamometer approached an isoresistive instrument.

The contribution of these accelerative forces to the total force at the hands reduced as piston resistance increased. At the other extreme when exertions were performed against a very heavy resistance , the physical characteristics of the hydrodynamometer approached that of an isokinetic device.

The Kinematics and Impedance of Dynamic Lifting

A kinematic analysis of the subjects CB and DF performing maximal dynamic lifts on the hydrodynamometer revealed very similar lifting techniques against the very light, light, medium and heavy resistances. The initial stages of the lifting action were characterized by an extension of the legs, hips and back. By the time the hands had reached hip height the trunk had become fully erect and the knees fully extended. Continuation of the lift beyond this point was completed entirely by the displacement of the upper limbs.

Lifting technique did however change significantly when exertions were performed against the very heavy resistance. The change in technique was reflected by the erratic nature of the force and velocity curves and was the result of sudden changes in posture.

These changes in posture were characterized by a marked drop in the hips (relative to the ground) through flexion of the knees, in an attempt to bring the body underneath the handle and continue the lift with an upward thrust. Lifting beyond shoulder height also required rotation of the grip to occur at the handle interface. Similar postural changes were noted in the other subjects, especially when performing one-handed exertions against the heavy resistance.

It would seem that a critical point in the lifting action occurs when the hands approach shoulder height. It is possible that the change in lifting technique against heavy resistances is an attempt by the subject to adopt a more advantageous posture for continuation of the lift above shoulder height. A more advantageous posture would reduce the torque about the upper limbs and attempt to involve the larger and stronger musculature of the lower limbs in the lifting action. Cinematographic analysis of dynamic lifting provided evidence that such changes in posture did occur against the very heavy resistance.

The above observations have particular relevance to manual handling activities. The present findings suggests that lifting technique plays an important role in the strength of dynamic exertions particularly when exertions are performed against very heavy resistances. If for some reason the object lifted prevents the individual from adopting a favourable lifting posture (i.e. when the hand-object interface does not permit repositioning of the grip during the lift) dynamic lifting strength may be severely impaired. The ability to adopt these postures may be critical for the success of the lift when lifting very heavy isoinertial loads above shoulder height.

The influence of lifting technique on the dynamic characteristics of lifting has been investigated by Grieve (1974). In this study subjects were required to lift loads weighing between 4 and 29 kg through a distance of 61 or 78 cm using either a crouch or stoop technique. The results indicated considerable differences in the way in which the upper and lower body contributed to the dynamics of the lifts in the two lifting styles. However, since the lifts did not progress beyond 78 cm the dynamic nature of the lift at shoulder height was not investigated.

One major difference in the dynamic characteristics of lift between the current study and that by Grieve (1974) was the substantial changes in lift impedance observed when lifting isoinertial loads in comparison to the nature of lifting exertions on the hydrodynamometer. For exertions against light loads (<25 kg), lift impedance varied from a very large and almost infinite positive value as the lift commenced to an infinite negative value as the load reached the top of its trajectory. However, for inertial loads of 25 kg or more lift impedance remained largely positive throughout the duration of the lift.

As the temporal patterns of lift impedance were found to be insensitive to technique and the height to which the load was lifted, it was suggested by Grieve (1974) that this quantity could be "developed as a relatively simple measure by which performances in a variety of industrial lifting task might be classified."

A comparison of the current results with those of Grieve (1974) illustrates the differences between lifting an isoinertial load and dynamic exertions on the hydrodynamometer. Unless the objective is to lift and project a heavy load as far as possible (i.e. as in the case of caber tossing) most lifting activities will not require full activation of all the muscles throughout the entire lifting range. In many cases the load or object is required to be lifted and then placed at some position above the ground. While maximal strength may be required during the early stages of lifting a very heavy load, it is necessary at some point in time to control and reduce muscular activation in order to place the load.

In comparison, exertions on the hydrodynamometer required the subjects to maintain maximal activation of the muscles throughout the entire lifting range. While this procedure may not be directly comparable with most real life situations, the data affords a useful indication of the maximum forces capable at different velocities of lift at any height within the lifting range. The force, velocity and power data also provide an insight into the dynamic characteristics of whole body lifting actions in an analogous way to that provided by early investigations of the mechano-physiological properties of isolated muscle fibres.

The range of resistances under which the subject group was tested were chosen following an initial pilot experiment. This pilot experiment investigated a total of 13 different piston resistances in order to find the most appropriate resistances that would result in expected maximum velocities close to those velocities commonly observed for normal lifting activities.

Troup *et al.*, (1983) observed peak velocities ranging from 1.0 m/s to 1.48 m/s during lifting of a 15 kg tote box from the floor to knuckle height. Similarly, Aghazadeh and Ayoub (1985) and Mital *et al.*, (1986) noted that the speed of lift during actual manual lifting tasks averages approximately 75 cm/s. This average lifting speed has commonly been used in isokinetic tests of lifting strength reported in the literature. The 75 cm/s testing speed has been recommended because of the finding that there is a close to one-to-one relationship between actual lifting capacity[8] and the peak force observed on an isokinetic lifting test (at 75 cm/s) performed between ankle and chest height (Kamon *et al.*, 1982).

According to the above observations the range of velocities recorded in the present study correspond favourably with the velocities of lift found during actual manual handling tasks. A summary of the dynamic characteristics for one and two-handed lifting exertions derived from the results of the current study are illustrated in Figures 6.22 and 6.23.

In Figures 6.22 and 6.23 surface plots have been generated from the mean force and velocity data measured at knee, knuckle, hip, elbow and shoulder heights under both the dynamic and static conditions. The shape of the surface plots represent a mean view of the force-velocity, force-displacement and velocity-

[8] In this context lifting capacity is defined as the maximum weight of a tote box which an individual can lift successfully from the floor to a shelf 113 cm high (Kamon *et al.*, 1982).

displacement characteristics for maximal one and two-handed whole body lifting exertions.

Although the dynamic characteristics of whole body lifting exertions closely resemble the traditional theoretical relationships of muscle mechanics, this similarity is likely to be a coincidental one. The whole body lifting action involves the contraction of a large number of individual muscles each with different resting lengths, architecture and mechanical advantages. Each muscle or muscle group will follow its own torque-velocity and torque-angle relationship and may contract concentrically, eccentrically or isometrically at different times throughout the lift. In addition, the level of activation of the individual muscles will change throughout the lift as they assume a greater or lesser role in the overall lifting performance. Thus the surface plots in Figures 6.22 and 6.23 represent a mean view of a complex set of interactions involving the physiological and mechanical characteristics of many different muscles being activated and deactivated according to the skill of the individual.

One of the more notable observations in Figures 6.22 and 6.23 is that peak lifting force occurs between knee and knuckle height. The results indicated that the position of peak force occurred at the same hand height above the ground irrespective of the lift resistance and the sex of the subject. The position of peak force did however occur at a slightly lower hand height during the one-handed exertions than during the two-handed exertions. This latter finding presumably reflects differences in lifting posture between one and two-handed exertions.

The current study also indicated that as hand height and lift resistance increased the difference in strength between one and two-handed exertions became greater. This observation may be explained on the basis that during the early stages of the lift the strength of the upper limb musculature played only a minor role in the force of exertion, whereas, in the upper region of the lift the force of exertion was almost entirely due to the strength of the upper limbs. Thus, as the upper limbs played a more dominant role in the lifting action the difference between one and two-handed exertions became more pronounced. By the time the lift had approached shoulder height the strength of one-handed exertions was half that of the two-handed exertions.

The relationship between one and two-handed exertions was one of the major differences between dynamic and static conditions. The larger strength differences between one and two-handed static lifts in comparison to those for the dynamic lifts possibly reflect slight differences in the postures adopted during the dynamic and static exertions. It is possible that the postures adopted under dynamic lifting conditions may have attempted to reduce the influence of muscular limitations in the upper limbs.

A second fundamental difference between static and dynamic lifting was illustrated by the similarity of the normalized static strengths of males and females. This finding was contrary to the significant sex differences in lifting performance observed under the dynamic conditions. The difference in performance between males and females was even more pronounced when the criterion measure of performance was power.

The similarity of normalized static lifting strengths of males and females confirms the findings of Sanchez (1991). As discussed in Chapter 2, Sanchez (1991) was able to generate gender free predictions for static lifting strength when lift performance was measured at heights relative to stature and expressed as a percentage of body weight. The reasons for the dramatic sex differences in normalized performance under dynamic conditions in comparison to those observed under static conditions is unclear. It is possible that the contribution of the force-velocity characteristics of muscle in dynamic exertions accentuates the difference in performance between males and females. Alternatively, there may be significant differences in the skill of producing maximal lifts between males and females that is more pronounced under dynamic than static conditions.

The power generated by dynamic lifting was found to decrease as the task resistance increased. If the lift velocities observed in this study are a fair representation of the velocities of lift for real industrial tasks, it would indicate that most heavy manual handling tasks are performed at power outputs well below the optimum. Unfortunately, the present study cannot provide a finite value for the task resistance at which the optimal power of lifting actions is observed. Evidence from the results of subject DF lifting against the light and very light resistances indicated that power output in excess of 1 HP is possible. As the time course of the lift producing this level of power was less than 1.0 second over the distance between knee and head height, it would seem that whole body power output for this type of action would only reach optimal levels when performing fast dynamic movements such as those involved in sporting activities.

The mechanical power developed during the snatch and the clean and jerk lifting action of elite weight lifters has recently been reported by Funato and Fukunaga (1989). In this study a purpose built inertial dynamometer was used to record the dynamic force, velocity and power over the course of the lift against different inertial loads. The authors mentioned that mean velocity decreased with increasing mean force in a hyperbolic manner and that mean power showed a peak. Unfortunately, they neglegted to report the magnitude of the inertial load at which this peak in mean power was observed.

The mean power output produced by one of the Japanese international weightlifters was found to be in excess of 2 HP. When the mean power output over the entire lifting range was correlated with total weights of individual's best records in the snatch and clean and jerk a statistically significant positive linear correlation ($r= 0.838$, $p<0.001$) was observed. It was concluded from this observation that mechanical power was a good indicator of weightlifting performance.

A final comment in this section of the discussion should also be made on the ability to predict dynamic and static whole body lifting forces. As discussed in Chapter 2 several biomechanical models of lifting (e.g. Sanchez 1991, Garg &

Chaffin 1975) utilize regression equations of body weight on strength to predict an individual's strength in given postures. Evidence from the current study suggests that body weight is a poor predictor of static and dynamic lifting strength. The low correlations in Table 6.8 illustrate that individual variation in body weight at best accounts for only 50% of the total variance in lifting strength. In the worst case (i.e. one-handed lifts at shoulder height) body weight only accounted for between 3% and 18% of the total variance in strength.

The above observations support the findings of Pheasant (1977) who showed that the strength of exertions are poorly correlated with body weight when the axis of force measurement is close to the "live axis" (see Chapter 2). In the current lifting experiments the axis of force measurement was directed through the foot base thus corresponding very closely with the line of the live axis. Under these conditions strength is predominantly limited by musculo-skeletal factors. This latter statement presumes that all other conditions are optimal (i.e. that there is a good hand/handle interface) and that the subject is fully motivated.

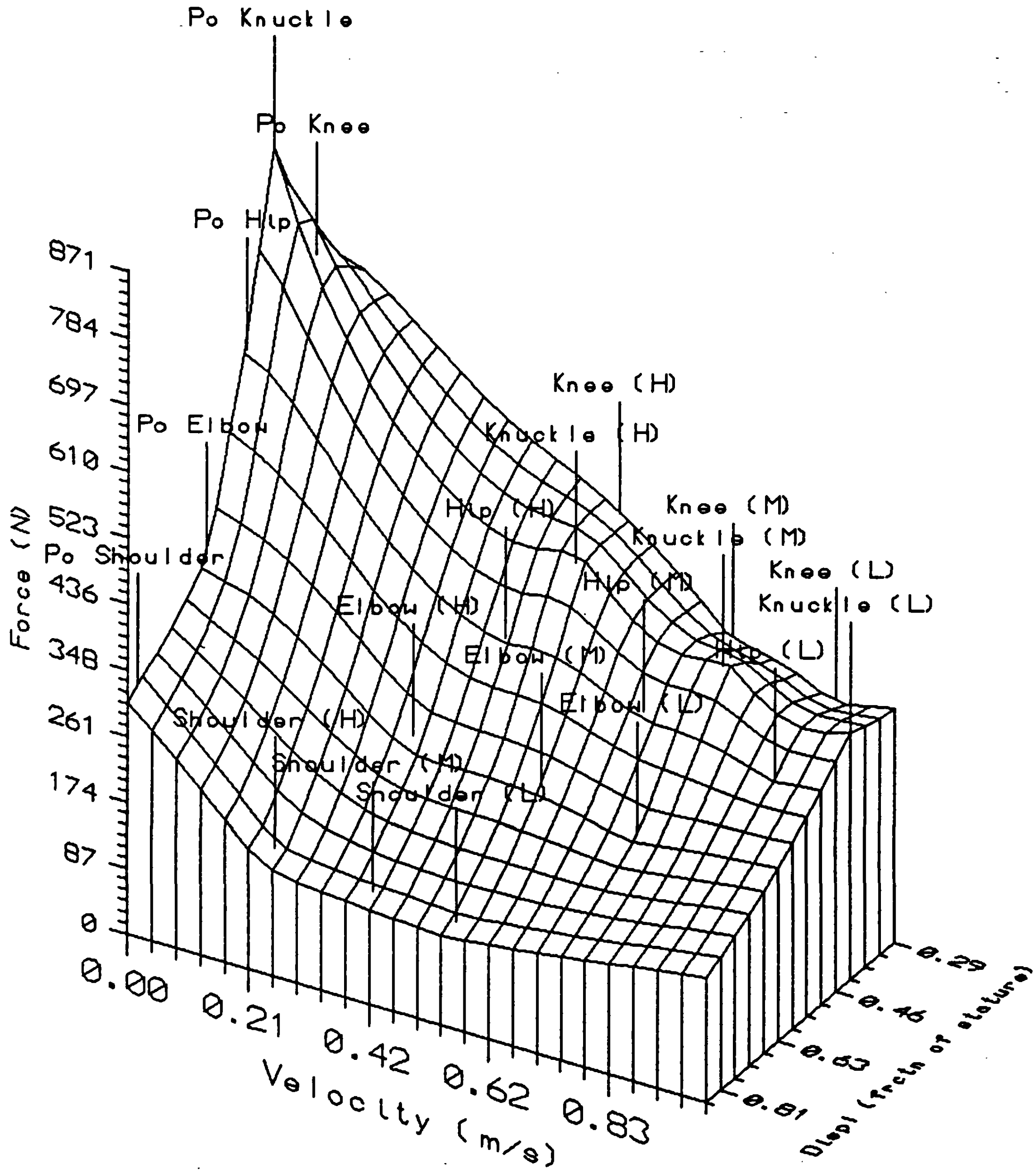


Figure 6.22: A surface plot representing the dynamic characteristics of two-handed lifting. The surface is based on the mean forces and velocities observed at knee, knuckle, hip and shoulder height during static lifts (Po) and dynamic lifts against the light (L), medium (M) and heavy resistances (H). The grid was created using Surfer software (Golden Software Inc. 1987).

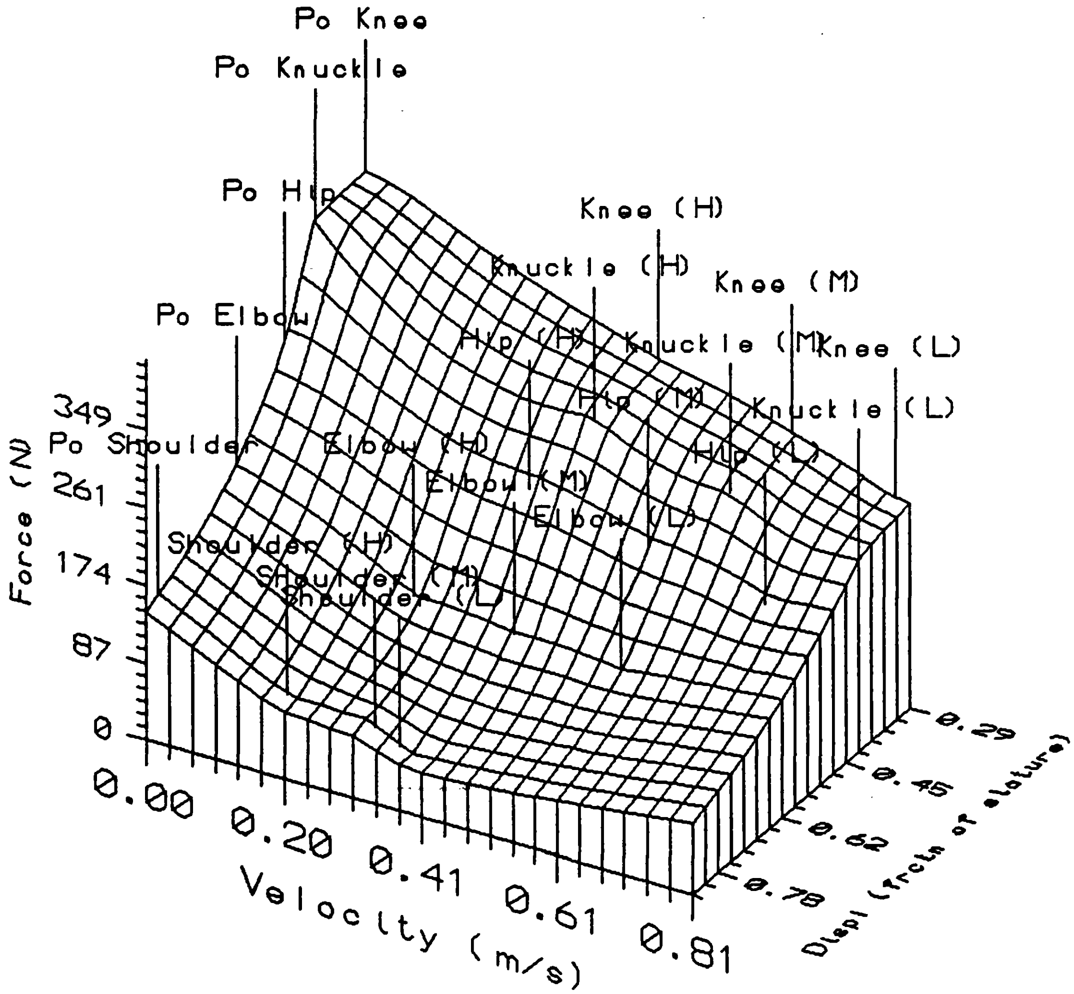


Figure 6.23: A surface plot representing the dynamic characteristics of one-handed lifting. The surface is based on the mean forces and velocities observed at knee, knuckle, hip and shoulder height during static lifts (Po) and dynamic lifts against the light (L), medium (M) and heavy resistances (H). The grid was created using Surfer software (Golden Software Inc. 1987).

Generality Versus Specificity of Whole Body Lifting Strength Against Different Task Resistances

The current results indicate a high degree of generality between dynamic and static measures of lifting strength, and between dynamic lifting exertions performed against the different resistances on the hydrodynamometer. This finding suggests that

(1) Dynamic and static tests of lifting strength measure a common intrinsic ability to produce maximal lifting forces.

(2) Individuals who perform well (or poorly) on static tests of strength attain the same relative level of performance on dynamic tests of lifting strength.

(3) The same relative level of performance is achieved between individuals on tests of whole body lifting strength irrespective of the task resistance and hence velocity of lift.

Studies investigating the interrelationships amongst different measures of strength have been discussed in Part II of Chapter 2. In light of the current findings the present work supports those studies which showed a high degree of generality between isometric and dynamic measures of strength. At this point it is appropriate to mention an unpublished study conducted by the Army Personnel Research Establishment (APRE) which compared lifting performance on a field version of the hydrodynamometer with a range of different dynamic and static measures of strength.

The study involved measuring the anthropometry and strength of 384 male army recruits. A description of the physical characteristics of the subjects, the experimental design, strength testing procedures and preliminary results are provided in Appendix D. Table 6.11 summarizes the degree of generality between performance on the hydrodynamometer (measured as the mean power over the lifting range between 0.7 and 1.0 m above the ground) and the strength of exertions on the other tests.

Unfortunately, the comparisons in Table 6.11 are complicated by the fact that mean power over a fixed range, rather than force at a hand height relative to stature, was taken as the performance measure on the hydrodynamometer for comparison with measures of force on the other strength tests. As there was no direct measure of the reliability of the different strength tests, including that for the field version of the hydrodynamometer, estimates of the reliability coefficients were determined from the literature. However, the studies in the literature often employed a different protocol or tested a different set of muscle groups than those measured in the APRE study.

The poor correlations obtained by some investigators (see Chapter 2) and those of the APRE study between different measures of strength may be the result of a number of factors related to methodological procedures. Firstly, as indicated above many studies do not account for the error variance in the different strength measures attributable to unreliability of the particular strength testing device or strength testing protocol. One finding of the APRE study was that the Quasi-isokinetic device was found to be particularly unreliable which may have contributed to its low correlation with performance on the hydrodynamometer.

A second reason for the low intercorrelations in the APRE study is that many of the strength tests compared performance over different lifting ranges and postures. Unless dynamic strength is measured at the same relative hand height which is also comparable with the other test conditions (i.e. isometric and dynamic strength measured at the same hand height relative to stature) it is highly likely that differences will exist in the active muscles involved in the different individuals and between the different test conditions. In addition, if lifting strength is measured at a fixed absolute height from the ground, individuals will perform the lift in different regions of their force-displacement and force-velocity characteristics. In this latter case it is impossible to make a realistic comparison between individuals or accurate statement about the generality of performance on different strength tests.

Care however should be taken when interpreting the results in the light of other subject populations. While the current study attempted to employ a subject group with a wide range of strengths, which was hopefully representative of the general population, quite different results may have been obtained if groups of athletes had been compared on the strength tests. One could hypothesize for example that the generality of performance on the current strength tests in a mixed group of strength and power trained athletes would be less clear.

In this latter case it would be expected that power athletes would show a better performance on the fast dynamic measures of strength than the strength trained athletes. On the other hand, the reverse would be true for the slow dynamic or isometric tests where the strength trained athletes may be expected to produce the better performance. The underlying phenomenon of this hypothetical study revolves around the concept of specificity of strength training. Issues surrounding this topic are addressed at length by Atha (1981) and will not be commented upon further in this discussion.

Table 6.11
Correlation coefficients and the generality component between performance on the hydrodynamometer and selected anthropometric variables and a number of dynamic and static tests of strength. Data from an unpublished study carried out by the Army Personnel Research Establishment

VARIABLE	Correlation Coefficient	Proportion of Generality
Age	0.28	
Weight	0.70	
Height	0.56	
Body Fat	0.28	
Fat Free Weight	0.74	
Isometric Elbow Flexion	0.66	51%
Isometric Knee Extension[1]	0.28	9%
Isometric Trunk Extension[1]	0.51	30%
Handgrip[1]	0.63	42%
Static Lift at 38 cm	0.66	51%
Static Lift at 85 cm	0.66	51%
Isokinetic Lift[2] at 8 cm/s	0.61	41%
Isokinetic Lift[2] at 47 cm/s	0.73	58%
Quasi-isokinetic lift	0.45	23%
Isoinertial lift[2]	0.67	51%

Notes:

Correction for attenuation was performed using reliability coefficients based on
[1] Asmussen *et al.*, (1965)
[2] Hortobagyi *et al.*, (1989)

In the absence of quotable values the remainder of the strength tests were assigned a notional reliability coefficient of 0.90. A value of 0.95 was used for the reliability coefficient of the hydrodynamometer.

Future Studies

The next stage in the development of the current work would be to formulate a model of whole body maximal dynamic lifting strength based on the observations. Clearly the major elements of the model would include the force-displacement and force-velocity relationships shown graphically in the surface plots of Figures 6.22 and 6.23. Since males and females demonstrated considerable differences in dynamic lifting performance the model should also take into account these sex differences.

If the current findings truly represent the characteristics of dynamic lifting under maximal conditions it would be expected that the force of lift would be governed by the three dimensional activation surfaces shown in Figs. 6.22 and 6.23. It would therefore be expected that maximal dynamic exertions commencing at different starting heights would attain the same level of force against a given resistance at all subsequent heights in the lifting range.

Evidence supporting the above assumption is provided in Figure 6.24. In this Figure, force versus hand height is shown for two-handed maximal lifting exertions by subjects CB and DF performing against the medium resistance on the hydrodynamometer, with the lifts commencing at starting heights of 400, 600 and 1000 cm. In all cases the lifts involved an initial activation phase where the force rose quickly to a maximum value at a given hand displacement. After this initial rise in force further changes in lifting strength with hand height above the ground followed very similar characteristics for the three starting conditions.

The observation of an initial activation phase is an important element that should be included in the model of dynamic lifting. Research by Bell and Jacobs (1986) has shown that the time to reach 100% of a maximal voluntary isometric contraction of the elbow flexors ranges between 275 and 375 ms and is unaffected by the strength or sex of the subject. For dynamic exertions against very light resistances a substantial portion of the lift may therefore have already been completed by the time the musculature had been fully activated (see Figure 6.9). In view of this, the majority of the lift against the very light resistance by subjects DF and CB is likely to have been performed under submaximal levels of muscle activation.

If the model of dynamic lifting is to be extended to explore lifting of isoinertial loads, input regarding the deactivation of muscles is also required. An insight into the way in which different muscles are activated and deactivated throughout the lifting action may be provided through EMG analysis of the major muscle groups involved. Alternatively, the study by Grieve (1974) provides a useful indication of how the force and velocity at the hands changes during the lifting and placing of various inertial loads. Evidence of this nature will be required before an accurate model of dynamic lifting can be developed to simulate lifting tasks involved in actual manual handling activities.

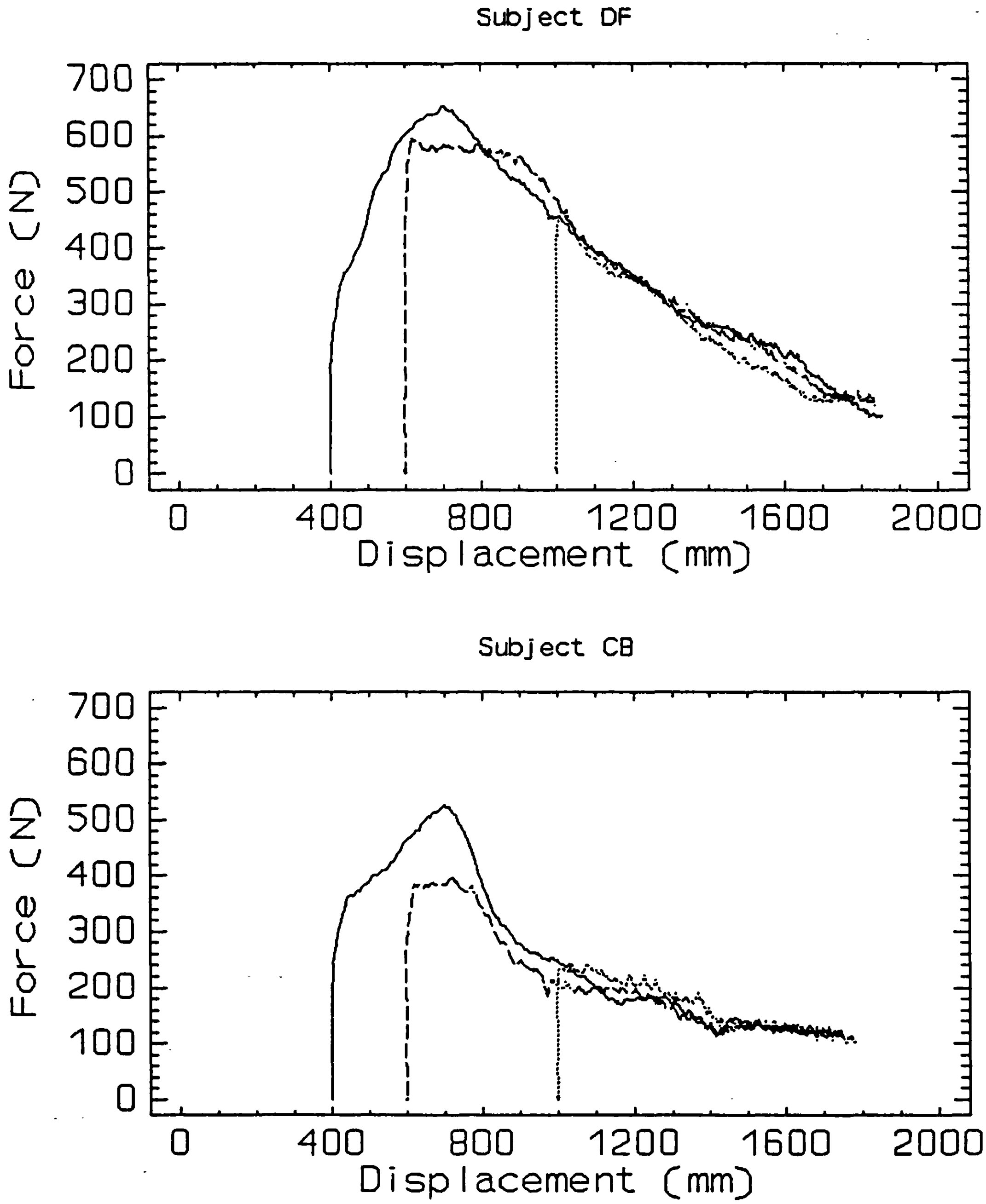


Figure 6.24: Force versus height of lift for maximal two-handed dynamic lifting exertions against the medium resistance by subjects DF and CB under different initial starting heights. The three starting heights shown for each subject were 400, 600 and 1000 cm above the ground respectively.

Conclusions

The main conclusions emerging from the study were:

(1) Lifting strength changed significantly according to the number of hands employed (i.e. one or two-handed) ($p < 0.0001$), hand height above the ground ($p < 0.0001$) and the task resistance (and hence velocity of lift) ($p < 0.0001$).

(2) The greatest forces were observed for two-handed static exertions and the least lifting forces for one-handed dynamic exertions against the light resistance.

(3) The power output of whole body lifting exertions decreased as the task resistance increased. Based on the observations of power output and the corresponding velocities of lift, it was concluded that most heavy manuals handling tasks fall well below the optimal conditions that would permit peak power output to be generated.

(4) When lifting strength was measured at a hand height relative to stature and normalized by dividing by body weight, sex differences in the strength of static exertions were insignificant ($p > 0.05$). Under dynamic conditions the same performance criterion illustrated significant differences between males and females ($p < 0.01$).

(5) When sex differences in dynamic lifting performance were expressed in terms of female/male ratios (f/m), the f/m ratios for power output were found to be much smaller than the f/m ratios for static lifting strength.

(6) Based on points 4 and 5 above it was concluded that sex differences in lifting performance are more pronounced under dynamic conditions than under static conditions.

(7) Sex differences in normalized dynamic and static lifting strength were largely independent of the height of the lift ($p > 0.05$).

(8) Strength differences between one and two-handed lifting exertions increased significantly, and in an almost linear fashion, as hand height increased ($p < 0.0001$).

(9) Strength differences between one and two-handed lifting exertions changed significantly with task resistance ($p < 0.005$), with the largest strength differences between one and two-handed exertions occurring under static conditions.

(10) A critical point in the performance of dynamic lifts occurred as the hands approached shoulder height. This point was reflected by large perturbations in the force trace, particularly against very heavy resistances, that were due to a change in lifting posture from an overhand lift to an upward thrust.

(11) Body weight was found to be a poor predictor of dynamic and static lifting strength. At shoulder height and above the correlations between body weight and dynamic and static lifting strength were largely insignificant ($p > 0.05$). At other heights above the ground the proportion of the total variance in lifting strength which could be explained by the variance in body weight was less than 50%.

(12) There is a high degree of generality between dynamic and static measures of lifting strength when maximal dynamic and static lifting exertions are compared in similar postures (i.e. at the same hand heights relative to stature). Measures of dynamic strength performed against different levels of resistance and hence at different lifting velocities also demonstrated high correlations and hence a high degree of generality. These observations suggest that

(i) Dynamic and static tests of lifting strength measure a common intrinsic ability of a given individual to produce maximal lifting forces.

(ii) Individuals who perform well (or poorly) on static tests of lifting strength attain the same relative level of performance on dynamic tests of lifting strength. In addition, the relative level of performance of individuals on dynamic tests of lifting strength is unaffected by the level of task resistance and hence velocity of lift.

CHAPTER 7

GENERAL SUMMARY AND CONCLUSIONS

The present work provides a detailed analysis of whole body strength capabilities of humans under a wide range of conditions of posture, hand height, direction of exertion and task resistance. Many of the conditions in which whole body strength was measured had not previously been investigated.

In studies I and II the influence and interrelationships of interface, gravitational and musculo-skeletal limitations on the ability of healthy male and female adults to produce maximal static forces were investigated. Study III introduced novel strength testing equipment, protocol, data processing and display techniques in order to extend the measurement and analysis of human static strength into three dimensions. The final study (IV) compared maximal dynamic lifting performance against a range of resistances on an isoresistive hydrodynamometer with static lifting strength.

Conclusions emerging from these studies (relating to the specific hypotheses stated in Chapter 2) are provided at the end of each Chapter. The objective of this section was to assimilate the findings with respect to the general aims of the thesis.

One of the main aims of the thesis was to determine the influence and relative importance of the hand/handle interface, as well as, sex, anthropometric, and musculo-skeletal factors on dynamic and static whole body strength.

The relative importance of the hand/handle interface on the ability to produce maximal whole body strength has often been overlooked. Study I showed that with poor conditions at the hand/handle interface whole body static pulling strength may be reduced by as much as 50% when compared with the same exertion performed against a good hand/handle interface. Under these adverse conditions whole body strength becomes completely dominated by interface limitations, with gravitational factors (i.e. the effective deployment of body weight) and musculo-skeletal factors (i.e. intrinsic muscular strength) playing a minor role in the strength of the exertion.

The findings of study I have important implications for models of human whole body strength (e.g. NIOSH 1981) that have up until the present assumed the hand/object interface to be optimal for most purposes. Clearly such models need to classify couplings between hand and object as strong or weak links to improve the accuracy and reliability of strength prediction for real life tasks.

Studies II and IV revealed that sex differences in strength varied widely with the direction and height of exertion and the task resistance. One of the more interesting findings however was that of the lack of a significant sex difference in strength when whole body static lifting strength was measured at hand heights relative to stature and normalized to body weight. In comparison, differences in normalized maximal lifting performance between males and females were statistically significant and much more pronounced under dynamic conditions.

Although reasons for the above finding are unclear, one possible explanation is that males and females exhibit different levels of skill in their ability to produce maximal lifting forces. It is these differences in skill between males and females that possibly become more pronounced under dynamic compared to static conditions and lead to much greater sex differences in strength. Quantifying and studying the skill element involved in producing maximal voluntary exertions is one avenue of future research that may prove useful in explaining part of the variance in strength between individuals.

One concept that has long been attractive to many researchers in the field of manual handling has been the prediction of individual strength capabilities from simple measures of their anthropometry. Many studies have explored this area of research with varying degrees of success. The findings of the current thesis suggest that dynamic and static whole body strength cannot be reliably predicted from body weight and stature alone (for the general population) when exertions are performed along or close to the live axis (i.e. along an axis connecting the centre of foot pressure to the centre of manual force application). In other directions of exertion, where gravitational limitations play a more dominant role on performance, the strength of static exertions may be more reliably predicted using a simple linear regression model with body weight and stature as independent variables.

A further aim of the thesis was to describe and compare maximal dynamic and static whole body exertions performed both one and two-handed. As in the case of sex differences in strength, the differences in strength between one and two-handed exertions varied widely according to the task resistance and the height and direction of exertion. Under certain circumstances one-handed exertions approached and even exceeded the strength of two-handed exertions. In other situations the strength of one-handed exertions was half that of two-handed whole body exertions.

As pointed out in Chapter 1 few studies have investigated one-handed whole body strength capabilities, and yet, there are many manual handling tasks which may require all or part of the task to be performed one-handed. The current work thus fills the gap of knowledge in this area by providing some indication of how strength demands of a given task may change, when, during the manoeuvring and handling of a load, part or all of the task is performed single handedly.

Study IV revealed that there is a high degree of association between static and dynamic measures of whole body strength. While the actual magnitude of maximal performance differed considerably against different task resistances, the high degree of association between dynamic and static strengths suggests that individuals achieve the same relative level of performance, irrespective of the mode of strength testing. This finding may provide some comfort to those investigators attempting to predict dynamic performance from static measures of strength. It is however pointed out that a high degree of association between dynamic and static strength is obtained only when strength measures on the different tests are compared under similar postures.

Finally, the current work provides some indication of the principles and characteristics governing whole body exertions in the human. Although the data in this thesis may afford a rough guide to the whole body strength capabilities of the "average" human under the different conditions studied, further research employing much larger subject populations are required before estimations of percentiles for whole body strength can be made.

If these studies are performed, and the suggestions and new approaches to whole body strength assessment described in this thesis are adopted, significant improvements to existing biomechanical models of human whole body strength, or new and more reliable models may be achieved. Such models of human whole body strength will provide the ergonomist with a powerful tool to aid in task design and analysis in the area of manual materials handling.

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APPENDIX A

SUBJECT INFORMATION PACKAGE AND INFORMED CONSENT FORMS

SUBJECT INFORMATION PACKAGE

HUMAN WHOLE BODY DYNAMIC AND STATIC LIFTING CAPABILITIES

ITEM 1 PROJECT OBJECTIVES:

The primary objective of this study is to describe the maximum voluntary strength capabilities of humans performing dynamic and static whole body lifting actions.

ITEM 2 TEST PROCEDURES:

Volunteers who participate in this study must first meet minimal standards of good health and be currently free of any musculoskeletal injury or disablement.
Subjects will be required to perform a total of (i) 6 tests of dynamic lifting strength on a water filled hydrodynamometer and (ii) 12 maximal voluntary isometric lifting exertions, both one and two-handed.

In test (i) subjects will lift maximally against 3 different resistances; light, (20 bungs), medium (28 bungs) and hard (36 bungs) using one and two hands starting from a height of 40cm from the floor until head height is reached.

In test (ii) subjects are requested to perform maximal voluntary lifting exertions using one hand and two hands at heights equivalent to knee, knuckle, hip, elbow, shoulder and head height. Isometric lifting exertions are required to be maintained for a period of 5 seconds.

ITEM 3 RISKS AND DISCOMFORTS:

During both the dynamic and static lifting exertions there is a small probability that subjects may sustain a muscle strain to the lower back or to muscles of the upper extremities. This risk however is minimal in the current experiment as all exertions are performed within the footbase thus minimising the horizontal distance between the lower back and the load. Previous experiments, with ethics clearance, testing dynamic lifting capabilities of both male and female military personnel (using a similar protocol as that described above) have however resulted in no significant injuries in over 1000 observations. During isometric exertions there will be a significant rise in blood pressure, which in a small number of persons (particularly those who suffer from hypertension) may lead to temporary dizziness. Some muscle stiffness may be apparent one to two days following the isometric exertions. This however is only temporary and should be unnoticeable within 4 days.

ITEM 4 INQUIRIES:

Questions concerning the procedures used are welcome. If you have any doubts please ask for further explanations.

ITEM 5 FREEDOM OF CONSENT:

Participation is on a voluntary basis. You are free to deny consent, if you so desire, at any time during or between trials.

ITEM 6 CONFIDENTIALITY:

All questions, answers and results from this study will be treated with absolute confidentiality. Subjects will be identified in the resultant manuscript and/or publications by use of subject codes only.

INFORMED CONSENT

University of London

Royal Free Hospital School of Medicine

Dept. of Anatomy.

The university and those conducting this project subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of subjects. This form and the information it contains are given to you for your own protection and full understanding of the procedures, risks and benefits involved. Your signature on this form will signify that you have received the document described below regarding this project, that you have received adequate opportunity to consider the information in the document, and that you voluntarily agree to participate in the project.

Having been asked by D. Fothergill of the Dept. of Anatomy of The Royal Free Hospital School of Medicine, University of London, to participate in a research project experiment, I have read the procedures specified in the document entitled:

SUBJECT INFORMATION PACKAGE:

HUMAN WHOLE BODY DYNAMIC AND STATIC LIFTING CAPABILITIES

I understand the procedures to be used in this experiment and the personal risks to me in taking part.

I understand that I may withdraw my participation in this experiment at any time. I also understand that I may register any complaint I might have about the experiment with the chief researcher named above or with Prof. D.W. Grieve, in the Dept of Anatomy, Royal Free Hospital.

I may obtain a copy of the results of this study, upon its completion, by contacting Prof. Don Grieve or David Fothergill.

I agree to participate by performing the isometric and dynamic lifting strength tests (as explained to me by the principle investigator and referred to in the document named above).

SURNAME ______________________________

GIVEN NAME______________________________

DATE OF BIRTH____________________________

ADDRESS_______________________________

____

____

SIGNATURE_____________________________

DATE__________________________________

SIGNATURE OF WITNESS______________________

APPENDIX B
SUMMARY DATA FOR CHAPTER 4

Table B1:
Group one-handed PSD data at the 1.0 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	67	18.1	464	171	10	61	16.2	425	157
20	55	14.3	387	152	30	55	12.8	384	136
40	57	13.1	393	131	50	56	12.1	384	123
60	56	12.7	388	128	70	59	10.8	407	125
80	64	12.5	444	151	90	67	10.4	458	115
100	63	8.98	429	103	110	63	10	434	99
120	60	8.23	412	98	130	58	10.3	395	83
140	54	8.920	368	89	150	54	11.1	370	112
160	56	11.8	387	116	170	67	16.5	463	163
180	64	15.4	446	160	190	56	10.7	386	126
200	49	8.670	333	91	210	45	9.129	309	103
220	45	8.289	309	98	230	43	9.07	295	93
240	45	9.48	311	109	250	48	12.9	332	127
260	51	12.7	349	126	270	57	13.3	393	128
280	63	17.79	440	170	290	72	20.2	498	190
300	76	20.8	529	206	310	80	27.9	565	278
320	73	25.7	513	236	330	69	24.6	475	200
340	68	26.2	474	217	350	71	26.4	494	215

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=22) are DG1M DF1M DS1M MS1M CG1M JG1M CB1M DP1M SM1M ZH1M PO1M JN1M AB1M AP1M JW1M KA1M KL1M LM1M MH1M PA1M RB1M TIMEOUT
BODY WEIGHT (KG)=69.65 S.D.=12.7

Table B2:
Group one-handed PSD data at the 1.75 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	49	27.5	335	200	10	33	7.92	230	82
20	26	7.689	185	77	30	22	6.390	156	65
40	19	4.98	135	57	50	18	6.01	125	57
60	16	5.17	116	51	70	17	4.960	119	51
80	17	6.119	118	57	90	21	6.970	148	67
100	26	8.850	186	91	110	31	11.4	225	110
120	35	9.850	250	103	130	44	11	308	115
140	50	11.4	345	115	150	58	10.6	403	105
160	61	11.5	418	109	170	68	14.9	465	127
180	67	16.6	460	141	190	55	17.9	376	136
200	48	17.29	329	134	210	38	13.5	260	103
220	31	10.7	218	89	230	28	10.3	193	83
240	24	7.68	167	73	250	22	7.810	155	71
260	22	7.24	154	69	270	25	8.300	174	81
280	26	9.030	187	89	290	31	11.8	223	112
300	43	20.5	307	187	310	62	28.7	439	251
320	72	27.2	498	241	330	70	27.5	481	219
340	65	29.7	446	228	350	54	27.4	376	217

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=22) are DG17 DF17 DS17 MS17 CG17 JG17 CB17 DP17 SM17 ZH17 PO17 JN17 AB17 AP17 JW17 KA17 KL17 LM17 MH17 PA17 RB17 TC17
BODY WEIGHT (KG)=69.9 S.D.=12.7

Table B3:
Male one-handed PSD data at the 1.0 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	74	16.2	551	161	10	69	14.5	515	136
20	63	12.4	472	142	30	61	11.7	456	129
40	61	10	458	118	50	61	9.91	450	104
60	62	10.9	460	110	70	64	6.99	478	101
80	71	8.57	528	133	90	70	8.530	521	94
100	66	6.91	488	73	110	66	7.210	484	79
120	62	8.18	461	90	130	60	12.4	437	74
140	57	6.609	419	64	150	59	9.23	436	94
160	61	9.41	448	96	170	76	13.7	562	138
180	72	14.5	534	151	190	61	9.879	457	120
200	52	8.190	385	77	210	50	7.369	373	91
220	50	7.710	369	91	230	46	9.57	344	89
240	49	10.5	369	115	250	53	14.2	397	132
260	56	13.8	414	129	270	63	13.9	463	122
280	73	13.9	542	141	290	83	13.2	615	140
300	87	15	652	170	310	95	25.6	720	274
320	89	20.5	659	200	330	80	24.7	591	187
340	80	27.5	590	213	350	81	28.5	601	220

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are DG1M JW1M DF1M DS1M MS1M CB1M DP1M MH1M PA1M JN1M PO1M TIMEOUT
BODY WEIGHT (KG)=75.9 S.D.=13.8

Table B4:
Male one-handed PSD data at the 1.75 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	52	29.5	379	209	10	35	7.02	264	78
20	30	7.220	225	75	30	25	6.060	187	67
40	22	4.130	168	55	50	21	4.880	159	50
60	19	4.189	144	46	70	19	4.33	148	49
80	20	4.58	152	49	90	25	5.93	191	58
100	31	7.76	236	89	110	36	9.09	278	102
120	41	7.24	308	91	130	48	7.77	366	101
140	54	7.539	402	94	150	61	8.710	451	88
160	63	10.8	465	95	170	68	13.5	503	108
180	68	17	504	138	190	57	19.5	424	135
200	50	16.2	373	127	210	40	13.8	297	102
220	34	9.859	252	84	230	29	6.970	214	62
240	26	6.27	194	70	250	25	7.49	188	69
260	24	6.57	185	69	270	28	8.109	216	82
280	31	8.52	235	88	290	36	12.4	275	118
300	50	24	383	217	310	72	32.8	544	286
320	77	31.7	579	277	330	72	32.7	532	258
340	66	34.7	487	265	350	56	31.7	418	251

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are DG17 JW17 DF17 DS17 MS17 CB17 DP17 MH17 PA17 JN17 PO17 TC17
BODY WEIGHT (KG)=76.4 S.D.=13.6

Table B5:
Female one-handed PSD data at the 1.0 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	58	17.5	359	120	10	51	12.7	317	104
20	46	11.3	285	89	30	48	10.9	296	85
40	51	14.8	314	104	50	50	12.2	305	96
60	49	11.4	301	91	70	52	11.1	322	96
80	56	12	344	103	90	63	11.3	384	92
100	58	9.48	358	89	110	61	12.5	373	89
120	58	7.939	353	74	130	56	7.380	345	65
140	50	10.2	307	78	150	47	10.3	291	76
160	51	12.7	312	94	170	56	13.1	343	100
180	55	11.3	340	93	190	49	7.76	300	68
200	44	7.58	272	65	210	38	6.41	233	51
220	39	4.130	237	42	230	38	6.48	237	58
240	40	4.189	242	45	250	41	7.609	254	63
260	44	7.82	271	64	270	51	9.41	310	76
280	51	15	318	113	290	58	18.9	358	141
300	62	18.29	382	138	310	62	18.4	380	136
320	55	18.7	338	134	330	55	16.79	337	108
340	54	16.9	335	122	350	60	18.79	366	124

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=10) are CG1M JG1M SM1M ZH1M AB1M AP1M KA1M KL1M LM1M RB1M
BODY WEIGHT (KG)=62.2 S.D.=5.3

Table B6:
Female one-handed PSD data at the 1.75 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	45	26.1	283	186	10	31	8.550	189	68
20	22	6.35	137	48	30	19	5.73	118	40
40	16	3.62	97	28	50	14	4.6	84	34
60	13	4.66	82	35	70	14	3.83	85	29
80	13	5.42	78	37	90	16	3.71	96	30
100	20	6.75	127	51	110	26	11.7	161	86
120	29	9.23	180	68	130	38	12.2	237	90
140	45	13.8	277	103	150	56	12.6	344	97
160	59	12.4	362	101	170	68	17.2	419	137
180	66	16.9	408	132	190	52	16.2	318	118
200	45	18.9	276	128	210	35	13.5	217	90
220	29	11.6	177	82	230	27	13.7	168	101
240	22	8.93	134	65	250	19	7.09	115	51
260	19	7.17	116	50	270	20	6.27	124	46
280	21	6.4	129	47	290	26	8.359	159	64
300	35	11.6	215	85	310	51	18.4	313	122
320	65	20.29	401	150	330	68	21.2	420	150
340	64	24.1	398	176	350	52	22.7	326	167

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=10) are CG17 JG17 SM17 ZH17 AB17 AP17 KA17 KL17 LM17 RB17
BODY WEIGHT (KG)=62.2 S.D.=5.3

Table B7:

Group one-handed PSD data at the 1.0 meter bar height (used for comparison with two-handed exertions at the same bar height).

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	72	20.7	519	190	10	64	18.7	464	172
20	58	13.7	419	142	30	58	12.1	417	119
40	59	13.1	422	127	50	58	13.3	416	122
60	60	13.6	426	124	70	61	10.2	440	115
80	66	11	477	138	90	68	10.5	485	126
100	63	9.120	451	107	110	63	8.390	448	107
120	61	7.939	433	102	130	58	8.039	414	86
140	54	7.52	381	80	150	54	9.190	391	115
160	56	10.8	401	122	170	68	16.1	489	167
180	64	14.8	465	154	190	57	9.59	410	111
200	50	9.129	354	90	210	47	8.850	336	106
220	47	8.16	335	91	230	43	9.210	308	84
240	45	7.439	321	83	250	50	11.2	353	98
260	49	9.98	351	93	270	57	12.6	406	117
280	64	15.2	463	152	290	73	17.79	531	183
300	76	18.1	560	216	310	89	26.3	663	308
320	81	25.8	595	259	330	75	24.6	536	206
340	72	30.1	520	249	350	77	31	557	258

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are DG1M DF1M DS1M MS1M CG1M JG1M CB1M DP1M SM1M ZH1M PO1M JN1M
BODY WEIGHT (KG)=72.7 S.D.=13.8

Table B8:

Group two-handed PSD data at the 1.0 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	96	24.1	690	221	10	82	15	586	162
20	71	11.9	512	143	30	70	11	505	168
40	63	7.359	456	121	50	62	6.5	446	112
60	61	6.25	439	105	70	61	5.73	438	100
80	63	6.050	450	93	90	70	8.190	494	94
100	68	8.050	484	94	110	66	8.030	465	88
120	66	7.16	464	83	130	66	8.27	472	96
140	67	5.74	479	85	150	68	4.939	483	82
160	72	6.98	515	106	170	82	8.949	588	154
180	90	8.690	644	135	190	68	9.32	488	111
200	61	8.260	442	120	210	57	8.620	406	104
220	54	6.140	387	92	230	54	6.23	386	80
240	54	7.67	387	91	250	56	8.879	396	90
260	63	9.32	449	111	270	74	13	527	139
280	84	17.2	600	174	290	98	22.9	697	199
300	105	33.2	742	256	310	111	31.6	781	223
320	111	38.40	777	257	330	91	21	645	161
340	92	19.2	655	184	350	97	24	697	230

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are 2DG1M 2DF1M 2DS1M 2MS1M 2CG1M 2JG1M 2CB1M 2DP1M 2SM1M 2ZH1M 2PO1M 2JN1M
BODY WEIGHT (KG)=72.6 S.D.=12.9

Table B9:
Group one-handed PSD data at the 1.75 meter bar height (used for comparison with two handed exertions performed at the same bar height).

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	37	9.609	267	102	10	33	6.93	242	83
20	27	7.32	197	72	30	23	6	167	61
40	21	4.710	152	56	50	19	6.140	143	58
60	18	5.07	132	52	70	19	5.24	141	56
80	19	5.529	140	54	90	23	6.560	168	59
100	28	9.460	210	99	110	34	12.5	255	121
120	39	10.8	285	110	130	48	12.3	350	122
140	52	12.9	375	126	150	57	12.7	414	127
160	59	12.6	425	123	170	63	11.6	454	129
180	63	14.8	457	150	190	51	13.2	370	128
200	45	15.3	326	138	210	36	12.4	259	102
220	31	10.2	228	88	230	27	6.65	195	62
240	25	6.84	180	74	250	22	6.869	164	66
260	23	6.68	169	68	270	25	6.960	185	70
280	28	8.010	202	74	290	33	10.8	238	91
300	43	18.4	311	149	310	64	32.09	464	255
320	73	32	524	267	330	67	30.4	479	235
340	59	29.2	424	229	350	45	15.1	333	175

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are DG17 DF17 DS17 MS17 CG17 JG17 CB17 DP17 SM17 ZH17 PO17 JN17
BODY WEIGHT (KG)=73.0 S.D.=13.7

Table B10:
Group two-handed PSD data at the 1.75 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	51	15.2	376	149	10	35	9.09	254	103
20	27	6.99	196	81	30	24	6.310	174	72
40	22	5.279	158	58	50	21	5.289	156	58
60	21	4.27	153	46	70	22	5.33	159	47
80	24	7.75	171	67	90	27	5.779	192	57
100	30	7.93	217	74	110	33	6.029	237	59
120	41	10.7	298	129	130	46	6.99	334	95
140	57	8.210	414	111	150	67	9.91	487	132
160	72	8.699	520	121	170	86	6.67	614	106
180	90	7.42	638	95	190	69	12.6	490	104
200	51	13.3	363	112	210	38	9.210	272	76
220	30	9.07	217	75	230	28	7.75	199	71
240	25	6.279	184	64	250	25	6.1	178	56
260	27	6.300	199	70	270	29	6.060	208	67
280	33	6.550	243	75	290	40	7.939	288	93
300	54	14.6	399	159	310	78	32.8	575	302
320	95	36.09	693	316	330	96	34.8	677	266
340	91	25.2	640	196	350	63	18.79	454	143

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are 2DG17 2DF17 2DS17 2MS17 2CG17 2JG17 2CB17 2DP17 2SM17 2ZH17 2PO17 2JN17
BODY WEIGHT (KG)=72.7 S.D.=12.9

Table B11:
Static strength capabilities when the maximum advantage of using components of deviated forces are calculated for one-handed exertions at the 1.0 meter bar height (Group data).

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	78	23	538	207	10	74	21.8	510	192
20	70	19.29	485	176	30	65	16.79	452	158
40	62	13.8	427	138	50	62	11.5	429	131
60	64	11.4	446	138	70	67	11.4	463	140
80	68	11	473	136	90	69	11.1	475	132
100	68	10.6	470	123	110	67	10.3	458	111
120	65	10.6	442	101	130	63	10.3	429	97
140	64	11	439	114	150	66	12.2	457	134
160	68	14.6	470	153	170	68	16.1	475	165
180	68	16.1	471	166	190	66	15.4	458	160
200	63	13.9	434	147	210	58	12.2	400	133
220	53	10.1	365	117	230	51	9.73	354	113
240	55	11.8	381	122	250	61	13.6	421	141
260	67	16.7	467	176	270	72	19.79	508	207
280	77	22.3	543	234	290	81	24.1	571	253
300	84	25	590	264	310	85	25.8	601	269
320	86	26.6	602	272	330	85	26.2	594	263
340	83	25.2	582	247	350	81	23.9	566	227

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=22) are DG1M KA1M AB1M DF1M DS1M MS1M CG1M JG1M CB1M DP1M JW1M KL1M MH1M PA1M SM1M ZH1M AP1M JN1M LM1M PO1M TIMEOUT RB1M
BODY WEIGHT (KG)=69.7 S.D.=12.7

Table B12:
Static strength capabilities when the maximum advantage of using components of deviated forces are calculated for one-handed exertions at the 1.75 meter bar height (Group data).

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	69	27.6	474	218	10	63	26.8	432	211
20	56	25.6	389	201	30	50	23.2	344	181
40	43	19.9	296	155	50	35	16.1	243	125
60	30	11.8	209	94	70	29	7.99	201	81
80	31	7.98	220	87	90	37	7.73	256	89
100	42	8.300	291	91	110	47	8.82	325	93
120	52	9.359	359	94	130	57	10.3	393	99
140	62	11.8	424	106	150	66	13.3	449	116
160	68	14.6	467	124	170	70	15.3	476	131
180	69	15.8	475	133	190	67	16	463	134
200	64	16	438	131	210	59	15.3	403	123
220	53	14	360	110	230	46	12.7	313	100
240	40	11.7	275	97	250	38	14	264	126
260	43	17.2	305	157	270	53	20.4	369	185
280	61	23	426	208	290	68	25.2	475	226
300	73	26.3	511	234	310	77	26.8	533	237
320	79	27.6	545	238	330	79	28.2	544	234
340	77	28.1	528	224	350	74	28.2	506	223

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=22) are DG17 KA17 AB17 DF17 DS17 MS17 CG17 JG17 CB17 DP17 JW17 KL17 MH17 PA17 SM17 ZH17 AP17 JN17 LM17 PO17 TC17 RB17
BODY WEIGHT (KG)=69.9 S.D.=12.7

Table B13:

Mean static strength of male subjects when the maximum advantage of using components of deviated forces are calculated for one-handed exertions at the 1.0 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	87	23.8	645	206	10	82	23.6	606	197
20	78	20.2	577	175	30	72	16.5	536	152
40	67	12	501	127	50	67	8.600	501	116
60	70	8.879	523	125	70	72	9.140	538	129
80	73	9.100	545	127	90	73	9.27	543	122
100	72	8.260	536	109	110	70	7.68	518	91
120	68	8.550	497	75	130	65	9.23	481	75
140	69	10.9	506	99	150	72	11.8	537	123
160	75	13.3	561	139	170	77	14.6	572	151
180	76	15	567	154	190	74	14.6	548	151
200	69	13.3	516	139	210	64	11.7	475	127
220	58	9.460	433	109	230	56	9.699	420	108
240	62	10.7	455	104	250	69	10	511	110
260	77	10.7	577	141	270	85	13.4	635	177
280	91	15.7	684	206	290	96	18.2	721	231
300	99	19.7	747	245	310	101	21.7	759	255
320	101	23.4	762	260	330	99	25.1	743	261
340	96	25.3	718	248	350	92	24	689	224

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are DG1M DF1M DS1M MS1M CB1M DP1M JW1M MH1M PA1M JN1M PO1M TIMEOUT
BODY WEIGHT (KG)=75.9 S.D.=13.8293331

Table B14:

Mean static strength of male subjects when the maximum advantage of using components of deviated forces are calculated for one-handed exertions at the 1.75 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	73	31.4	541	240	10	66	31	491	238
20	59	30	441	230	30	52	27	388	206
40	45	22.6	336	172	50	37	17.6	277	133
60	33	11.3	244	87	70	33	4.779	245	66
80	35	5.08	266	78	90	40	4.1	303	75
100	45	5.220	336	76	110	49	6.77	367	82
120	53	7.65	397	81	130	58	8.75	428	84
140	62	10.6	458	88	150	66	12.5	485	99
160	68	14.2	505	111	170	70	15	517	119
180	70	16.1	517	125	190	68	16.79	507	128
200	65	17	481	126	210	60	16.29	444	119
220	54	15.1	398	107	230	47	13.8	349	98
240	41	12	309	96	250	42	14.9	314	134
260	50	19.29	376	173	270	59	23.3	448	207
280	68	26.6	513	233	290	76	28.9	567	253
300	81	30	606	260	310	84	30.3	629	262
320	86	30.8	638	259	330	85	31.4	632	253
340	82	31.5	608	240	350	78	31.9	580	242

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=12) are DG17 DF17 DS17 MS17 CB17 DP17 JW17 MH17 PA17 JN17 PO17 TC17
BODY WEIGHT (KG)=76.4 S.D.=13.6

Table B15:

Mean static strength of female subjects when the maximum advantage of using components of deviated forces are calculated for one-handed exertions at the 1.0 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	67	17.29	409	119	10	65	16	396	110
20	61	14.5	374	100	30	57	13.8	350	95
40	55	13.3	339	95	50	56	11.9	343	91
60	58	10.8	354	89	70	61	11	372	93
80	63	10.9	385	91	90	64	11.5	393	93
100	64	11.7	391	91	110	63	12.1	387	92
120	62	12.3	377	91	130	60	11.1	366	83
140	59	8.93	359	72	150	59	8.59	362	73
160	59	10.8	362	85	170	58	11.8	359	92
180	58	11.5	356	90	190	57	11	349	88
200	54	9.91	334	81	210	51	8.59	310	72
220	46	6.640	282	60	230	45	5.34	276	54
240	47	7.939	292	72	250	51	10.2	312	88
260	54	13.8	335	111	270	58	15.8	356	123
280	61	17.4	375	133	290	63	17.7	390	134
300	65	17.29	402	130	310	67	16.7	411	126
320	67	16.5	410	122	330	68	15.6	415	116
340	68	15.8	419	113	350	68	16.9	417	118

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=10) are KA1M AB1M CG1M JG1M KL1M SM1M ZH1M AP1M LM1M RB1M
BODY WEIGHT (KG)=62.2 S.D.=5.3

Table B16:

Mean static strength of female subjects when the maximum advantage of using components of deviated forces are calculated for one-handed exertions at the 1.75 meter bar height

ANG	M%W	SD%W	MN	SDN	ANG	M%W	SD%W	MN	SDN
0	64	22.7	395	164	10	59	21.4	361	154
20	53	20	326	146	30	47	18.6	290	137
40	40	16.9	249	124	50	32	14.5	201	107
60	27	12	167	89	70	24	8.550	147	65
80	27	8.600	164	64	90	32	8.920	199	70
100	38	10	236	79	110	45	10.6	275	84
120	51	11.3	314	92	130	57	12.4	351	103
140	62	13.7	382	114	150	66	14.9	407	124
160	68	15.8	421	130	170	69	16.4	427	133
180	69	16.29	424	131	190	66	15.8	409	126
200	63	15.5	386	122	210	57	14.7	354	114
220	51	13.2	316	101	230	44	11.8	270	88
240	38	11.6	235	86	250	33	11.8	203	87
260	36	11	220	79	270	44	13	273	95
280	52	14.7	321	109	290	59	17	363	124
300	64	18.7	396	134	310	68	19.9	418	141
320	70	21.9	433	157	330	71	22.9	438	165
340	70	23.2	432	168	350	68	23.2	418	168

n.b. 0=LIFT 90=PULL 180=PRESS 270=PUSH
Files read (n=10) are KA17 AB17 CG17 JG17 KL17 SM17 ZH17 AP17 LM17 RB17
BODY WEIGHT (KG)=62.2 S.D.=5.3

Table B17:
Ratio files and MACE data for one and two-handed static exertions performed at a bar height of 1.0 and 1.75 meters

ANGLE	RF/M1M%W	RF/M1MAB	RF/M17%W	RF/M17AB	R1/2H1M	R1/2H17	QMACE1M	QMACE17
0	78	65	86	74	75	72	1.16	1.40
10	73	61	88	71	78	94	1.21	1.90
20	73	60	73	60	81	100	1.27	2.15
30	78	64	76	63	82	95	1.18	2.27
40	83	68	72	57	93	95	1.08	2.26
50	81	67	66	52	93	90	1.10	1.94
60	79	65	68	56	98	85	1.14	1.87
70	81	67	73	57	100	86	1.13	1.70
80	78	65	65	51	104	79	1.06	1.82
90	90	73	63	50	97	85	1.02	1.76
100	87	73	64	53	92	93	1.07	1.61
110	92	77	72	57	95	103	1.06	1.51
120	93	76	70	58	92	95	1.08	1.48
130	93	78	79	64	87	104	1.08	1.29
140	87	73	83	68	80	91	1.18	1.24
150	79	66	91	76	79	85	1.22	1.13
160	83	69	93	77	77	81	1.21	1.11
170	73	61	100	83	82	73	1.01	1.02
180	76	63	97	80	71	70	1.06	1.02
190	80	65	91	75	83	73	1.17	1.21
200	84	70	90	73	81	88	1.28	1.33
210	76	62	87	73	82	94	1.28	1.55
220	78	64	85	70	87	103	1.17	1.70
230	82	68	93	78	79	96	1.18	1.64
240	81	65	84	69	83	100	1.22	1.66
250	77	63	76	61	89	88	1.27	1.72
260	78	65	79	62	77	85	1.31	1.95
270	80	66	71	57	77	86	1.26	2.12
280	69	58	67	54	76	84	1.22	2.34
290	69	58	72	57	74	82	1.12	2.19
300	71	58	70	56	72	79	1.10	1.69
310	65	52	70	57	80	82	1.06	1.24
320	61	51	84	69	72	76	1.17	1.09
330	68	57	94	78	82	69	1.23	1.12
340	67	56	96	81	78	64	1.22	1.18
350	74	60	92	77	79	71	1.14	1.37

Key to File Names:

ANGLE = Angle of exertion in the fore and aft plane (degrees) (0°=lift, 90°=pull, 180°=press, 270°=push).
RF/M1M%W = Ratio of female/male static strength at the 1.0 meter bar height (calculated using strength per unit body weight).
RF/M1MAB = Ratio of female/male static strength at the 1.0 meter bar height (calculated using absolute strength in Newtons).
RF/M17%W = Ratio of female/male static strength at the 1.75 meter bar height (calculated using strength per unit body weight).
RF/M17AB = Ratio of female/male static strength at the 1.75 meter bar height (calculated using absolute strength in Newtons).
R1/2H1M = Ratio of one-handed/two-handed static strength at the 1.0 meter bar height.
R1/2H17 = Ratio of one-handed/two-handed static strength at the 1.75 meter bar height.
QMACE1M = The maximum advantage of using a component of exertion at the 1.0 meter bar height (group data).
QMACE17 = The maximum advantage of using a component of exertion at the 1.75 meter bar height (group data).

APPENDIX C

SUMMARY DATA FOR CHAPTER 5

Mean Force and Friction Data over the Sphere of Exertion for One-handed Maximal Static Exertions at the 1.0 m (initial and repeat) and 1.75 m Handle Heights.

Table C1:

Strength data for one-handed exertions at a hand height of 1.0 m. The values are the means and standard deviations over the entire sphere of exertion for the four males subjects following the fifth session.

		NEWTONS		% BODY WEIGHT		FRICTION COEFFICIENT	
		UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED
ABSOLUTE VALUES	MEAN	209	209.3	28.58	28.64	0.2055	0.2085
	SD	75.6	75.4	10.27	10.23	0.1117	0.1098
TIME DIFFERENCE[9]	MEAN	5	4.8	0.67	0.69	5.5E-3	4.7E-3
	SD	8.6	8.5	1.18	1.18	0.0112	0.0124

Table C2:

Summary data for one-handed exertions (repeat trials) at a hand height of 1.0 m. The values are the means and standard deviations over the entire sphere of exertion for the four males subjects following the fourth session.

		NEWTONS		% BODY WEIGHT		FRICTION COEFFICIENT	
		UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED
ABSOLUTE VALUES	MEAN	208.9	209.5	28.54	28.62	0.2041	0.2068
	SD	78.9	78.4	10.71	10.66	0.1095	0.1078
TIME DIFFERENCE	MEAN	8.4	8.3	1.15	1.13	9.4E-3	9E-3
	SD	14.1	14.2	1.96	1.98	0.0139	0.0144

Table C3:

Summary data for one-handed exertions at the 1.75m hand height. The values are the means and standard deviations over the entire sphere of exertion for the four males subjects following the fourth session .

		NEWTONS		% BODY WEIGHT		FRICTION COEFFICIENT	
		UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED
ABSOLUTE VALUES	MEAN	134.7	134.8	18.83	18.84	0.1234	0.125
	SD	79.8	79.7	11.16	11.16	0.0712	0.0706
TIME DIFFERENCE	MEAN	5.3	5.2	0.74	0.72	5.4E-3	5.6E-3
	SD	9.1	9.1	1.32	1.33	9.4E-3	9.8E-3

[9] This value represents the difference in force (or value for the coefficient of limiting friction) between the final and penultimate 20 minute session.

Two Dimensional Postural Stability Diagrams Encompassing the Sphere of Exertion

Figure C1: The following graphs represent PSD's of normalized forces for each 10° vertical plane in the sphere of exertion (as well as for one horizontal plane when the vertical force is zero) for one-handed maximal whole body static exertions on the 3D dynamometer. On each page the upper and lower figures represent exertions at the 1.75 m and 1.0 m handle height respectively. The plane of exertion viewed is indicated in each case by the arrows on the smaller circle. The data is based on the mean and SD of the forces recorded on four male subjects with horizontal foot placements 0.5 m from the handle.

NOTES

In the following PSDs the mean and SD for the pole values are slightly overestimated due to a computational error. The true values are

For 1.0 m

	NEWTONS		% Body Wt	
	Mn	SD	Mn	SD
LIFT	143	13	19.5	2.7
PRESS	445	54	60.7	8.2

For 1.75 m

	NEWTONS		% Body Wt	
	Mn	SD	Mn	SD
LIFT	90	17	12.6	2.7
PRESS	358	101	50.0	14.5

SMOOTHED FORCE ARRAY

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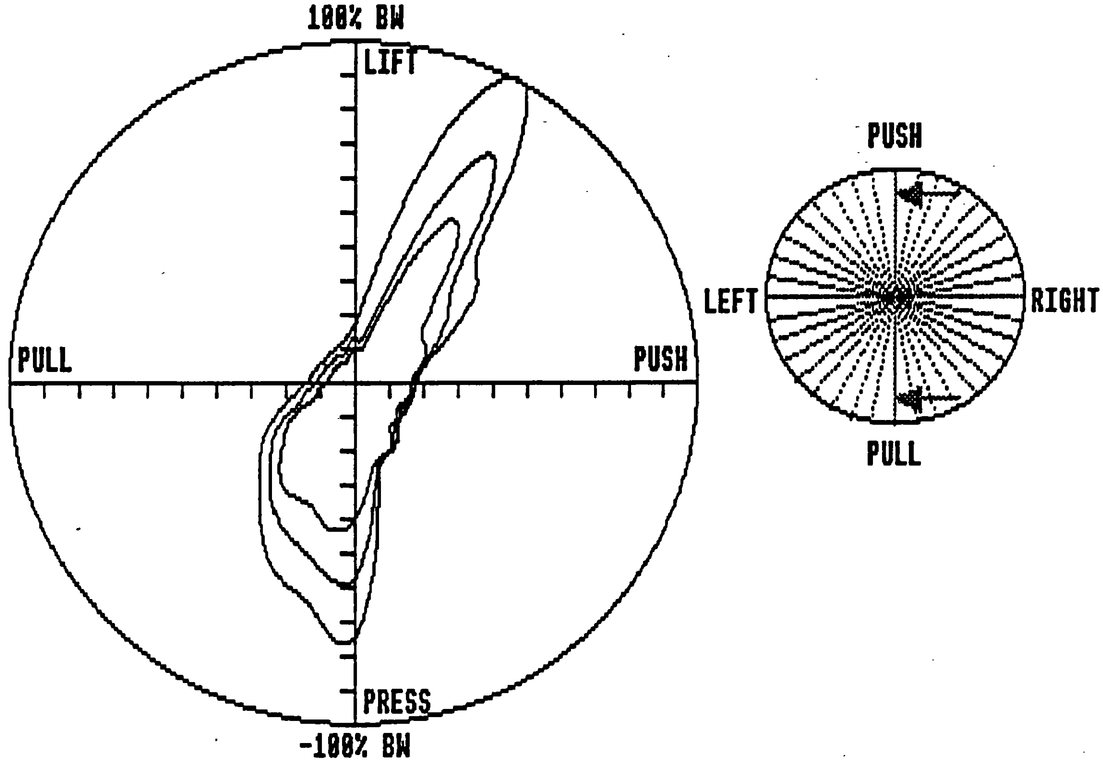

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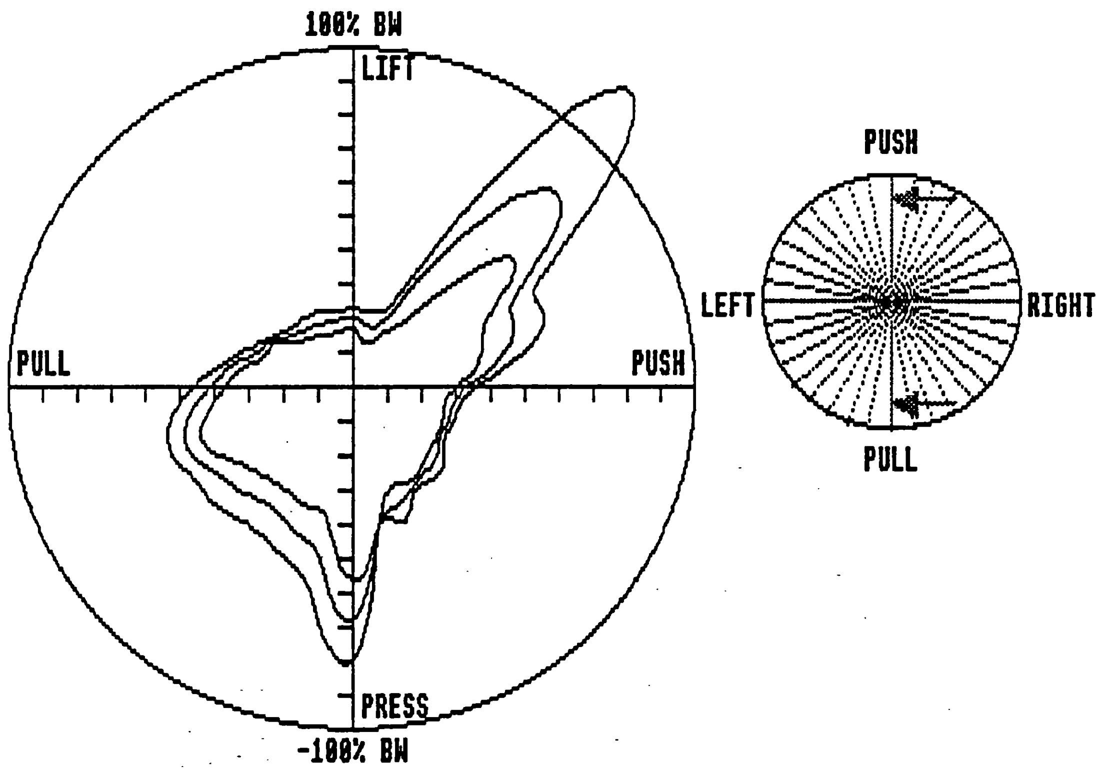

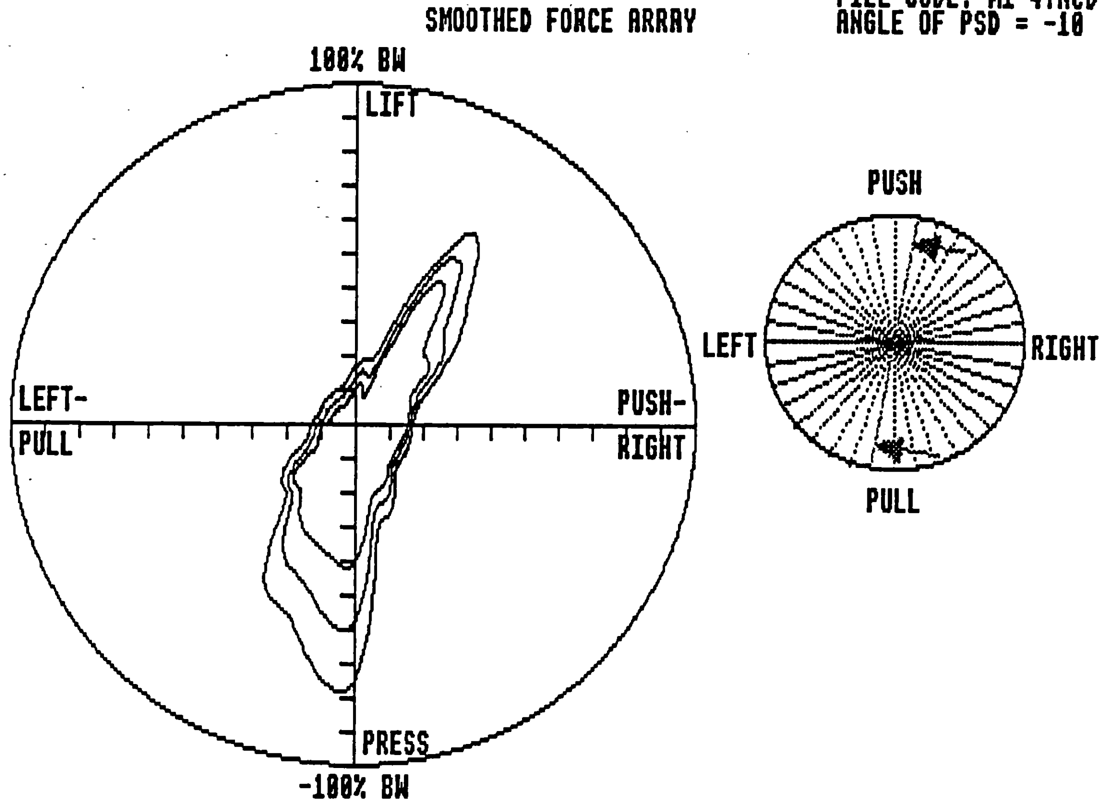
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PULL
PUSH-
RIGHT
PRESS
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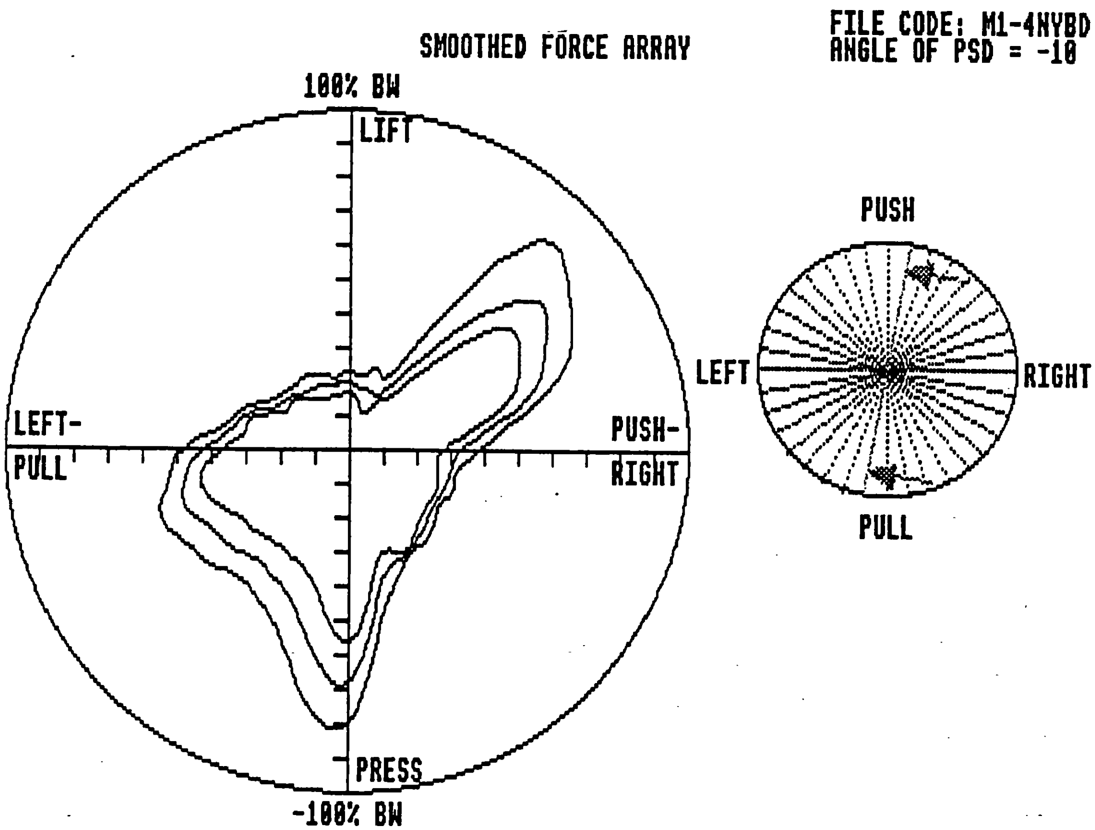
PUSH
LEFT
RIGHT
PULL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PULL
PUSH-
RIGHT
PRESS
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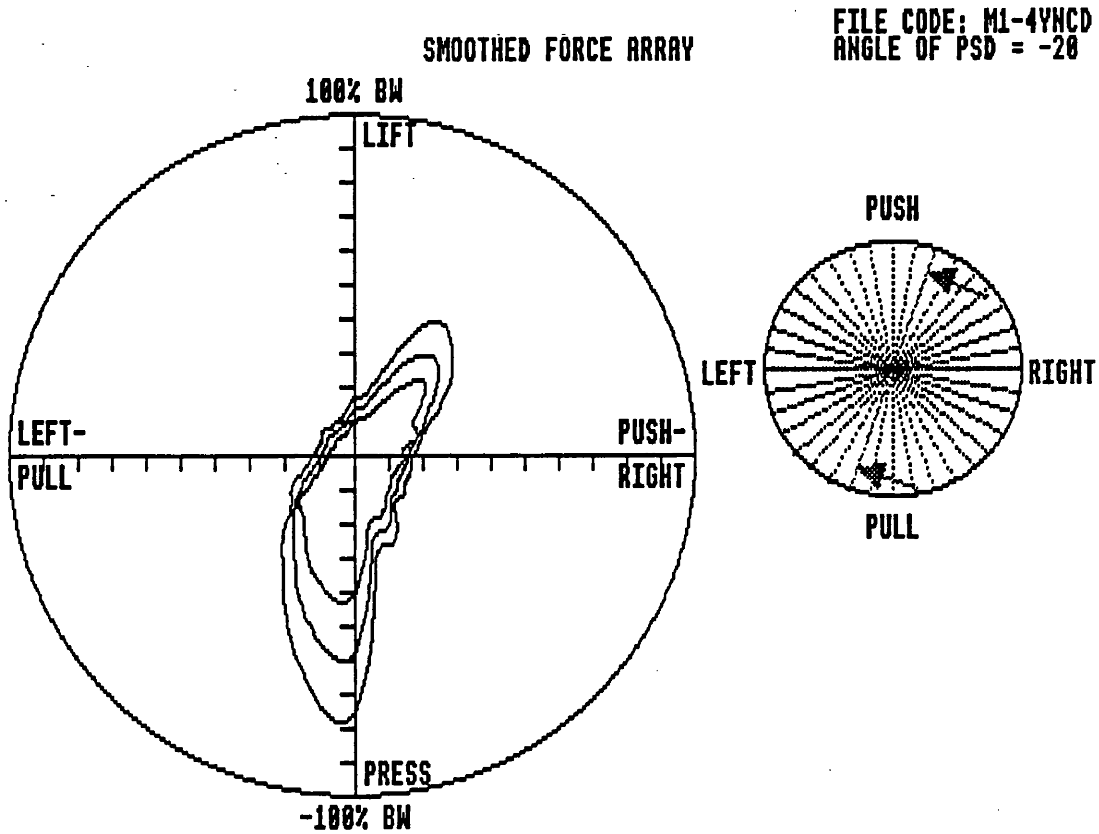
LEFT
RIGHT
PULL



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PUSH-
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PRESS
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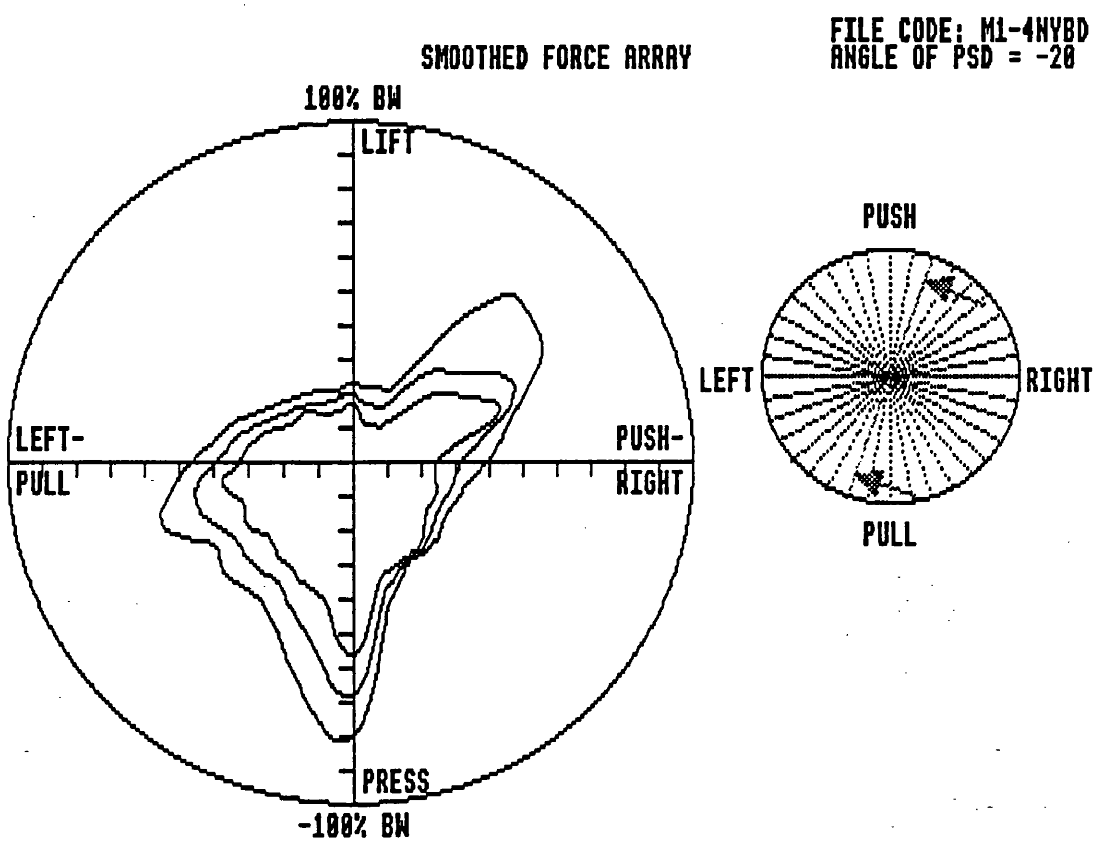
LEFT
RIGHT
PULL



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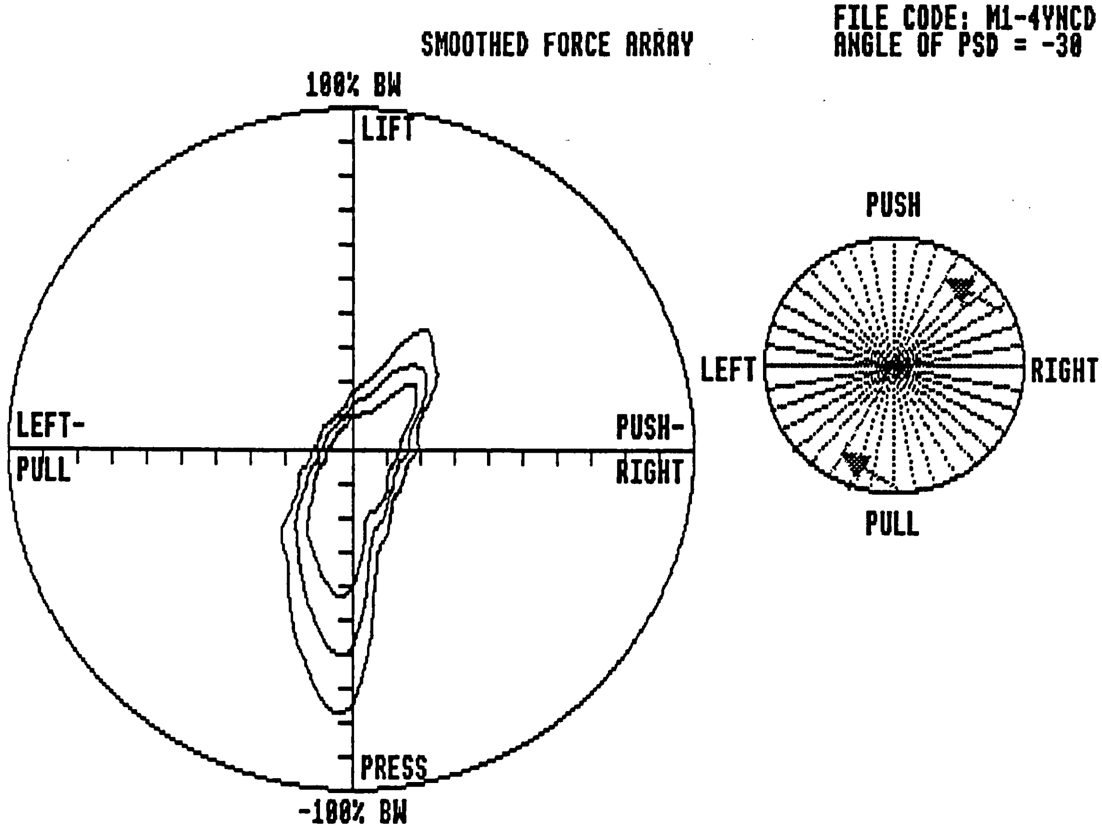
PULL
PUSH-
RIGHT
PRESS
-100% BW
PUSH
LEFT
RIGHT
PULL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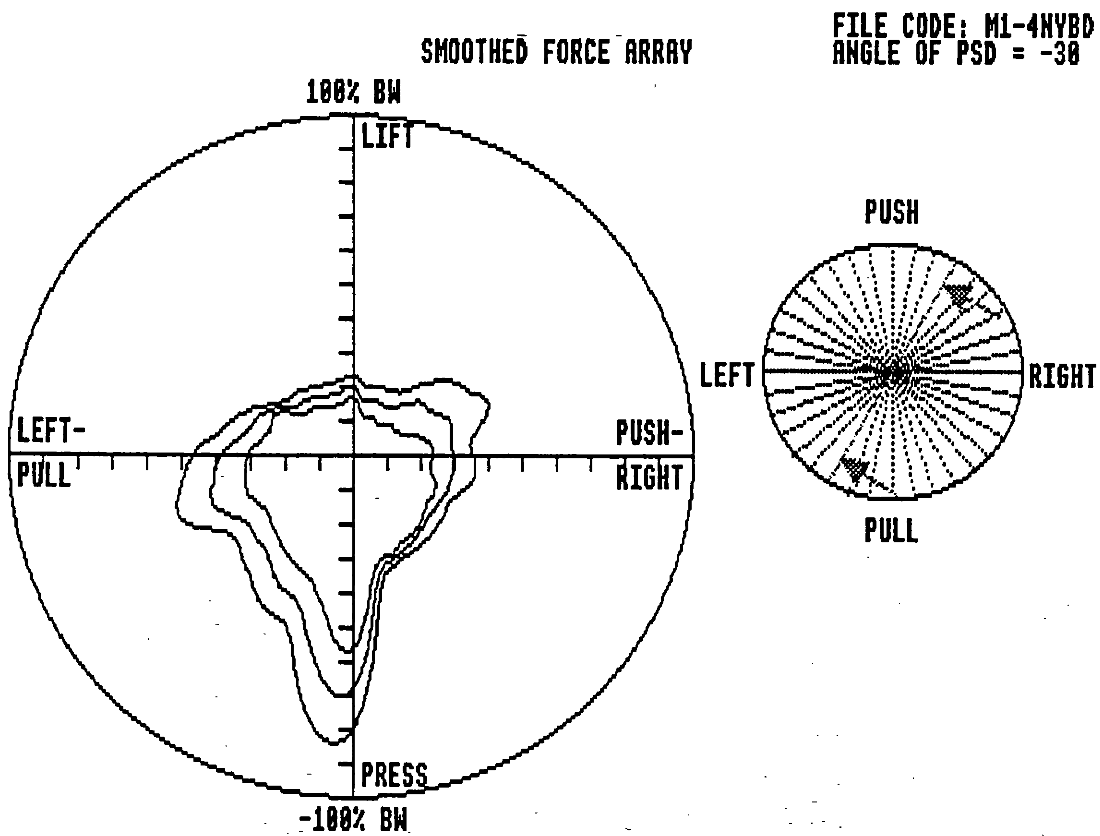
RIGHT
PULL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PUSH-
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-100% BW
PUSH
LEFT
RIGHT
PULL

SMOOTHED FORCE ARRAY

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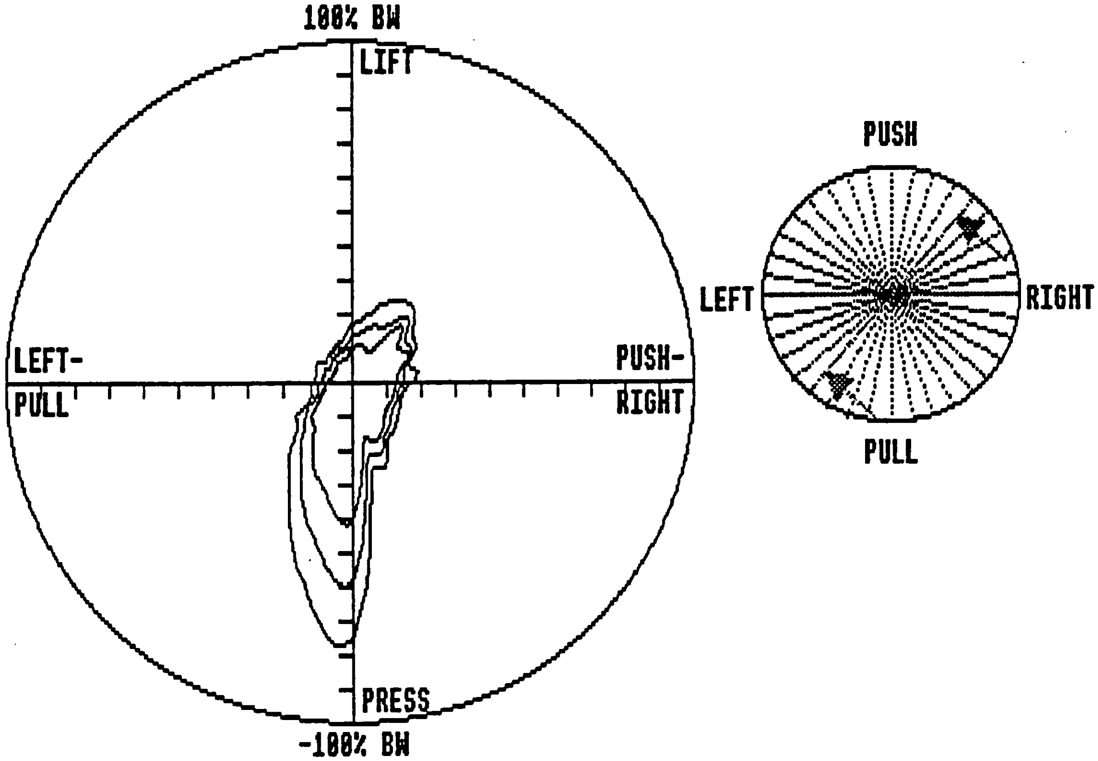

SMOOTHED FORCE ARRAY

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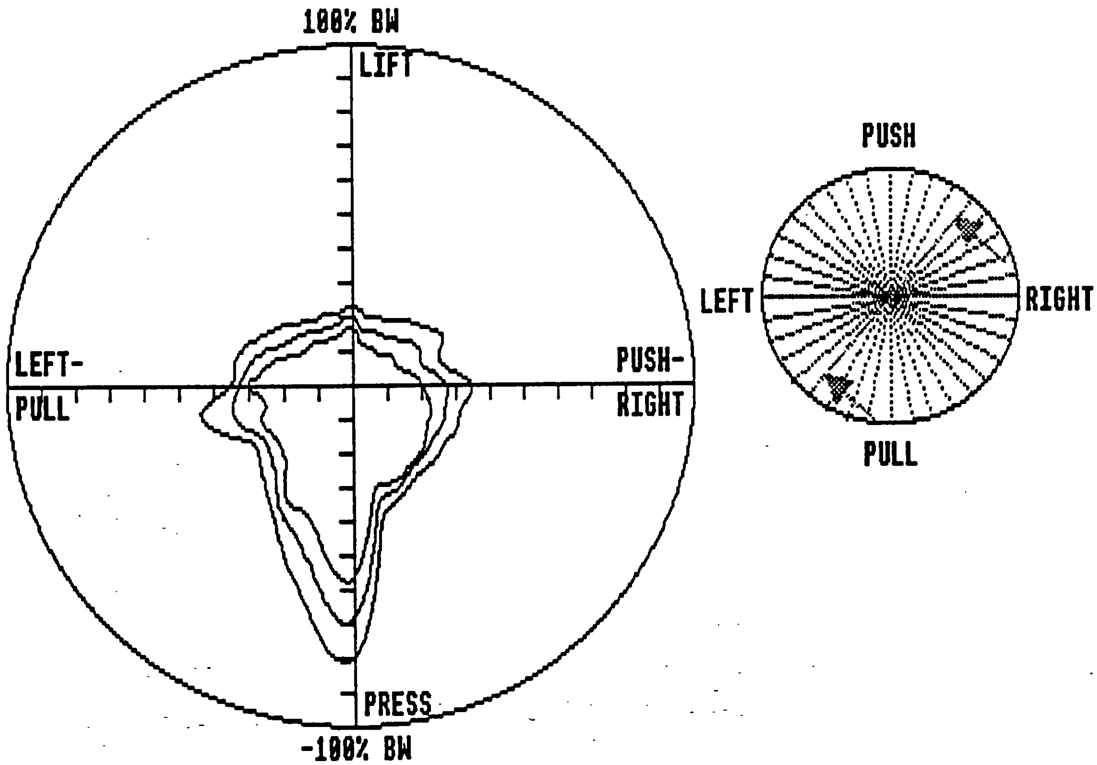

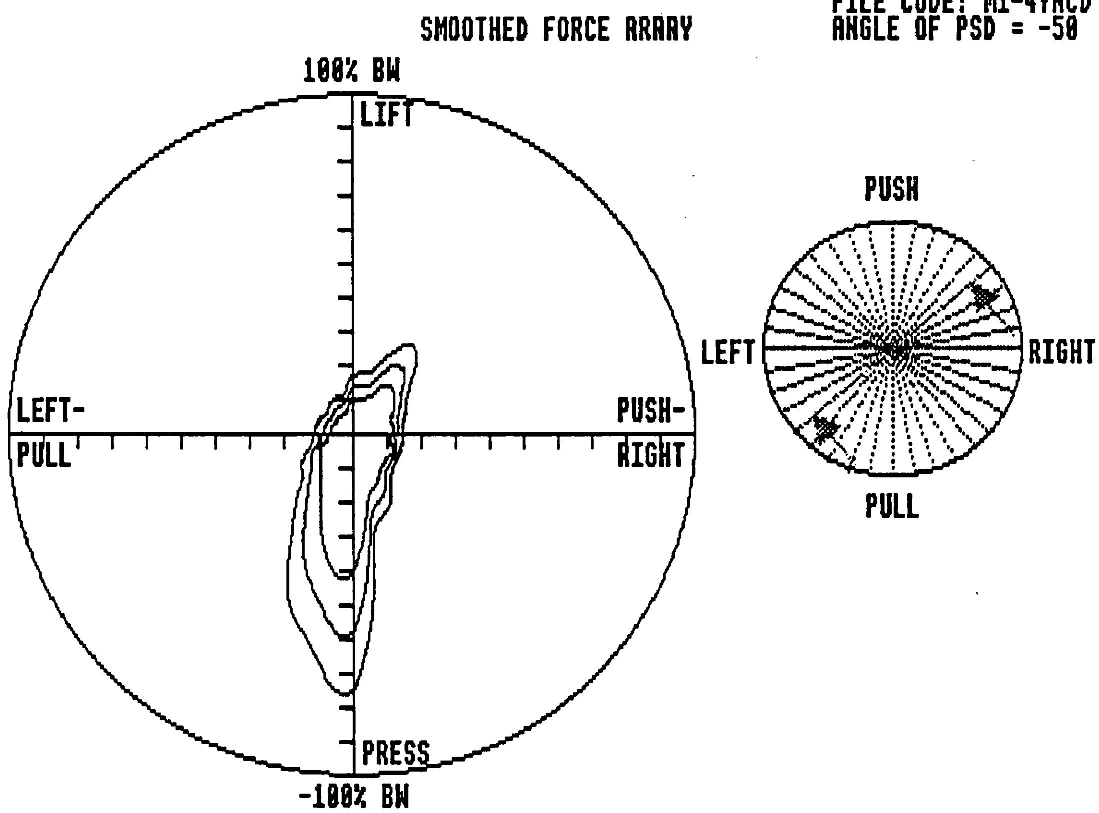
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PUSH-
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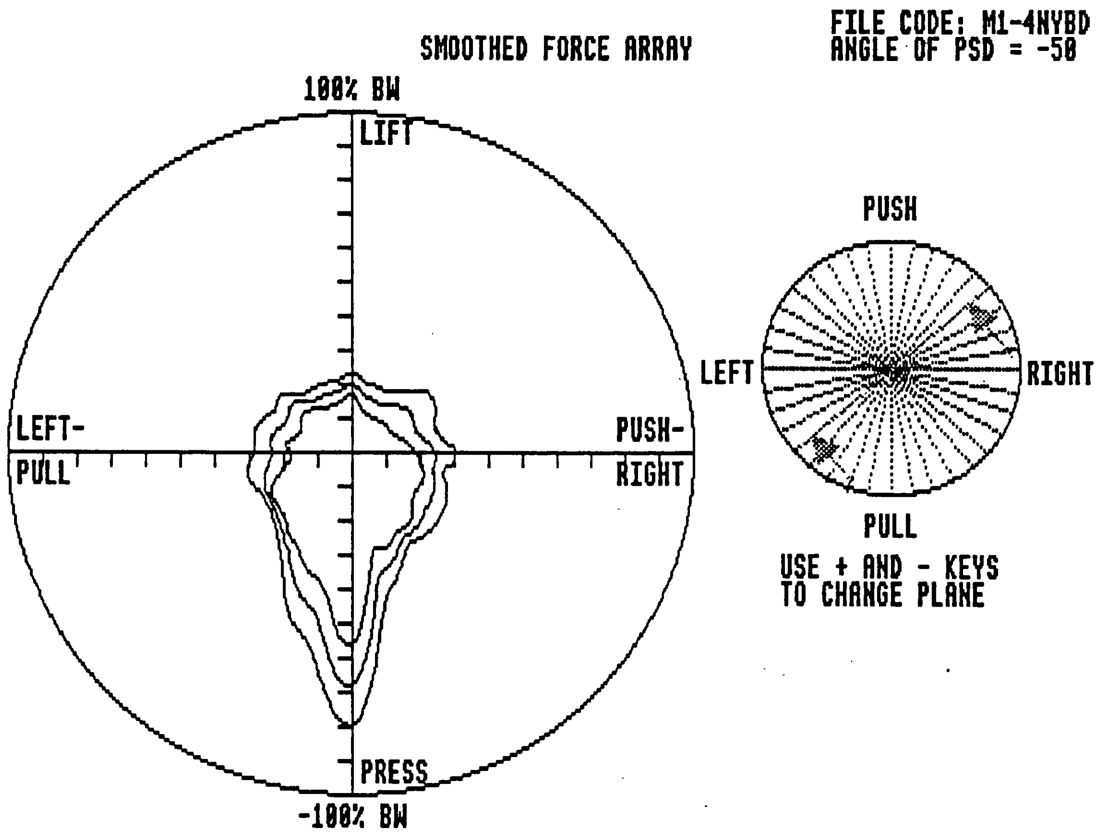
PUSH
LEFT
RIGHT
PULL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PULL
PUSH-
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PRESS
-100% BW
PUSH
LEFT
RIGHT
PULL
USE + AND - KEYS
TO CHANGE PLANE

FILE CODE: M1-4YNCD
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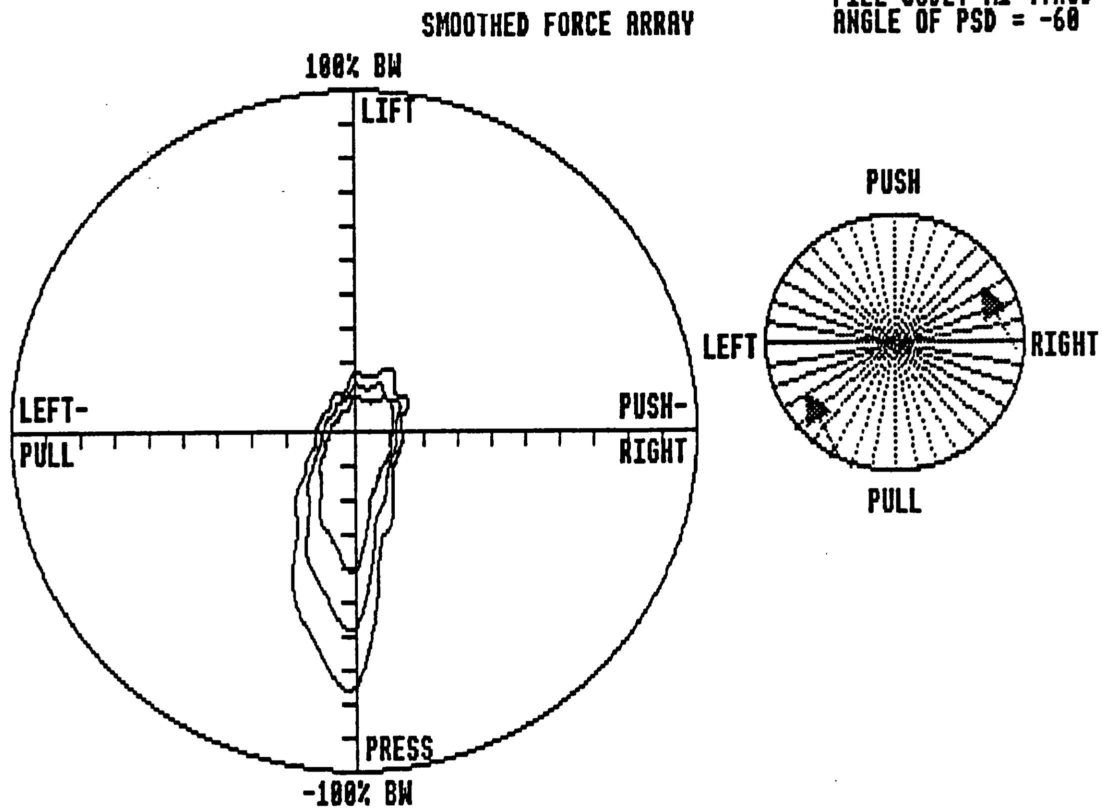

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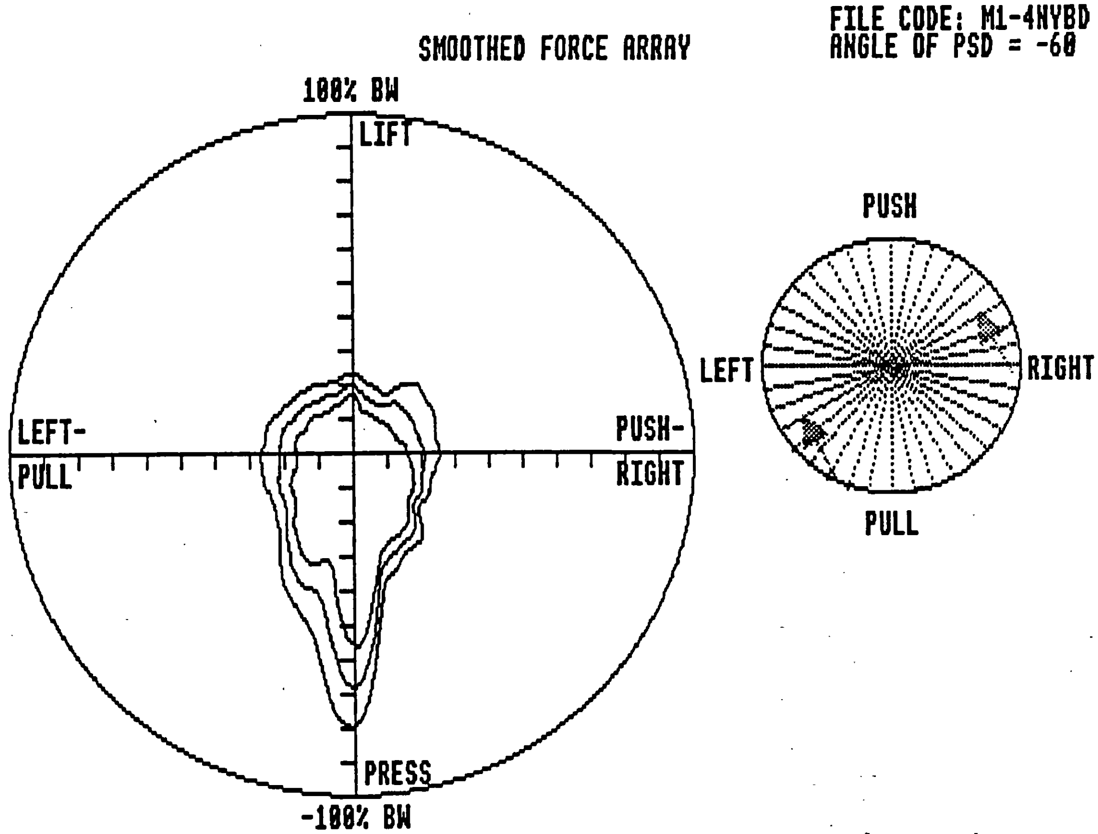

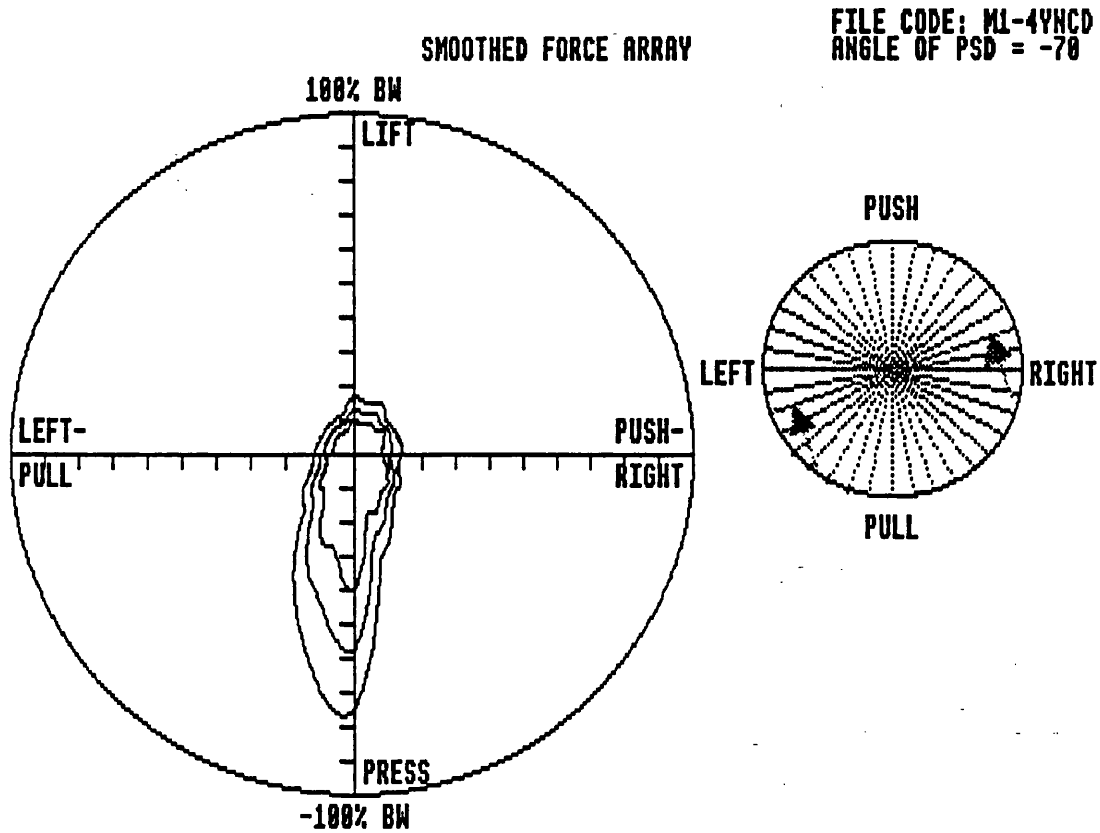
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PULL
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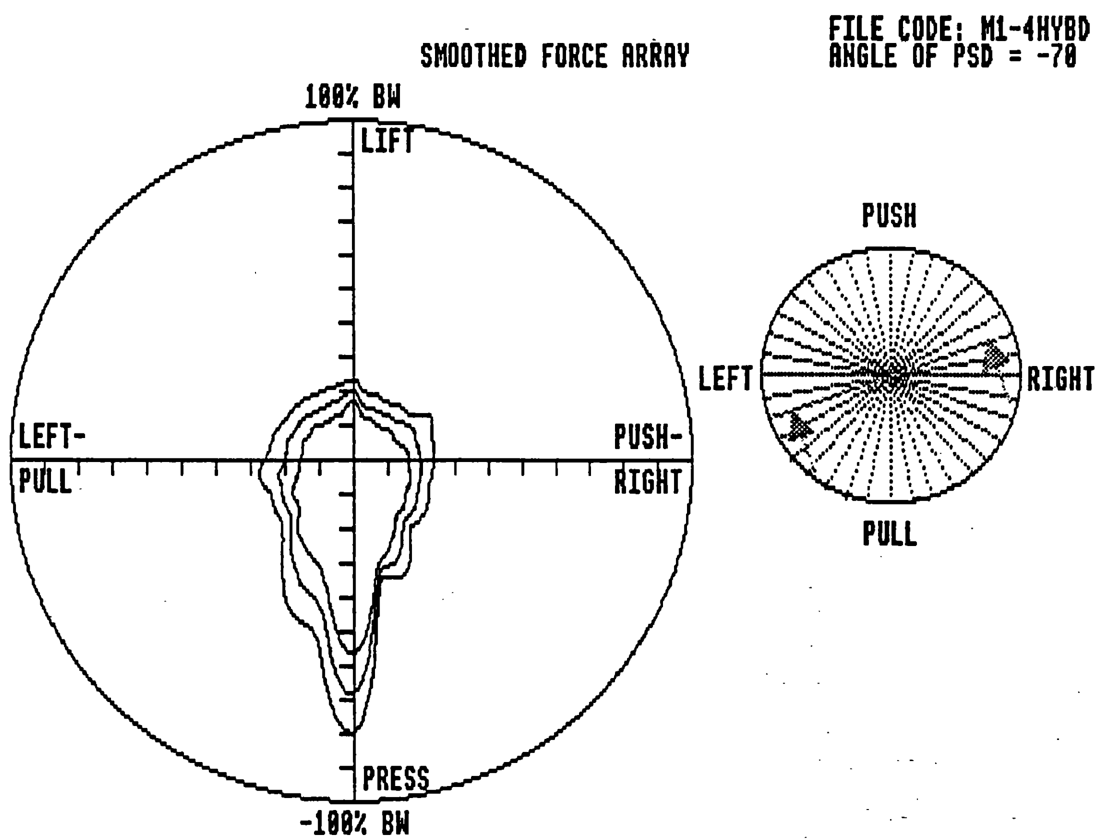
RIGHT
PULL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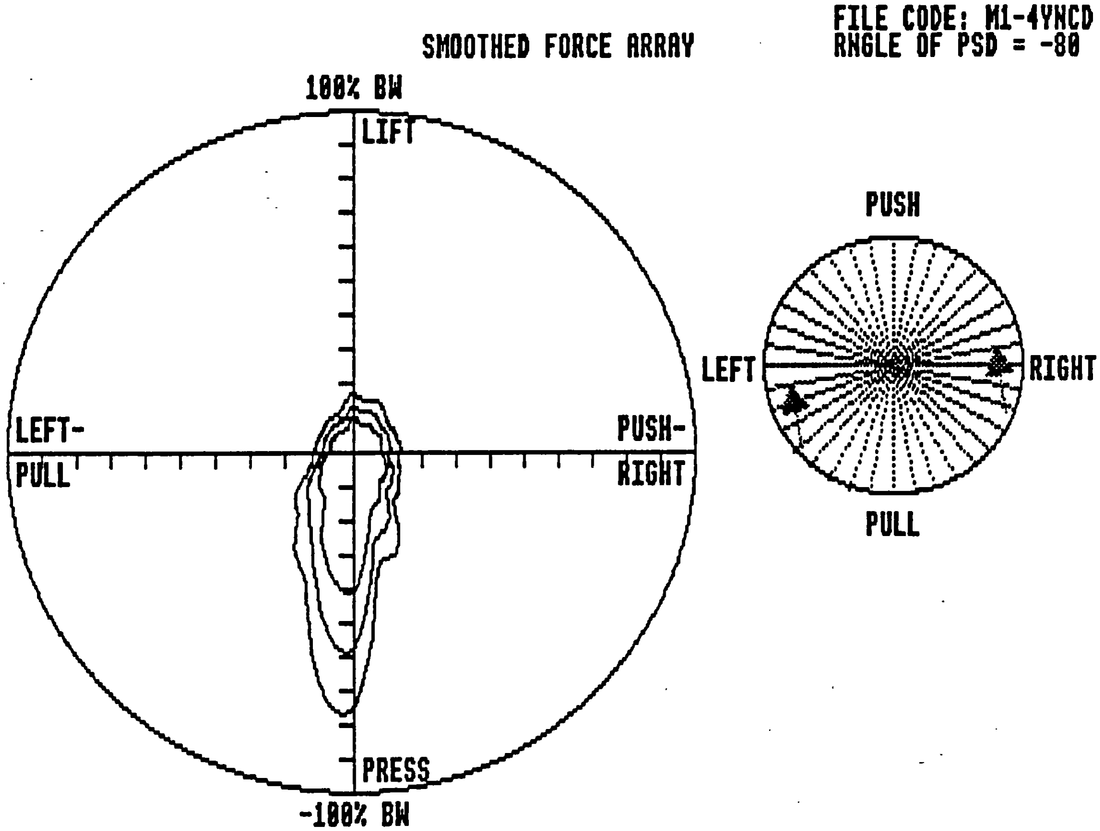
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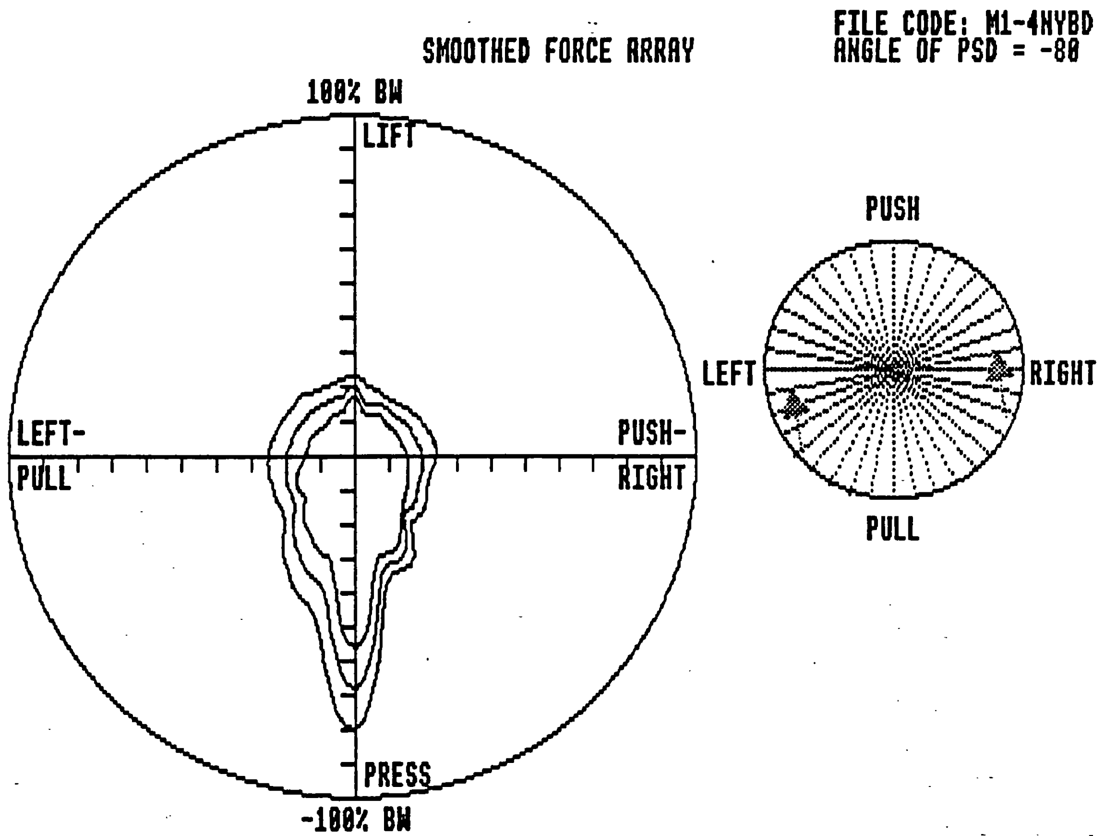
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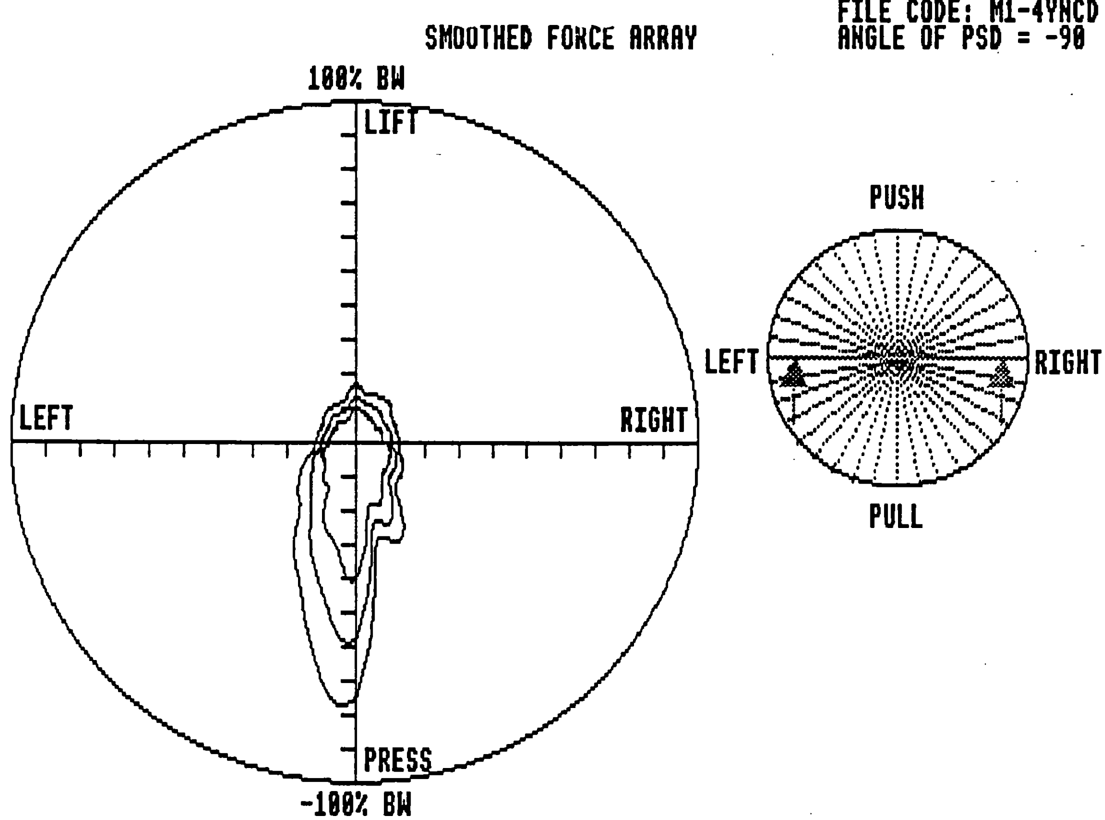
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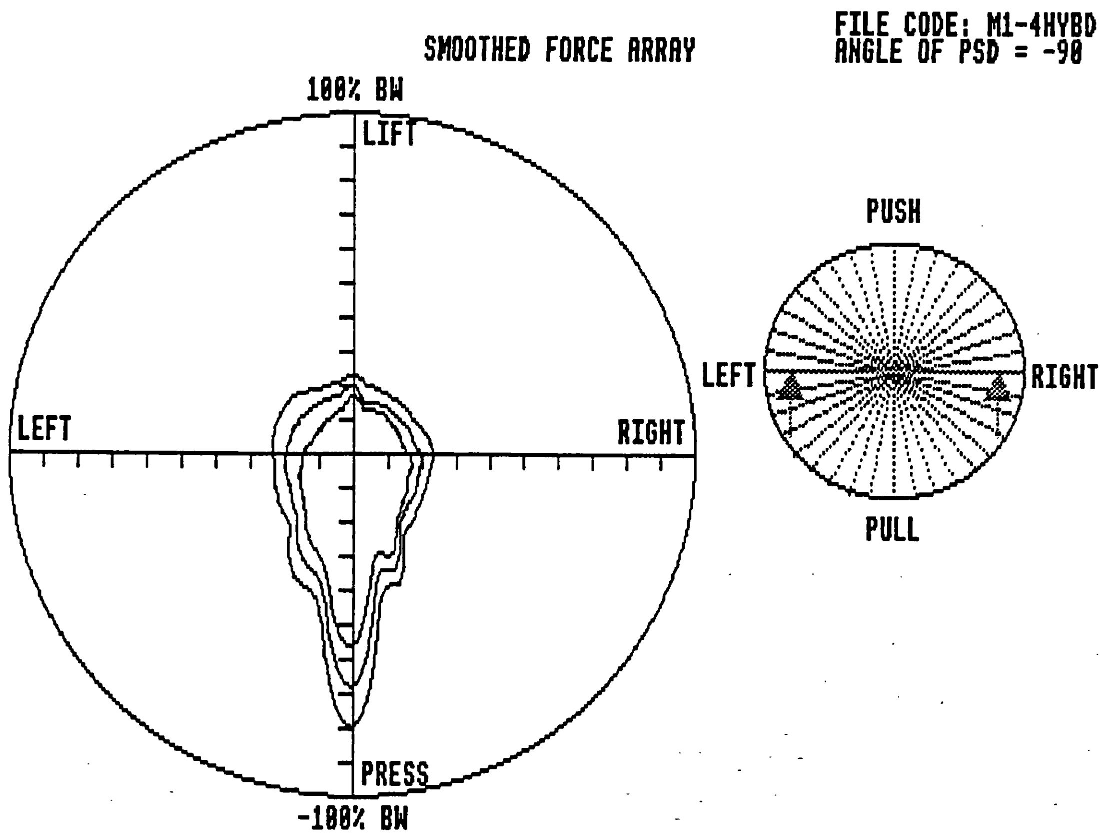
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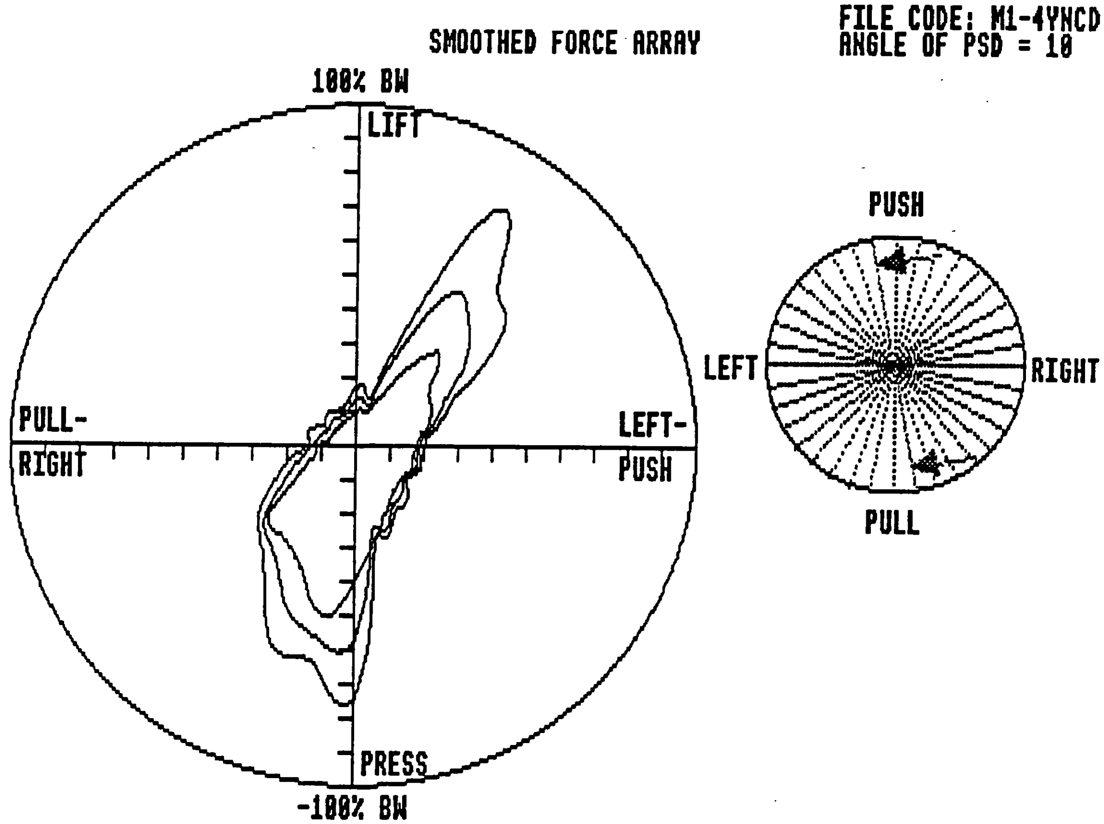
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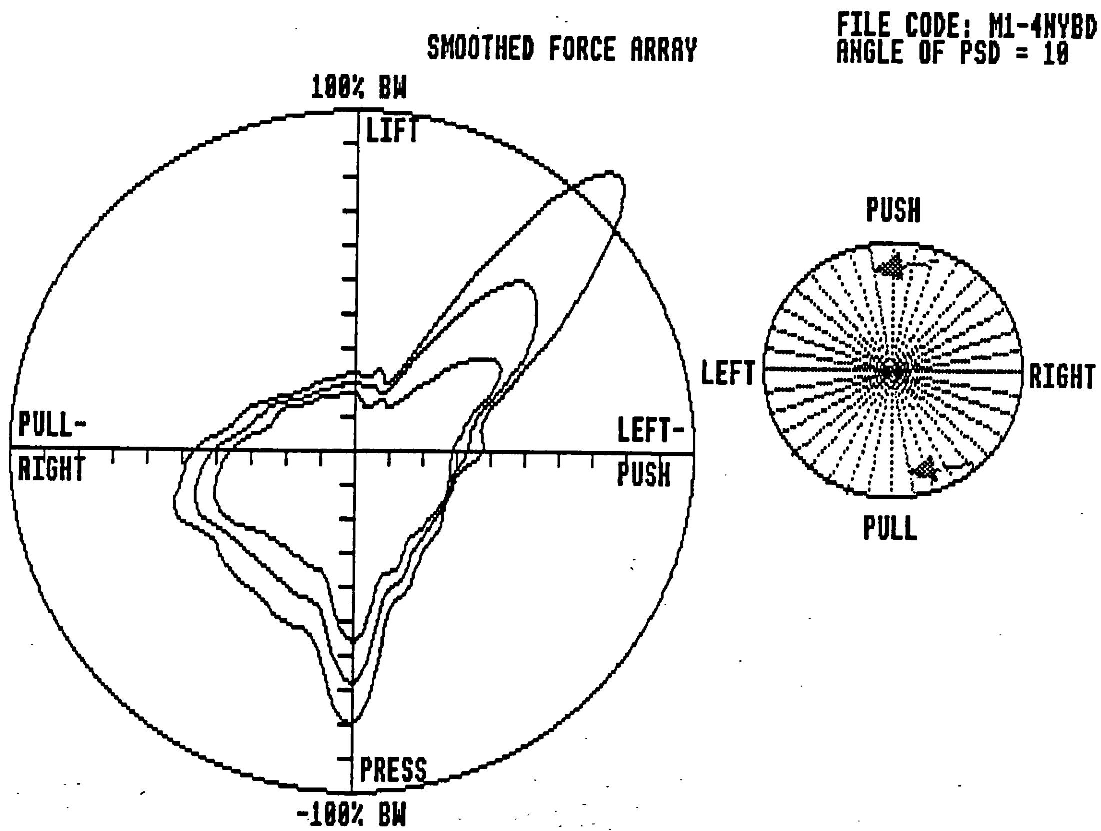
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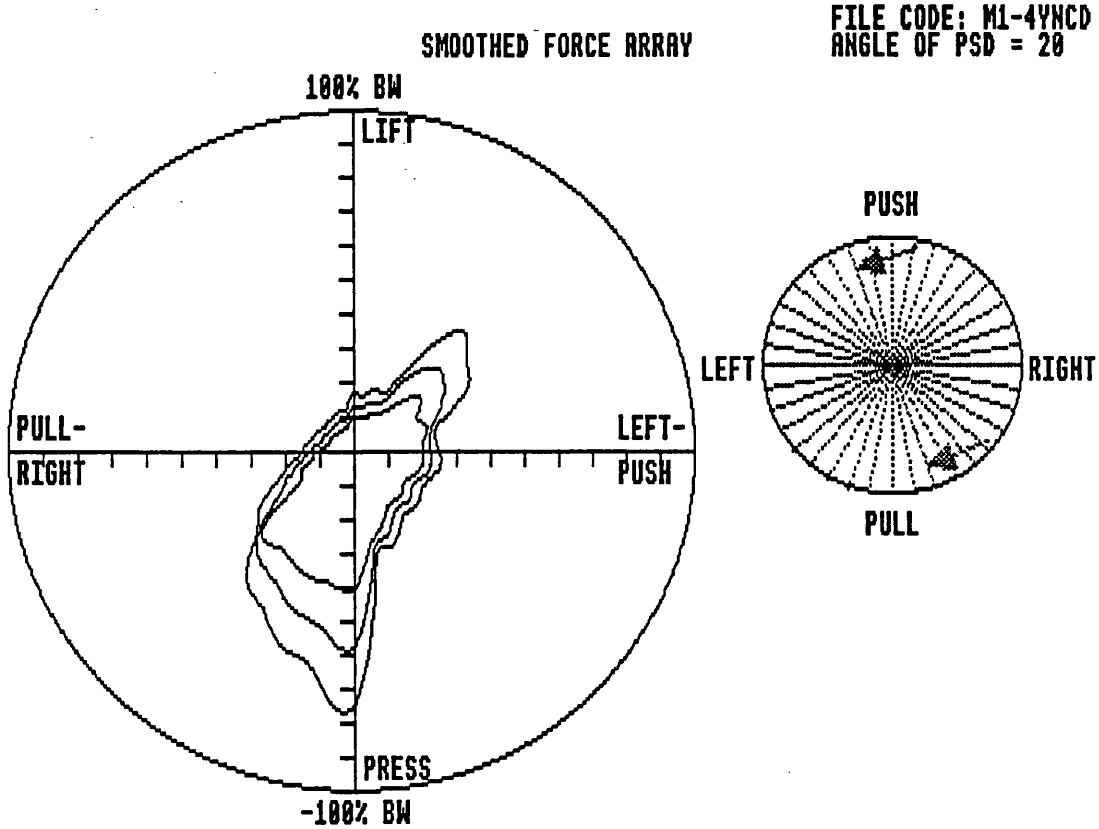
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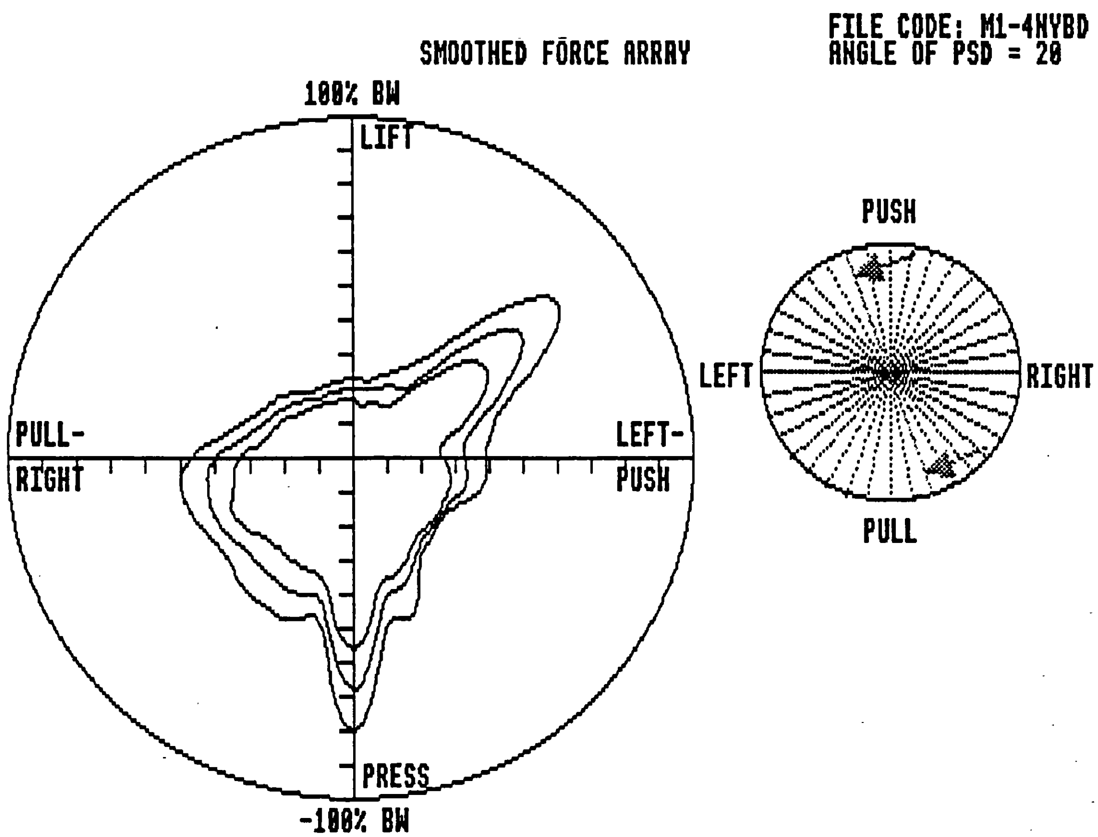
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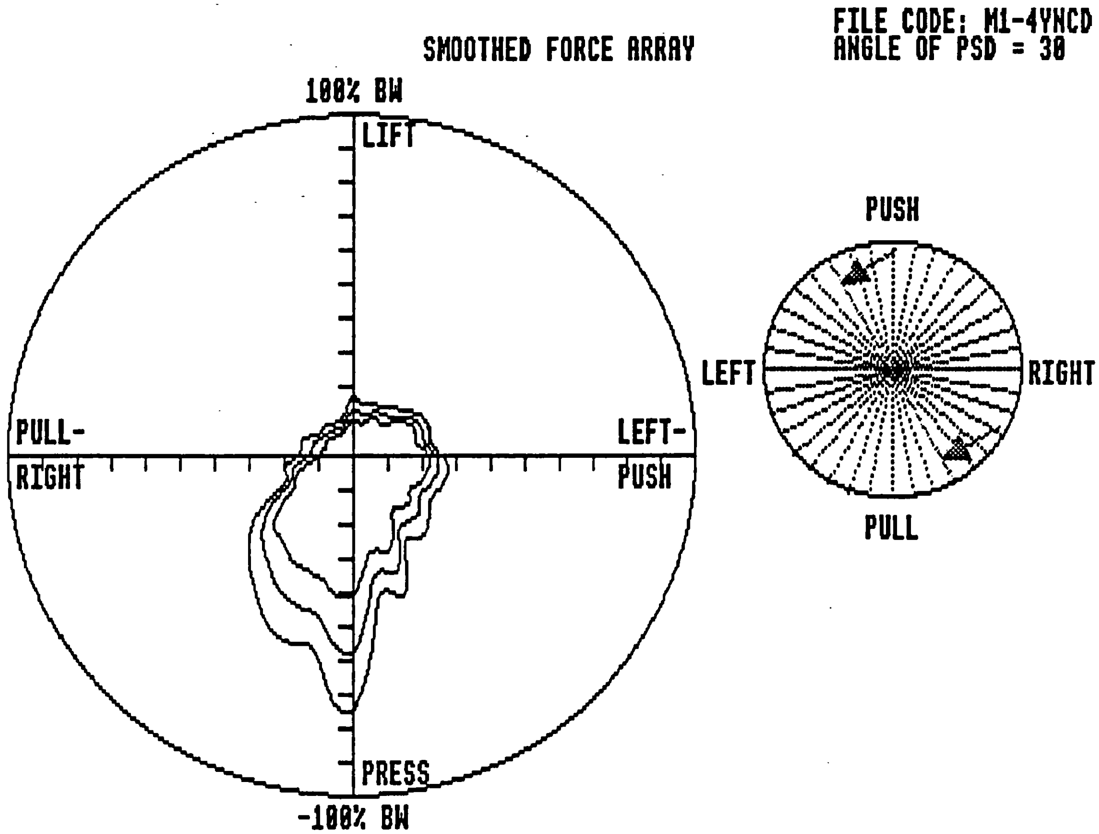
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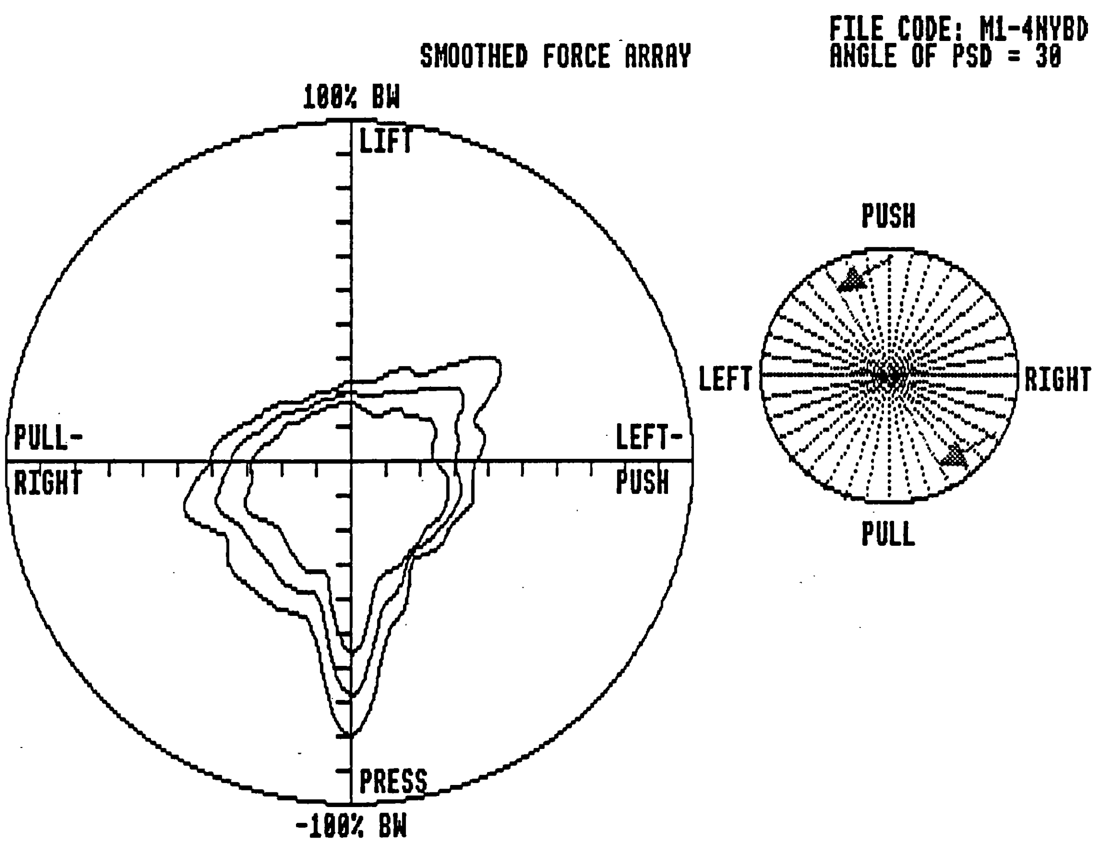
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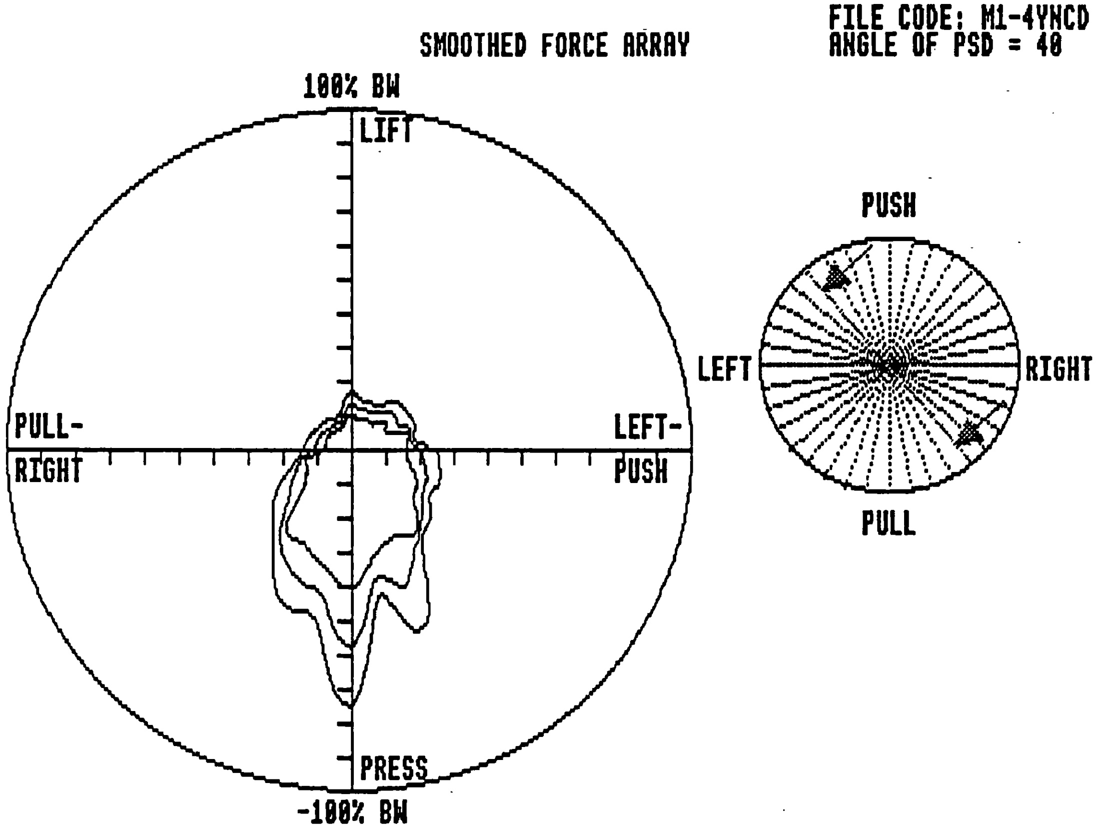

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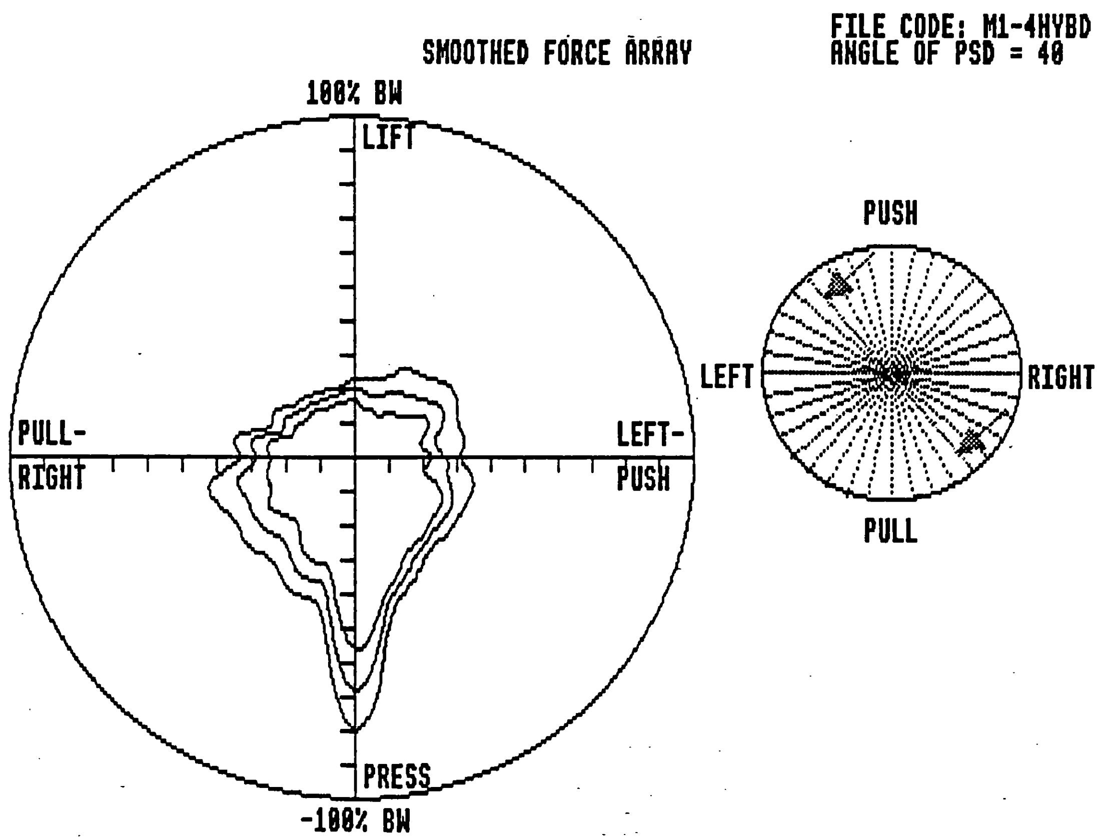

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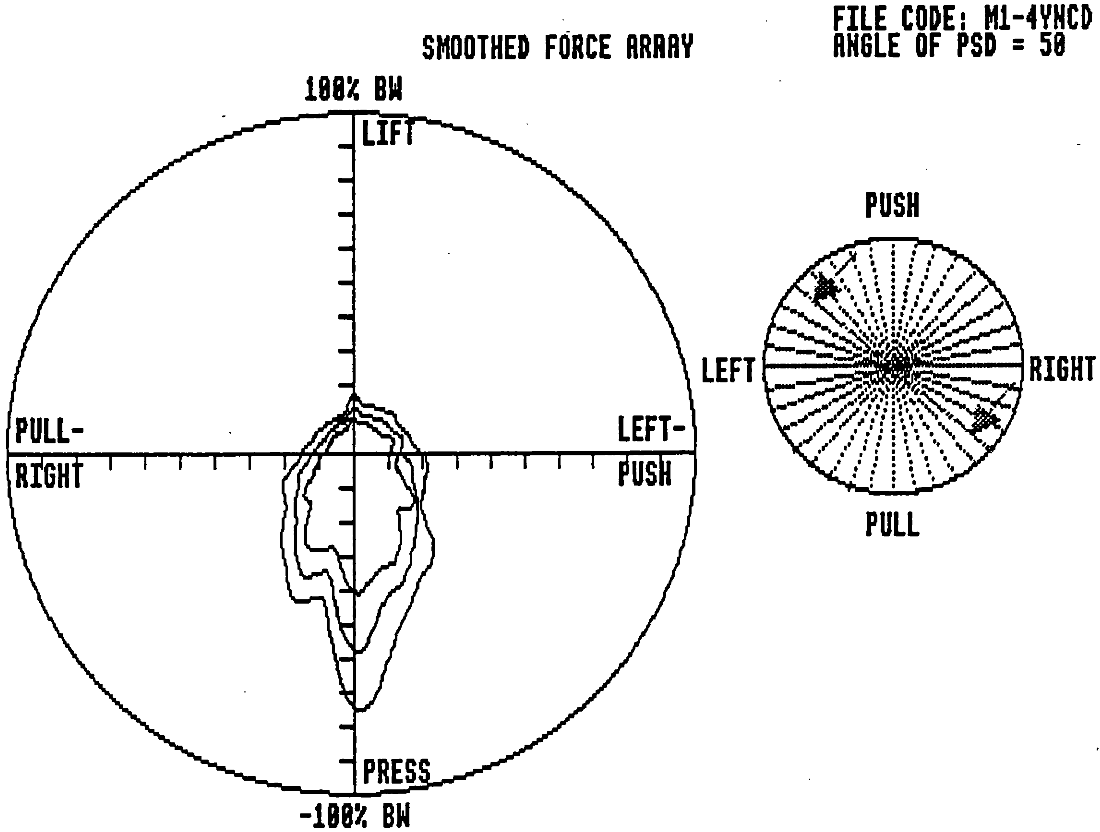
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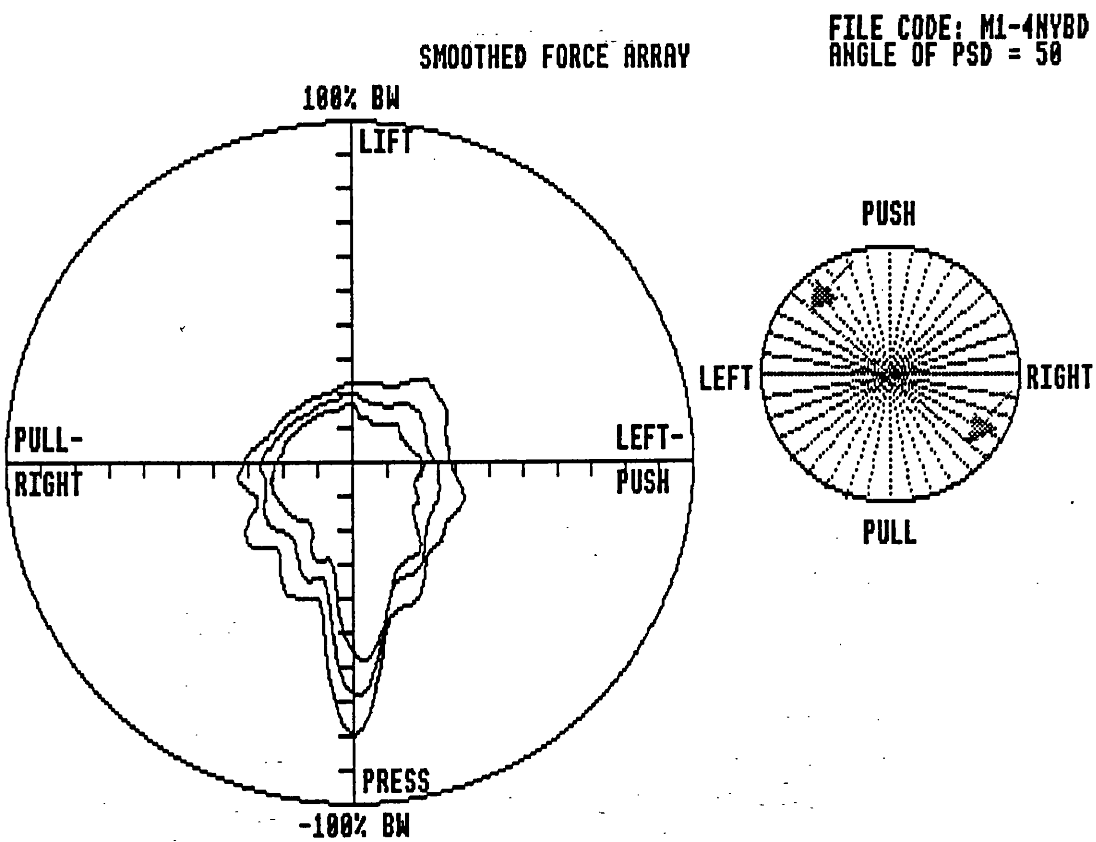
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SMOOTHED FORCE ARRAY

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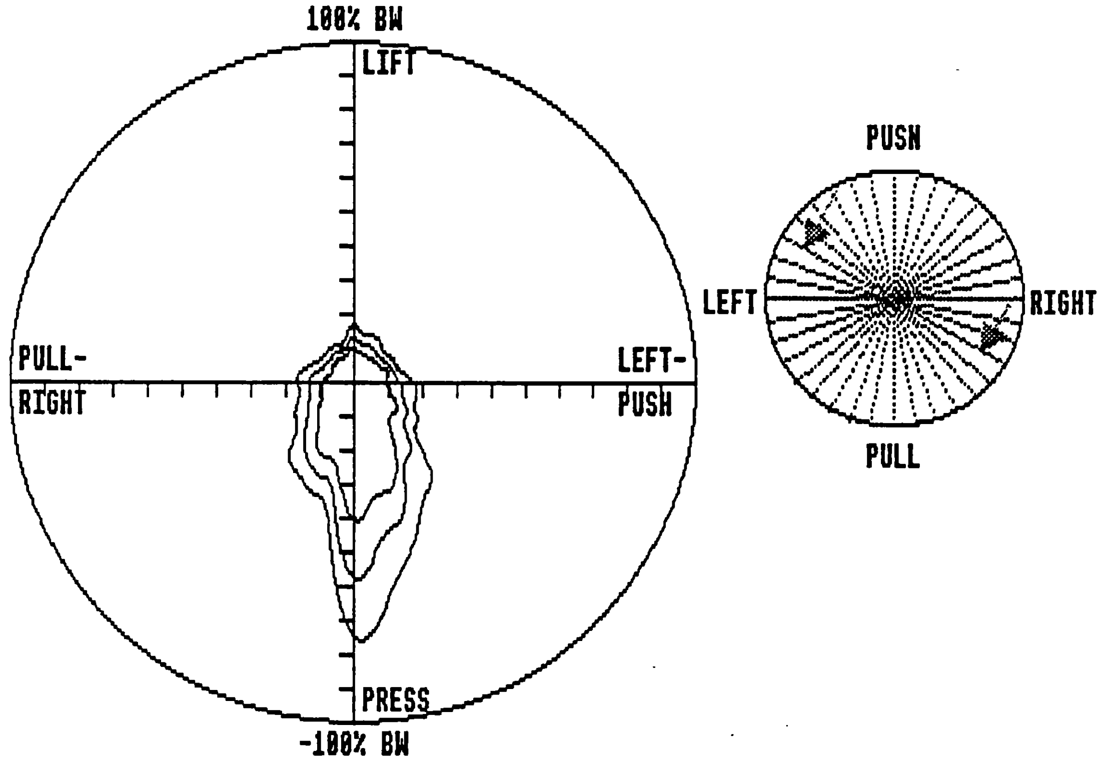

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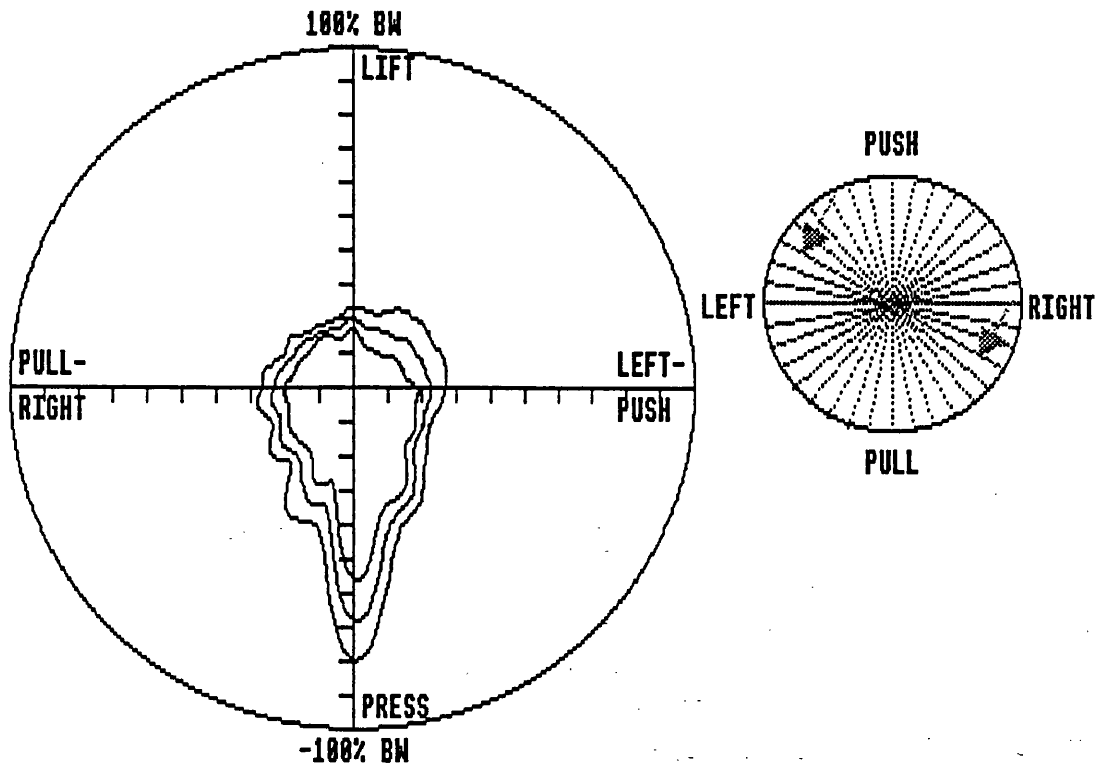

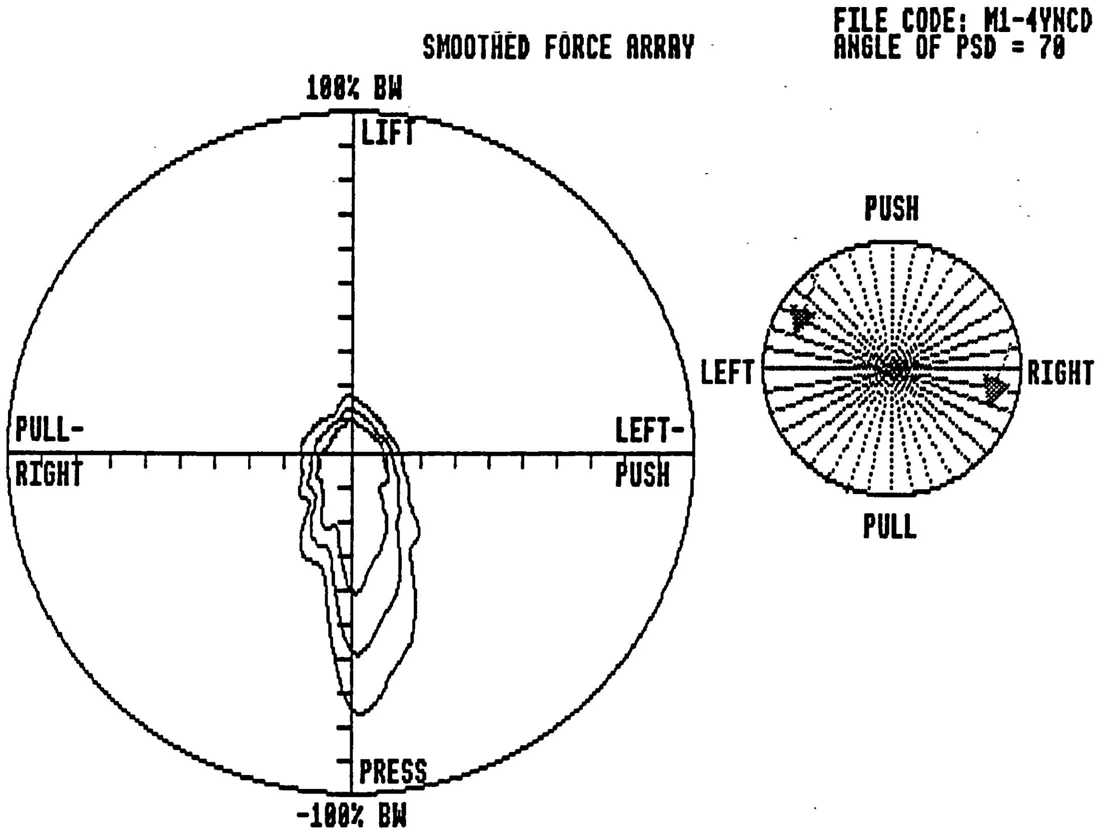
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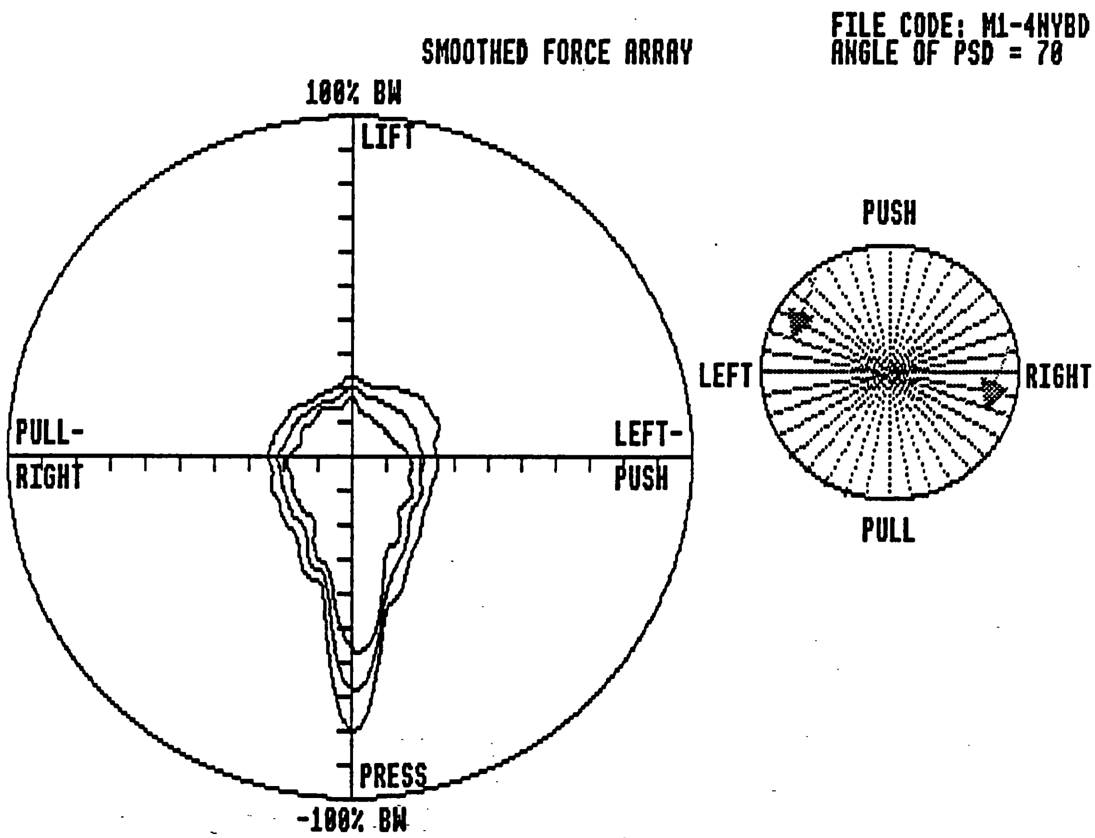
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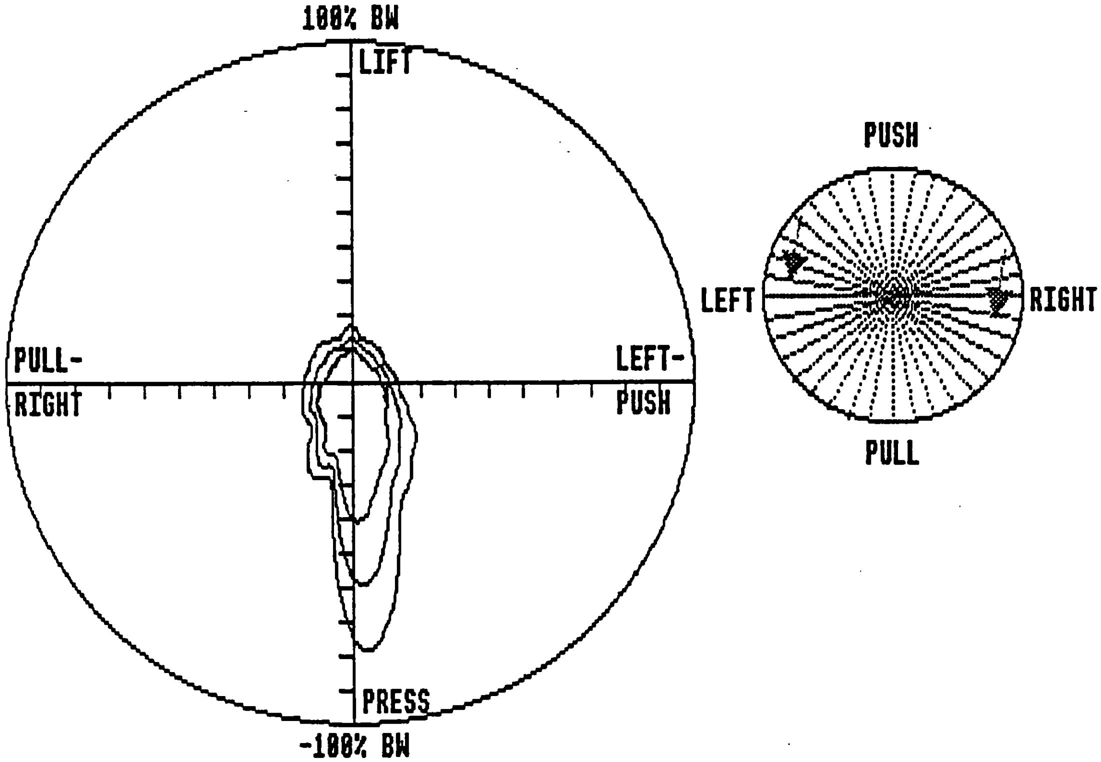
FILE CODE: M1-4YNCD
ANGLE OF PSD = 80

SMOOTHED FORCE ARRAY



FILE CODE: M1-4NYBD
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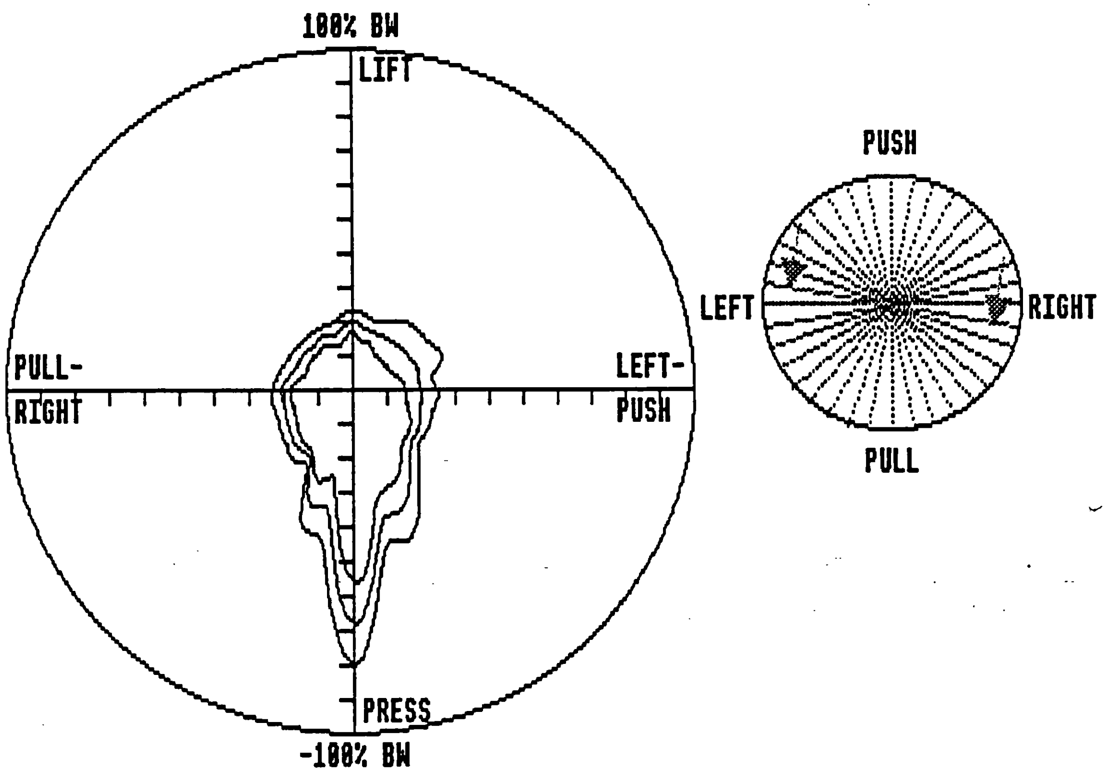
SMOOTHED FORCE ARRAY



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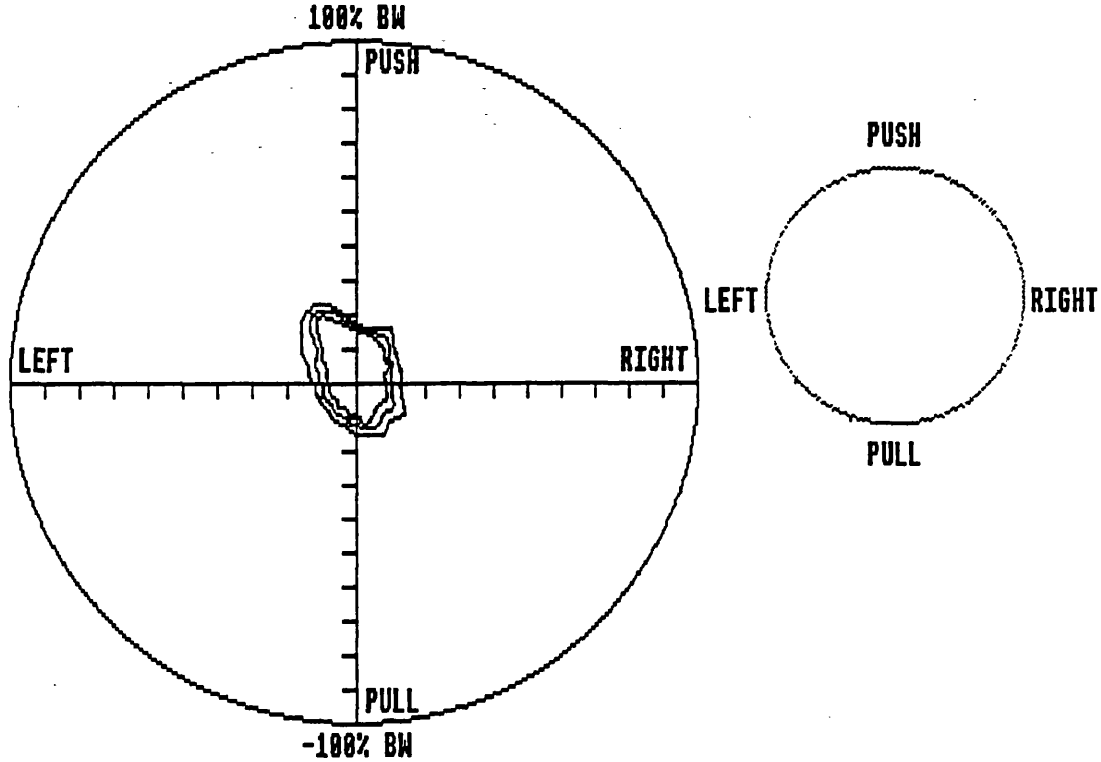

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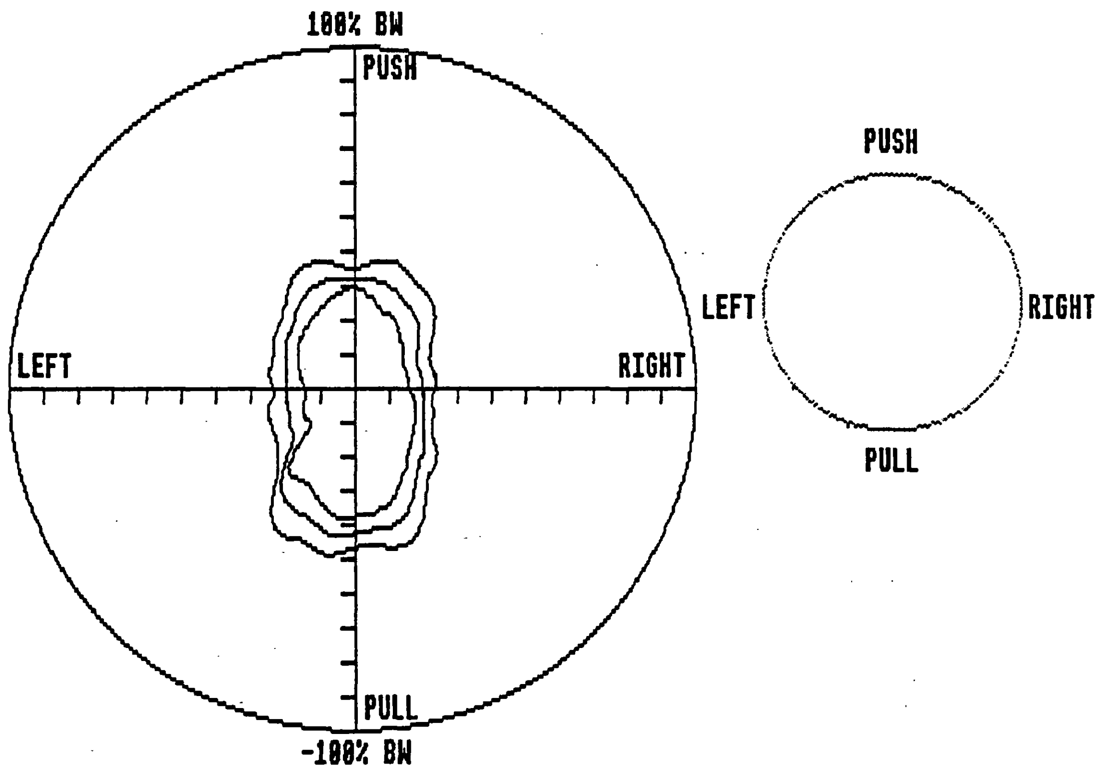
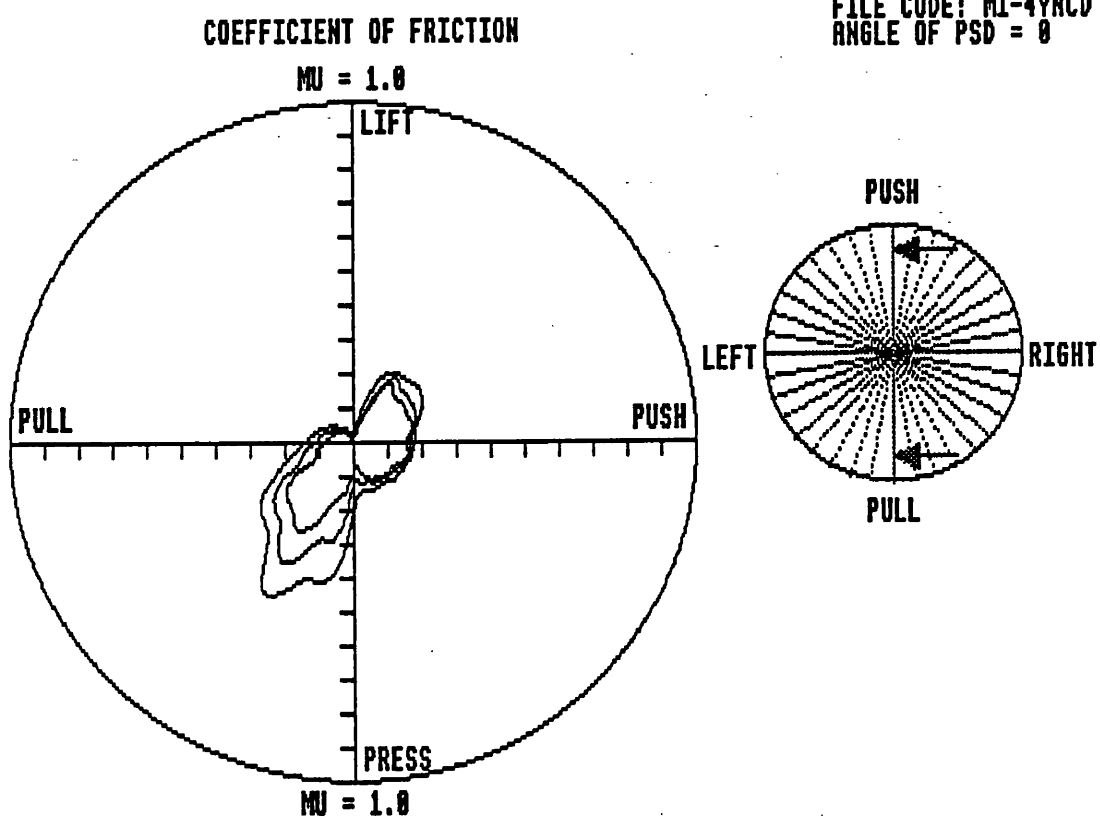


Figure C2: The following graphs represent PSD's of the minimum value of the coefficient of friction (at the foot floor interface) for each 10° vertical plane in the sphere of exertion (as well as for one horizontal plane when the vertical force is zero) for one-handed maximal whole body static exertions on the 3D dynamometer. On each page the upper and lower figures represent exertions at the 1.75 m and 1.0 m handle height respectively. The plane of exertion viewed is indicated in each case by the arrows on the smaller circle. The data is based on the mean and SD of the forces recorded on four male subjects with horizontal foot placements 0.5 m from the handle.

NOTES

If manual forces are directed exactly along the vertical axis by definition the magnitude of the limiting coefficient of friction becomes zero. In the following figures mean and SD values of the coefficient of static friction in the vertical lift and vertical press directions are shown greater than zero in a number of cases. This anomaly is a result of smoothing the data using the algorithms described in Chapter 5.



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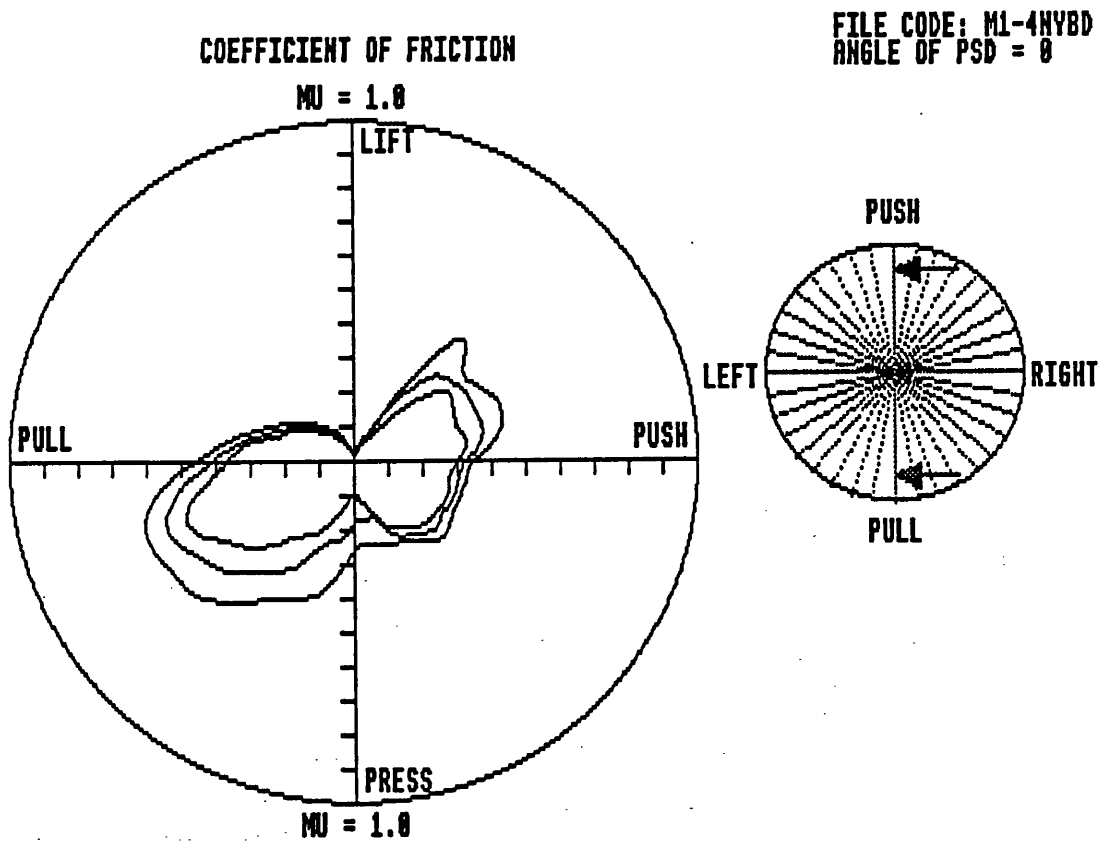

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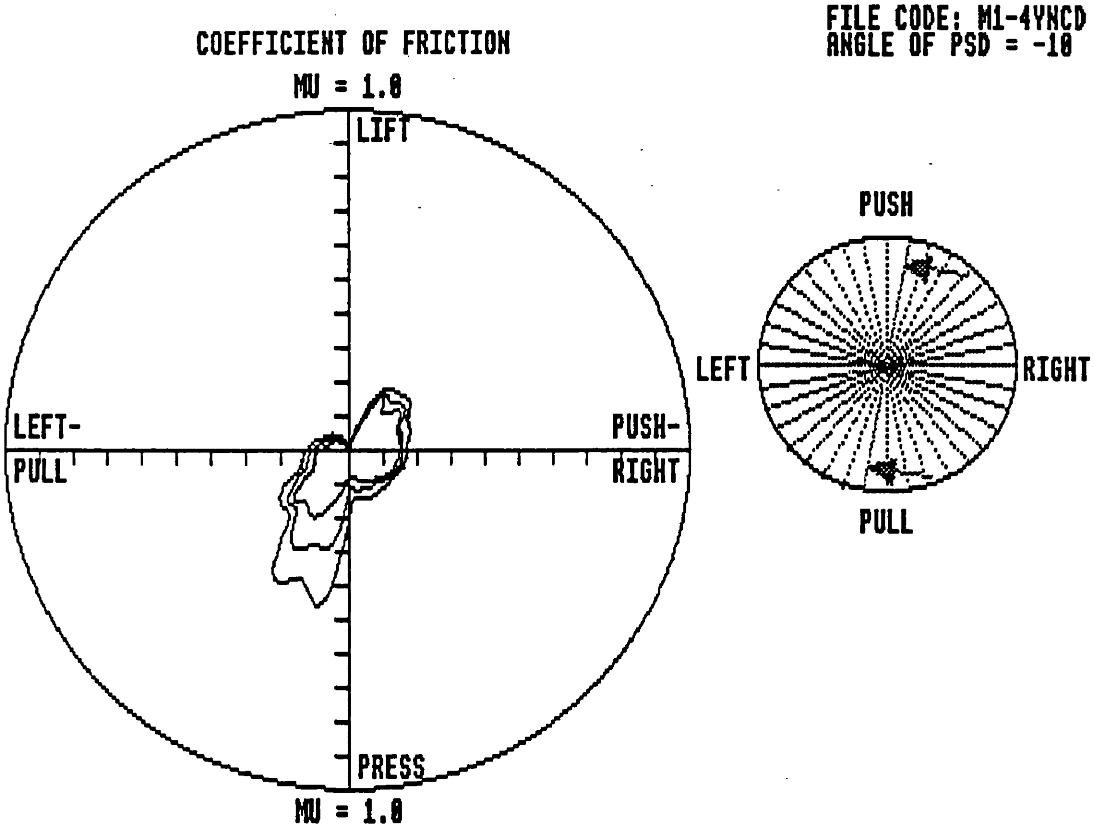
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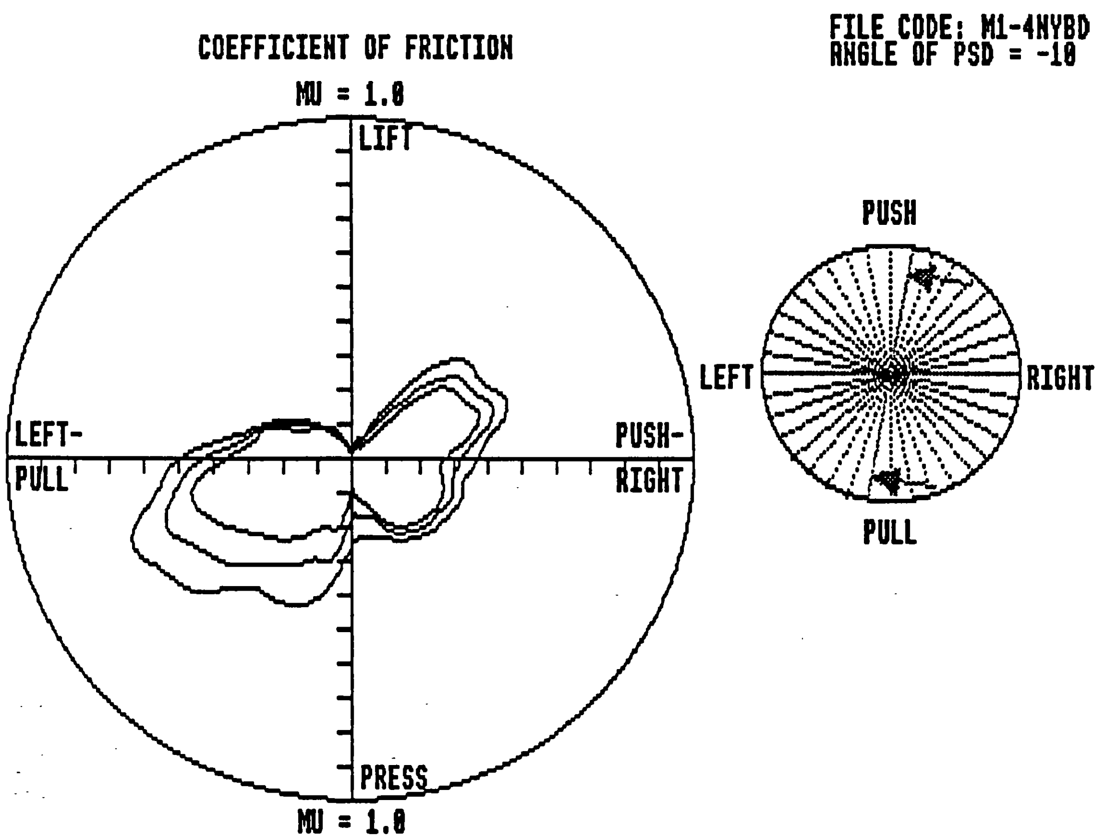
RIGHT
PULL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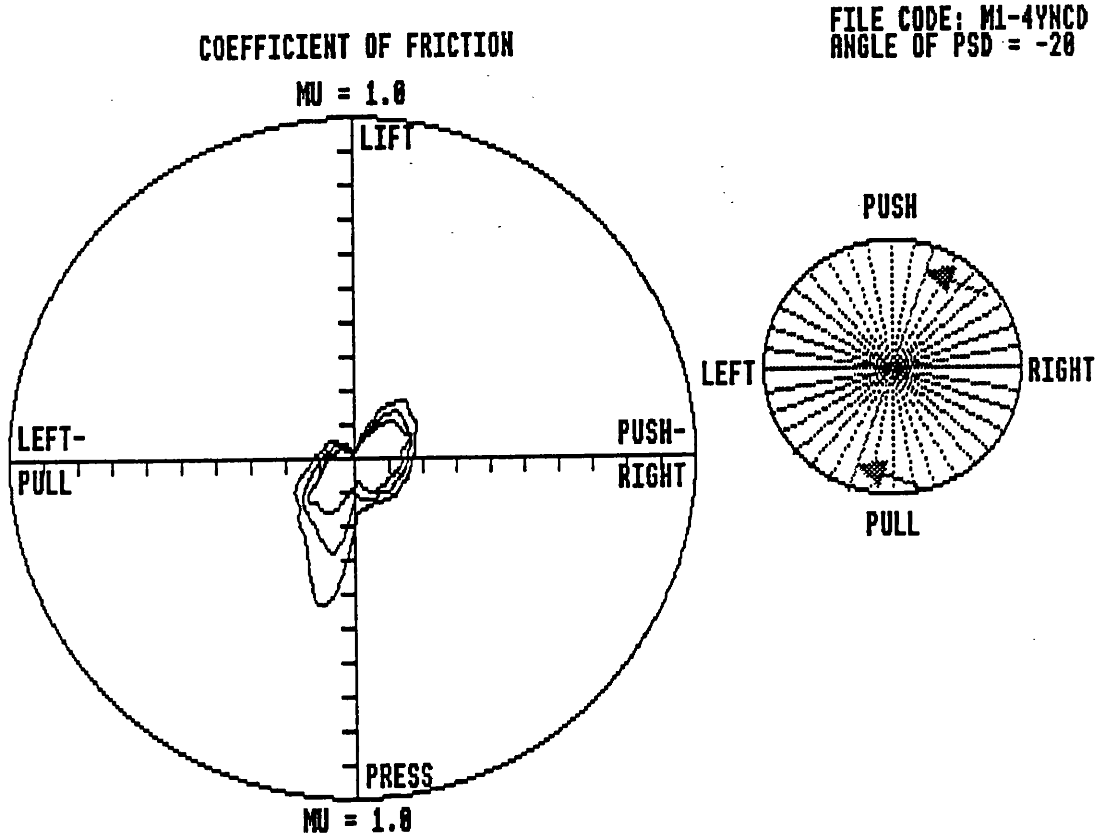
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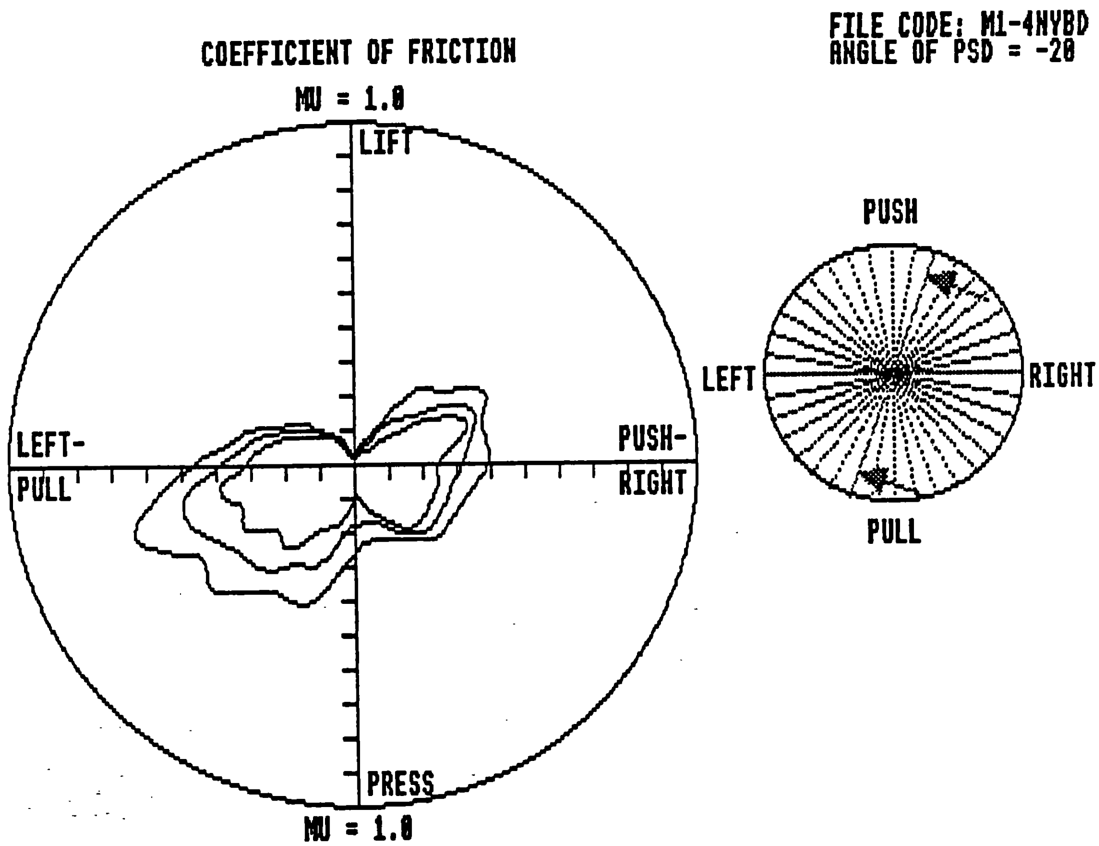
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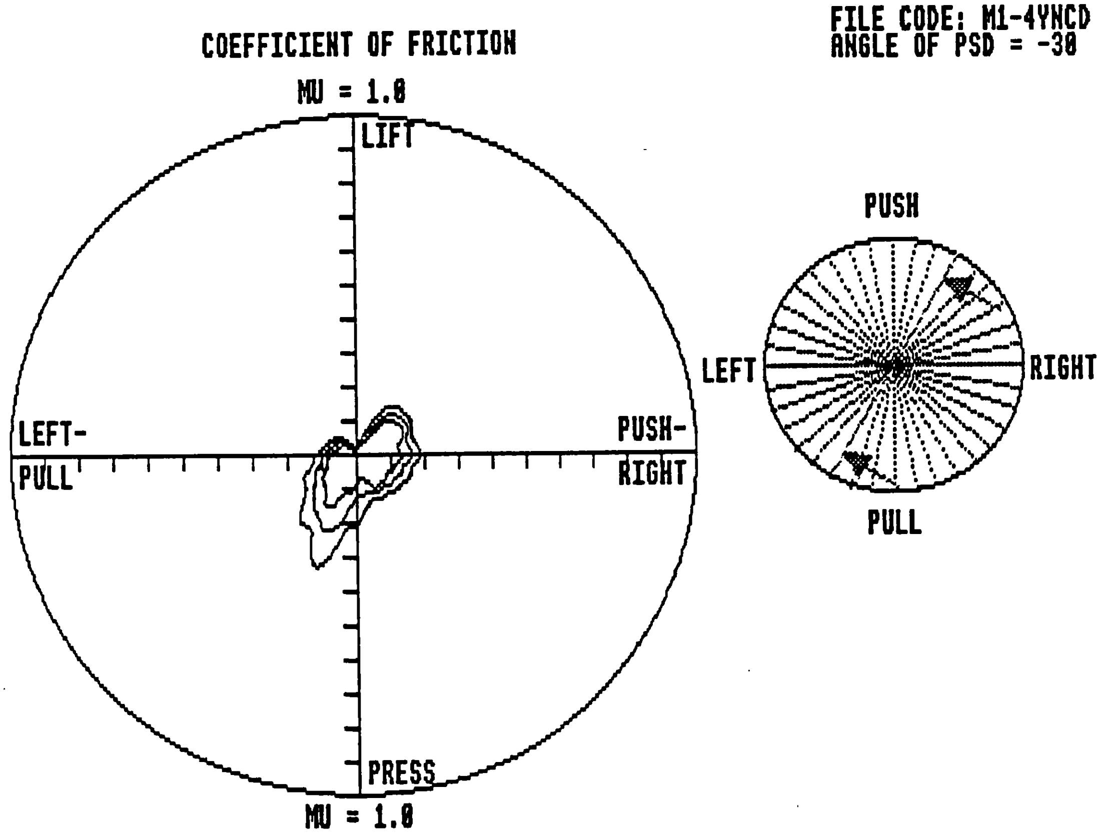
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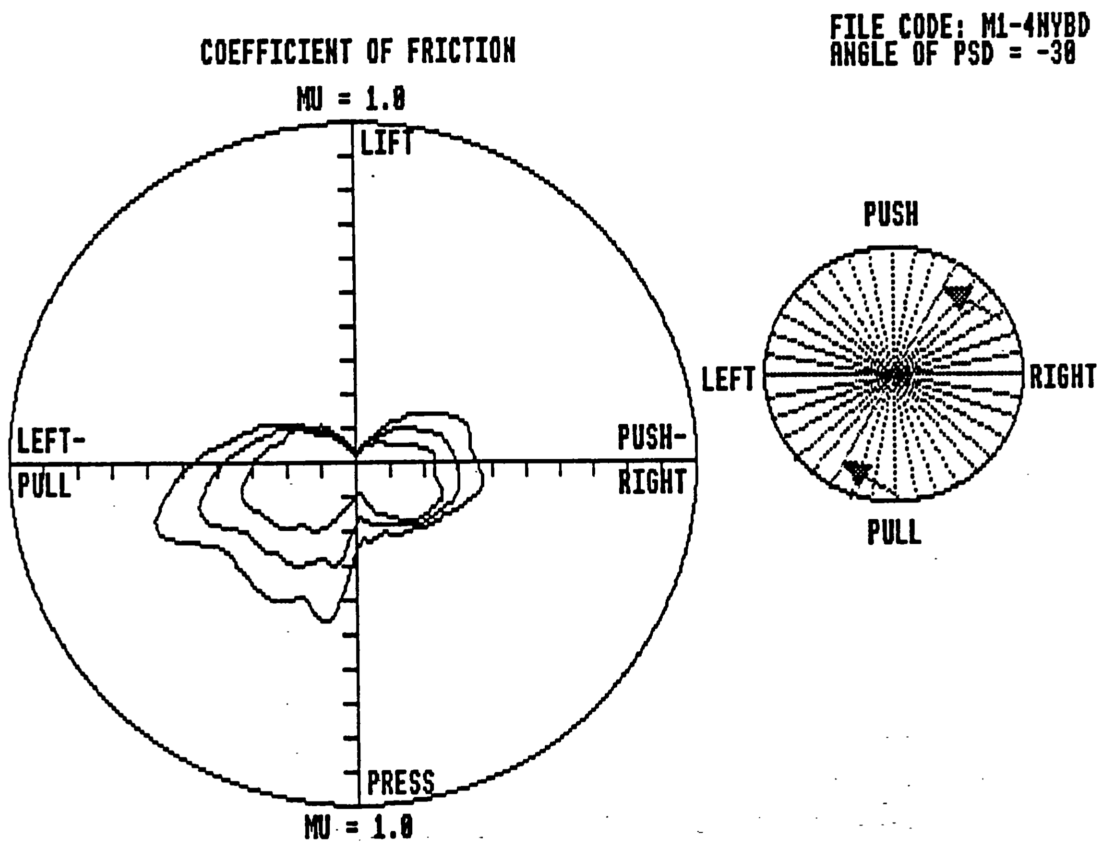
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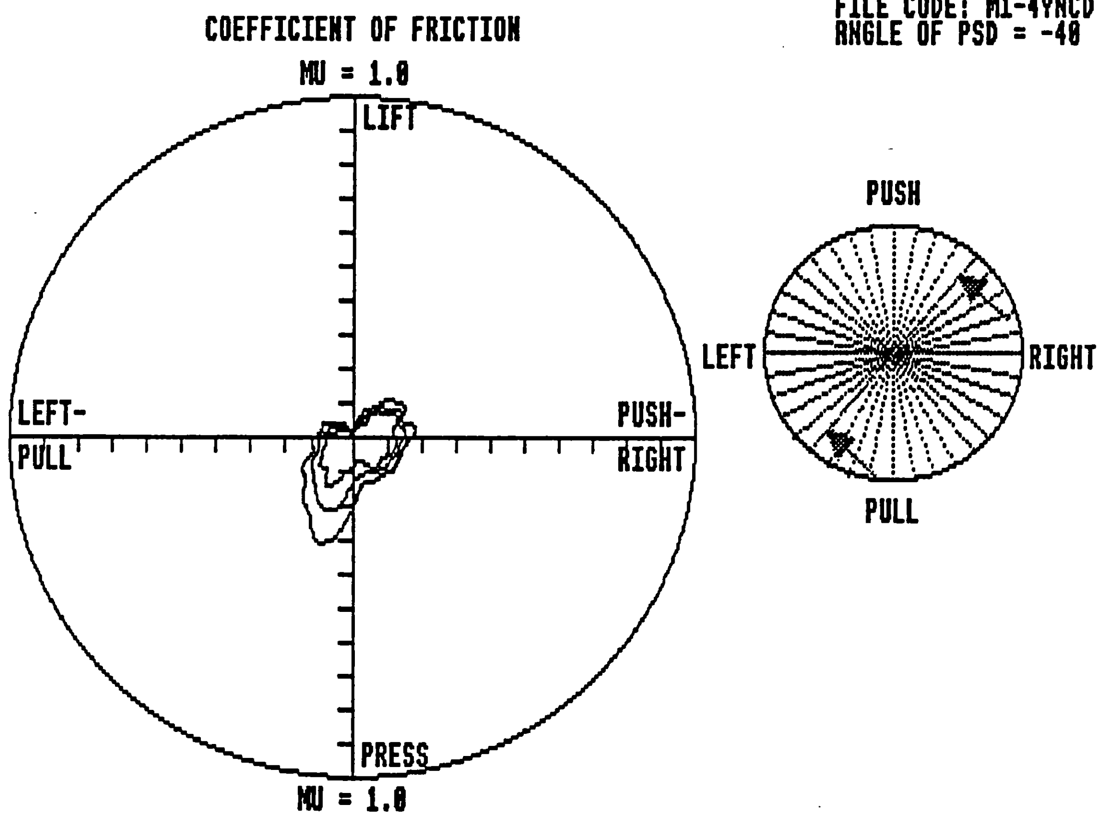
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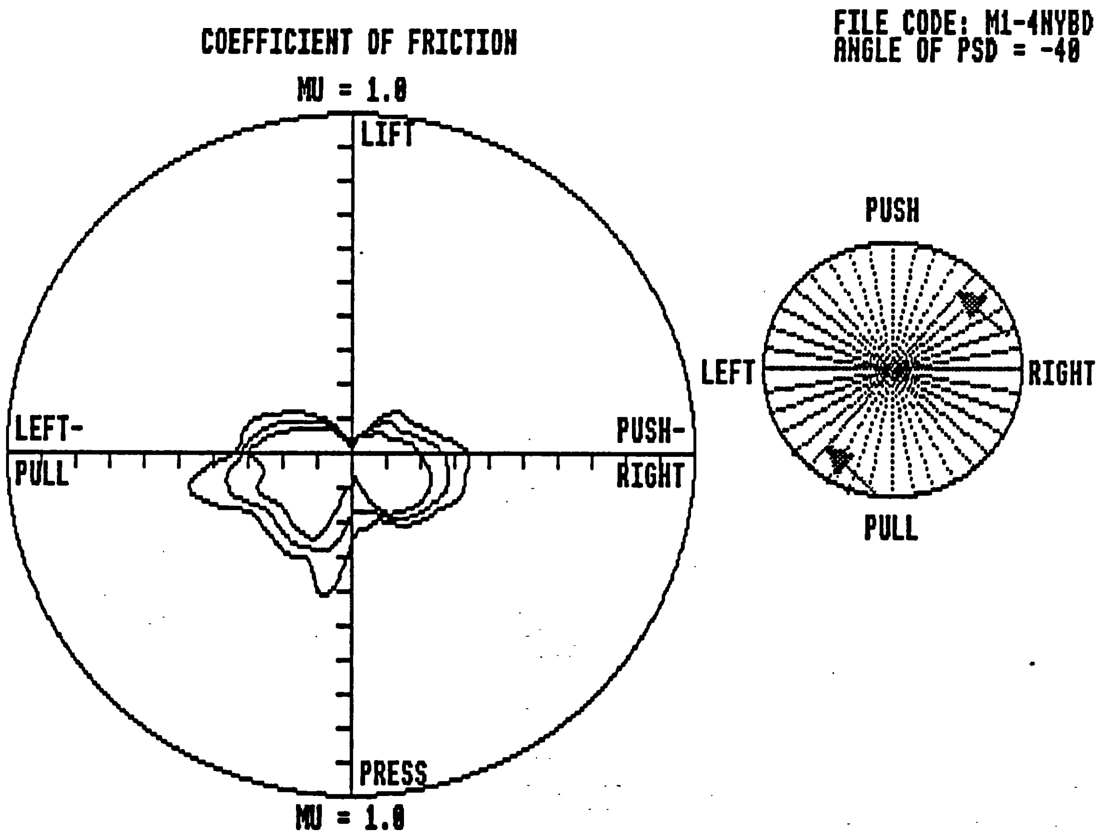
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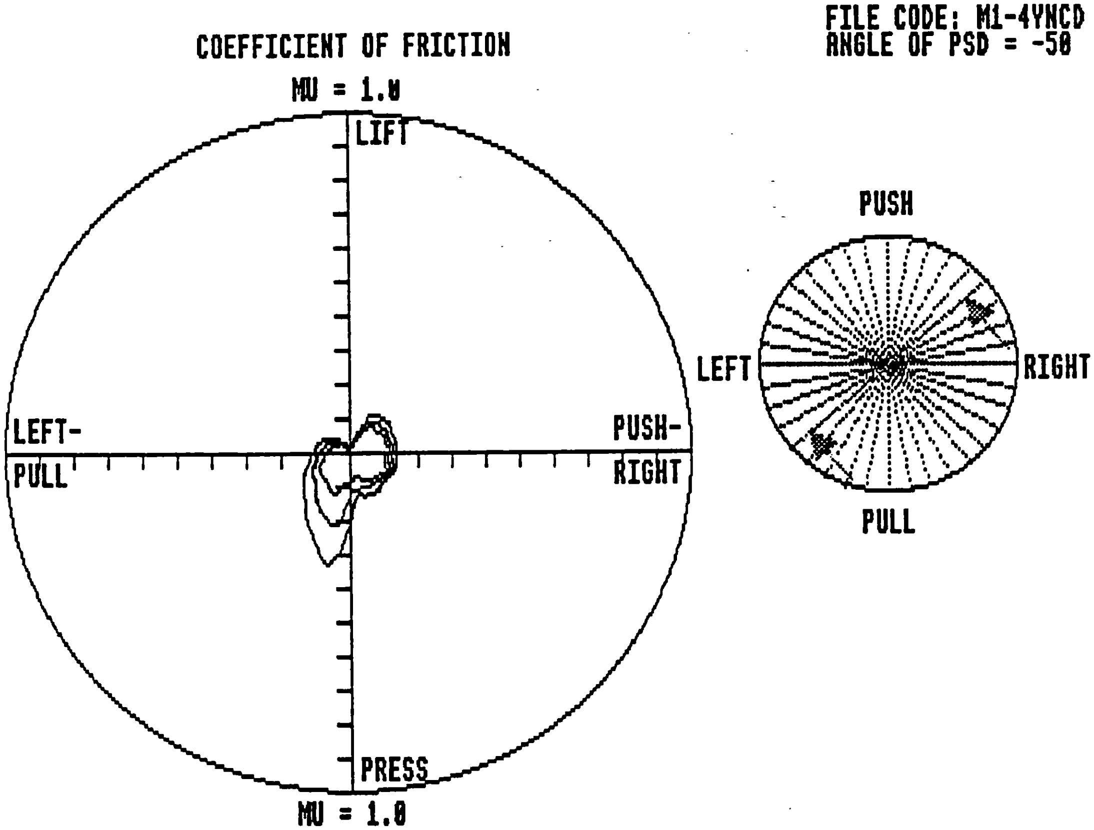
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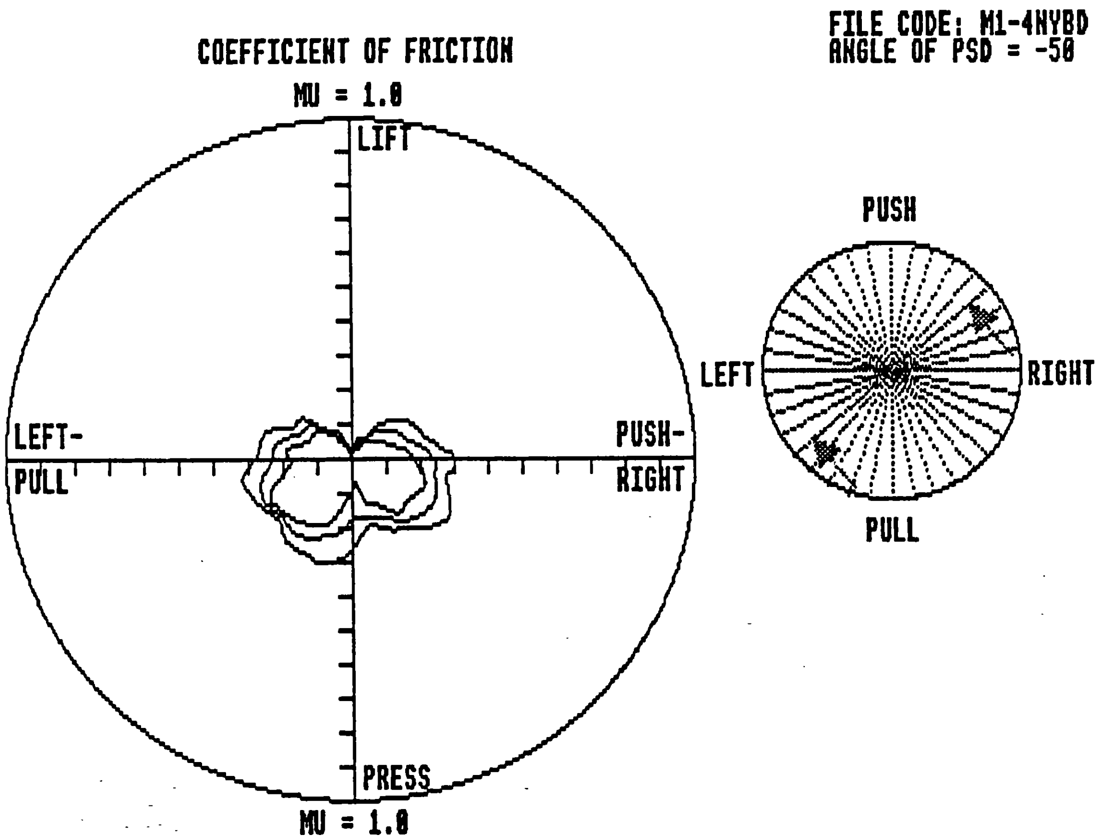
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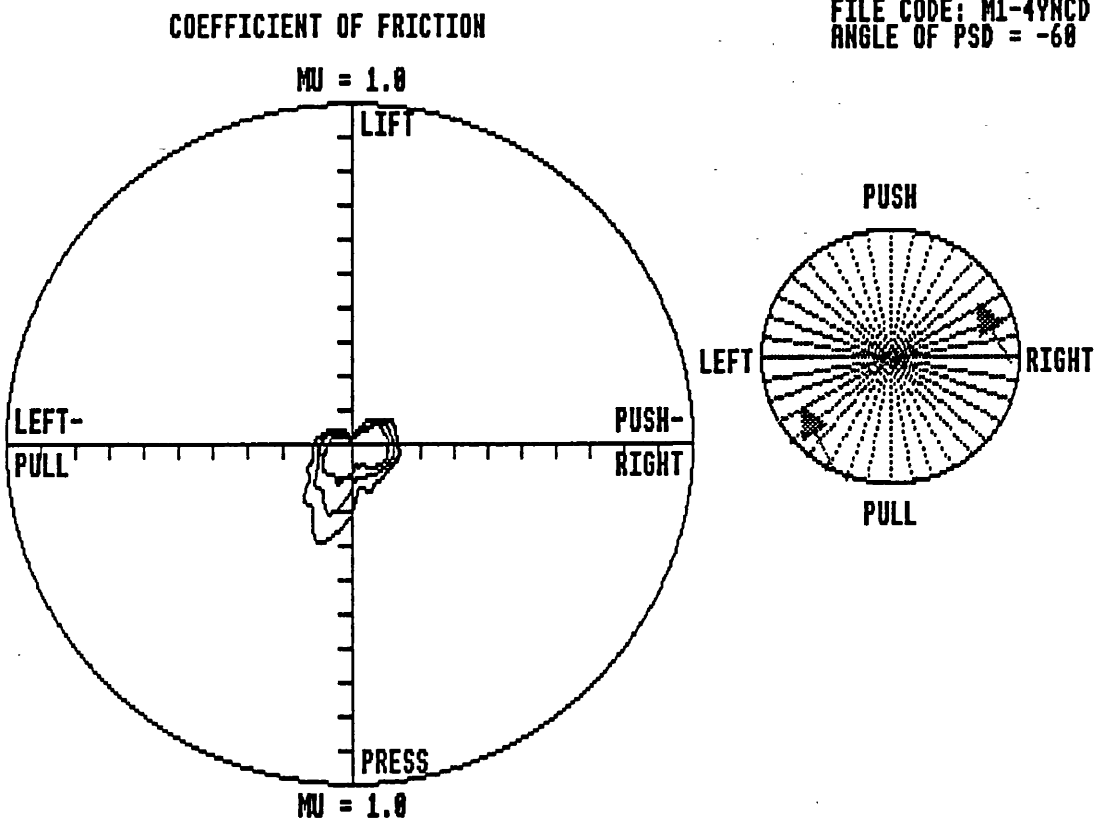
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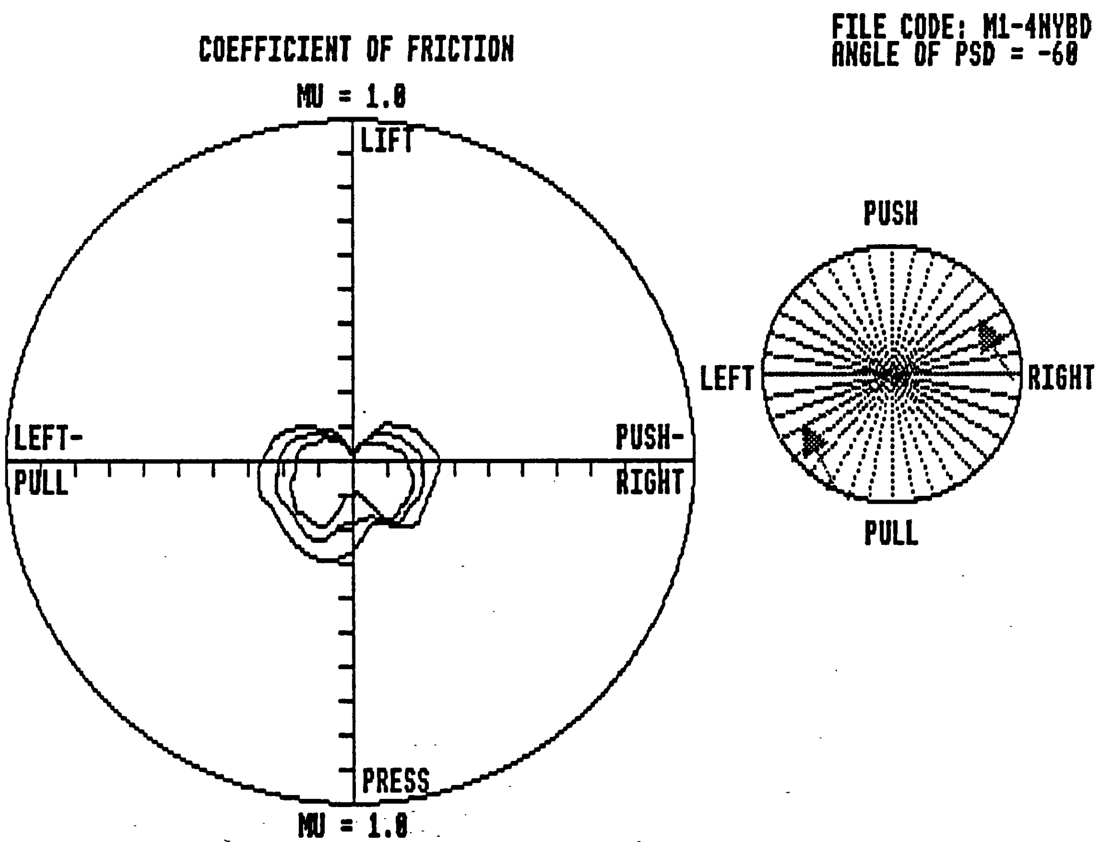
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COEFFICIENT OF FRICTION

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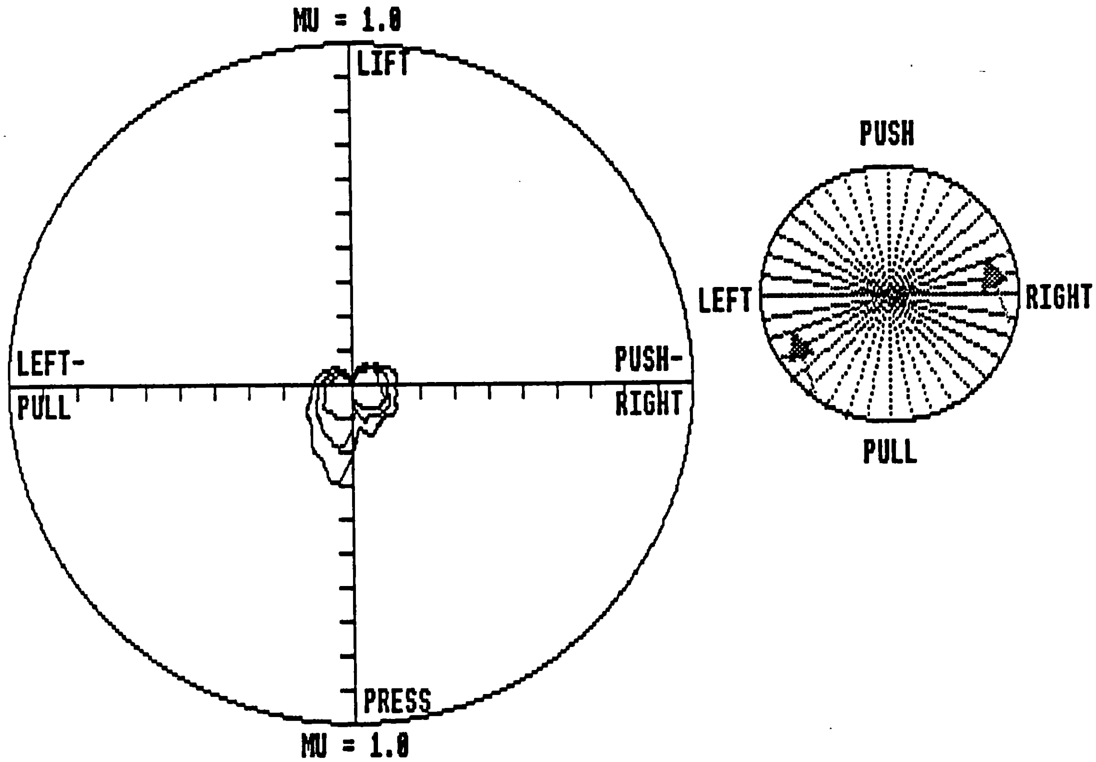

COEFFICIENT OF FRICTION

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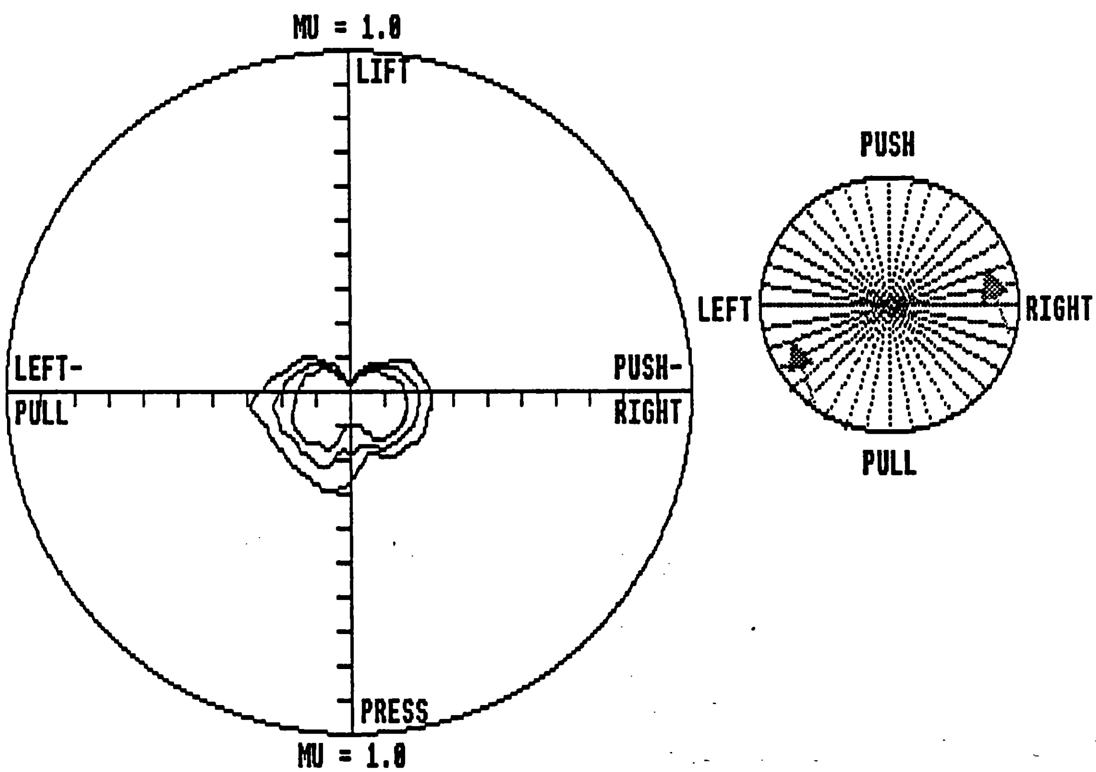

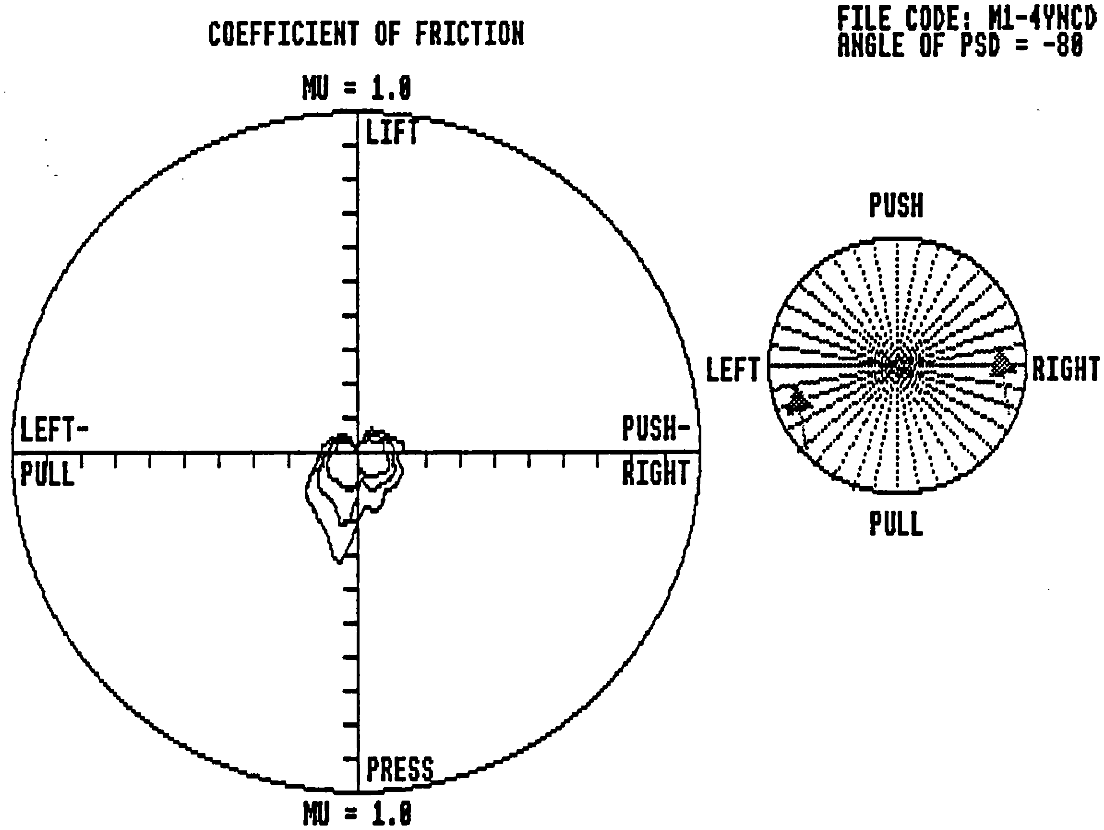
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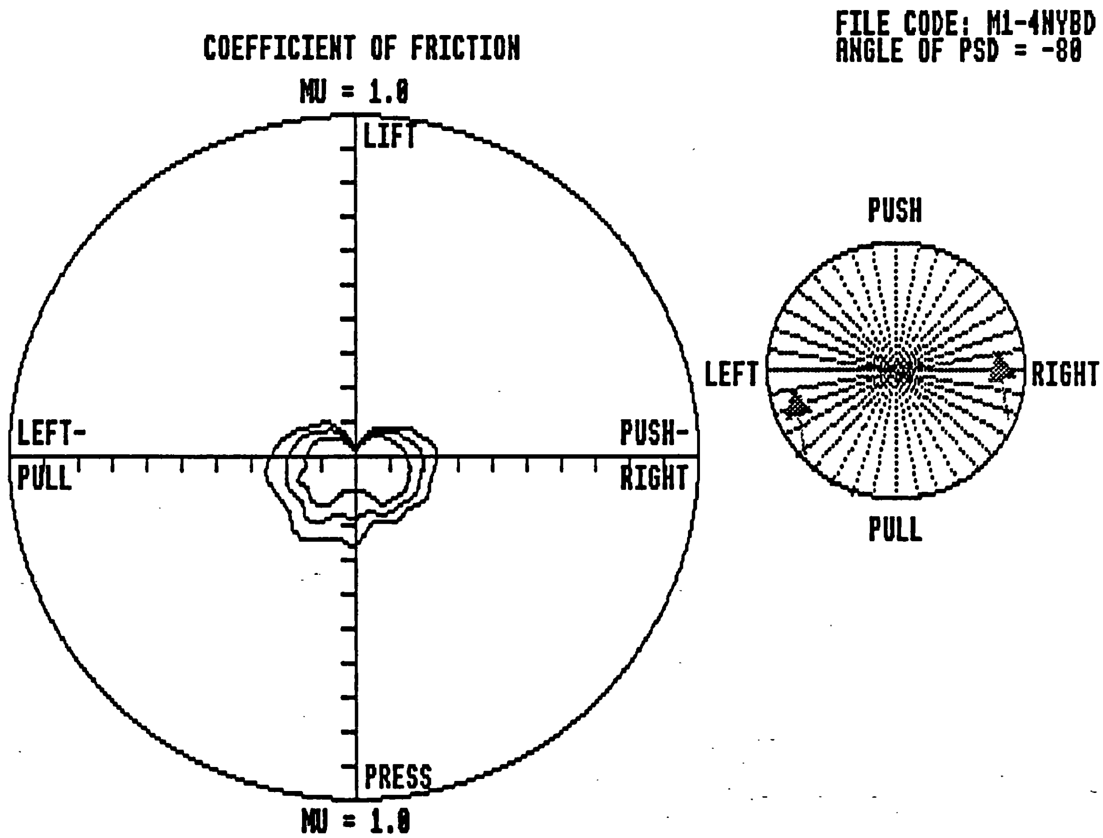
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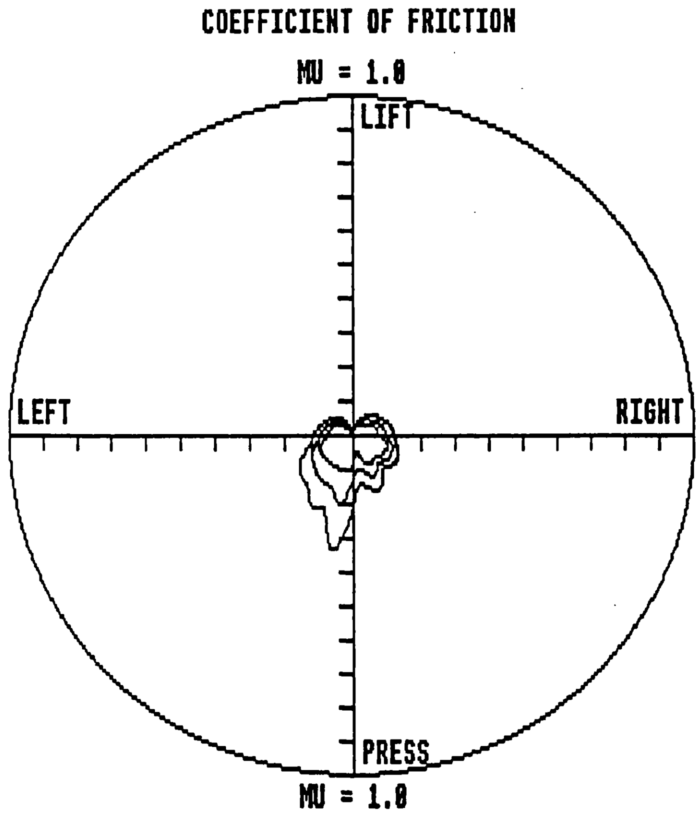
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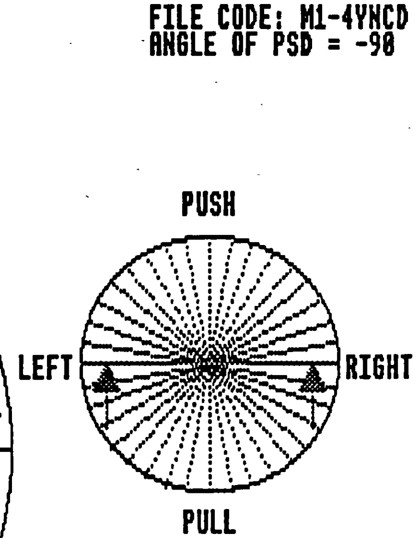
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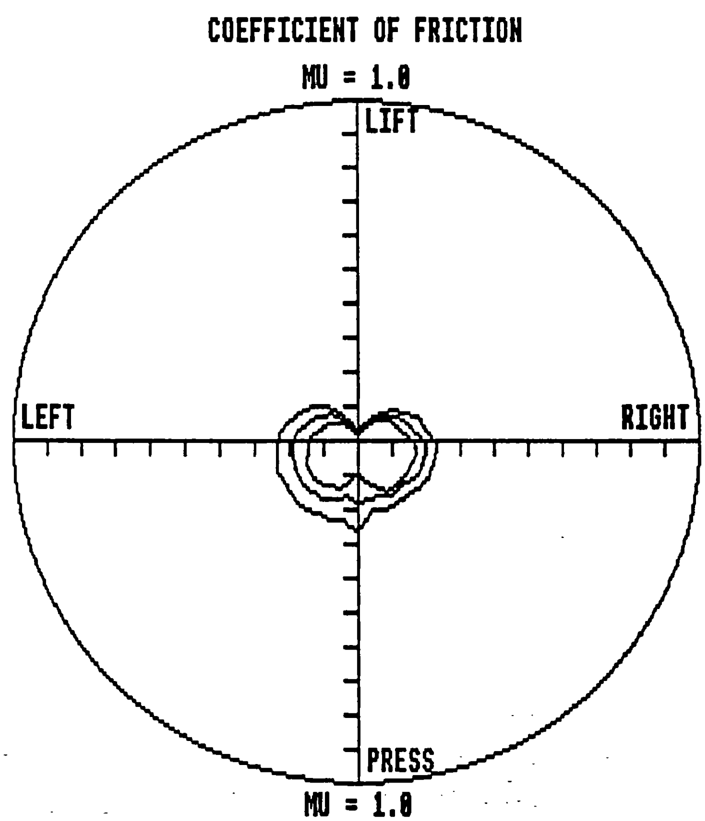
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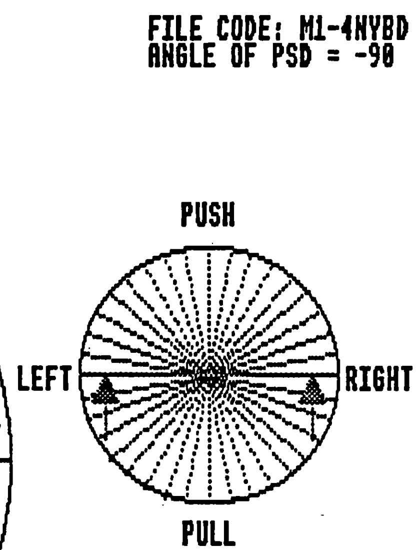
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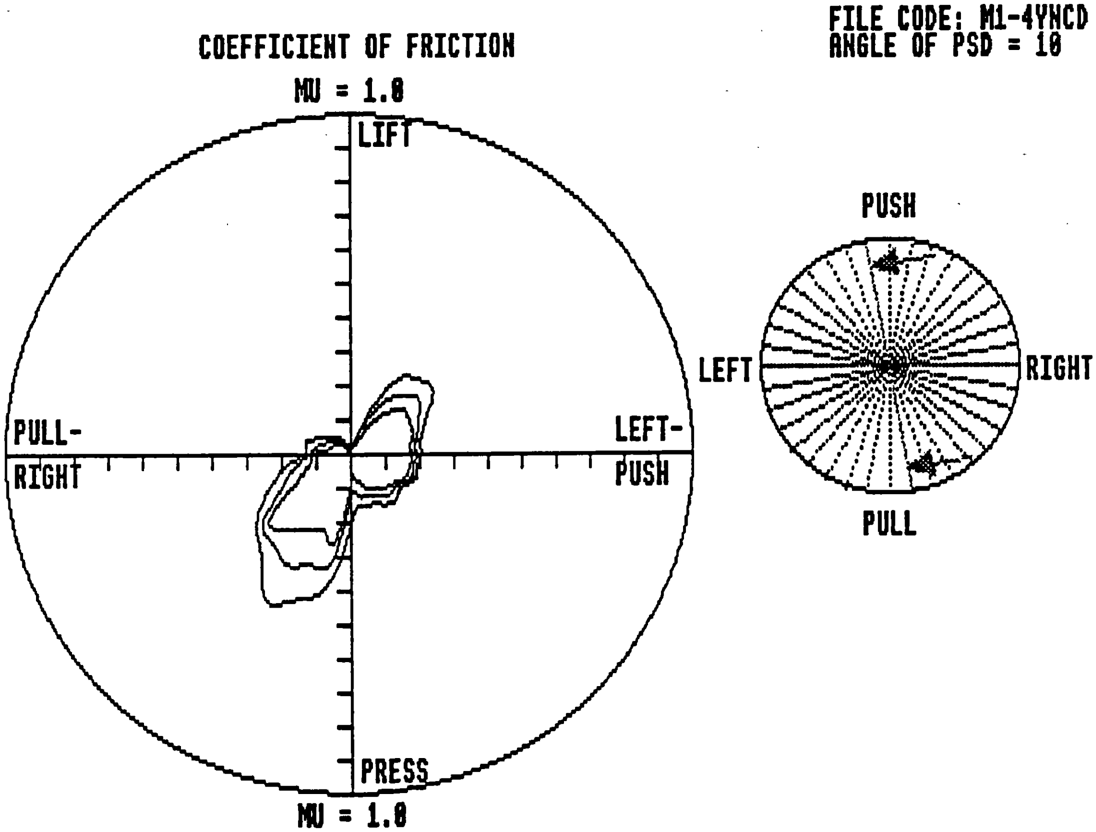
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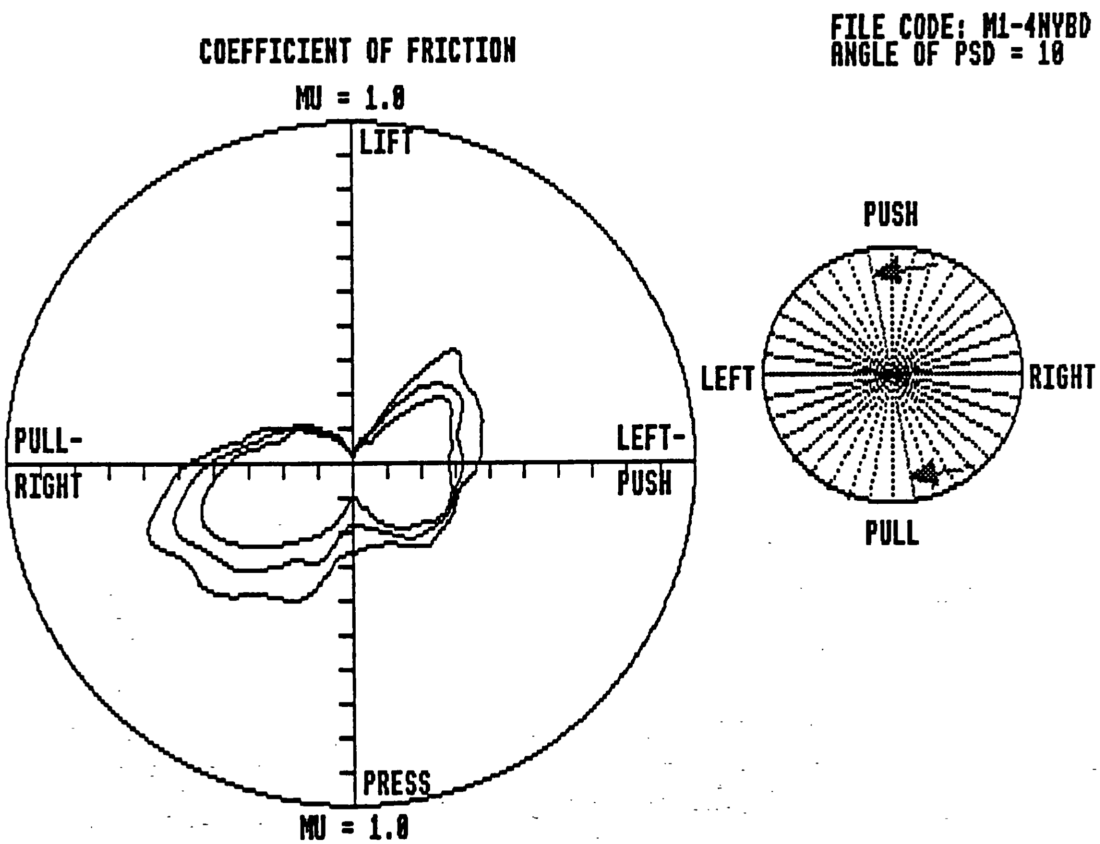
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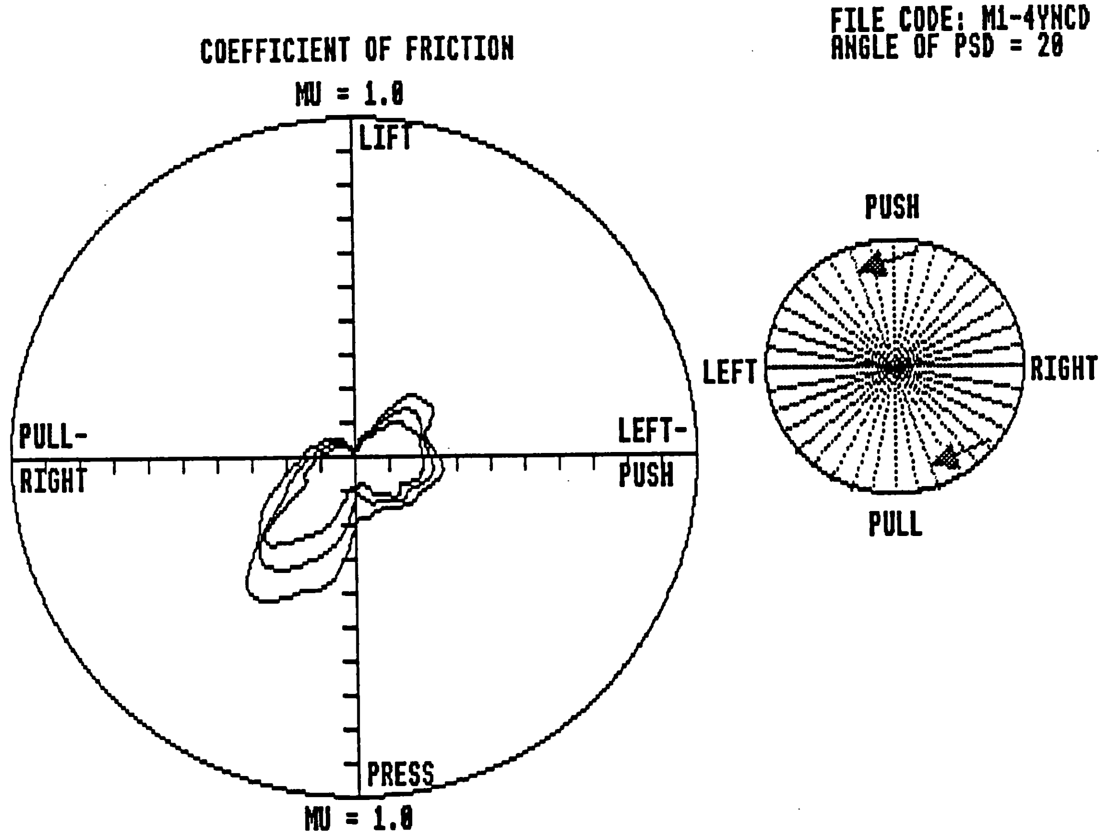
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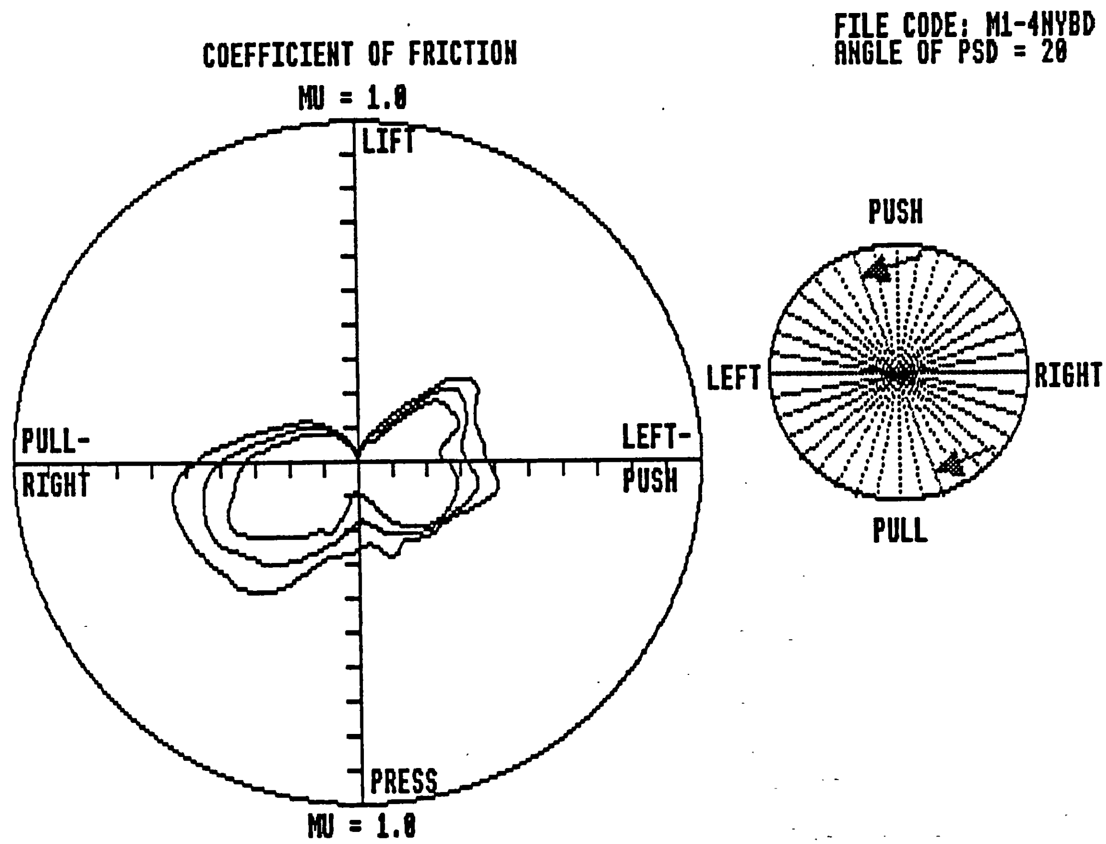
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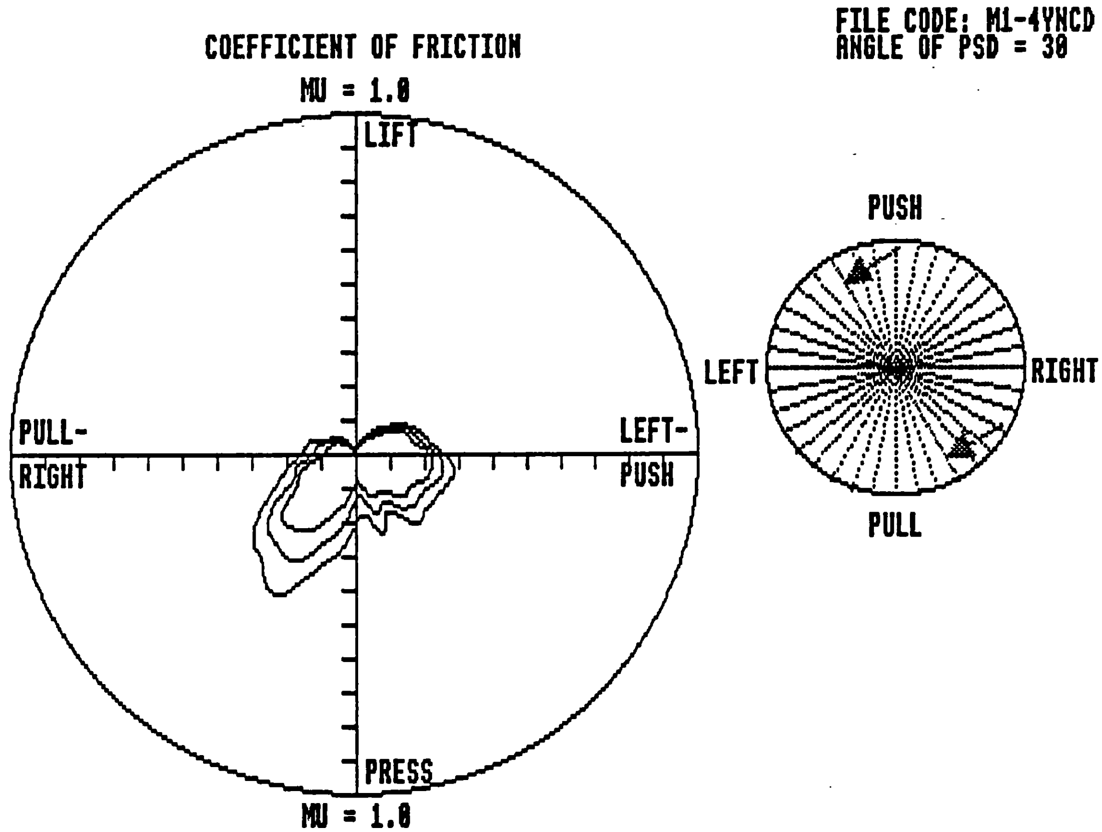
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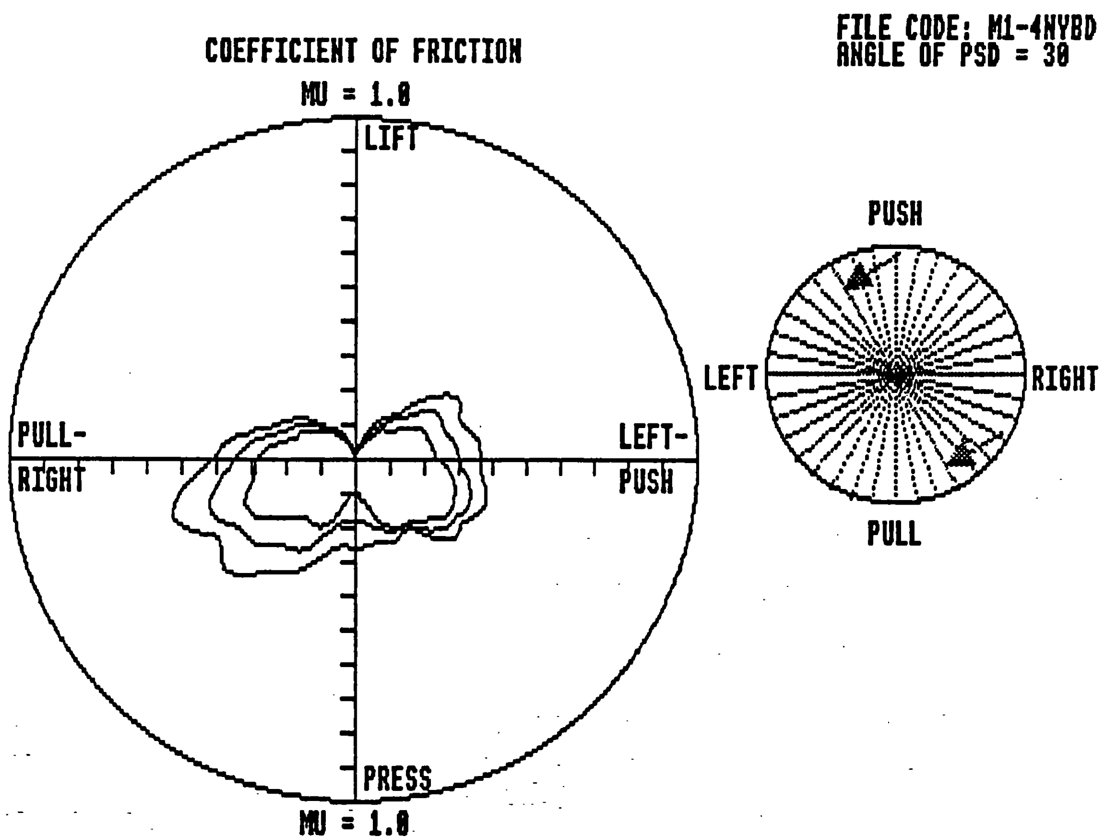
PULL-
RIGHT
LEFT-
PUSH
PULL
PRESS
MU = 1.0


FILE CODE: M1-4NYBD
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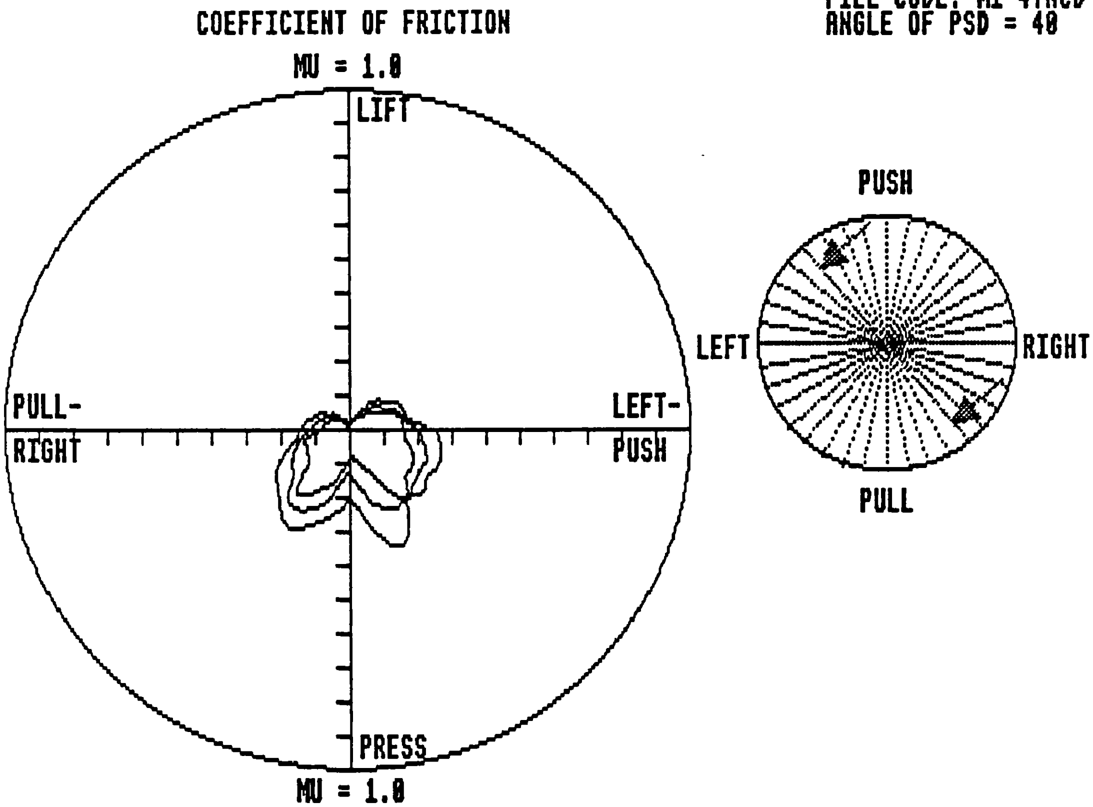
MU = 1.0



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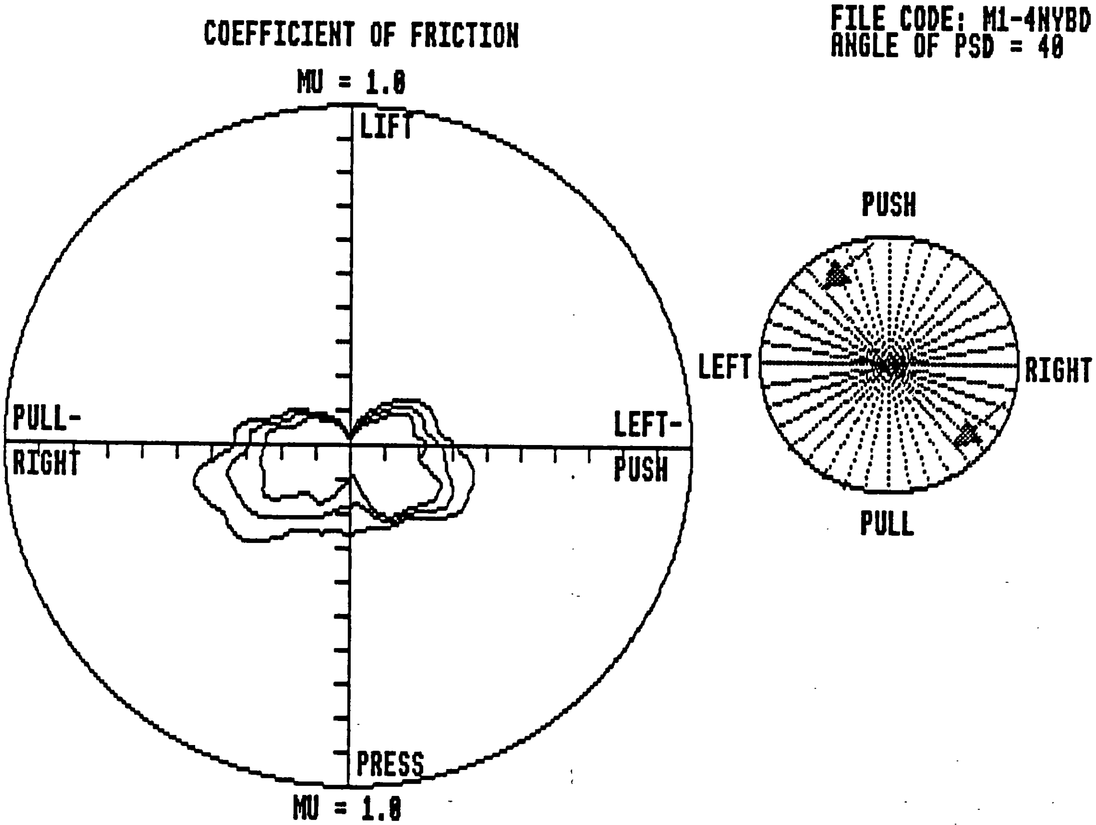
RIGHT
PULL



COEFFICIENT OF FRICTION
FILE CODE: M1-4NYBD
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LEFT-
PUSH
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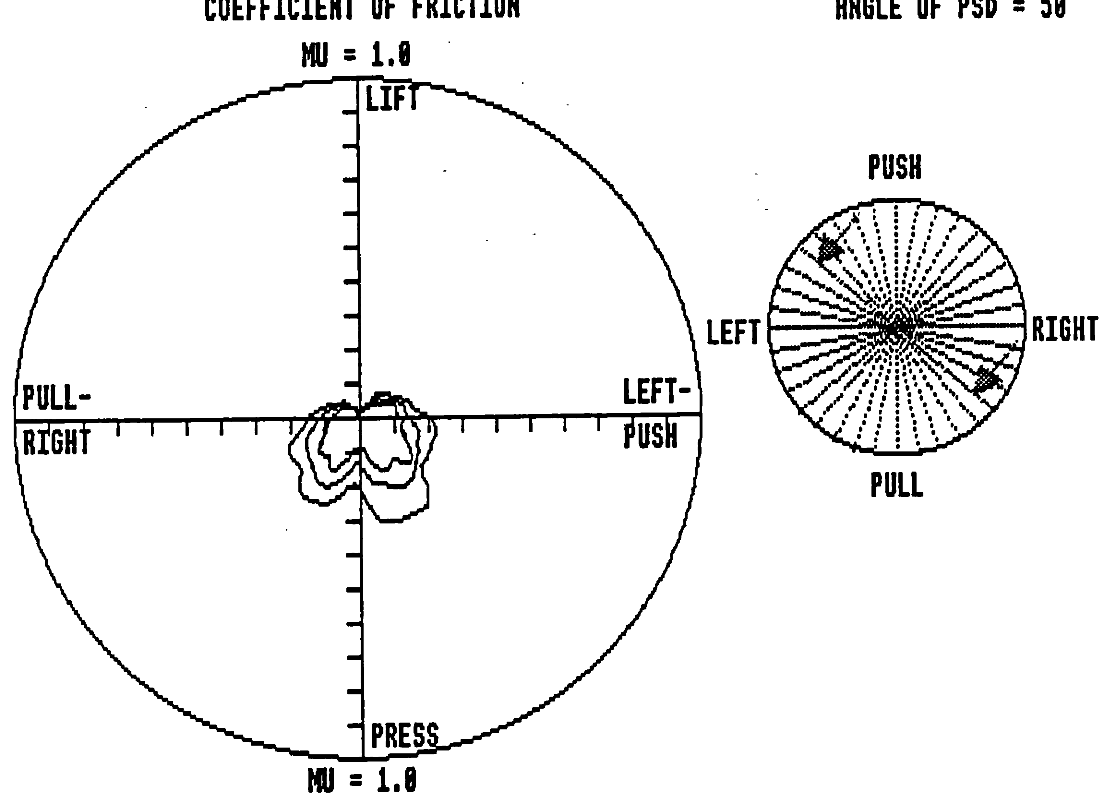
LEFT
RIGHT
PULL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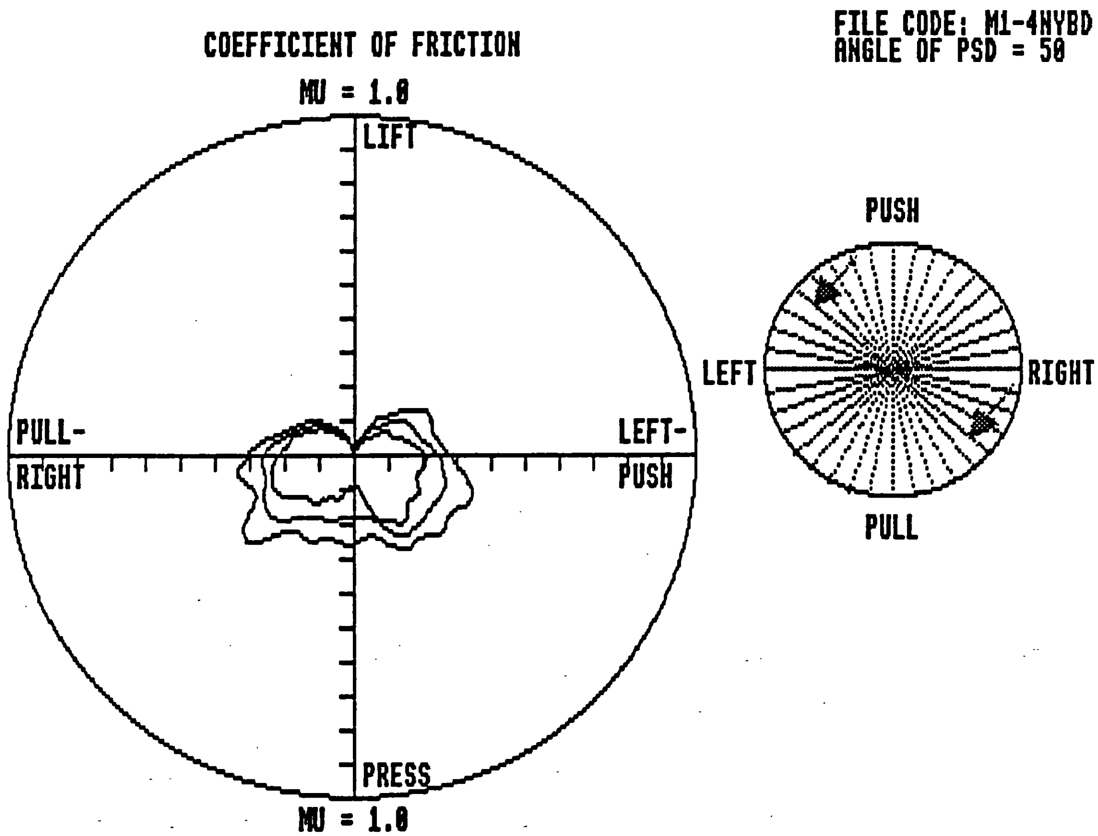
LEFT
RIGHT
PULL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ANGLE OF PSD = 50
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RIGHT
LEFT-
PUSH
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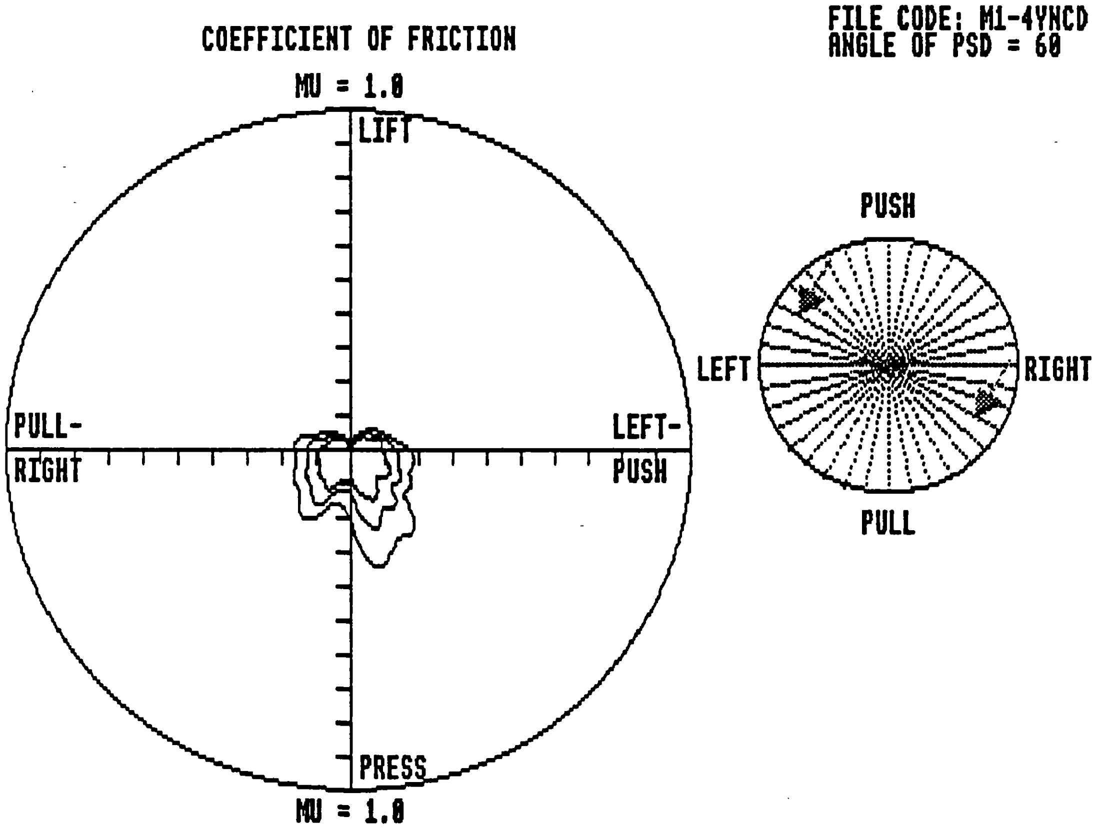
LEFT
RIGHT
PULL



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LEFT-
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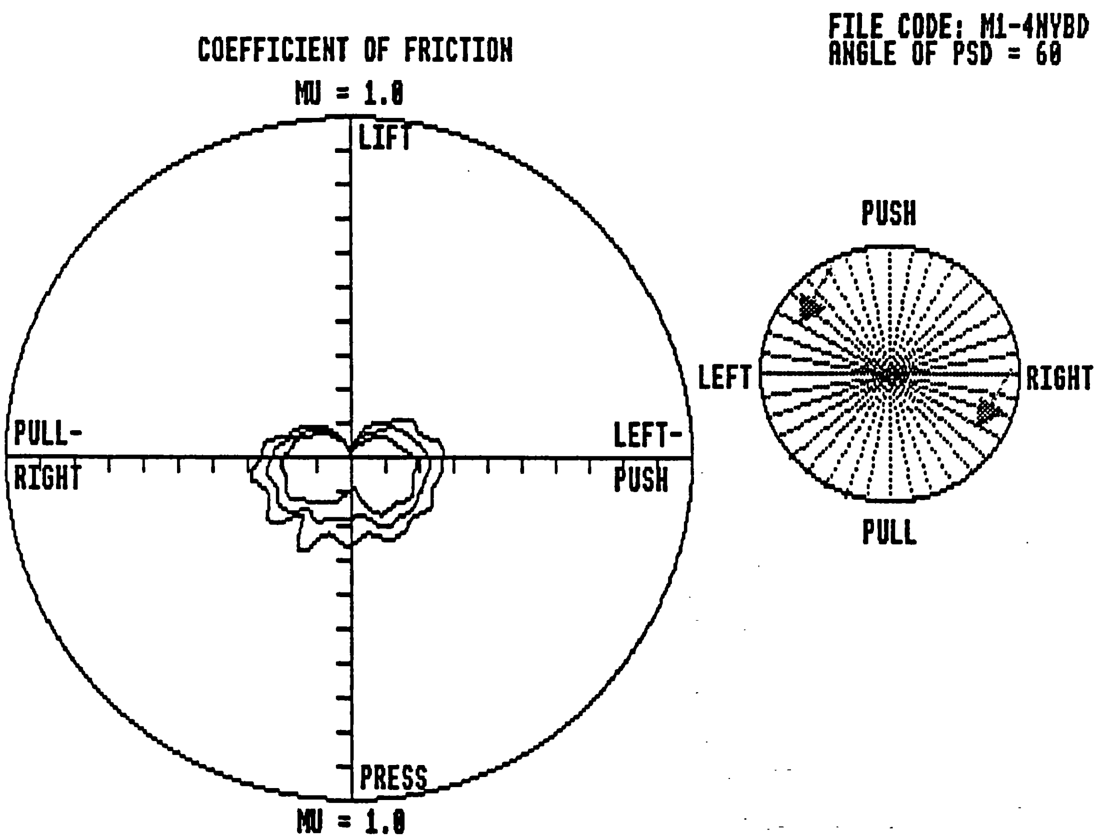
LEFT
RIGHT
PULL



COEFFICIENT OF FRICTION
FILE CODE: M1-4NYBD
ANGLE OF PSD = 60
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LEFT-
PUSH
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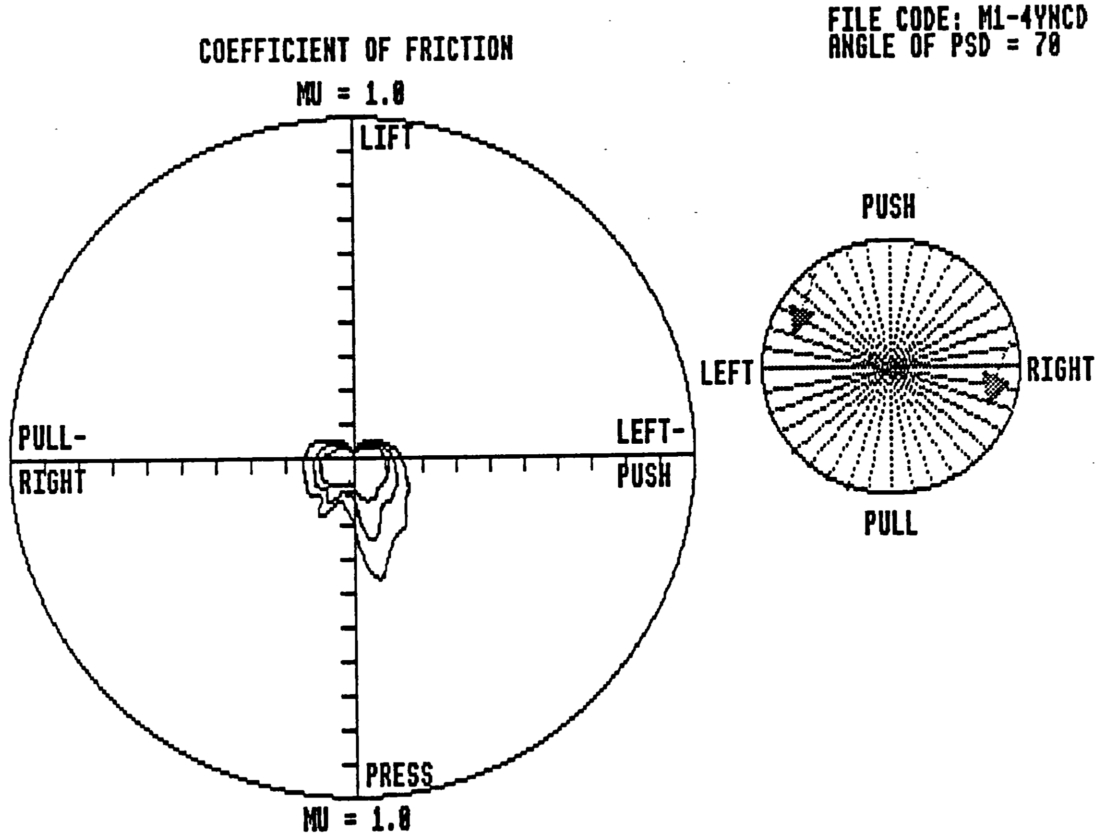
LEFT
RIGHT
PULL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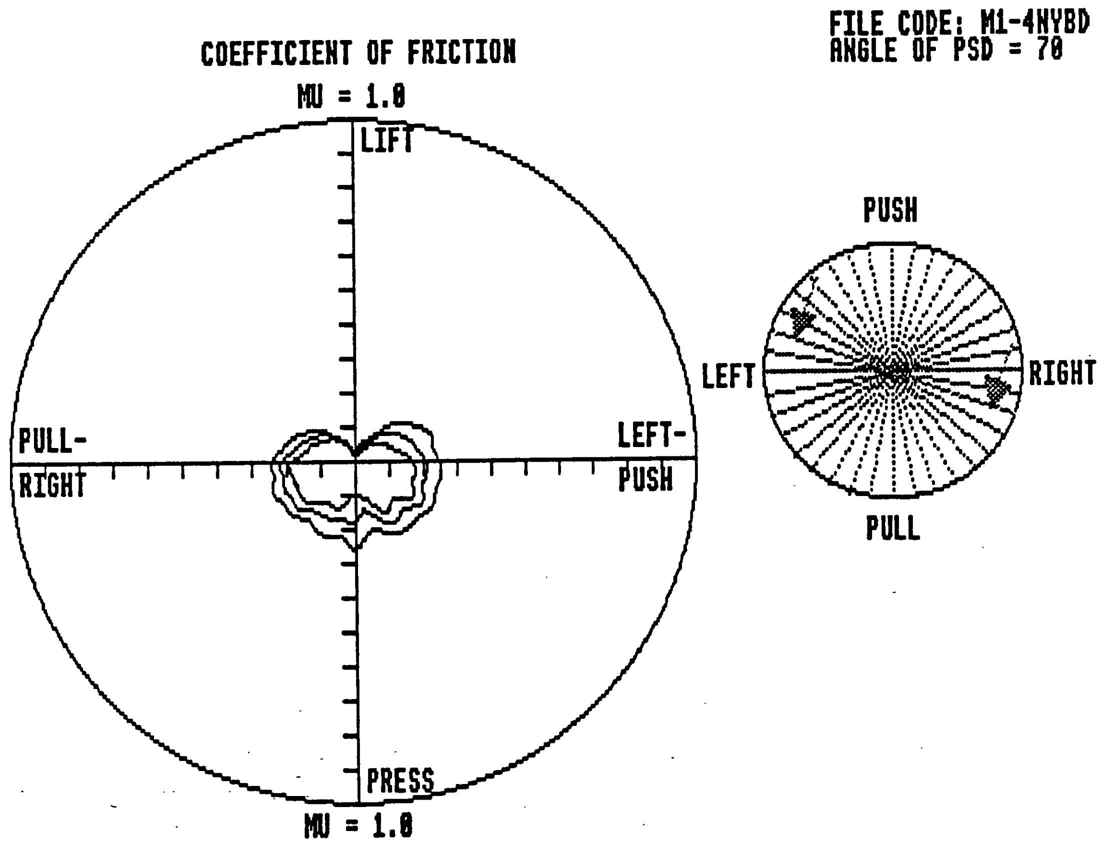
RIGHT
PULL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LEFT-
PUSH
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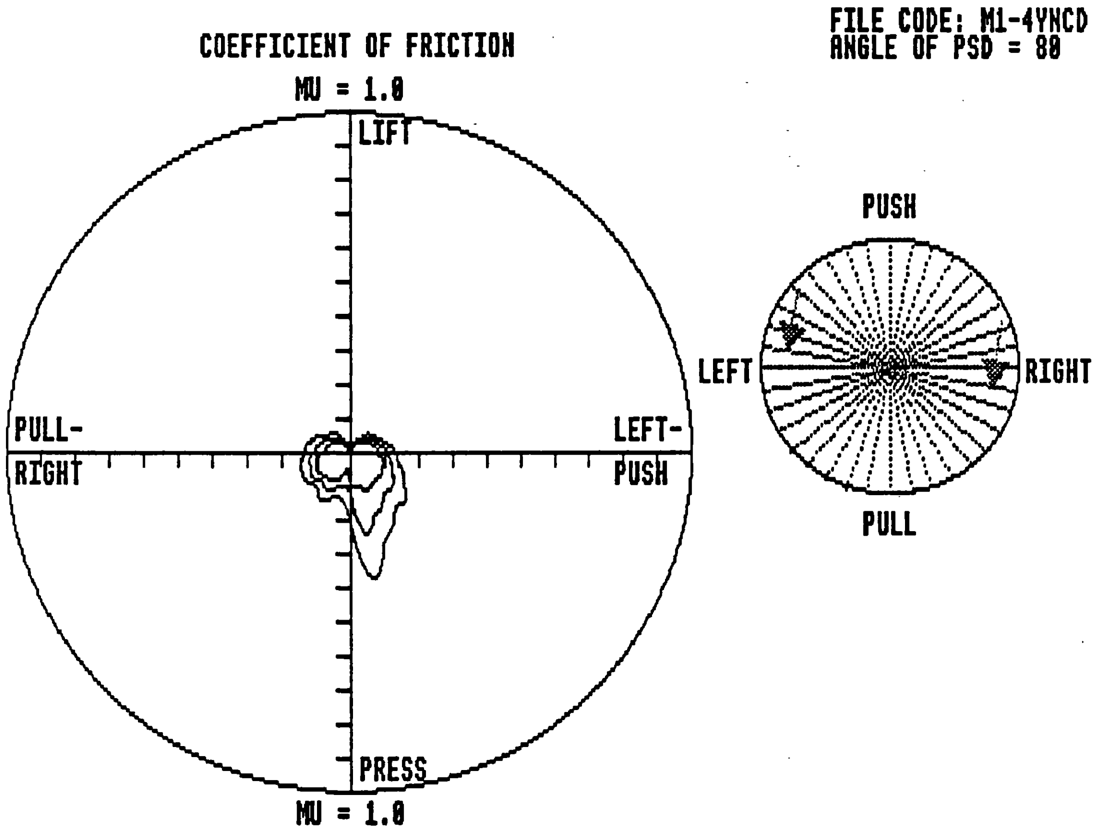
PUSH
LEFT
RIGHT
PULL



COEFFICIENT OF FRICTION
FILE CODE: M1-4YNCD
ANGLE OF PSD = 80
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RIGHT
LEFT-
PUSH
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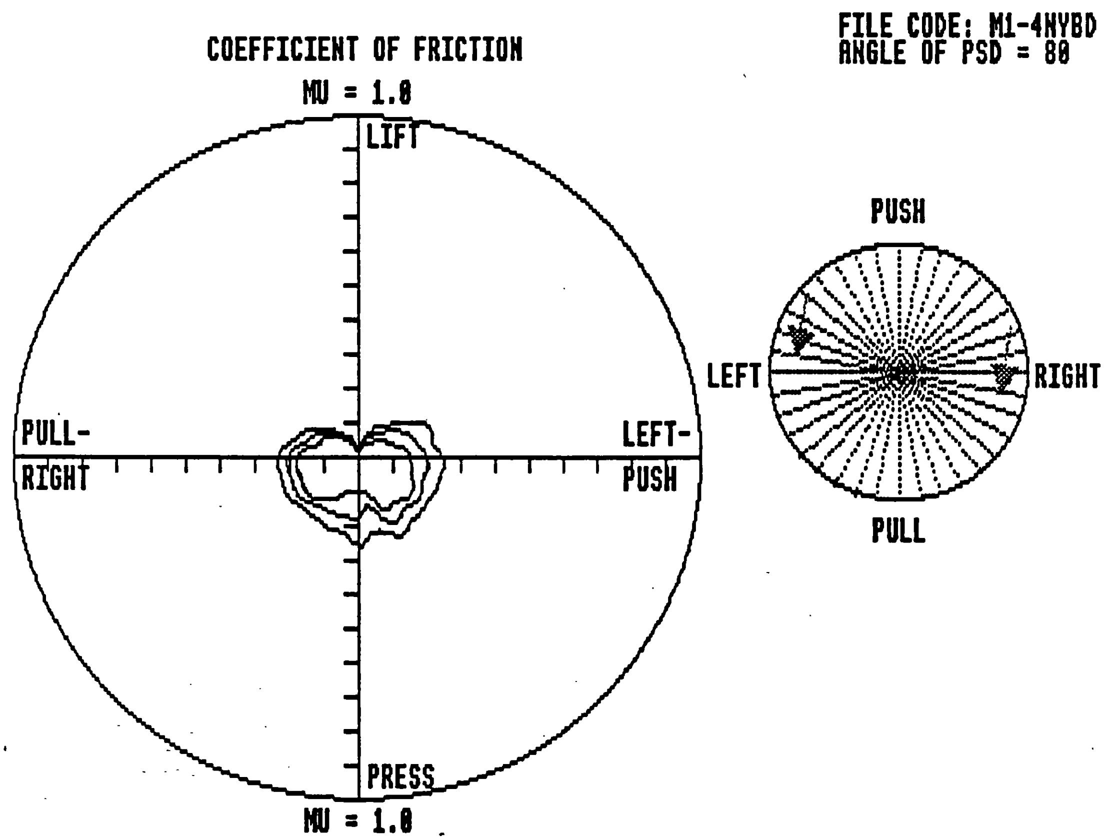
LEFT
RIGHT
PULL



COEFFICIENT OF FRICTION
FILE CODE: M1-4NYBD
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LEFT-
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MU = 1.0
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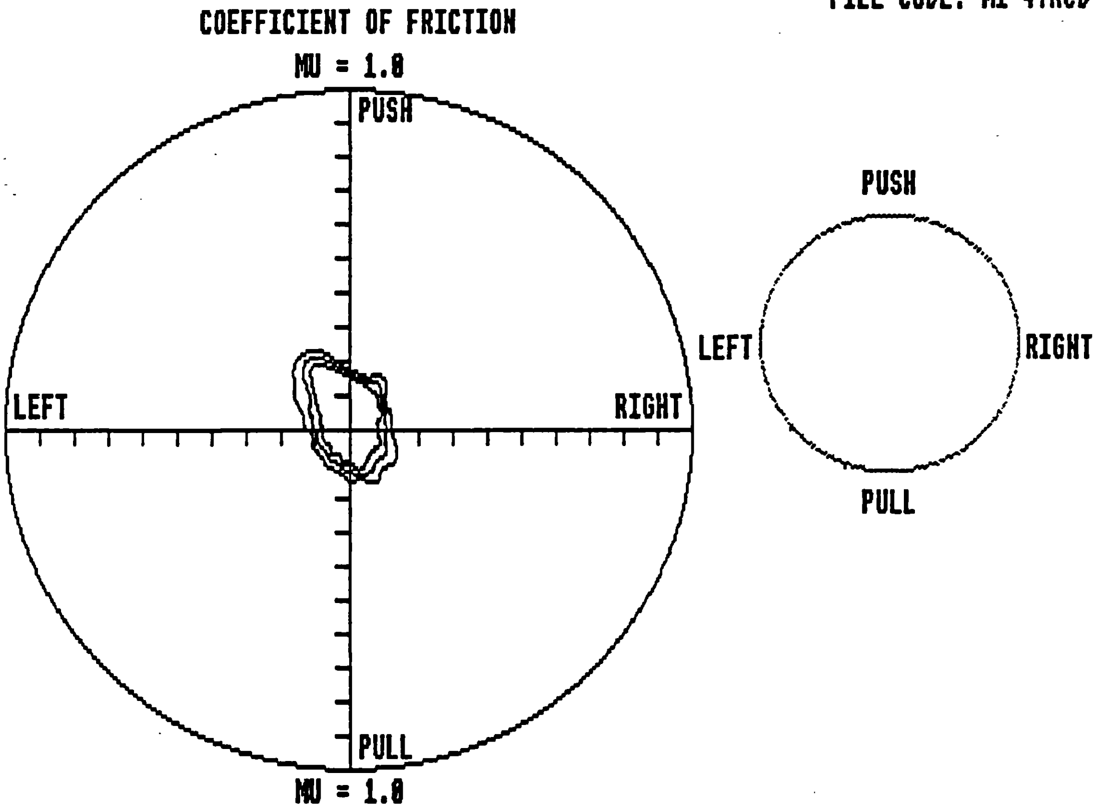
RIGHT
PULL

FILE CODE: M1-4YHCD

COEFFICIENT OF FRICTION
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PULL
MU = 1.0
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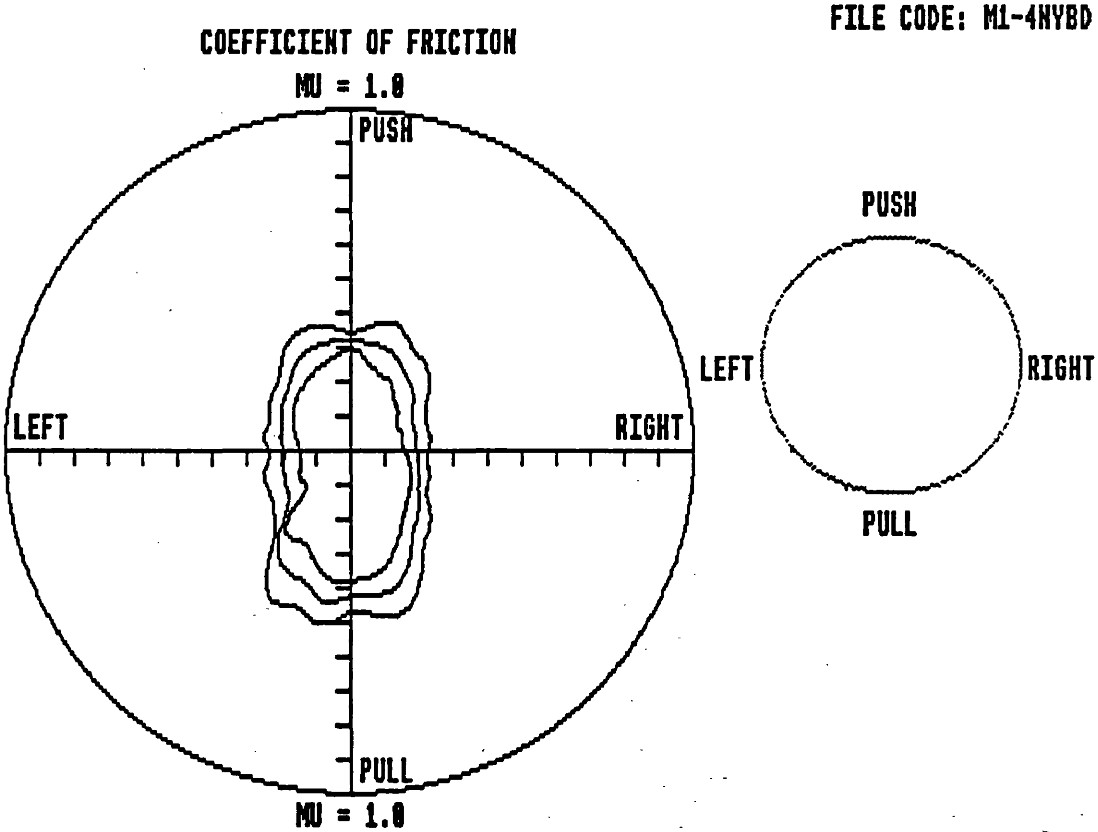
LEFT
RIGHT
PULL

FILE CODE: M1-4NYBD

COEFFICIENT OF FRICTION
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LEFT
RIGHT
PULL
MU = 1.0
PUSH
LEFT
RIGHT
PULL

NOTES

In Tables C4-C6 strength as a % of body weight and the coefficients of static friction have been multiplied by 10 and 100 respectively in order to express the values as integers.

Mean Force and Friction Data over the Sphere of Exertion for One-handed Maximal Static Exertions at the 0.5 m, 1.0 m and 1..5 m Handle Heights.

Table C4:

The following data is based on semi-freestyle exertions performed at a handle height of 0.5 m by 11 military personnel.

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF NEWTONS ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	646	327	247	261	353	374	339	281	233	230	233	238	236	230	244	253	273	329	447	BACK
SD	93	107	77	120	181	218	186	155	68	68	70	69	75	78	84	93	98	117	47	
MEAN	646	380	278	267	270	286	266	232	203	200	204	206	201	216	218	224	234	279	447	
SD	93	154	108	110	116	165	146	98	70	62	53	79	61	74	69	67	83	84	47	
MEAN	646	349	260	235	248	236	217	202	181	186	182	170	174	173	184	204	212	262	447	
SD	93	130	107	96	105	116	79	72	60	63	49	46	53	57	65	62	61	48	47	
MEAN	646	356	261	234	226	220	211	187	174	175	166	160	169	167	176	187	195	241	447	
SD	93	155	111	95	78	64	61	54	52	47	37	40	67	66	69	56	47	57	47	
MEAN	646	369	299	273	245	233	213	195	191	176	166	161	163	165	158	163	181	221	447	
SD	93	129	130	114	85	69	54	49	47	34	34	34	64	65	46	50	50	53	47	
MEAN	646	398	329	307	272	258	221	197	199	182	179	170	160	154	152	154	173	241	447	
SD	93	92	103	123	97	92	67	56	67	38	47	42	46	40	35	46	55	41	47	
MEAN	646	416	343	356	285	272	239	205	205	204	184	168	162	157	153	159	165	228	447	
SD	93	103	110	162	99	110	83	68	71	78	48	36	39	32	26	33	45	38	47	
MEAN	646	405	353	338	317	283	246	215	212	198	188	170	164	163	163	171	171	220	447	
SD	93	106	108	116	97	95	97	70	62	61	51	38	37	35	19	22	28	58	47	
MEAN	646	438	358	361	335	316	277	242	218	200	190	180	176	164	162	171	174	244	447	RIGHT
SD	93	128	116	140	109	112	90	97	70	54	47	46	47	33	28	25	27	69	47	
MEAN	646	448	374	360	359	351	305	256	246	238	205	195	184	163	160	166	174	219	447	
SD	93	113	124	121	133	159	105	82	87	64	46	47	50	34	27	33	40	57	47	
MEAN	646	439	397	372	380	345	337	271	262	237	203	201	196	183	165	172	180	239	447	
SD	93	109	117	95	155	122	109	80	98	70	36	46	63	53	31	34	46	68	47	
MEAN	646	454	382	363	373	345	323	275	263	249	208	204	195	182	166	166	185	229	447	
SD	93	77	91	103	152	97	99	80	87	95	56	56	57	49	36	43	56	64	47	
MEAN	646	435	389	381	382	352	330	296	264	253	223	216	196	186	179	175	187	232	447	
SD	93	110	104	113	140	84	104	92	71	96	67	65	54	47	39	36	57	60	47	
MEAN	646	440	387	368	374	345	328	297	275	273	245	215	207	195	175	178	195	254	447	
SD	93	148	118	131	140	111	97	90	70	99	67	57	61	57	43	31	48	63	47	
MEAN	646	466	424	395	349	345	335	320	287	271	258	220	208	200	174	188	202	261	447	
SD	93	184	158	133	117	104	102	110	91	108	94	65	58	55	41	34	52	67	47	
MEAN	646	458	409	415	356	359	335	316	296	290	258	218	203	193	174	193	209	263	447	
SD	93	192	142	146	118	98	101	99	93	104	91	60	58	43	37	44	58	76	47	
MEAN	646	449	376	404	370	366	356	344	317	310	278	238	217	212	189	196	234	279	447	
SD	93	195	151	162	93	78	92	117	120	124	91	74	60	56	51	47	84	84	47	

MEAN	646	428	364	349	350	344	343	333	339	335	300	259	225	230	205	200	247	292	447	FRONT
SD	93	122	126	117	101	94	107	116	155	147	96	78	52	56	58	46	87	92	47	
MEAN	646	387	346	333	329	327	322	298	307	316	271	224	208	198	202	202	277	316	447	
SD	93	132	111	105	102	99	95	88	116	128	109	77	64	52	56	48	108	107	47	
MEAN	646	387	332	346	355	321	302	301	294	291	267	215	205	189	197	211	282	333	447	
SD	93	99	103	117	111	109	96	80	103	125	127	81	74	46	58	60	112	131	47	
MEAN	646	387	326	328	356	312	289	279	283	267	256	206	197	175	212	236	287	350	447	
SD	93	68	85	78	115	99	106	95	104	123	127	86	80	47	96	77	127	137	47	
MEAN	646	397	336	330	323	326	258	250	251	250	205	190	169	168	191	222	325	372	447	
SD	93	79	93	86	95	109	106	106	103	131	93	85	67	49	51	74	145	140	47	
MEAN	646	381	325	330	321	290	231	229	225	196	189	170	167	169	184	233	320	375	447	
SD	93	82	99	102	97	111	92	103	110	108	100	82	85	41	31	65	152	175	47	
MEAN	646	342	304	301	316	253	221	213	201	176	162	158	161	170	193	229	316	383	447	
SD	93	82	81	87	102	119	99	111	92	76	73	71	54	38	50	80	129	149	47	
MEAN	646	354	309	276	263	233	211	185	166	157	165	167	171	184	202	238	292	365	447	
SD	93	108	103	98	90	107	117	81	40	41	64	61	61	58	52	69	96	95	47	
MEAN	646	350	277	252	244	200	194	172	166	172	167	162	170	189	203	232	299	348	447	
SD	93	107	88	80	98	77	77	53	40	49	60	60	55	68	49	67	100	98	47	
MEAN	646	322	261	217	181	165	174	176	181	183	179	152	161	181	204	227	284	331	447	LEFT
SD	93	118	83	59	52	57	48	45	52	63	56	49	41	45	50	64	61	100	47	
MEAN	646	319	227	189	183	171	183	185	177	187	179	159	161	188	206	221	283	342	447	
SD	93	156	98	54	50	33	33	51	45	69	62	45	44	51	55	55	94	80	47	
MEAN	646	294	237	180	181	176	181	180	174	173	165	165	162	193	203	227	268	333	447	
SD	93	128	117	35	49	31	28	51	54	50	40	45	38	43	46	50	81	99	47	
MEAN	646	301	220	175	195	202	191	193	186	180	174	171	181	189	205	224	274	321	447	
SD	93	141	124	33	59	53	38	61	50	43	50	41	50	38	51	53	101	104	47	
MEAN	646	290	198	182	217	227	230	223	204	189	176	177	176	177	191	216	261	316	447	
SD	93	128	44	34	63	50	80	79	68	68	56	51	45	42	46	56	85	97	47	
MEAN	646	315	228	208	248	251	257	237	224	203	190	187	186	181	201	225	283	312	447	
SD	93	83	48	45	60	77	64	57	68	67	61	50	46	43	51	57	96	97	47	
MEAN	646	313	240	238	270	268	282	276	244	228	197	189	186	197	198	210	267	332	447	
SD	93	62	66	52	78	106	103	96	80	76	47	44	48	54	57	53	91	88	47	
MEAN	646	317	244	266	319	370	318	330	269	218	219	209	215	226	224	235	285	325	447	
SD	93	73	64	77	91	155	153	162	88	46	56	55	70	69	69	52	84	64	47	
MEAN	646	297	247	271	361	515	400	334	298	271	273	238	252	245	248	255	302	337	447	
SD	93	69	71	132	136	250	185	133	115	94	135	81	91	73	67	55	101	65	47	
MEAN	646	306	244	263	368	445	379	332	287	274	270	278	263	264	259	273	289	345	447	BACK
SD	93	67	80	152	227	249	176	158	115	110	90	73	87	89	82	76	83	71	47	

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF % BODY WEIGHT ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	892	453	345	368	500	531	479	396	328	321	326	327	323	315	337	352	378	453	620	BACK
SD	181	156	125	192	280	342	290	240	124	114	121	98	95	98	120	138	140	150	126	
MEAN	892	523	389	377	380	406	376	328	287	281	285	288	280	300	306	315	333	390	620	
SD	181	193	168	186	186	253	223	159	118	109	95	124	96	112	112	119	160	139	126	
MEAN	892	480	365	331	348	333	306	284	255	262	256	238	243	242	258	288	299	366	620	
SD	181	166	169	162	166	180	130	120	105	108	90	80	83	93	110	114	115	98	126	
MEAN	892	490	369	330	319	308	295	263	246	245	232	225	233	234	248	262	274	336	620	
SD	181	209	185	159	136	107	103	95	94	86	70	75	89	105	116	97	90	99	126	
MEAN	892	515	417	384	343	327	299	272	269	244	231	224	225	231	222	228	253	309	620	
SD	181	200	187	180	137	116	98	85	90	66	66	63	86	102	80	81	86	93	126	
MEAN	892	551	459	436	383	362	307	273	277	252	248	236	222	214	211	214	240	335	620	
SD	181	155	163	210	164	146	101	88	107	66	82	76	74	67	62	73	82	81	126	
MEAN	892	571	474	489	396	380	331	285	282	282	255	233	226	220	213	221	229	318	620	
SD	181	144	156	201	143	168	113	112	105	112	77	67	72	64	53	60	71	79	126	
MEAN	892	558	486	466	440	395	339	296	291	274	261	237	228	228	225	237	237	308	620	
SD	181	150	144	154	150	147	132	98	89	95	84	72	70	70	44	49	54	105	126	
MEAN	892	602	489	492	459	438	383	333	301	277	263	250	243	228	225	237	243	344	620	RIGHT
SD	181	171	136	162	140	165	131	141	107	88	80	82	75	68	54	50	65	126	126	
MEAN	892	613	509	489	488	479	419	354	342	333	286	272	256	228	222	231	245	308	620	
SD	181	146	142	137	154	190	139	120	136	111	86	88	84	68	56	61	80	104	126	
MEAN	892	601	541	507	514	474	464	372	359	328	283	282	276	255	229	240	252	332	620	
SD	181	143	135	112	173	170	151	109	124	103	78	94	115	88	59	63	82	107	126	
MEAN	892	627	526	497	507	477	452	382	363	342	287	285	274	253	231	232	259	320	620	
SD	181	129	127	134	174	142	161	124	121	122	81	99	107	84	69	77	95	108	126	
MEAN	892	597	534	518	522	487	463	411	365	346	306	296	274	260	249	244	263	323	620	
SD	181	145	147	138	174	134	170	136	106	118	84	89	98	85	74	70	97	102	126	
MEAN	892	601	531	505	512	480	461	411	380	372	336	297	286	273	246	248	274	356	620	
SD	181	183	164	174	177	166	165	134	98	112	86	83	93	96	84	67	92	115	126	
MEAN	892	630	576	537	482	479	465	440	393	370	354	304	287	278	244	263	283	365	620	
SD	181	212	185	156	166	160	149	143	109	125	118	98	84	90	79	74	97	124	126	
MEAN	892	619	559	562	490	495	464	434	405	396	355	300	279	268	243	271	294	368	620	
SD	181	218	176	160	162	141	145	131	115	120	117	81	78	77	71	89	111	130	126	
MEAN	892	608	514	548	507	504	489	470	433	426	385	328	299	296	263	274	331	391	620	
SD	181	224	191	177	129	119	127	156	144	155	130	108	87	99	90	89	158	150	126	
MEAN	892	587	501	480	482	475	474	458	463	459	415	356	311	316	284	277	348	412	620	FRONT
SD	181	168	170	159	149	142	156	161	198	189	141	106	78	81	91	77	159	165	126	
MEAN	892	533	478	461	455	452	446	411	422	429	371	309	285	274	279	278	389	443	620	
SD	181	185	159	154	148	144	142	126	159	158	146	114	86	79	86	75	183	174	126	
MEAN	892	532	458	477	490	443	419	414	403	395	363	294	281	261	271	291	391	466	620	
SD	181	142	146	163	159	159	144	117	141	154	162	105	100	68	76	86	167	207	126	
MEAN	892	533	449	453	491	430	398	386	389	362	349	282	270	239	289	324	398	487	620	
SD	181	102	118	112	164	143	147	142	148	148	157	110	113	57	117	107	185	209	126	
MEAN	892	545	459	453	444	448	357	344	346	342	280	258	229	229	264	304	448	515	620	
SD	181	106	117	113	131	154	150	144	149	171	121	109	79	59	81	95	208	203	126	
MEAN	892	526	446	453	442	395	316	313	308	266	257	229	224	231	254	319	439	513	620	
SD	181	118	125	134	135	134	119	127	145	138	129	93	90	52	49	90	204	220	126	

MEAN	892	467	417	415	435	346	300	288	274	239	218	214	219	235	268	315	432	525	620	
SD	181	111	113	125	139	146	114	123	112	88	76	75	62	66	85	120	155	188	126	
MEAN	892	485	424	381	363	317	285	251	228	214	225	232	235	254	278	328	403	505	620	
SD	181	147	141	137	127	130	135	98	57	49	79	91	87	88	76	102	132	151	126	
MEAN	892	480	380	349	336	275	266	238	228	238	234	224	235	261	280	320	411	482	620	
SD	181	142	108	113	138	102	108	79	62	79	99	87	84	101	73	102	129	147	126	
MEAN	892	445	361	299	250	228	240	243	251	255	249	210	222	248	280	313	395	454	620	LEFT
SD	181	162	123	85	71	77	77	73	85	101	91	73	62	58	72	93	108	133	126	
MEAN	892	435	314	262	253	235	253	256	246	261	248	219	223	257	283	302	392	468	620	
SD	181	198	146	87	74	45	60	82	75	107	92	67	66	61	76	71	136	99	126	
MEAN	892	398	326	249	248	242	250	250	242	240	228	226	224	266	280	313	369	455	620	
SD	181	176	166	56	66	42	48	86	85	76	62	63	60	64	71	75	111	130	126	
MEAN	892	407	299	241	269	279	265	269	257	248	239	237	252	262	286	311	377	442	620	
SD	181	188	168	52	87	81	70	100	74	65	72	65	84	64	85	86	135	138	126	
MEAN	892	390	270	252	299	316	319	309	281	262	244	245	245	245	266	301	361	433	620	
SD	181	164	57	55	88	85	125	122	94	101	87	80	73	69	81	92	125	122	126	
MEAN	892	438	316	288	345	344	352	324	304	278	261	258	258	252	278	310	385	428	620	
SD	181	135	85	75	104	105	82	72	79	85	80	74	74	73	79	85	114	126	126	
MEAN	892	431	334	330	379	368	384	373	329	308	271	261	259	274	275	292	363	456	620	
SD	181	106	112	94	141	148	120	102	83	79	70	69	78	90	87	90	106	116	126	
MEAN	892	441	343	375	442	509	435	445	370	301	304	289	298	314	312	324	389	446	620	
SD	181	132	121	148	145	210	182	187	118	72	93	90	108	108	108	82	101	95	126	
MEAN	892	408	344	384	508	702	550	466	418	381	383	331	349	341	346	355	414	467	620	
SD	181	98	119	221	221	309	242	204	187	161	216	133	134	120	115	103	126	115	126	
MEAN	892	425	340	371	524	623	526	465	402	383	378	383	361	365	359	379	400	478	620	BACK
SD	181	125	127	244	356	376	249	239	182	176	153	110	115	135	119	121	120	116	126	

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF FRICTION COEFFICIENT ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	39	54	87	134	227	276	305	308	301	320	340	348	336	314	302	256	214	156	157	BACK
SD	7	18	29	53	93	133	138	153	110	115	135	116	116	113	129	133	122	115	105	
MEAN	39	57	89	137	174	228	256	268	262	279	295	305	286	294	261	231	202	108	157	
SD	7	24	37	57	61	106	124	114	103	108	104	145	111	133	118	112	192	62	105	
MEAN	39	49	84	123	161	206	224	236	236	258	261	244	242	223	215	195	150	107	157	
SD	7	9	33	51	56	90	87	89	93	102	95	89	91	102	119	105	83	67	105	
MEAN	39	50	90	121	159	199	219	223	230	241	235	228	230	214	207	178	122	89	157	
SD	7	16	37	52	56	59	71	73	86	83	73	83	101	116	125	85	53	45	105	
MEAN	39	54	98	128	174	197	223	232	248	242	236	225	214	212	170	138	110	79	157	
SD	7	21	36	49	58	57	70	68	82	67	72	66	88	112	77	59	42	39	105	
MEAN	39	68	104	155	179	209	227	233	258	249	255	242	216	191	163	125	105	77	157	
SD	7	21	36	62	63	72	68	70	98	65	90	86	80	71	58	43	40	32	105	
MEAN	39	70	107	165	192	225	233	243	261	279	262	238	221	194	163	136	105	87	157	
SD	7	25	29	55	61	82	74	85	95	111	83	74	81	64	51	48	42	40	105	
MEAN	39	56	115	167	204	226	248	248	268	273	268	242	224	209	169	150	106	81	157	
SD	7	26	31	42	64	68	88	73	76	97	90	81	80	80	40	43	34	48	105	
MEAN	39	65	113	171	209	250	275	279	273	276	270	257	241	202	174	149	108	87	157	RIGHT
SD	7	20	24	39	53	84	83	106	88	88	87	94	88	71	49	40	37	62	105	
MEAN	39	66	110	173	230	268	296	293	315	329	297	283	256	206	169	146	101	95	157	
SD	7	16	25	43	65	87	86	96	112	105	95	102	99	70	54	49	36	50	105	
MEAN	39	69	116	176	238	268	314	304	327	322	292	295	283	239	183	149	116	88	157	
SD	7	18	21	40	62	86	82	86	102	100	84	112	143	103	55	42	49	46	105	
MEAN	39	74	112	171	230	266	311	301	340	338	296	299	282	232	182	149	116	80	157	
SD	7	18	30	33	56	59	94	83	111	119	87	117	129	91	74	59	54	45	105	
MEAN	39	74	116	173	237	284	318	333	336	345	316	311	279	246	198	160	115	92	157	
SD	7	22	31	41	52	62	103	95	92	116	91	103	115	95	74	54	61	55	105	
MEAN	39	74	115	169	236	275	315	340	350	371	346	311	292	259	200	159	131	94	157	
SD	7	23	34	49	61	80	98	103	90	112	91	96	107	112	87	52	62	48	105	
MEAN	39	75	122	171	220	277	313	352	357	366	368	321	292	263	195	171	132	99	157	
SD	7	25	30	36	65	73	88	105	99	119	127	114	93	98	86	57	63	64	105	
MEAN	39	68	123	187	227	288	313	354	368	391	371	315	283	246	197	177	144	120	157	
SD	7	28	34	36	66	73	85	98	98	115	128	92	87	86	65	75	90	83	105	
MEAN	39	72	108	174	227	295	345	387	392	417	407	349	308	288	211	179	200	136	157	
SD	7	26	30	36	44	54	67	118	123	148	145	125	103	121	99	83	181	119	105	
MEAN	39	67	114	160	225	275	326	367	420	454	443	383	320	308	239	179	209	157	157	FRONT
SD	7	21	31	45	60	70	91	120	166	186	159	128	91	97	106	62	244	121	105	
MEAN	39	57	101	163	213	262	308	336	387	426	392	327	291	254	230	190	269	185	157	
SD	7	27	26	49	61	72	86	98	142	154	164	132	98	88	96	73	258	144	105	
MEAN	39	60	117	158	226	263	299	335	377	396	382	307	285	242	225	202	228	236	157	
SD	7	20	36	45	60	79	95	85	129	160	180	120	117	72	76	78	195	227	105	
MEAN	39	65	111	155	225	246	283	314	360	363	366	296	276	215	249	239	244	279	157	
SD	7	19	29	34	64	65	97	99	134	152	175	126	137	64	139	111	233	275	105	
MEAN	39	63	112	162	207	252	260	283	319	338	292	269	226	205	209	206	337	289	157	
SD	7	19	25	41	54	64	102	104	133	172	135	125	88	61	79	85	397	275	105	
MEAN	39	71	102	154	211	238	230	259	285	267	265	234	221	204	200	226	299	319	157	
SD	7	20	34	42	52	71	79	93	128	145	140	106	108	52	50	94	257	313	105	

MEAN	39	55	92	154	210	210	215	239	255	235	222	216	211	212	216	233	257	241	157	
SD	7	19	25	41	61	81	72	87	101	85	83	85	68	70	97	153	161	221	105	
MEAN	39	58	100	133	175	197	210	211	213	214	231	237	233	235	229	227	212	202	157	
SD	7	23	29	42	54	76	89	75	50	49	85	105	102	103	88	101	88	164	105	
MEAN	39	59	92	135	170	175	203	202	215	238	239	228	233	245	231	232	220	157	157	
SD	7	16	25	40	57	59	71	59	56	82	106	99	99	133	84	113	95	109	105	
MEAN	39	47	84	113	128	149	186	206	235	257	257	213	214	228	230	220	198	187	157	LEFT
SD	7	25	19	28	36	47	57	55	78	106	101	82	71	68	75	96	73	113	105	
MEAN	39	55	76	106	136	149	196	218	232	259	254	222	218	230	233	208	206	158	157	
SD	7	25	22	26	39	24	46	67	69	107	99	73	76	70	77	64	105	84	105	
MEAN	39	46	82	99	129	161	192	215	226	237	233	231	220	245	230	207	189	166	157	
SD	7	24	33	22	25	22	35	72	77	74	67	68	67	73	74	63	72	100	105	
MEAN	39	44	72	95	140	180	198	230	237	246	245	241	252	241	240	220	189	143	157	
SD	7	16	28	19	43	39	47	80	68	67	77	72	98	71	93	86	92	84	105	
MEAN	39	58	75	103	160	200	235	255	262	260	250	251	241	224	214	210	199	138	157	
SD	7	28	16	19	47	51	81	83	86	103	93	89	80	77	80	81	130	75	105	
MEAN	39	51	81	113	174	214	256	269	285	274	267	265	258	230	236	204	194	158	157	
SD	7	21	18	28	41	57	56	59	70	85	85	82	83	76	78	71	92	95	105	
MEAN	39	58	80	137	184	222	279	305	304	306	277	268	260	257	225	199	179	175	157	
SD	7	11	19	40	52	80	72	71	71	81	74	77	87	108	92	81	75	106	105	
MEAN	39	52	87	144	210	286	301	345	336	300	314	304	310	309	268	225	223	161	157	
SD	7	20	27	51	56	92	111	120	100	72	102	105	133	139	121	75	97	85	105	
MEAN	39	44	90	142	241	350	358	368	373	376	411	358	377	343	324	267	254	158	157	
SD	7	18	23	62	91	122	132	148	156	156	246	169	173	157	156	104	142	96	105	
MEAN	39	57	81	141	230	310	356	359	367	374	401	418	392	382	336	287	231	162	157	BACK
SD	7	20	32	71	116	122	138	151	159	162	178	140	149	188	140	127	125	81	105	

Table C5:

The following data is based on semi-freestyle exertions performed at a handle height of 1.0 m by 11 military personnel.

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF NEWTONS ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	626	320	357	351	327	305	284	263	252	187	167	167	169	178	173	184	215	263	448	BACK
SD	131	139	206	214	145	158	140	123	152	99	82	60	55	65	54	61	77	71	27	
MEAN	626	286	240	294	308	275	214	185	195	163	151	149	153	158	159	173	202	256	448	
SD	131	122	90	166	172	166	101	81	89	73	61	52	46	58	53	52	64	86	27	
MEAN	626	301	220	227	205	174	170	153	152	143	138	142	143	145	154	163	183	217	448	
SD	131	83	73	91	90	63	68	67	64	61	54	49	46	49	49	37	52	45	27	
MEAN	626	286	210	197	179	154	147	140	141	141	136	139	141	145	150	163	182	223	448	
SD	131	82	88	94	69	54	58	58	62	67	55	53	58	42	38	36	37	41	27	
MEAN	626	301	210	195	177	160	173	169	161	157	151	145	137	147	158	178	176	232	448	
SD	131	111	103	102	85	65	66	70	56	64	52	46	47	52	58	71	47	38	27	
MEAN	626	305	232	217	197	178	180	216	210	197	178	163	147	160	180	204	198	247	448	
SD	131	123	115	117	95	77	66	72	56	63	69	62	48	53	71	98	70	52	27	
MEAN	626	307	236	225	239	227	219	244	231	226	218	205	190	194	205	208	204	254	448	
SD	131	137	119	112	107	75	70	131	68	78	96	86	71	65	78	87	69	63	27	
MEAN	626	306	248	258	261	246	246	257	272	254	258	237	228	217	221	212	218	243	448	
SD	131	139	119	121	125	107	108	127	106	85	82	78	86	84	85	90	82	90	27	
MEAN	626	318	268	275	277	264	253	267	287	264	261	242	241	245	223	213	216	262	448	RIGHT
SD	131	151	134	133	140	146	96	91	92	84	98	79	91	95	92	92	95	92	27	
MEAN	626	339	274	276	267	242	238	248	265	262	257	248	246	247	248	224	236	285	448	
SD	131	130	120	137	134	109	80	85	88	83	96	81	89	100	95	108	104	73	27	
MEAN	626	341	284	252	236	236	241	241	254	265	244	264	245	238	238	227	245	265	448	
SD	131	128	119	113	98	97	81	83	82	101	77	101	93	97	89	112	127	103	27	
MEAN	626	329	267	229	216	216	232	232	248	265	242	239	229	239	246	245	238	288	448	
SD	131	109	103	82	79	77	81	86	96	91	80	81	86	96	103	120	119	94	27	
MEAN	626	355	248	222	219	215	224	227	246	250	249	249	252	251	255	254	268	290	448	
SD	131	95	96	69	71	78	84	90	96	92	82	78	91	103	102	123	139	108	27	
MEAN	626	359	236	222	215	213	225	250	250	254	265	256	261	271	275	291	271	308	448	
SD	131	141	76	65	72	72	100	136	111	99	79	75	98	95	90	128	120	73	27	
MEAN	626	334	248	228	215	219	218	247	247	270	264	277	276	270	270	282	282	308	448	
SD	131	108	106	65	69	75	93	110	97	98	85	81	82	92	83	118	123	83	27	
MEAN	626	333	246	215	217	208	223	248	258	273	276	278	292	289	291	284	282	307	448	
SD	131	104	99	72	83	90	105	115	101	114	93	79	82	103	88	104	112	87	27	
MEAN	626	337	259	241	225	221	221	251	270	297	324	299	326	333	304	301	282	315	448	
SD	131	124	118	123	88	103	105	118	116	114	116	82	85	106	97	113	108	82	27	
MEAN	626	349	251	225	220	239	245	246	276	308	328	314	339	350	327	320	285	309	448	FRONT
SD	131	114	97	94	91	130	114	105	129	122	110	106	101	115	125	131	118	89	27	
MEAN	626	318	237	218	217	229	225	232	255	273	312	334	330	335	311	333	292	319	448	
SD	131	131	96	79	88	92	94	94	110	101	120	124	108	110	120	140	141	90	27	

MEAN	626	311	228	207	212	221	217	225	266	275	289	297	306	324	308	304	284	316	448	
SD	131	102	92	81	91	95	86	95	102	93	97	103	109	103	117	117	123	95	27	
MEAN	626	343	242	206	212	217	214	222	242	271	289	296	288	301	287	267	270	327	448	
SD	131	77	75	81	90	94	78	72	74	93	94	99	108	114	109	107	119	114	27	
MEAN	626	307	229	207	209	219	211	216	245	281	299	272	251	260	272	257	283	345	448	
SD	131	81	68	73	83	94	77	72	85	105	126	95	94	96	119	103	143	124	27	
MEAN	626	298	225	202	219	232	217	226	253	279	281	255	241	242	254	241	274	341	448	
SD	131	86	74	76	79	93	80	74	84	103	119	87	92	105	120	105	126	123	27	
MEAN	626	314	223	204	211	248	215	225	269	294	265	240	217	212	210	231	252	308	448	
SD	131	99	88	78	87	117	85	84	102	118	131	100	83	83	80	98	107	116	27	
MEAN	626	320	233	200	192	205	205	209	253	253	252	216	208	214	199	216	264	324	448	
SD	131	86	107	83	78	94	93	98	111	115	117	78	77	79	69	82	105	91	27	
MEAN	626	323	246	200	185	194	184	209	216	227	217	194	194	207	189	236	286	347	448	
SD	131	96	119	73	71	90	75	98	79	93	83	57	59	85	54	83	79	99	27	
MEAN	626	300	226	205	198	178	180	188	192	207	179	170	178	179	189	222	279	362	448	LEFT
SD	131	97	92	79	88	66	58	53	60	75	53	47	44	46	46	54	66	84	27	
MEAN	626	285	208	206	185	173	173	173	182	189	173	166	166	181	206	226	282	365	448	
SD	131	77	70	77	56	55	52	41	44	55	46	41	36	39	44	45	57	85	27	
MEAN	626	303	202	197	187	180	173	175	175	183	177	170	170	187	206	229	273	360	448	
SD	131	70	61	54	55	53	48	48	40	43	52	40	35	38	35	36	62	100	27	
MEAN	626	289	209	198	197	194	181	184	176	178	173	177	182	181	203	223	276	315	448	
SD	131	41	47	53	52	55	47	46	42	42	40	45	47	42	42	44	69	79	27	
MEAN	626	311	232	212	215	216	192	187	186	179	177	180	178	189	201	225	276	316	448	
SD	131	61	51	55	65	56	44	42	37	34	42	38	34	33	37	43	60	73	27	
MEAN	626	320	233	238	227	221	212	203	197	191	188	175	182	191	199	225	285	305	448	
SD	131	63	57	72	56	47	54	52	45	39	46	34	47	38	33	49	65	63	27	
MEAN	626	307	249	254	256	242	256	255	241	234	205	189	189	190	208	219	264	337	448	
SD	131	81	69	85	91	67	89	85	80	80	59	54	46	37	41	43	80	88	27	
MEAN	626	315	280	285	295	308	286	277	278	240	218	194	200	194	193	217	253	315	448	
SD	131	94	94	102	131	153	117	107	132	104	85	54	59	63	34	53	68	86	27	
MEAN	626	335	326	339	391	371	333	323	274	242	219	203	206	196	196	208	242	294	448	
SD	131	98	124	148	243	203	199	205	157	135	118	95	92	83	60	59	67	70	27	
MEAN	626	354	375	365	372	341	289	279	252	200	191	191	179	184	192	192	234	269	448	BACK
SD	131	137	204	175	154	167	121	125	133	95	83	77	65	61	50	59	64	62	27	

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF % BODY WEIGHT ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	868	443	500	495	459	432	400	362	340	257	231	232	233	244	236	253	293	360	620	BACK
SD	229	192	305	325	224	239	213	174	184	145	128	95	79	90	70	84	99	91	106	
MEAN	868	396	333	409	435	393	302	260	271	227	211	207	212	217	219	238	277	347	620	
SD	229	170	129	235	262	261	158	131	139	114	98	83	73	80	76	74	88	95	106	
MEAN	868	421	303	314	285	245	239	215	212	199	192	198	198	201	213	225	253	301	620	
SD	229	141	105	130	129	105	110	107	97	96	86	79	72	75	72	57	77	87	106	
MEAN	868	401	294	274	251	216	205	196	196	196	189	194	198	201	210	226	252	311	620	
SD	229	145	137	142	106	91	91	90	97	99	86	86	94	71	72	61	63	81	106	
MEAN	868	421	294	274	251	229	245	235	225	220	210	201	190	205	221	248	245	322	620	
SD	229	174	158	161	137	115	110	102	93	103	84	73	77	87	96	108	82	80	106	
MEAN	868	431	325	304	281	254	254	298	292	275	248	227	204	225	255	286	278	343	620	

SD	229	194	178	178	159	131	113	103	97	106	111	99	76	93	123	152	123	96	106	
MEAN	868	430	330	314	334	313	301	329	321	313	304	286	266	274	289	293	287	356	620	
SD	229	204	178	166	165	111	96	143	108	111	144	131	111	115	129	138	120	118	106	
MEAN	868	432	346	358	362	338	335	347	372	351	358	327	315	302	313	300	308	344	620	
SD	229	216	176	175	179	139	123	140	135	126	127	115	121	125	140	147	140	157	106	
MEAN	868	438	374	380	379	357	345	368	396	366	359	335	335	338	315	301	306	370	620	RIGHT
SD	229	209	199	187	175	166	115	128	132	127	136	114	132	128	144	148	155	160	106	
MEAN	868	467	379	379	365	329	325	340	368	365	355	343	341	341	344	312	330	398	620	
SD	229	185	165	181	159	128	99	112	135	129	139	115	133	134	137	155	159	131	106	
MEAN	868	471	393	345	324	324	333	331	349	366	336	365	338	328	330	315	340	372	620	
SD	229	181	164	142	122	124	113	103	108	140	104	143	122	128	129	156	172	162	106	
MEAN	868	451	368	317	296	296	317	316	339	364	333	328	314	329	338	341	332	402	620	
SD	229	146	133	114	101	98	98	98	117	118	105	105	109	126	138	175	175	150	106	
MEAN	868	487	341	306	301	295	305	309	337	343	342	342	345	344	353	354	371	404	620	
SD	229	120	124	97	93	96	101	103	114	114	108	104	115	132	145	182	186	165	106	
MEAN	868	496	326	306	296	292	303	336	342	347	364	351	359	372	380	403	377	427	620	
SD	229	182	106	88	97	90	110	147	138	120	108	101	128	125	124	182	169	118	106	
MEAN	868	458	338	311	294	299	296	333	337	372	363	382	380	370	371	392	388	427	620	
SD	229	130	123	79	86	89	106	124	122	133	118	119	109	112	109	166	159	129	106	
MEAN	868	460	336	295	294	284	301	335	352	371	379	383	403	396	400	393	389	427	620	
SD	229	141	119	94	101	110	120	130	123	133	125	111	118	131	119	144	147	134	106	
MEAN	868	460	353	328	309	301	301	338	368	403	445	411	450	454	417	415	392	435	620	
SD	229	154	144	142	120	130	128	137	140	136	156	110	119	136	124	153	160	125	106	
MEAN	868	481	343	306	301	323	331	334	372	415	446	428	464	477	447	445	397	427	620	FRONT
SD	229	160	118	112	116	156	137	130	162	142	133	125	131	139	161	192	173	137	106	
MEAN	868	429	322	299	297	314	305	315	345	369	422	452	450	456	421	453	402	440	620	
SD	229	161	115	104	112	120	114	111	131	119	141	138	141	130	141	176	193	136	106	
MEAN	868	423	310	283	289	300	295	306	362	375	396	409	419	444	416	413	392	437	620	
SD	229	127	109	102	111	114	104	110	117	110	118	130	137	126	132	141	170	146	106	
MEAN	868	468	329	281	290	295	293	304	330	372	397	409	395	411	390	364	372	455	620	
SD	229	92	85	99	114	116	100	95	93	125	117	135	132	135	129	129	159	182	106	
MEAN	868	423	314	284	286	300	289	296	339	388	408	373	343	356	369	353	389	479	620	
SD	229	117	88	91	106	124	101	94	115	139	147	117	118	128	141	141	182	185	106	
MEAN	868	414	311	277	301	319	299	311	350	390	384	349	328	330	346	331	380	475	620	
SD	229	138	104	95	105	121	108	96	117	153	152	115	116	128	143	142	177	197	106	
MEAN	868	428	305	280	290	342	296	309	373	410	358	329	297	292	291	317	349	427	620	
SD	229	133	112	99	112	154	111	106	145	170	150	138	112	115	123	133	150	176	106	
MEAN	868	443	317	274	264	284	281	286	350	346	342	295	285	294	275	300	365	446	620	
SD	229	132	128	108	104	133	125	128	155	151	139	103	104	113	104	127	148	138	106	
MEAN	868	444	336	274	256	269	256	285	297	312	298	268	266	283	261	324	394	474	620	
SD	229	142	154	94	99	132	112	126	112	131	115	86	84	108	81	109	110	133	106	
MEAN	868	414	310	281	275	248	251	261	265	285	247	235	246	245	260	306	387	492	620	LEFT
SD	229	133	125	101	129	103	94	82	92	105	76	73	71	61	66	75	103	90	106	
MEAN	868	397	288	282	260	242	242	242	251	261	239	229	229	247	284	314	389	497	620	
SD	229	130	103	99	96	93	87	73	69	78	71	64	55	52	62	79	87	90	106	
MEAN	868	422	284	275	264	253	242	244	243	250	245	235	235	255	283	317	376	490	620	
SD	229	123	104	91	99	93	84	81	65	60	78	63	54	47	53	67	88	113	106	
MEAN	868	397	291	278	277	274	254	255	243	245	240	244	250	248	283	309	380	432	620	
SD	229	70	85	94	94	101	84	73	62	62	61	66	65	56	75	78	95	95	106	

MEAN	868	435	325	298	302	304	271	261	258	248	244	247	246	264	279	308	377	435	620	
SD	229	121	96	101	112	108	85	74	63	58	60	56	57	67	64	63	79	96	106	
MEAN	868	448	326	334	319	310	297	284	275	263	258	241	252	264	275	309	388	417	620	
SD	229	131	105	124	103	91	98	92	79	55	60	55	79	67	57	74	74	80	106	
MEAN	868	428	348	353	358	337	360	357	336	324	281	260	261	262	285	299	359	460	620	
SD	229	137	118	130	143	108	145	135	126	116	78	81	73	64	57	47	88	106	106	
MEAN	868	434	389	397	409	431	396	384	382	330	299	268	274	264	264	294	344	430	620	
SD	229	131	144	151	178	238	161	149	165	133	112	79	72	72	48	56	79	105	106	
MEAN	868	460	451	469	527	504	454	439	374	329	299	275	279	265	266	283	329	403	620	
SD	229	148	169	202	275	248	249	251	195	162	142	110	107	94	68	67	79	88	106	
MEAN	868	484	524	515	519	474	398	382	341	273	261	263	246	251	261	263	318	367	620	BACK
SD	229	195	301	278	233	252	169	168	160	120	109	106	87	76	57	77	69	78	106	

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF FRICTION COEFFICIENT ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	37	65	112	152	215	254	273	287	308	256	237	238	229	231	186	166	130	91	133	BACK
SD	10	29	50	62	87	118	118	117	155	146	138	106	89	102	66	68	61	51	75	
MEAN	37	54	84	147	186	218	221	217	246	226	216	210	206	193	172	151	124	93	133	
SD	10	26	24	73	84	111	99	94	115	115	106	91	79	84	70	55	51	50	75	
MEAN	37	59	80	124	141	164	182	185	198	196	195	200	192	175	161	133	114	88	133	
SD	10	14	24	49	53	64	76	91	89	96	91	87	80	72	66	47	49	39	75	
MEAN	37	52	74	106	129	141	156	168	172	194	187	194	192	177	162	138	109	88	133	
SD	10	22	29	51	48	55	68	74	107	101	93	95	106	73	67	46	39	48	75	
MEAN	37	60	71	100	124	145	185	201	211	218	213	202	181	183	172	165	104	83	133	
SD	10	31	31	43	53	64	76	79	86	102	88	80	84	92	92	118	62	36	75	
MEAN	37	63	85	113	141	157	193	246	273	275	256	232	198	203	211	206	145	91	133	
SD	10	28	42	56	66	70	76	78	88	109	126	115	85	103	128	155	131	40	75	
MEAN	37	48	85	117	163	190	224	268	295	311	318	302	269	261	253	210	152	114	133	
SD	10	23	45	52	66	53	63	96	92	115	159	153	134	135	147	139	104	83	75	
MEAN	37	49	93	131	167	204	246	279	344	351	374	350	332	295	277	221	164	100	133	
SD	10	24	39	52	65	72	84	97	121	127	139	136	144	149	165	160	116	82	75	
MEAN	37	44	93	137	186	213	249	306	367	367	381	358	356	342	284	233	160	137	133	RIGHT
SD	10	19	40	55	73	74	66	99	114	126	157	134	159	152	161	164	130	129	75	
MEAN	37	61	90	147	176	204	237	288	339	362	372	368	366	350	321	227	189	103	133	
SD	10	26	24	54	57	67	65	86	119	126	151	138	165	169	162	157	151	62	75	
MEAN	37	64	98	123	163	203	241	278	323	362	349	395	359	329	300	244	205	144	133	
SD	10	25	34	40	47	67	71	78	100	135	112	174	149	152	150	164	152	118	75	
MEAN	37	53	91	121	150	187	234	265	315	363	348	351	327	326	314	282	198	159	133	
SD	10	20	31	36	41	59	66	80	107	118	116	123	128	146	162	202	151	110	75	
MEAN	37	58	81	113	156	187	228	259	312	341	355	365	365	351	333	281	239	132	133	
SD	10	16	26	33	40	54	70	79	103	114	114	124	140	163	201	205	183	97	75	
MEAN	37	64	83	111	154	182	222	282	312	341	384	375	388	387	351	348	241	141	133	
SD	10	22	23	25	48	51	72	112	124	119	121	119	160	158	142	260	177	74	75	
MEAN	37	55	84	119	153	190	222	277	308	373	383	417	408	377	348	327	236	142	133	
SD	10	16	27	28	39	51	70	99	108	135	130	152	136	134	133	207	140	73	75	
MEAN	37	53	85	113	149	177	223	275	321	371	400	415	444	422	382	320	243	141	133	
SD	10	22	23	28	40	57	85	96	108	139	140	132	150	172	146	148	129	79	75	
MEAN	37	60	88	120	161	185	226	284	337	406	477	452	512	513	404	367	246	160	133	

SD	10	20	30	38	56	69	86	111	120	139	178	138	165	207	159	179	179	124	75	
MEAN	37	57	77	113	151	201	240	283	346	421	478	474	533	553	463	428	268	139	133	FRONT
SD	10	21	22	31	52	83	83	102	145	147	157	158	188	240	227	261	191	85	75	
MEAN	37	48	87	119	147	196	220	265	315	372	451	507	516	513	426	421	280	145	133	
SD	10	14	31	37	46	63	73	88	114	123	169	177	195	187	188	233	253	76	75	
MEAN	37	42	81	106	149	184	219	258	337	371	422	453	468	489	408	341	242	158	133	
SD	10	15	27	33	54	57	70	85	101	109	135	160	176	164	174	168	156	110	75	
MEAN	37	59	88	107	148	183	217	256	307	373	426	453	434	443	379	291	241	197	133	
SD	10	17	25	35	50	62	72	74	84	125	135	165	173	187	175	164	189	192	75	
MEAN	37	45	82	109	148	187	221	246	315	388	429	402	365	360	357	269	264	169	133	
SD	10	15	23	31	54	68	69	72	104	144	164	139	145	165	182	155	218	126	75	
MEAN	37	40	80	110	160	203	223	268	324	385	406	374	347	331	328	246	232	197	133	
SD	10	18	20	30	51	72	72	82	108	147	167	135	146	156	197	167	173	181	75	
MEAN	37	53	81	115	149	204	222	258	351	400	376	353	306	279	250	231	198	142	133	
SD	10	16	32	32	53	77	77	82	133	164	164	168	134	136	144	134	138	98	75	
MEAN	37	52	82	106	145	178	207	240	331	342	355	310	292	282	233	211	202	147	133	
SD	10	23	29	38	52	77	81	101	145	147	151	117	122	137	111	121	114	55	75	
MEAN	37	55	82	106	133	165	190	243	274	312	309	278	267	276	210	222	220	160	133	
SD	10	24	28	32	49	65	74	102	100	132	123	97	94	130	75	104	78	66	75	
MEAN	37	50	74	114	144	160	193	223	250	286	253	240	243	222	204	200	205	170	133	LEFT
SD	10	23	25	36	63	49	66	68	88	107	81	82	83	67	63	61	90	53	75	
MEAN	37	47	75	110	137	153	179	206	235	259	243	232	223	222	229	202	199	155	133	
SD	10	15	18	33	43	50	58	63	63	77	74	72	60	55	60	61	73	57	75	
MEAN	37	51	81	110	140	168	182	208	225	249	250	238	226	230	231	208	182	180	133	
SD	10	15	29	29	47	53	55	65	56	61	83	71	60	47	54	56	50	67	75	
MEAN	37	50	78	109	142	171	189	218	225	244	244	250	250	225	238	205	202	152	133	
SD	10	22	23	32	39	57	58	61	56	64	64	73	74	62	79	62	71	46	75	
MEAN	37	55	82	116	151	190	205	226	239	246	250	252	241	242	226	200	182	145	133	
SD	10	16	19	38	42	60	63	61	59	57	65	62	61	73	67	55	55	51	75	
MEAN	37	57	80	124	163	192	220	238	252	262	264	246	253	242	222	210	187	146	133	
SD	10	19	31	39	43	56	66	71	69	54	65	61	92	73	56	80	45	44	75	
MEAN	37	59	91	135	172	201	262	287	308	324	288	270	258	238	233	201	178	144	133	
SD	10	24	32	45	57	58	98	102	109	119	83	91	81	71	65	42	73	47	75	
MEAN	37	59	99	144	197	252	282	312	343	326	308	277	273	248	214	193	158	111	133	
SD	10	19	30	50	75	116	107	110	140	130	119	88	83	80	48	49	53	43	75	
MEAN	37	60	111	169	231	269	311	341	332	329	309	287	286	253	217	182	153	95	133	
SD	10	25	32	63	93	108	146	168	162	172	156	129	128	107	69	62	49	30	75	
MEAN	37	57	118	177	222	270	282	306	311	269	270	274	246	230	208	178	139	97	133	BACK
SD	10	26	51	71	74	116	112	121	138	117	118	119	97	82	54	70	44	36	75	

Table C6:

The following data is based on semi-freestyle exertions performed at a handle height of 1.5 m by 11 military personnel.

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF NEWTONS ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	525	355	293	268	264	394	447	366	277	202	169	154	136	128	131	133	154	194	436	BACK
SD	133	177	168	190	138	230	172	97	105	74	73	63	33	33	35	39	55	74	96	
MEAN	525	379	306	225	194	200	246	229	168	147	136	128	122	125	141	146	166	239	436	
SD	133	178	208	121	89	105	150	101	43	34	37	33	30	30	31	41	52	65	96	
MEAN	525	336	275	191	163	150	137	143	136	132	131	124	125	125	133	140	160	203	436	
SD	133	148	192	84	72	44	34	40	30	31	31	34	31	31	36	41	51	83	96	
MEAN	525	315	253	160	135	132	126	128	128	130	129	133	136	138	137	143	160	209	436	
SD	133	166	168	45	22	21	25	30	33	34	32	36	36	35	37	36	53	80	96	
MEAN	525	301	209	161	142	136	125	123	127	133	144	141	154	147	149	164	192	226	436	
SD	133	183	115	48	32	32	21	22	26	42	48	44	55	44	42	52	62	74	96	
MEAN	525	307	176	163	145	133	131	122	131	140	155	157	155	165	174	185	211	247	436	
SD	133	174	55	42	38	36	21	21	26	41	47	54	54	53	53	50	59	87	96	
MEAN	525	268	179	153	141	128	137	139	127	137	158	162	170	184	191	216	219	271	436	
SD	133	118	56	39	38	36	39	37	25	28	33	45	53	63	51	65	67	86	96	
MEAN	525	246	174	160	143	136	128	132	135	142	159	200	182	215	212	243	243	284	436	
SD	133	93	51	37	33	32	36	42	36	35	34	54	49	60	59	69	67	124	96	
MEAN	525	246	165	145	130	127	119	128	140	146	177	202	230	223	234	261	266	292	436	RIGHT
SD	133	99	47	36	34	47	42	42	43	47	71	67	83	71	74	76	84	110	96	
MEAN	525	236	165	140	132	122	118	120	134	142	174	188	211	205	217	265	307	323	436	
SD	133	85	41	33	43	39	41	38	53	59	71	71	56	52	66	103	114	119	96	
MEAN	525	242	161	139	131	126	114	119	127	141	158	176	208	212	234	257	293	329	436	
SD	133	103	42	35	38	38	37	39	40	46	48	64	59	63	91	102	101	108	96	
MEAN	525	220	155	128	122	122	118	123	133	145	154	170	207	221	238	266	290	333	436	
SD	133	93	48	48	42	43	45	40	39	39	40	46	70	63	89	93	87	102	96	
MEAN	525	189	147	137	121	120	119	131	136	138	152	175	201	220	247	281	303	336	436	
SD	133	58	47	48	41	45	37	32	36	38	45	48	73	79	85	84	68	68	96	
MEAN	525	167	134	127	122	126	117	127	133	141	163	181	213	231	249	275	325	356	436	
SD	133	53	36	36	40	40	18	23	31	40	49	64	74	95	93	74	97	47	96	
MEAN	525	187	130	117	117	114	115	122	126	137	153	172	211	232	253	272	339	380	436	
SD	133	76	23	27	28	23	23	20	24	24	28	46	65	76	84	85	79	82	96	
MEAN	525	184	135	116	112	110	116	119	130	139	162	208	226	255	283	289	349	386	436	
SD	133	57	31	23	23	24	26	25	24	23	33	62	59	58	78	80	94	81	96	
MEAN	525	195	133	122	117	109	116	125	146	163	177	230	270	296	310	320	340	384	436	
SD	133	61	36	25	22	29	33	29	41	39	50	98	81	81	89	91	102	88	96	
MEAN	525	165	134	126	117	115	119	135	155	165	191	234	301	315	340	352	377	439	436	FRONT
SD	133	63	42	28	25	26	28	41	56	41	56	69	74	81	91	95	85	93	96	
MEAN	525	173	141	123	112	115	120	124	144	147	173	201	259	281	305	320	363	436	436	
SD	133	61	36	29	26	23	25	32	48	28	63	69	61	72	112	101	100	108	96	
MEAN	525	188	143	127	115	116	118	126	135	135	161	181	207	233	259	278	324	374	436	
SD	133	87	43	46	35	28	26	29	34	26	66	63	63	53	67	61	88	117	96	
MEAN	525	229	173	157	135	116	123	121	125	124	144	178	216	222	254	256	303	359	436	
SD	133	95	95	118	74	35	33	30	34	27	38	67	68	61	64	53	85	87	96	

MEAN	525	236	182	154	151	128	117	117	119	125	138	163	189	195	229	256	270	314	436	
SD	133	118	118	112	124	49	30	30	25	30	29	40	59	60	87	120	98	118	96	
MEAN	525	265	185	165	160	120	111	115	114	128	134	154	180	198	222	228	259	323	436	
SD	133	118	125	107	114	41	33	27	22	24	22	29	59	68	83	67	77	85	96	
MEAN	525	265	204	176	131	109	114	108	109	115	127	149	177	182	205	213	272	317	436	
SD	133	122	126	99	39	26	32	20	22	22	37	49	68	58	53	56	76	82	96	
MEAN	525	246	229	159	137	116	110	109	106	110	136	167	170	164	193	211	259	290	436	
SD	133	104	120	60	47	31	27	25	25	27	54	119	92	75	62	74	93	83	96	
MEAN	525	254	205	164	146	124	116	111	120	121	132	167	181	190	222	227	252	280	436	
SD	133	105	90	56	50	35	28	30	39	38	46	96	98	95	104	100	99	93	96	
MEAN	525	257	225	177	154	137	129	119	122	123	137	146	174	167	181	193	234	264	436	LEFT
SD	133	113	100	67	55	44	42	33	40	47	58	66	87	70	77	84	82	87	96	
MEAN	525	267	245	195	159	145	129	123	121	121	131	131	153	143	158	187	219	258	436	
SD	133	115	124	86	48	41	33	34	33	49	48	53	77	67	64	75	83	107	96	
MEAN	525	288	242	203	164	150	136	119	120	128	131	133	133	142	143	167	209	255	436	
SD	133	99	101	80	45	44	28	30	35	50	54	66	64	61	48	56	72	92	96	
MEAN	525	296	245	233	186	161	136	127	118	117	118	118	118	125	138	159	183	214	436	
SD	133	99	99	72	52	38	38	34	34	37	40	35	35	35	44	43	67	94	96	
MEAN	525	265	252	255	197	168	142	134	122	116	114	114	110	116	127	136	164	210	436	
SD	133	104	97	109	63	69	55	43	35	32	32	34	27	26	30	31	48	67	96	
MEAN	525	294	267	267	222	176	146	151	137	123	120	118	112	122	127	143	164	195	436	
SD	133	109	98	119	94	70	52	58	47	33	34	46	25	27	32	40	55	73	96	
MEAN	525	308	284	268	257	206	170	172	150	134	126	123	122	129	137	152	163	211	436	
SD	133	88	113	112	116	88	51	66	40	37	35	34	32	30	33	45	54	69	96	
MEAN	525	319	299	260	220	246	240	230	183	154	136	129	134	138	141	143	153	209	436	
SD	133	76	136	111	74	129	101	88	57	41	34	33	32	39	35	29	36	60	96	
MEAN	525	353	288	239	235	293	399	386	290	220	171	147	146	137	137	139	149	211	436	
SD	133	95	161	98	68	123	164	115	136	72	58	28	28	25	23	23	35	46	96	
MEAN	525	358	288	248	270	389	516	419	298	224	174	155	142	134	134	140	153	192	436	BACK
SD	133	144	143	112	143	221	179	121	110	64	35	35	34	23	38	31	50	66	96	

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF % BODY WEIGHT ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	734	505	405	361	372	537	614	498	371	270	224	207	186	176	181	184	212	268	605	BACK
SD	228	287	227	216	220	311	232	120	108	77	73	68	45	48	50	56	81	102	169	
MEAN	734	530	419	307	269	279	332	308	230	199	184	175	168	173	196	203	229	328	605	
SD	228	279	269	147	127	159	178	114	56	40	43	45	45	48	53	65	78	95	169	
MEAN	734	465	372	260	224	207	190	197	186	181	179	171	171	172	185	194	223	285	605	
SD	228	224	234	98	99	68	57	62	47	45	47	51	46	45	58	66	84	131	169	
MEAN	734	434	341	224	188	184	175	177	177	178	178	183	187	189	188	197	224	292	605	
SD	228	243	194	77	47	46	44	46	52	52	50	54	52	47	52	53	88	130	169	
MEAN	734	421	295	226	199	191	175	170	176	184	200	194	210	201	204	226	265	311	605	
SD	228	271	186	85	66	63	47	40	45	71	80	66	77	60	57	75	95	112	169	
MEAN	734	430	244	227	203	186	182	169	181	195	216	218	214	226	239	255	294	343	605	
SD	228	267	91	72	71	66	40	39	45	70	77	87	79	75	78	77	95	139	169	
MEAN	734	370	249	213	197	179	186	190	174	188	216	223	233	251	263	295	306	377	605	
SD	228	174	88	63	67	61	45	44	36	42	50	66	78	84	75	83	110	141	169	
MEAN	734	343	241	220	200	187	173	179	184	193	219	275	250	298	295	334	336	398	605	

SD	228	147	83	53	59	45	41	50	44	40	49	82	75	93	103	97	103	194	169	
MEAN	734	342	227	198	177	172	163	175	191	199	240	276	315	308	326	362	370	407	605	RIGHT
SD	228	153	70	44	43	53	51	54	54	52	82	91	118	108	123	118	135	173	169	
MEAN	734	324	227	192	181	166	160	163	180	191	233	251	286	279	295	362	430	454	605	
SD	228	130	67	44	51	44	48	45	55	63	76	65	58	58	76	125	180	201	169	
MEAN	734	341	222	192	181	172	154	161	172	189	212	235	280	288	318	351	403	458	605	
SD	228	173	64	51	51	43	41	44	40	45	44	56	50	76	108	121	133	171	169	
MEAN	734	308	212	177	167	166	160	167	180	196	209	229	279	300	321	362	400	463	605	
SD	228	153	64	71	52	46	48	44	41	44	40	41	71	67	92	115	122	162	169	
MEAN	734	259	202	190	165	163	161	177	183	186	206	235	270	296	333	384	417	465	605	
SD	228	77	62	74	47	47	39	30	34	38	46	42	70	80	87	104	95	115	169	
MEAN	734	229	186	177	166	172	161	173	181	191	220	242	286	310	336	372	441	491	605	
SD	228	71	59	58	47	45	28	22	30	41	50	60	75	100	99	68	102	88	169	
MEAN	734	260	179	162	162	157	159	167	173	188	210	232	286	313	340	367	461	527	605	
SD	228	112	43	47	45	37	37	31	33	31	35	46	64	74	83	84	82	138	169	
MEAN	734	254	188	162	156	152	161	165	180	191	220	283	307	347	386	392	476	538	605	
SD	228	86	55	44	41	39	42	38	40	40	36	70	61	59	92	79	102	144	169	
MEAN	734	268	186	170	162	151	160	171	199	225	242	308	364	400	422	434	466	534	605	
SD	228	87	59	47	42	45	49	42	49	62	62	98	75	77	99	97	126	150	169	
MEAN	734	229	188	178	163	160	166	183	214	226	261	317	408	431	466	485	522	607	605	FRONT
SD	228	95	69	58	49	47	49	46	86	52	67	74	68	112	114	136	138	145	169	
MEAN	734	240	197	172	157	160	166	171	200	202	235	272	354	383	417	437	496	599	605	
SD	228	96	63	54	47	43	40	48	74	39	71	75	69	79	134	118	130	145	169	
MEAN	734	260	200	177	161	161	163	173	185	185	218	245	280	318	357	383	446	514	605	
SD	228	124	70	74	58	46	42	43	50	37	68	65	67	67	104	91	125	159	169	
MEAN	734	316	242	221	189	162	169	165	172	171	200	240	293	306	351	354	415	495	605	
SD	228	141	143	174	112	59	53	42	51	43	65	69	80	90	102	87	115	124	169	
MEAN	734	325	255	216	212	179	162	160	163	173	191	223	256	268	317	354	370	428	605	
SD	228	169	175	165	183	77	48	43	34	46	50	49	63	88	133	176	130	154	169	
MEAN	734	375	260	232	224	167	154	158	157	174	186	212	244	272	308	317	358	446	605	
SD	228	188	185	158	168	63	48	40	34	27	44	43	63	100	126	107	114	131	169	
MEAN	734	374	286	247	181	149	155	149	150	157	175	203	240	248	283	296	379	439	605	
SD	228	191	187	150	60	34	38	30	30	30	50	57	80	79	85	96	130	131	169	
MEAN	734	346	321	218	186	158	150	151	146	153	186	224	231	227	269	295	367	405	605	
SD	228	165	179	82	59	37	33	35	32	42	68	135	111	105	97	117	172	138	169	
MEAN	734	360	287	228	201	171	159	153	165	167	182	228	250	265	312	319	357	393	605	
SD	228	178	141	86	74	46	36	41	53	56	62	117	137	136	155	153	176	159	169	
MEAN	734	364	313	245	213	189	178	165	166	170	191	204	243	233	253	266	327	366	605	LEFT
SD	228	190	140	100	84	64	58	47	54	71	94	100	132	108	115	118	140	140	169	
MEAN	734	376	339	269	218	199	178	167	164	166	181	183	212	199	219	259	304	352	605	
SD	228	186	170	121	65	56	49	41	43	71	73	86	115	103	98	111	133	133	169	
MEAN	734	405	339	277	225	206	186	163	164	177	180	186	186	197	198	233	290	346	605	
SD	228	166	156	107	58	53	36	39	47	75	79	106	101	98	73	91	110	104	169	
MEAN	734	413	342	320	254	220	186	174	162	161	161	163	162	172	190	217	249	287	605	
SD	228	165	148	96	63	45	44	42	46	51	52	52	49	54	64	52	74	95	169	
MEAN	734	373	351	350	268	228	193	183	166	158	157	157	151	161	175	187	226	284	605	
SD	228	168	146	146	77	76	60	50	41	41	41	45	37	40	42	43	66	70	169	
MEAN	734	409	369	362	299	238	198	204	185	167	163	159	153	167	175	197	223	266	605	
SD	228	176	147	146	104	76	61	66	46	37	38	50	33	39	45	52	66	84	169	

MEAN	734	428	391	362	348	279	232	232	205	183	171	168	166	177	188	206	222	294	605	
SD	228	145	155	132	140	102	60	69	48	43	39	40	37	40	41	47	60	104	169	
MEAN	734	445	409	355	302	329	325	312	249	209	186	176	182	187	191	195	210	288	605	
SD	228	142	174	138	99	137	107	102	70	43	40	39	36	40	38	34	48	89	169	
MEAN	734	496	393	328	326	399	549	528	388	297	231	200	199	187	187	190	204	288	605	
SD	228	177	193	126	108	152	227	146	139	69	58	31	27	27	27	32	45	62	169	
MEAN	734	502	398	343	380	533	707	573	402	303	237	211	194	183	185	192	210	264	605	BACK
SD	228	239	195	154	229	297	215	152	113	63	47	46	44	33	52	43	69	94	169	

MEAN / SD VALUES FOR INDIVIDUAL CELLS OF FRICTION COEFFICIENT ARRAY

	UP									HORIZONTAL									DOWN	
MEAN	17	50	87	131	179	291	397	386	329	264	229	210	178	153	136	108	85	66	159	BACK
SD	1	22	38	56	77	125	120	80	86	75	79	74	48	45	43	35	37	41	107	
MEAN	17	62	94	113	140	175	233	258	214	198	186	173	158	148	145	125	99	71	159	
SD	1	29	48	40	56	90	101	90	52	40	45	48	45	47	47	45	48	34	107	
MEAN	17	51	76	96	118	140	149	171	175	178	181	169	162	146	139	113	101	65	159	
SD	1	23	32	25	42	46	44	54	42	44	49	54	47	41	50	49	63	37	107	
MEAN	17	56	75	87	101	122	138	154	167	176	179	181	177	163	143	118	92	67	159	
SD	1	28	32	24	22	27	35	40	50	51	52	59	59	51	47	40	50	40	107	
MEAN	17	53	67	91	109	124	137	151	166	183	203	196	204	172	154	141	135	93	159	
SD	1	36	25	32	37	35	34	34	41	72	84	72	84	61	55	59	74	37	107	
MEAN	17	51	60	92	114	124	143	149	173	194	221	222	210	203	191	163	129	85	159	
SD	1	27	13	30	39	37	28	31	43	72	82	98	89	84	83	74	57	53	107	
MEAN	17	37	63	84	104	121	145	164	165	187	220	225	229	231	212	197	145	109	159	
SD	1	13	21	27	30	41	36	36	35	42	53	75	87	96	82	82	82	57	107	
MEAN	17	46	64	91	108	130	135	159	173	191	223	284	249	288	256	238	174	134	159	
SD	1	16	16	21	25	27	29	44	39	40	51	96	87	107	122	100	79	96	107	
MEAN	17	37	69	79	96	114	128	154	180	198	247	288	330	303	292	283	228	131	159	RIGHT
SD	1	13	21	18	21	31	38	46	49	51	89	113	158	144	158	140	124	79	107	
MEAN	17	35	59	79	101	111	127	145	170	189	240	257	289	260	244	284	286	217	159	
SD	1	13	16	13	25	29	36	40	52	61	83	74	71	66	85	148	211	159	107	
MEAN	17	38	59	80	100	118	123	141	163	188	216	238	281	274	275	267	227	160	159	
SD	1	16	15	17	23	28	30	37	38	46	47	63	61	89	125	129	115	81	107	
MEAN	17	35	58	72	93	114	127	146	171	196	211	232	280	287	276	281	231	162	159	
SD	1	13	20	24	28	31	35	37	38	46	42	45	88	85	121	136	107	89	107	
MEAN	17	37	55	73	94	113	127	154	174	184	208	238	269	285	295	296	215	148	159	
SD	1	17	19	27	28	28	27	22	31	37	48	48	85	104	115	136	69	71	107	
MEAN	17	31	52	72	97	118	128	153	171	191	224	247	291	301	310	274	239	165	159	
SD	1	9	17	23	28	24	19	20	28	43	54	67	91	131	133	97	116	40	107	
MEAN	17	35	53	68	90	108	123	149	165	187	213	237	289	301	298	279	246	206	159	
SD	1	18	13	17	23	29	27	27	31	31	37	51	80	96	114	109	79	165	107	
MEAN	17	32	52	65	87	104	128	146	171	190	224	295	316	340	364	279	282	200	159	
SD	1	12	15	14	21	26	31	33	38	40	39	82	74	75	127	97	113	117	107	
MEAN	17	46	50	71	92	103	126	152	190	226	248	326	385	412	416	346	271	203	159	
SD	1	19	16	19	22	29	36	36	45	65	67	122	106	108	142	131	151	99	107	
MEAN	17	29	51	73	95	112	132	163	202	225	269	335	445	469	484	447	379	302	159	FRONT
SD	1	12	21	18	27	30	37	39	82	52	73	90	97	186	183	214	215	193	107	
MEAN	17	27	52	68	89	111	132	152	190	201	240	282	372	396	407	377	319	314	159	

SD	1	11	17	21	28	27	31	41	67	38	76	88	87	108	196	188	146	186	107	
MEAN	17	35	53	74	91	108	129	153	175	184	222	250	279	304	330	292	279	233	159	
SD	1	17	17	25	31	26	30	35	48	38	74	74	78	77	132	100	130	212	107	
MEAN	17	40	63	82	100	108	133	145	163	169	204	245	298	294	315	263	217	168	159	
SD	1	22	36	43	44	36	37	36	46	42	70	79	96	108	130	104	91	81	107	
MEAN	17	41	67	88	103	119	124	142	156	171	192	224	254	247	287	330	202	141	159	
SD	1	25	38	60	59	47	33	36	33	46	52	53	76	103	204	371	110	103	107	
MEAN	17	53	65	90	107	113	120	141	149	173	189	213	240	258	281	220	172	148	159	
SD	1	26	34	54	56	37	33	34	32	27	47	47	75	124	188	116	72	85	107	
MEAN	17	38	71	90	96	103	121	131	142	155	176	204	235	228	233	198	210	145	159	
SD	1	17	34	47	28	22	28	25	29	31	53	63	94	89	102	85	163	67	107	
MEAN	17	46	79	88	102	107	119	133	139	152	187	234	232	209	221	211	213	131	159	
SD	1	22	33	29	30	23	26	31	31	42	71	160	130	118	96	117	199	92	107	
MEAN	17	41	71	91	109	115	124	137	157	166	185	237	258	256	282	258	197	135	159	
SD	1	25	25	32	32	30	27	37	52	56	65	133	165	167	176	178	200	84	107	
MEAN	17	48	76	98	111	128	138	145	158	169	194	209	247	216	216	176	166	138	159	LEFT
SD	1	19	25	35	33	38	43	40	51	71	98	111	155	119	123	93	117	113	107	
MEAN	17	43	84	97	112	129	139	148	157	164	183	184	210	182	171	168	152	92	159	
SD	1	19	39	28	30	32	38	35	40	71	77	96	131	114	96	103	90	54	107	
MEAN	17	43	85	112	120	134	147	143	155	176	182	190	182	177	148	153	138	98	159	
SD	1	15	34	33	26	29	28	31	44	77	84	123	116	114	69	85	86	49	107	
MEAN	17	44	87	118	130	140	142	151	153	159	162	162	153	145	142	128	105	85	159	
SD	1	13	29	27	26	27	31	35	42	50	55	55	52	55	57	36	40	49	107	
MEAN	17	44	95	124	131	143	145	157	156	156	157	154	138	135	122	108	93	74	159	
SD	1	15	38	37	28	41	37	40	38	41	42	47	38	37	31	30	29	25	107	
MEAN	17	50	94	130	153	152	156	176	173	165	163	157	143	138	129	116	90	60	159	
SD	1	18	34	40	44	42	45	51	42	37	39	53	34	33	34	36	34	30	107	
MEAN	17	53	89	137	168	174	176	198	190	180	172	166	156	151	141	121	91	78	159	
SD	1	16	33	38	56	51	41	52	42	42	40	42	37	37	34	30	33	50	107	
MEAN	17	49	100	133	153	204	236	258	229	208	188	176	173	157	142	115	83	71	159	
SD	1	16	42	41	37	72	61	81	60	44	42	41	37	36	34	25	24	31	107	
MEAN	17	61	91	122	161	242	371	406	344	291	235	201	191	160	143	109	87	76	159	
SD	1	18	35	41	35	71	119	94	107	63	62	33	30	26	27	23	24	25	107	
MEAN	17	55	89	123	183	295	437	421	359	300	242	214	188	160	137	114	82	71	159	BACK
SD	1	23	36	43	89	128	106	89	89	64	50	49	46	33	46	34	32	46	107	

Table C7:
Strength data for one-handed exertions at a hand height of 0.5 m. The values are the means and standard deviations over the entire sphere of exertion for 11 military male subjects.

		NEWTONS		% BODY WEIGHT		FRICTION COEFFICIENT	
		UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED
ABSOLUTE VALUES	MEAN	253.4	254.8	35.02	35.19	0.2197	0.2225
	SD	74.8	74.2	10.22	10.14	0.086	0.0832
TIME DIFFERENCE[10]	MEAN	18.9	18.6	2.6	2.51	0.0167	0.0166
	SD	13.2	13.1	1.76	1.74	0.0127	0.0134

Table C8:
Strength data for one-handed exertions at a hand height of 1.0 m. The values are the means and standard deviations over the entire sphere of exertion for 11 military male subjects.

		NEWTONS		% BODY WEIGHT		FRICTION COEFFICIENT	
		UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED
ABSOLUTE VALUES	MEAN	240.4	241.1	33.16	33.24	0.2243	0.2257
	SD	54.9	54.4	7.52	7.48	0.1045	0.103
TIME DIFFERENCE	MEAN	19.9	19.5	2.54	2.44	0.0181	0.0177
	SD	13.3	13.1	1.74	1.68	0.0157	0.0164

Table C9:
Strength data for one-handed exertions at a hand height of 1.5 m. The values are the means and standard deviations over the entire sphere of exertion for 11 military male subjects.

		NEWTONS		% BODY WEIGHT		FRICTION COEFFICIENT	
		UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED	UNSMOOTHED	SMOOTHED
ABSOLUTE VALUES	MEAN	187.7	188.3	25.82	25.89	0.1674	0.1704
	SD	73.3	73.1	10.12	10.1	0.0833	0.0814
TIME DIFFERENCE	MEAN	16	15.9	2.21	2.2	0.0151	0.0158
	SD	16.3	16.4	2.18	2.17	0.0154	0.0154

[10] This value represents the difference in strength (or coefficient of friction) between the final and penultimate session (i.e. between the 3rd and 4th 20 min session).

APPENDIX D

SUMMARY DATA FOR CHAPTER 6

Table D1:
Dynamic and Static Lifting strength at Shoulder Height. (Data in Newtons).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	64	7	41	9	53	6
	Medium	89	15	68	13	79	10
	Heavy	89	11	70	12	80	8
	Isometric	185	26	118	17	152	17
TWO-HANDED	Low	164	21	85	11	125	15
	Medium	164	23	106	15	134	15
	Heavy	193	21	98	14	146	17
	Isometric	386	37	257	39	322	30

Table D2:
Dynamic and Static Lifting Strength at Elbow Height. (Data in Newtons).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	162	11	72	10	117	13
	Medium	163	14	81	8	122	13
	Heavy	173	10	90	8	132	12
	Isometric	280	31	162	24	221	24
TWO-HANDED	Low	298	15	128	26	213	25
	Medium	329	24	159	21	244	26
	Heavy	330	27	170	18	250	25
	Isometric	521	47	299	34	410	39

Table D3:
Dynamic and Static Lifting Strength at Hip Height. (Data in Newtons).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	229	17	115	18	172	18
	Medium	260	19	134	23	197	21
	Heavy	300	22	156	20	228	23
	Isometric	378	48	238	42	308	35
TWO-HANDED	Low	375	26	180	27	278	30
	Medium	420	30	202	23	311	32
	Heavy	495	28	223	30	359	38
	Isometric	844	77	447	68	646	69

Table D4:
Dynamic and Static Lifting Strength at Knuckle Height. (Data in Newtons).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	285	24	150	28	217	24
	Medium	323	27	181	32	252	27
	Heavy	371	26	218	28	294	26
	Isometric	530	36	312	51	425	40
TWO-HANDED	Low	423	28	229	36	326	32
	Medium	484	33	269	32	377	34
	Heavy	604	35	321	38	463	42
	Isometric	1101	70	648	79	874	75

Table D5:
Dynamic and Static Lifting Strength at Knee Height. (Data in Newtons).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	301	40	159	38	230	32
	Medium	356	55	189	39	272	38
	Heavy	396	42	226	36	311	34
	Isometric	536	32	320	51	427	39
TWO-HANDED	Low	401	40	184	37	292	37
	Medium	421	54	251	41	336	39
	Heavy	594	64	331	53	463	51
	Isometric	862	78	506	74	684	68

Table D6:
Velocity of Dynamic Lift at Shoulder Height against the Low, Medium and Heavy Resistances. (All data in mm/s).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	403	29	307	32	355	24
	Medium	337	33	299	30	318	22
	Heavy	195	17	182	18	189	12
TWO-HANDED	Low	645	44	457	43	551	38
	Medium	455	32	355	32	405	25
	Heavy	302	16	204	19	253	17

Table D7:
Velocity of Dynamic Lift at Elbow Height against the Low, Medium and Heavy Resistances. (All data in mm/s).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	680	24	461	37	571	34
	Medium	475	24	346	19	410	22
	Heavy	299	10	222	16	260	13
TWO-HANDED	Low	917	29	579	78	748	57
	Medium	684	26	480	35	582	33
	Heavy	420	18	301	21	360	20

Table D8:
Velocity of Dynamic Lift at Hip Height against the Low, Medium and Heavy Resistances. (All data in mm/s).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	841	37	591	53	716	44
	Medium	625	26	459	38	542	30
	Heavy	417	18	311	23	364	82
TWO-HANDED	Low	1090	49	741	68	916	58
	Medium	810	28	569	34	689	36
	Heavy	543	20	358	24	450	27

Table D9:
Velocity of Dynamic Lift at Knuckle Height against the Low, Medium and Heavy Resistances. (All data in mm/s).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	954	52	666	75	810	56
	Medium	715	37	524	55	619	39
	Heavy	476	21	355	29	416	23
TWO-HANDED	Low	1156	46	842	87	999	61
	Medium	886	36	675	48	780	39
	Heavy	615	21	438	30	526	28

Table D10:
Velocity of Dynamic Lift at Knee Height against the Low, Medium and Heavy Resistances. (All data in mm/s).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	974	86	604	83	789	73
	Medium	746	61	526	62	636	50
	Heavy	501	25	372	36	436	27
TWO-HANDED	Low	1110	69	688	76	899	71
	Medium	822	65	617	59	720	49
	Heavy	607	30	443	41	525	32

Table D11:
Power of Dynamic Lift at Shoulder Height against the Low, Medium and Heavy Resistances. (All data in Watts).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	27	4	14	5	21	3
	Medium	33	9	23	7	28	6
	Heavy	18	4	14	4	16	3
TWO-HANDED	Low	112	22	42	9	77	14
	Medium	79	18	40	9	60	11
	Heavy	60	9	21	5	41	7

Table D12:
Power of Dynamic Lift at Elbow Height against the Low, Medium and Heavy Resistances. (All data in Watts).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	112	11	36	8	74	11
	Medium	79	11	28	5	54	8
	Heavy	52	4	21	3	36	5
TWO-HANDED	Low	275	20	90	23	183	27
	Medium	228	23	82	16	155	22
	Heavy	141	15	54	8	97	13

Table D13:
Power of Dynamic Lift at Hip Height against the Low, Medium and Heavy Resistances. (All data in Watts).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	196	21	75	17	136	20
	Medium	165	17	68	18	117	17
	Heavy	127	13	52	11	89	12
TWO-HANDED	Low	417	46	147	29	282	42
	Medium	344	35	120	20	232	34
	Heavy	271	22	85	16	178	26

Table D14:
Power of Dynamic Lift at Knuckle Height against the Low, Medium and Heavy Resistances. (All data in Watts).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	281	33	116	31	198	30
	Medium	237	28	108	28	173	25
	Heavy	180	19	84	17	132	17
TWO-HANDED	Low	498	48	217	46	358	47
	Medium	436	47	193	34	315	41
	Heavy	375	31	149	25	262	34

Table D15:
Power of Dynamic Lift at Knee Height against the Low, Medium and Heavy Resistances. (All data in Watts).

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	320	60	121	38	220	42
	Medium	289	60	118	34	203	40
	Heavy	205	29	94	21	149	22
TWO-HANDED	Low	465	64	147	38	306	53
	Medium	373	67	174	42	273	45
	Heavy	374	55	163	34	269	41

Table D16:
Peak Dynamic Lifting Strength against the Light, Medium and Heavy Resistances. (All data in Newtons)

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	354	35	204	40	279	31
	Medium	408	48	235	43	321	37
	Heavy	438	34	274	39	356	32
TWO-HANDED	Low	465	26	270	45	368	35
	Medium	517	39	336	46	427	37
	Heavy	676	52	444	64	560	49

Table D17:
Hand Height Position for Peak Dynamic Lifting Strength against the Light, Medium and Heavy Resistances. (All data expressed as a % of stature)

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	35.1	2.2	38.8	4.0	37.0	2.3
	Medium	35.1	2.2	37.6	2.4	36.3	1.6
	Heavy	32.5	1.0	36.3	1.8	34.5	1.1
TWO-HANDED	Low	37.4	3.2	40.4	2.2	38.9	1.9
	Medium	39.0	1.9	40.9	3.4	39.9	1.9
	Heavy	34.8	1.5	38.0	2.0	36.4	1.3

Table D18:
Peak Velocity of Lift against the Light, Medium and Heavy Resistances. (All data in mm/s)

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	1090	66	784	96	937	68
	Medium	819	49	620	66	719	46
	Heavy	539	22	419	38	479	26
TWO-HANDED	Low	1243	47	921	98	1082	66
	Medium	940	40	763	65	852	43
	Heavy	675	28	534	45	604	31

Table D19:
Peak Power of Lift against the Light, Medium and Heavy Resistances. (All data in Watts)

Hands	Resistance	Male (n=9)		Female (n=9)		Group (n=18)	
		Mean	SE	Mean	SE	Mean	SE
ONE-HANDED	Low	394	54	186	48	290	43
	Medium	348	55	164	43	256	41
	Heavy	236	25	124	26	180	22
TWO-HANDED	Low	582	48	281	62	432	53
	Medium	492	58	277	54	384	47
	Heavy	460	51	256	52	358	43

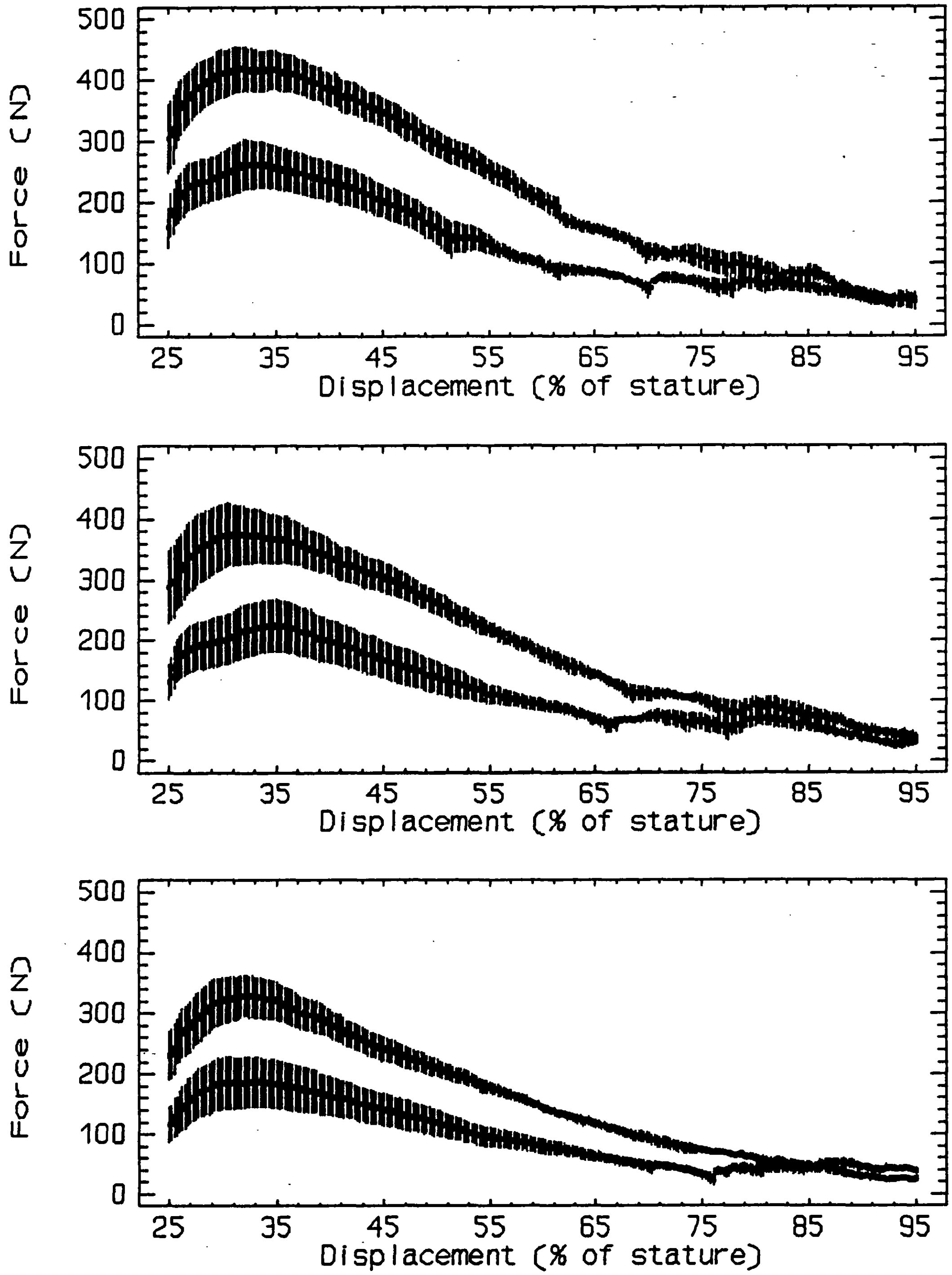

Figure D1: Force - displacement curves for one-handed dynamic lifts against the heavy, medium and light resistances (top, centre and lower figures respectively) on the hydrodynamometer. The top curve in each Figure represents the male data (mean $\pm$ SEM) and the lower curve the female data.

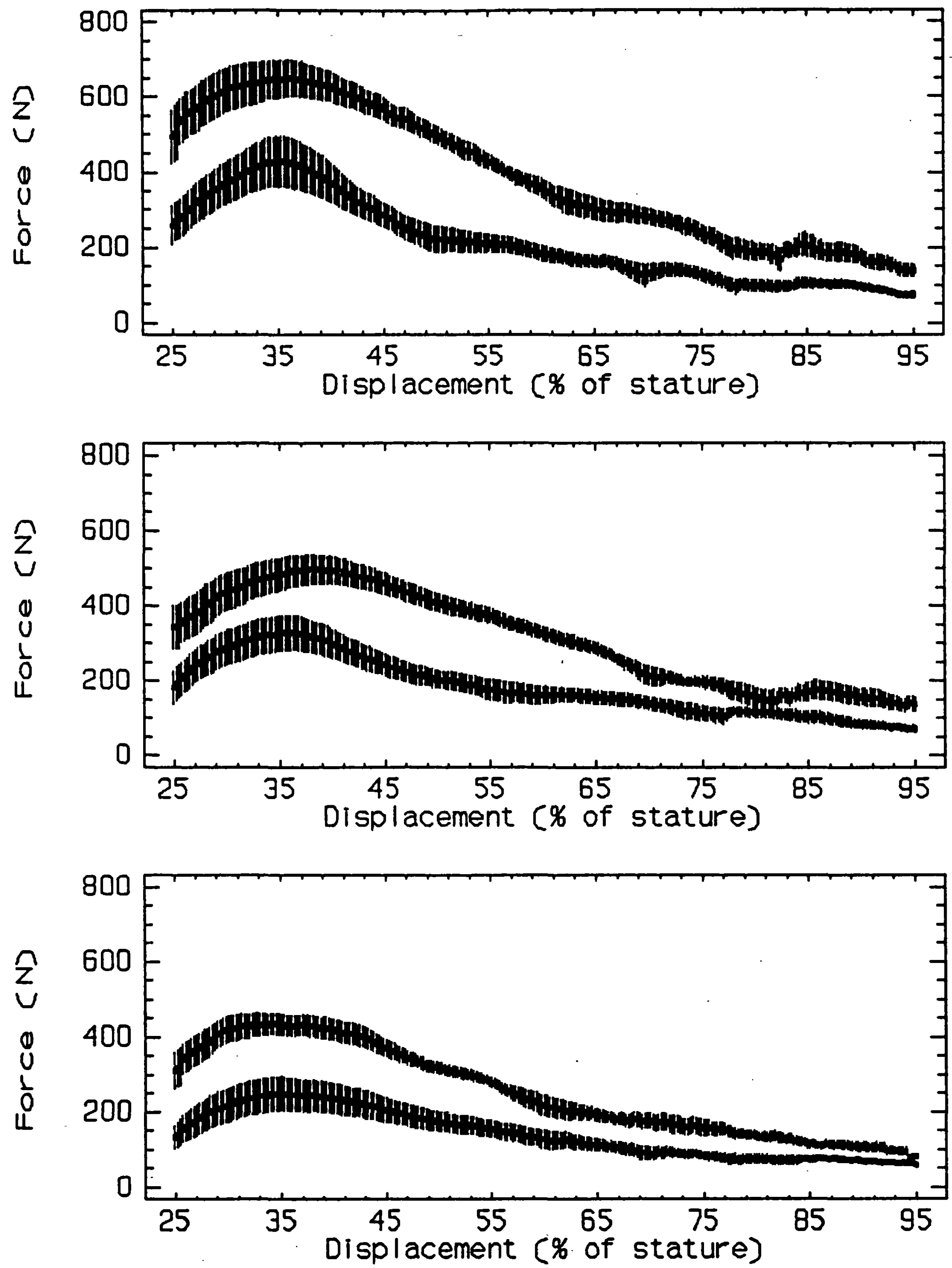

Figure D2: Force - displacement curves for two-handed dynamic lifts against the heavy, medium and light resistances (top, centre and lower figures respectively) on the hydrodynamometer. The top curve in each Figure represents the male data (mean $\pm$ SEM) and the lower curve the female data.

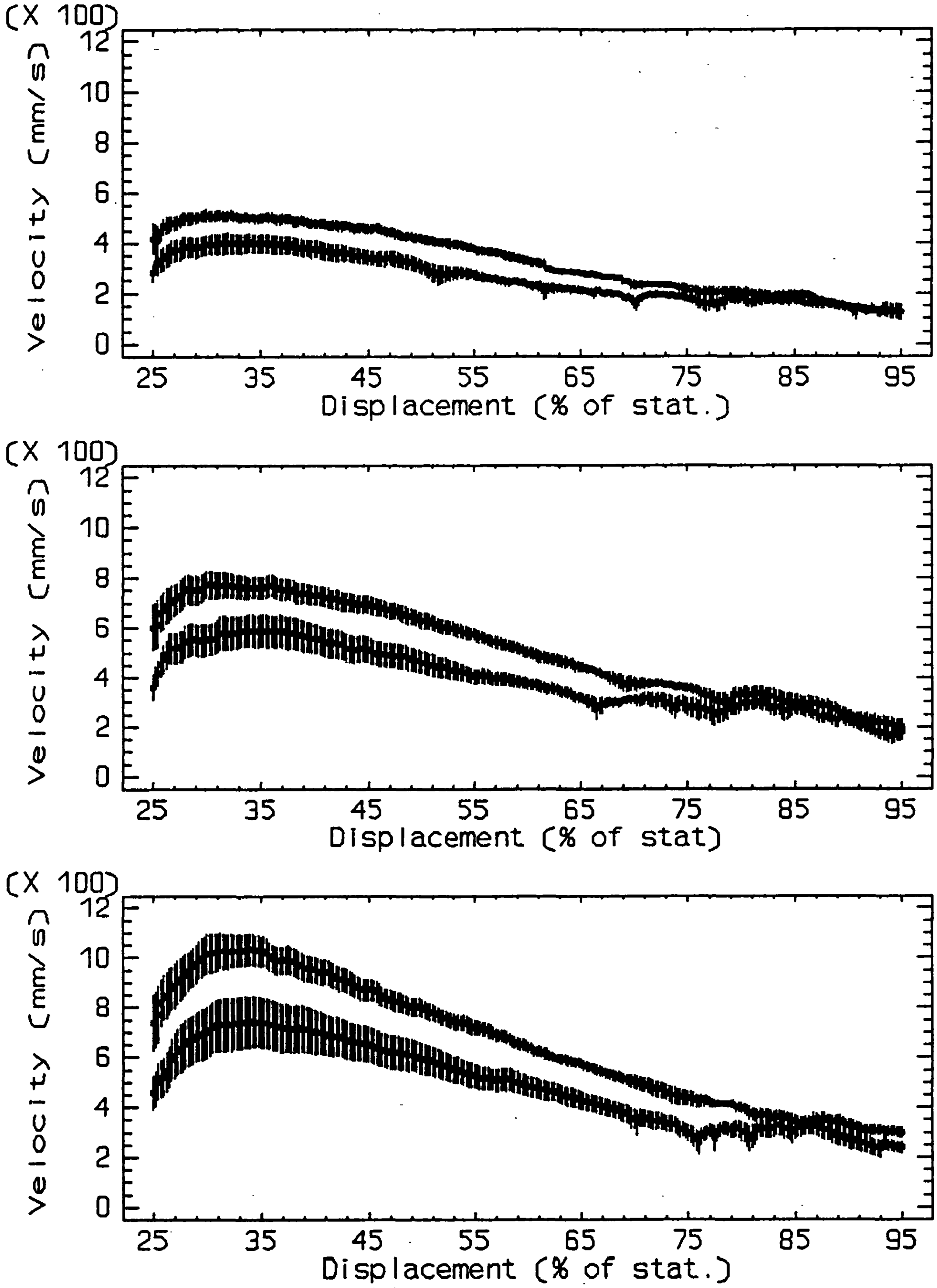

Figure D3: Velocity - displacement curves for one-handed dynamic lifts against the heavy, medium and light resistances (top, centre and lower figures respectively) on the hydrodynamometer. The top curve in each Figure represents the male data (mean $\pm$ SEM) and the lower curve the female data.

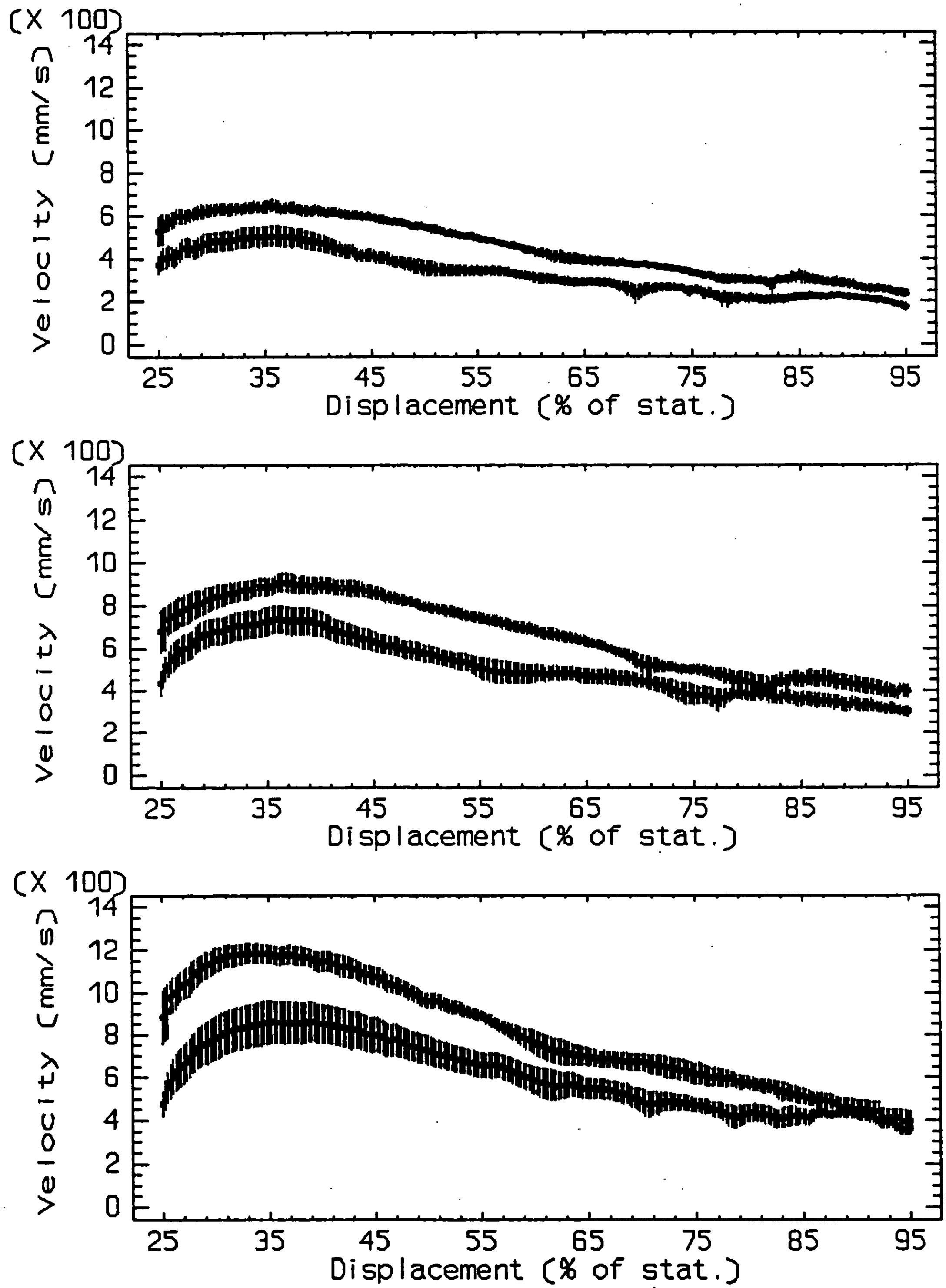

Figure D4: Velocity - displacement curves for two-handed dynamic lifts against the heavy, medium and light resistances (top, centre and lower figures respectively) on the hydrodynamometer. The top curve in each Figure represents the male data (mean $\pm$ SEM) and the lower curve the female data.

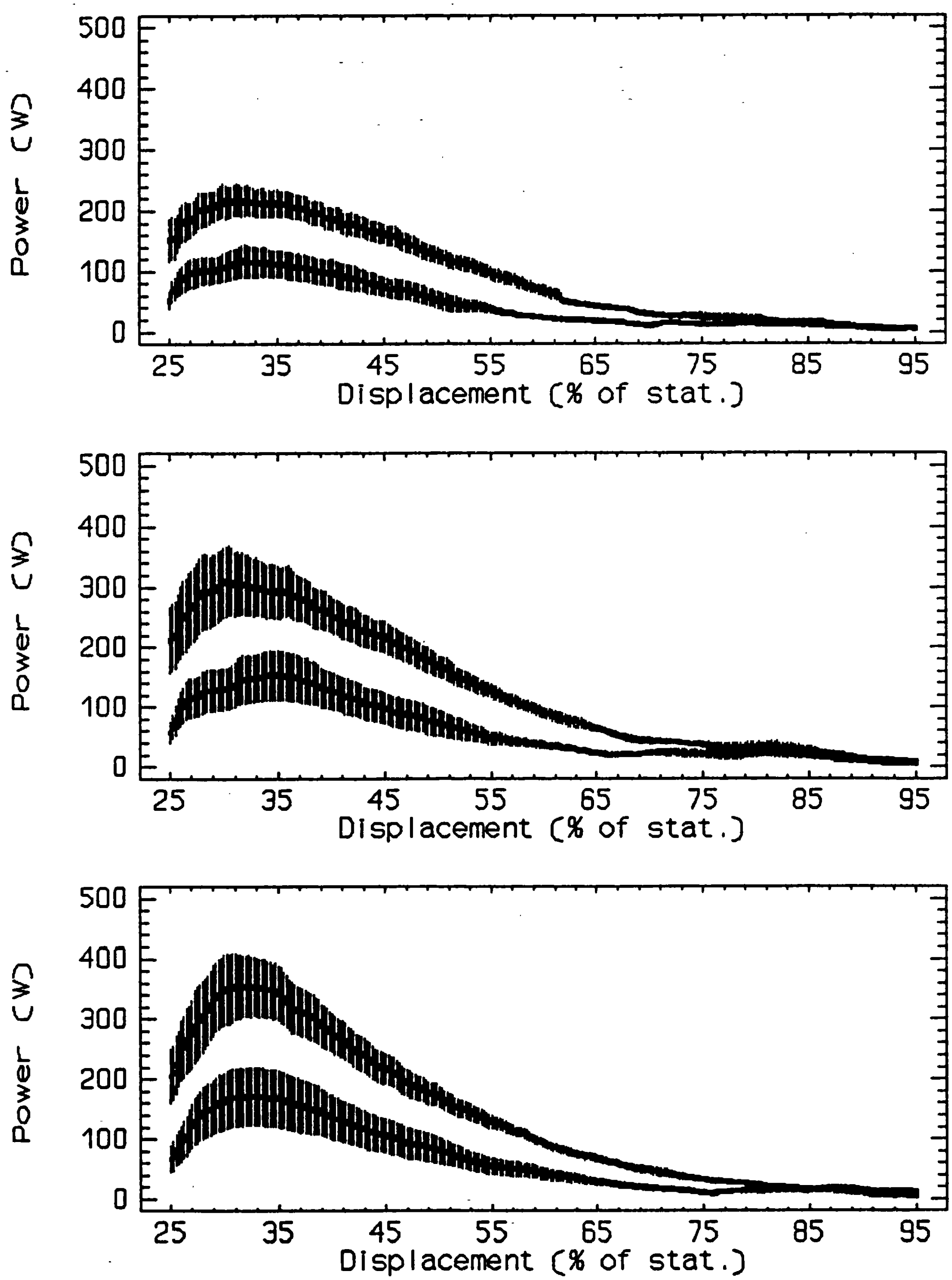

Figure D5: Power - displacement curves for one-handed dynamic lifts against the heavy, medium and light resistances (top, centre and lower figures respectively) on the hydrodynamometer. The top curve in each Figure represents the male data (mean $\pm$ SEM) and the lower curve the female data.

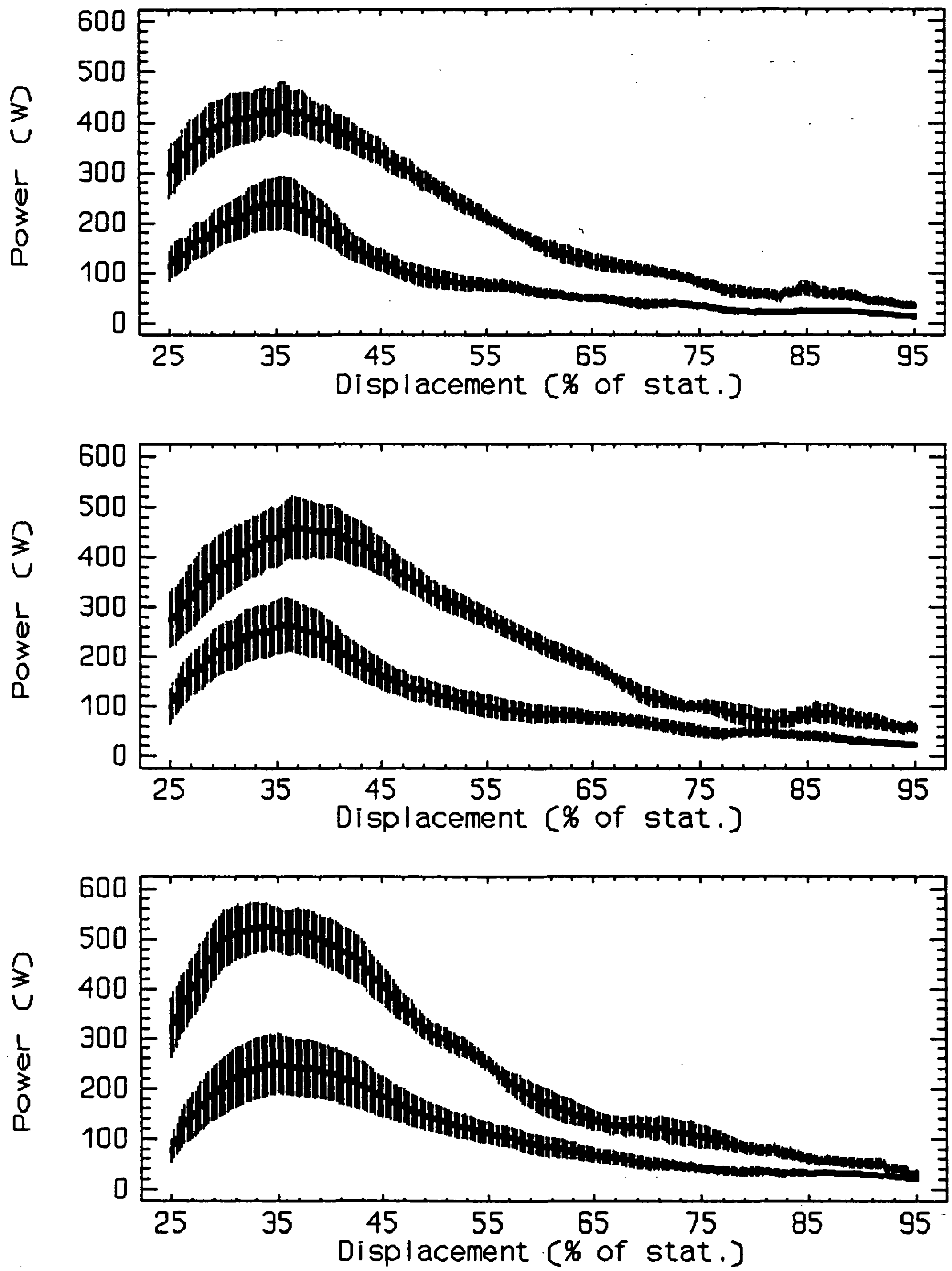

Figure D6: Power - displacement curves for two-handed dynamic lifts against the heavy, medium and light resistances (top, centre and lower figures respectively) on the hydrodynamometer. The top curve in each Figure represents the male data (mean $\pm$ SEM) and the lower curve the female data.

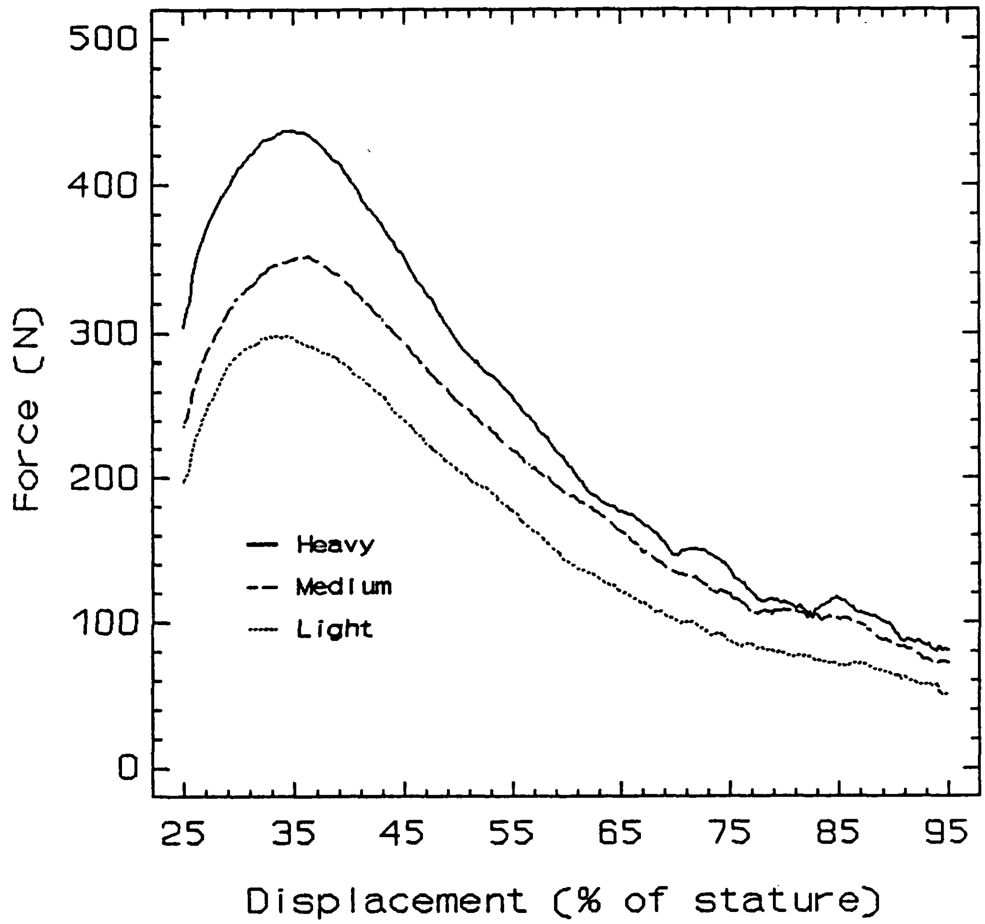

Figure D7: Force - displacement curves for dynamic lifts against the heavy, medium and light resistances on the hydrodynamometer. The curves were derived from force data averaged over the one and two-handed conditions for the 18 subjects.

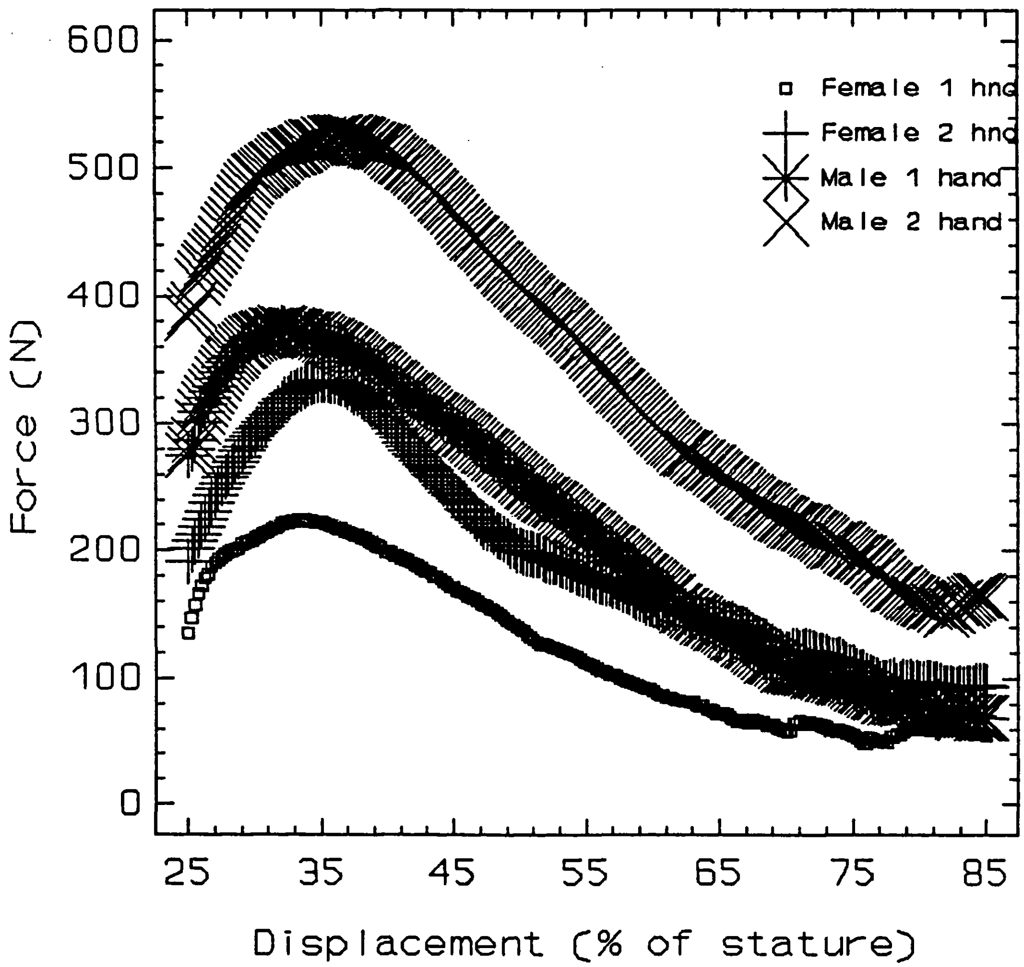

Figure D8: Force - displacement curves for the one and two handed dynamic lifts on the hydrodynamometer. Each of the curves were derived from force data averaged over the three piston resistances.

PREDICTION OF MAXIMAL LIFTING CAPABILITY IN MALE ARMY RECRUITS

by

A Duggan and S J Legg

The following is a description of subjects and methods employed in a study of the prediction of maximal lifting capability in male armyrecruits. The study was carried out by the Army Personel Research Establishment and presented as a draft report to APRE by A Duggan and S.J. Legg.

METHODS

Subjects

The subjects were 384 Artillery and Infantry recruits to the British Army who were within one week of the commencement of their basic military training. They all gave informed consent to participation in the study. The recruits were of mean (SD) age 19.8 (1.9) y, weight 66.5 (8.8) kg and height 1.74 (0.07) m.

Experimental Design

The following test battery was performed in the following order within a period of approximately 20 minutes: isometric strength of the elbow flexors, knee extensors and trunk extensors, grip strength, isometric upright pulls on bars 0.38 m and 0.85 m above ground level, isokinetic upright pulls at 30 and 180 degrees/s, quasi-isokinetic upright pull, isoresistive upright pull, and the IDL(1.52). On all of the above tests with the exception of the IDL(1.52) subjects made a submaximal practice effort followed by two maximal efforts separated by a rest of approximately 30-60 seconds; the test score was taken as the higher of the two maximal efforts. Within a few days of the above tests, simple anthropometric and body composition measurements were made and subjects performed the gymnasium tests from the current Army Physical Fitness Assessment ie a standing vertical jump, trunk curls, heaves and dips.

Procedures

Isometric Elbow Flexion, Knee Extension and Trunk Extension Strengths

Strengths in these muscle groups were measured by strain gauge dynamometry using apparatus described by Hermansen et al (1974). Elbow flexion strength was measured on the right side of the body. The subject was seated with his elbow resting on a metal plate and the elbow angle at 90 degrees. The pronated hand gripped a horizontal handle against which the subject made a maximal pull. For the knee extension test the subject sat with his arms folded and his knees at an angle of 90 degrees with the middle of the arches of his feet (whilst wearing training shoes) pushing against a horizontal bar attached to a strain gauge. He sat back as far as possible in the seat and leant forward slightly prior to and during application of maximal force to the bar. For the trunk extension test, the subject stood upright with knees locked straight and he pushed back against a strap around his thorax at a height 2-3 cm above the nipples.

Grip Strength

Grip strength of the right hand was measured using a handgrip dynamometer (MIE Co Ltd). The gap between the bars was 3 cm. The measurement was made with the subject standing with his arm hanging by his side.

0.38 m Upright Pull

This test was based upon that described by Knapik et al (1981). The equipment comprised a 0.32 m long horizontal handlebar connected by a vertical chain to an isometric dynamometer (Takei back muscle dynamometer) which was bolted to a metal baseplate. The handlebar was 0.38 m above the baseplate. The subject stood on the baseplate with his feet apart and to either side of the dynamometer. He adopted a squatting posture with his knees and hips flexed, back straight and head looking straight forward. With elbows fully extended and using a double overhand grip he held the handlebar. The subject was instructed to pull vertically on the handlebar and, without jerking, to build up to maximal force after 2-3 seconds. The highest force developed during the pull was displayed on the dynamometer's digital display.

0.85 m Upright Pull

Using an overhand grip the subject pulled vertically upwards on a straight horizontal handlebar fixed immediately in front of him at a height of 0.85 m above ground level. The handlebar was attached by a shaft to one end of a lever arm. The other end of the lever arm exerted a force onto the pan of a man-weighing balance when the subject pulled upwards on the handlebar. The subject was instructed to pull up without jerking and to maintain maximum force for 5 seconds. The test administrator monitored the display on the balance and took the test score as the maximum force that was sustained on the balance over the 5 second period.

Isokinetic Upright Pulls

These tests used an isokinetic dynamometer (Cybex II) which had been modified in a manner similar to that described by Aghazadeh and Ayoub (1985) to enable it to be used for the measurement of upright pull strength. Thus, a drum (0.3 m diameter) was attached to the shaft of the dynamometer. A steel rope was attached to and wound around the drum at one end and passed via 2 pulleys to a horizontal handlebar to which it was connected at the other end. This allowed the isokinetic dynamometer, normally employed for measuring activity in a circular path, to be used to measure the dynamic force exerted in a linear vertical upright pull. The modified dynamometer was calibrated by the application of known loads to the handlebar and the unit of measurement used was the kilogramme.

Initially the handlebar was positioned on a rest 0.25 m above ground level. The subject held the handlebar having adopted the posture described above for the 0.38 m upright pull and was instructed to make a maximal upright pull on the handlebar until it reached chest height. In performing this manoeuvre the subject extended both the knees and hips and by the end of the pull was standing up straight with elbows flexed. The peak force developed during the pull was displayed on a digital peak hold display and recorded.

The above procedure was carried out for 2 separate tests: the first with the drum rotating at 30 degrees/second (giving a lifting speed of 0.08 m/s) and the second with it rotating at 180 degrees/second (lifting speed of 0.47 m/s).

The utilisation of an isokinetic dynamometer for these lifting tests led to them being described as "isokinetic upright pulls". It should be noted, however, that the term "isokinetic" is usually used to describe contractions in which the angular velocity of the joint is constant. In these pull tests the isokinetic dynamometer was used in such a manner that the speed at which the metal rope uncoiled and hence speed at which the lift took place were constant but the angular velocities of the various joints involved varied during the course of the lifts.

Quasi-isokinetic lift test (QLI)

This test utilised an ergometer (H&M Engineering, Brynmawr, Gwent) in which a length of rope was uncoiled from a drum by pulling on one end of the rope. The rate at which the rope uncoiled during the pull was restricted by a centrifugal clutch mechanism. The ergometer measured the force exerted on the rope during uncoiling.

A peak hold digital display was constructed to enable easy measurement of the peak force developed during a pull. The ergometer was mounted on a baseplate and the rope was fed over a pulley wheel on this. Above the pulley wheel was a stand upon which a horizontal handlebar attached to the end of the rope rested at a height of 0.25 m above the baseplate. The subject performed an upright pull test on this device in the same manner as the isokinetic upright pulls described above.

The ergometer was not, however, truly isokinetic in nature and lifting speed was found to increase to some extent with the force on the rope (eg at the setting used in this study lift speed increased from approximately 0.75 m/s with an applied load of 15 kg to approximately 1.0 m/s at a load of 50 kg).

Isoresistive Lift Test

This test utilised a Grieve dynamometer (Royal Free Hospital, London) in which resistance to a single dynamic lifting action was provided by a leaky piston as it was drawn through a column of water. A length of pre-stretched nylon rope was attached to the piston at one end and passed through a pulley system to a horizontal handlebar to which it was attached at the other end. The subject performed a maximal upright pull on the handlebar as described above for the isokinetic lift tests except that the initial height of the handlebar was in this case 0.4 m. A timer was triggered by optical sensors such that it started when the handle reached a height of 0.7 m and stopped when the handlebar reached 1.0 m. This allowed the calculation of lift velocity over that part of the lift.

The characteristic of the dynamometer has been described in Chapter 6. At 20 degrees C, the resistance of lift was 2 kN((m/s^2) but, because the viscosity of water varies with temperature, the resistance varied slightly during the study. The actual resistance was obtained for the measured water temperature by using the manufacturer's calibration table which had been derived by timing the fall of known weights at different water temperature (Grieve, 1987). Power output was calculated for each subject from velocity and resistance (including that arising from the weight of the handle and apparent weight of the piston in water).

IDL(1.52)

The device used was based upon the weight lift machine described by McDaniel et al (1983). It was a free standing machine with a weight carriage which rode vertically between upright support channels on low friction teflon rollers. The carried assembly weighed 18.2 kg (40 lb) and up to sixteen 4.5 kg (10 lb) weights could be added by inserting a pin into a weight stack at the back of the carriage. There was also the facility to add one 2.3 kg (5 lb) weight to the weight carriage. There were horizontal handles to the front of the weight stack with which the stack could be lifted. On the ends of the handles were knurled handgrips which rotated on the shafts of the handles. The handgrips were separated by a 0.46 m gap to allow room for the subjects knees. A mark was made on the upright support channel and the carriage to indicate a weight carriage handle height above floor level of 1.52 m.

The subject adopted a crouching posture with knees bent, back straight, toes on a line below the carriage handgrips, hands holding the handgrips with an overhand grip and arms straight. He then proceeded to lift the weight carriage by the handles to the 1.52 m mark. On completing the lift, 2 supervisors assisted the subject to lower the carriage. The initial lift of 18.2 kg (i.e. the carriage assembly alone) was followed by lifts of 27.3 kg (60 lb) and 36.4 kg (80 lb), after which the load was increased by 4.5 kg for each lift until the subject was unable to lift the required height; the load was then reduced by 2.3 kg for the subject's final lift. The test score was the highest load lifted to the 1.52 m mark.

Table D20:
Anthropometry and strength measures of male militatry personnel involved in the maximal lifting trials at Woolwich and Winchester.

Variable	Mean	SD	Min	Max	n
ANTHROPOMETRY					
Age (y)	19.9	1.9	16.6	27.1	384
Weight (kg)	66.5	8.8	47.1	107.3	384
Height (cm)	174.3	6.7	157.0	195.0	384
Body Fat (%)	13.3	3.9	5.9	25.1	384
Fat Free Weight (kg)	57.4	6.2	40.9	84.7	384
ISOMETRIC TESTS					
Elbow flex (kg)	26.3	4.4	14	41	384
Knee ext (kg)	200.9	48.8	97	325	376
Trunk ext (kg)	81.4	15.6	22	125	364
Handgrip (N)	426.1	70.9	152	722	384
38 cm lift (kg)	117.2	21.7	28	177	384
85 cm lift (kg)	47.3	11.5	8	92	384
DYNAMIC TESTS					
Cybex lift 30°/s (kg)	121.2	21.9	49.5	184.6	323
Cybex lift 180°/s (kg)	90.8	18.5	37.8	165.9	323
Quasi-isokinetic (kg)	90.5	19.0	18.7	147.3	384
Hydrodynamometer (W)	431.1	119.0	104.3	1003.4	384
Hydrodynamometer (W/kg)	6.4	1.3	1.6	11.7	384
Hydrodynamometer (W/kg FFW)	7.4	1.5	1.8	13.4	384
IDL (kg)	54.1	9.7	32	91	384

APPENDIX E
RELATED PUBLICATIONS

ERGONOMICS, 1991, VOL. 34, NO. 5, 563–573

Human strength capabilities during one-handed maximum voluntary exertions in the fore and aft plane

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Keywords: One-handed whole body strength; Direction of exertion; Sex differences; Isometrics.

Maximal static strengths were determined for one-handed exertions in all directions in the fore and aft plane. Data from 12 males and 10 females (mean age 30·7 yrs, standard deviation (SD)=8·9 yrs, $n=22$) were obtained with handle heights of 1·0 and 1·75 m. Twelve of the subjects also performed two-handed exertions at the same handle heights. The ratio of mean strengths of females to that of males ranged from 0·50 to 0·83 (for absolute forces) and from 0·63 to 1·00 for forces normalized to body weight. The ratios of one-handed to two-handed strengths ranged from 0·64 to 1·04. Two-handed strengths commonly exceeded one-handed strengths at the lower handle height, but showed fewer significant strength differences ($p<0·05$) according to direction at 1·75 m. Both female/male and one-handed/two-handed strength ratios were found to be dependent on direction of exertion and handle height. The observed strength dependencies upon number of hands (one or two-handed), direction of exertion, handle height and sex are discussed. The strength data have implications for use in biomechanical models and task analysis.

1. Introduction

Although musculoskeletal injuries incurred as a result of manual materials handling have stimulated extensive research into the capacities and limitations of the human, gaps in our knowledge still exist in many areas associated with work-related activities.

One area where data are scarce is in whole-body human strength capabilities during tasks requiring one-handed exertions. Most studies of whole-body exertion have been concerned with vertical two-handed lifting or horizontal pushing and pulling (Whitney 1957, Chaffin 1974, Yates *et al.* 1980, Kroemer 1974, Ayoub and MacDaniel 1974), with very few reports on one-handed strengths (Davis and Stubbs 1980, Warwick *et al.* 1980, Chaffin *et al.* 1983). In all but one of these papers (i.e., Chaffin *et al.* 1983) foot and hand placement have been rigidly defined, thereby limiting the choice of posture available to the subject. In addition, few investigators have explored human strength capabilities in the more general case involving exertions in all directions in the fore and aft plane. As a consequence, whole-body static strength data have been more representative of the conditions imposed by experimental constraints than of the real strength capabilities of human beings in the freely chosen postures that they would normally use in real-world working tasks.

The first objective of the current study was therefore to describe human strength capabilities during one-handed maximal voluntary exertions in the fore and aft plane in free-style postures. In order for the strength data to be potentially useful as an aid in task design and in the recognition of hazards during manual exertion, forces are presented in vector form as a Postural Stability Diagram (PSD) (see Grieve and Pheasant 1982).

Further objectives of the present study were to investigate the influence and interactions of sex, handle height and direction of exertion on one-handed strength; and to compare the strength of one- and two-handed exertions.

2. Methods

2.1. *Subjects*

The 22 subjects (18 right-handed, 4 left-handed) were unpaid volunteer staff or students of this institute. Their physical characteristics are summarized in table 1.

Table 1. Physical characteristics of subjects (values are means (±SD)).

	Male	Female	
n	12	10	22
Age (yrs)	32·9 (10·7)	28·0 (5·5)	30·7 (8·9)
Weight (kg)	76·3 (13·6)	62·2 (5·3)	69·9 (12·7)
Height (cm)	178·4 (8·6)	167·4 (7·0)	173·3 (19·5)
Grip (N)	493 (71)	348 (53)	427 (97)

2.2. *Apparatus*

A force bar, which measured vertical and horizontal components of static exertions, was used (see Whitney 1957, Grieve 1979a). Using a 64 kbyte BBC microcomputer, customized software was designed to sample and then plot the maximal horizontal and vertical components of the force vectors applied to the bar in all possible directions in the fore and aft plane. A plot of these force vectors on a VDU screen presented the strength data in the form of a Postural Stability Diagram (see Grieve 1979a, b).

A combination of emery-cloth floor and rubber-soled shoes provided a unity coefficient of limiting friction (Pheasant and Grieve 1981). Despite some of the extreme postures adopted during exertions, slippage did not occur.

Grip strengths were measured with a hand grip dynamometer (Takei and Company Ltd) where grip size was adjusted to the preference of the subjects.

2.3. *Procedure*

The subjects' unshod weight and stature were measured. Grip strength was determined from the best of two efforts with the dominant hand. Free-style manual strengths, with the dominant hand, were measured on the force bar while standing. The only limitation placed on the subject's posture was that the leading foot should not be placed anterior to the handle. Subjects performed steady maximal exertions in all possible directions in the fore and aft plane with the force bar set at 1·0 or 1·75 m above the ground. No 'jerking' or 'swinging' on the force bar was allowed. The procedure for obtaining a PSD has been described previously (Pheasant and Grieve 1981). At least one day separated tests at the two heights. Half the subjects started with the 1·0 m bar height, the remainder started at 1·75 m. One month later, 12 subjects who had completed the one-handed exertions followed the same procedures and protocol using two hands.

2.4. *Analysis*

Strength data were stored on disc as sets of 36 force vectors 10° apart. Group mean strengths and standard deviations in each condition were calculated. Before being plotted on a PSD chart, the strength data were fitted with a cubic spline function as described by Pheasant and Grieve (1981).

The Maximum Advantage of using a Component of Exertion (MACE) was also calculated from the PSD data for each subject at each bar height (Grieve and Pheasant 1981). Briefly, for a given force vector plotted on the PSD, a circle can be described around it representing the components of that vector in other directions. If this procedure is repeated for all force vectors on the PSD envelope a new outer envelope is described representing the maximum components that are possible in each direction. The MACE, in a given direction, is defined as the ratio of the maximum available component compared with the directed resultant in that direction.

PSD and MACE were obtained based both on absolute strengths (in Newtons) and normalized strengths (as a percentage of body weight).

3. Results

3.1. *Sex differences in the strength of one-handed exertions*

PSD plots for one-handed exertions at the two bar heights (1·0 m and 1·75 m) are shown in figure 1. The data are presented as strength/weight ratios and show the group means ± one standard deviation.

A comparison of the PSDs in figure 1, between male and female subjects, shows almost identical shapes for the vector diagrams with only small differences in their normalized strengths for exertion at the two bar heights. When the female/male (f/m) strength ratios were calculated, for the normalized data in each of the 36 directions at the two bar heights, a mean value of 0·79 (SD = 0·09) was obtained ($n = 72$). This f/m strength ratio decreased to 0·65 (SD = 0·08) when absolute strength values were considered.

Female/male strength ratios (calculated from the normalized strength data) for all 36 force vectors at the two bar heights are presented in figure 2. Although the mean f/m strength ratios at the two bar heights were very similar (Bar = 1·0 m, ratio = 0·78 (SD = 0·08); Bar = 1·75 m, ratio = 0·80 (SD = 0·11); $n = 36$), figure 2 clearly shows that the magnitude of this ratio varies according to direction of exertion and bar height.

At the 1·0 m bar height, males were significantly stronger ($p < 0·05$) than females in most directions, except for exertions performed in the pull/press quadrant. In this latter quadrant the normalized f/m strength ratio averaged 0·86 (SD = 0·07, $n = 9$) with a peak ratio of 0·93 occurring between 120° and 130°. Over a large area of this quadrant there was no significant difference in strength ($p > 0·05$) between males and females when forces were normalized against body weight.

At the 1·75 m bar height, normalized female strength approached that of the males in many more directions. Figure 2 indicates large areas in the fore and aft plane where there were no significant differences ($p > 0·05$) in normalized strength between males and females. Large strength differences between males and females were observed in the directions of horizontal pulling/pushing and most of the pull/lift quadrant).

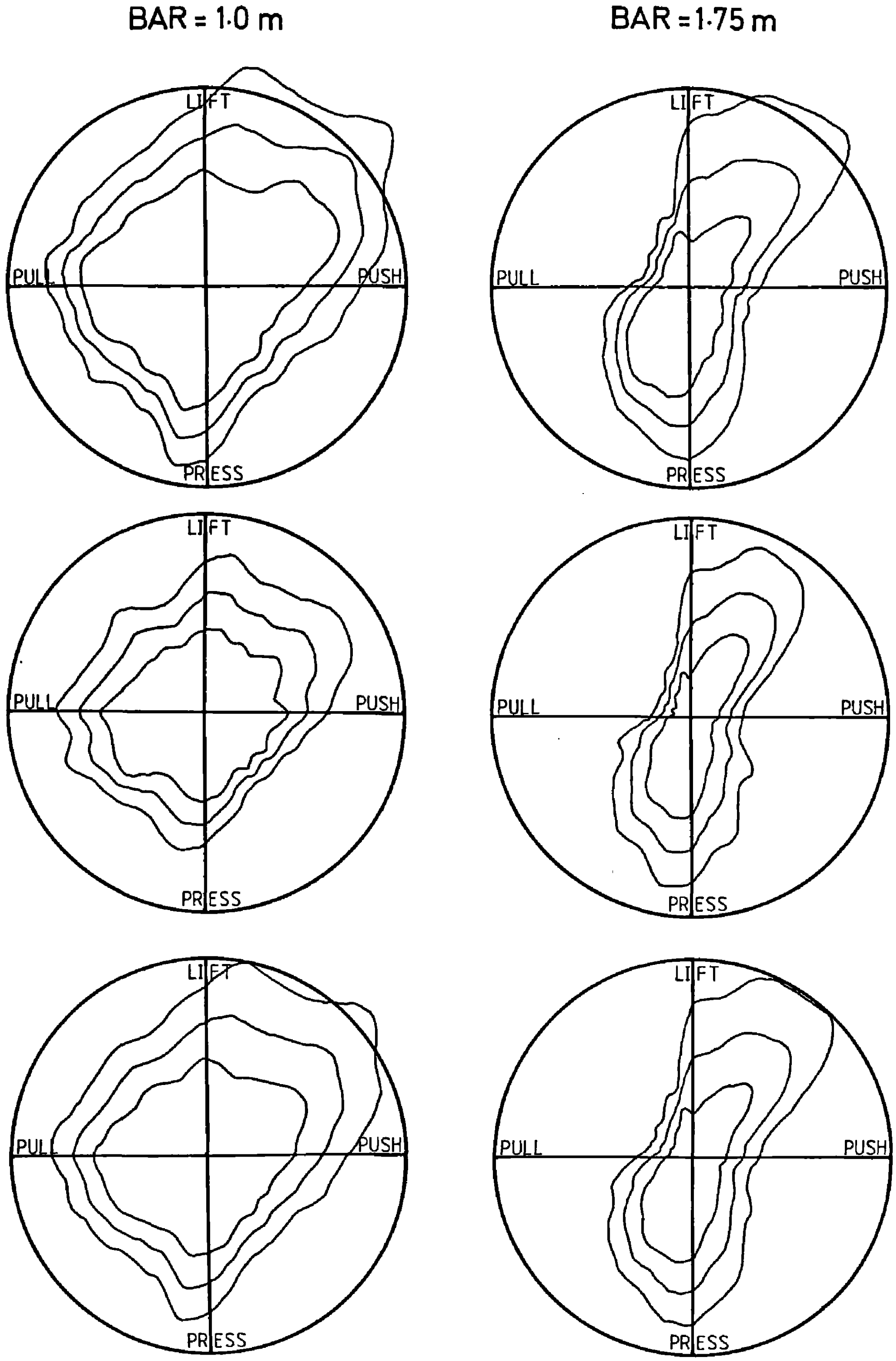

Figure 1. PSDs for one-handed exertions, in the fore and aft plane, at handle placements of 1·0 m and 1·75 m above the floor. The data are average maximal strengths (± one SD) as a percentage of body weight for males, females and all subjects in the top, middle and lower figures respectively. The centre of each diagram represents zero manual exertion and the edges represent forces equal in magnitude to body weight. The posture adopted was free-style.

3.2. *MACE for one-handed exertions*

Using individual PSD data, advantages of using components of deviated forces were calculated for all directions in the fore and aft plane, at both bar heights. An example

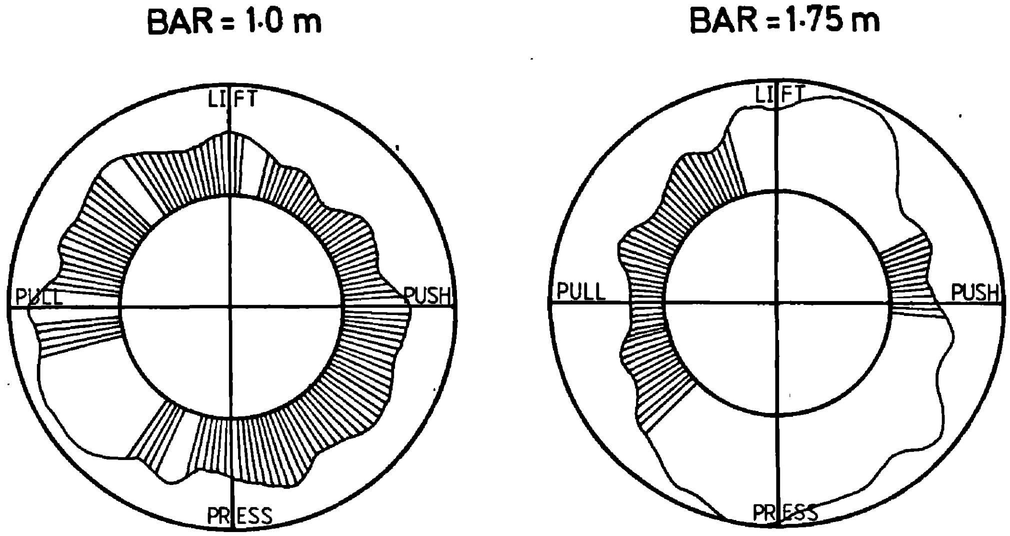

Figure 2. Female/male strength ratios in all directions in the fore and aft plane, for one-handed maximal exertions, under two conditions of handle placement (1·0 m and 1·75 m). The centre of each plot represents a f/m strength ratio of zero, the inner circle an f/m strength ratio of 0·5 and the outer circle an f/m strength ratio equal to unity. The hatched areas represent directions in the fore and aft plane where males were significantly stronger than females ($p<0·05$). All data calculated from strengths expressed as a percentage of body weight.

of the plot obtained for one subject is shown in the upper diagrams of figure 3. In these two diagrams the advantage of using the components of deviated forces (outer envelope) is superimposed on the raw PSD data (inner envelope). A plot of the average maximal forces (as well as standard deviations), which may be obtained by employing components of deviated forces for the subject population ($n=22$) at the two bar heights, is shown in the lower two diagrams of figure 3.

Using the group data in figures 1 and 3, MACE values were calculated for the 90°, 180°, 270° and 360° force vectors at both bar heights. These results, along with their angular deviations from the maximum horizontal or vertical force vectors, are presented in table 2.

Table 2. MACE values for pulls (90°), presses (180°), pushes (270°) and lifts (360°) and the angular deviations, *D*, of the force vectors from the vertical or horizontal which give a greater component than forces generated exactly in those directions. Positive and negative values refer to anticlockwise and clockwise deviations respectively.

Bar height		Lift	Pull	Press	Push
1·75 m	MACE	1·42	1·76	1·03	2·12
	D (°)	−20	+40	−10	+40
1·00 m	MACE	1·16	1·03	1·06	1·26
	D (°)	−10	0	−10	+20

3.3. *One-handed versus two-handed exertions*

PSD plots showing the average maximal strength (±1·0 SD) of 12 subjects who performed two-handed exertions at the 1·0 and 1·75 m bar height are shown in the upper portion of figure 4. The PSDs are displayed relative to body weight. These data were compared with their one-handed exertions to produce one-handed/two-handed strength ratios for all 36 directions at each bar height. The resulting mean one-hand/two-hand strength ratios are presented in the lower portion of figure 4 in the same format as that described for the f/m strength ratios in figure 2.

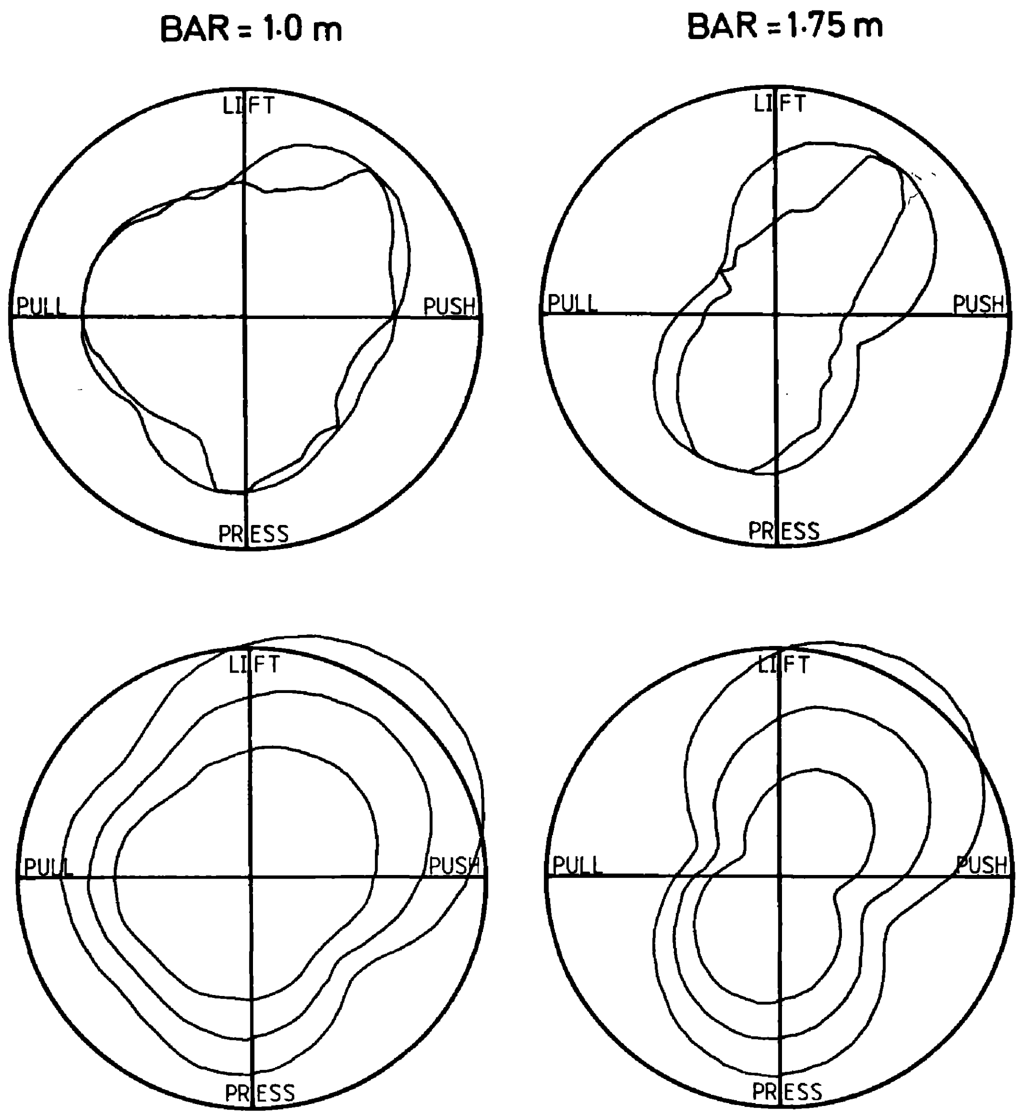

Figure 3. Upper diagrams: PSD plots of subject DS for one-handed maximal exertions in the fore and aft plane at bar heights of 1·0 and 1·75 m above the ground (inner envelopes). The advantages of using components of deviated forces are shown by the outer envelopes. Lower diagrams: PSD plots illustrating the average maximal forces (±one standard deviation) which may be obtained by using components of deviated forces at the two bar heights (n=22). Presentation of data is as described in figure 1.

At the 1·0 m bar height, one-handed exertions were significantly weaker ($p<0·05$) than two-handed exertions over most directions in the fore and aft plane. Exertions performed in the lower half of the pull/lift quadrant were, however, the exception. For force vectors between 30° and 100° one-handed and two-handed exertions were virtually equivalent, with one-handed/two-handed strength ratios approaching and actually exceeding unity.

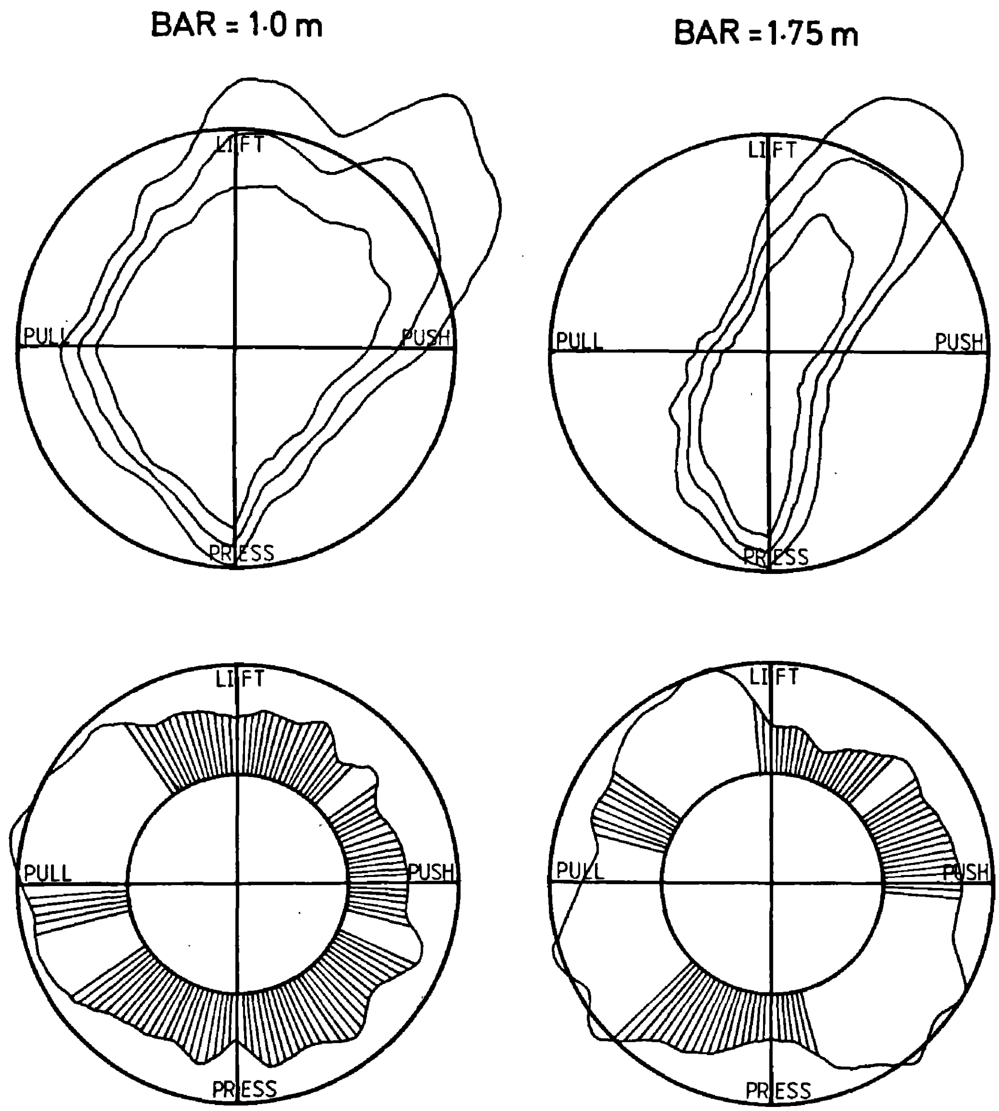

Figure 4. Upper diagrams: PSD plots of two-handed maximal exertions in the fore and aft plane with the force bar placed at 1·0 m and 1·75 m above the floor ($n=12$). Presentation of the data is as described for figure 1. Lower diagrams: plots showing the mean one-handed/mean two-handed strength ratios for all directions in the fore and aft plane at the 1·0 m and 1·75 m bar heights. Scaling of the strength ratios is the same as that described in figure 2. The hatch areas represent directions in the fore and aft plane where two-handed exertions are significantly stronger than one-handed exertions ($p<0{\cdot}05$).

Fewer significant differences between one- and two-handed exertions were found at 1·75 m. The main strength differences (figure 4, lower right) resided in the lift/push quadrant and the lower portions of the pull/press–push/press quadrants. Outside these regions, strength differences between one- and two-handed exertions were largely insignificant ($p>0{\cdot}05$).

4. Discussion

4.1. *Sex differences in the strength of one-handed exertions*

Part of the variation in f/m strength ratios (shown in figure 2) is likely to reflect differences in stature between the male and female subject population. In addition, sex differences in the strength of the principal muscle groups involved during exertions in different postures are likely to add to this variance.

In those regions where sex differences were small, it may be assumed that the physical strength of the individual played only a minor role in the force of exertion. Under these circumstances, the deployment of body weight may therefore be the predominant factor dictating force output.

The above argument does not explain the similarity of forces produced by males and females in the lift/push quadrant at the 1·75 m bar height. It was in this region of the PSD that the largest forces were recorded by both sexes. As described by Pheasant and Grieve (1981), these peak forces arise from postural configurations in which the muscular torque required about the major articulations is minimized. This occurs when the trunk, upper and lower limbs approximate a straight line and the whole body is brought as close as possible to the line of thrust. One reason for the similarity of strengths between the sexes under the above conditions may be that the postures adopted employed muscle groups with minimal sex differences in strength.

Based on 112 data sets, Pheasant (1983) noted that the ratio of f/m average strengths can vary from 0·37 to 0·90 depending on a number of factors including the direction of exertion and muscle group tested. Upper and lower extremity strengths of women were reported to be, on average, 58% and 66% of men's respectively (Pheasant 1983). In view of this fact, it may be hypothesized that sex differences in whole-body strength will be greatest in directions of exertion that require mainly upper body strength. Alternatively, sex differences in whole-body strength will be minimized where the force produced is limited predominantly by leg strength.

In general, the present data illustrate the large variability in strength between the sexes under different conditions. The findings also depict the complex interactions between angle of exertion and handle height (implying changes in posture and the use of different muscle groups) as well as body weight in the determination of strength.

Although there is a strong argument for separate load limits for men and women in the field of manual handling; the current results indicate that it would be inappropriate to use a single mean ratio to predict female strength from male data.

4.2. *Advantages of using a component of exertion*

The closer the MACE values are to unity, the smaller the benefit that can be obtained by using the component of a deviated force vector. Consequently, the data in table 2 indicate that there is little to be gained by using a deviated component in horizontal pulling, vertical lifting or vertical pressing actions at 1·0 m. The MACE value shown for horizontal pushing, however, shows that if a subject exerts a maximal one-handed push at this height it is likely that a small vertical lifting component of force will also be exhibited (providing the subject chooses to take advantage of the deviated resultant force).

At 1·75 m, aside from vertical pressing, the MACE values indicated that a substantial advantage may be gained by using a deviated resultant force during exertions. For example, if the objective is to produce a maximal horizontal push at this particular height, it is best to direct the resultant force at approximately 40° above the horizontal, rather than directly along the horizontal plane. Similarly, if the goal is to produce maximal horizontal pulling at 1·75 m, the resultant force should be directed approximately 40° below the horizontal plane of the handle.

In practice, the individual will only benefit from the above resultant forces in tasks where the vertical component of the force is unimportant. Similarly, for deviated forces to be useful in lifting tasks, their horizontal components must not compromise any frictional or task limitations. The possible use of deviated resultants should therefore be accounted for when designing equipment or considering tasks which may require heavy exertions.

Data provided by Grieve and Pheasant (1981) have shown (at least for two-handed exertions with defined foot placement) that adult males instinctively know that force exerted in a deviated direction may be used to achieve an improved result in another.

4.1. *One-handed versus two-handed exertions*

In many directions of exertion, the difference in strength between one- and two-handed maximal efforts was surprisingly small.

In theory, strength differences between one and two-handed exertions should be minimized when: (1) deployment of body weight relative to the centre of foot pressure is the limiting factor in the strength of the exertions; or (2) the weak link limiting the amount of force produced and/or transmitted by the musculoskeletal system lies in a part of the body other than the upper limbs.

The implications of weak links, either at the hand–handle interface or within the musculoskeletal system were investigated in a related study. Based on this work, it was assumed that the coupling between the hand and bar in the present study was an effective one and unlikely to be the weakest link determining force outcome.

The current data show regions in the fore and aft plane at both bar heights where one-handed exertions actually exceeded the strength of two-handed exertions. Under these circumstances, the greater freedom of postures available under the one-handed condition permitted the subject a more advantageous use of the body's centre of gravity. For example, in the case of exertions directed in the pull/press quadrant at 1·75 m, releasing one hand from the bar permits the subject to rotate about an axis connecting the leading foot and the hand grasping the bar. If the body is rotated about this axis until perpendicular to the bar, and the free leg and arm splayed out as far as possible from the axis in the direction of the exerted force (as shown in figure 5), displacement of the body's centre of gravity away from the bar will be maximized. Thus, for a given force vector, the moment arms about which the horizontal and vertical components of the body weight act will be optimal. Consequently, in exertions where deployment of body weight is the predominant factor limiting force production, postures possible using one hand only may permit greater forces to be applied than when performed using two hands.

As one-handed exertions performed in certain directions can approach the strength of two-handed exertions, the stress on the load-bearing shoulder and arm may reach close to double that found during two-handed efforts. Due to the anatomical nature of the shoulder joint and the inherent instability of the articulation as a consequence of its degrees of freedom, the high stresses possible during one-handed efforts may lead to an increased risk of injury. Further epidemiological studies on upper limb injuries incurred during heavy manual exertion may provide evidence to support this hypothesis.

4. Summary and conclusions

The current data give some indication of whole-body strength capabilities of one-handed exertions in the fore and aft plane. These data may be more applicable to the working environment than previous research as exertions were performed using free-style rather than experimentally defined postures.

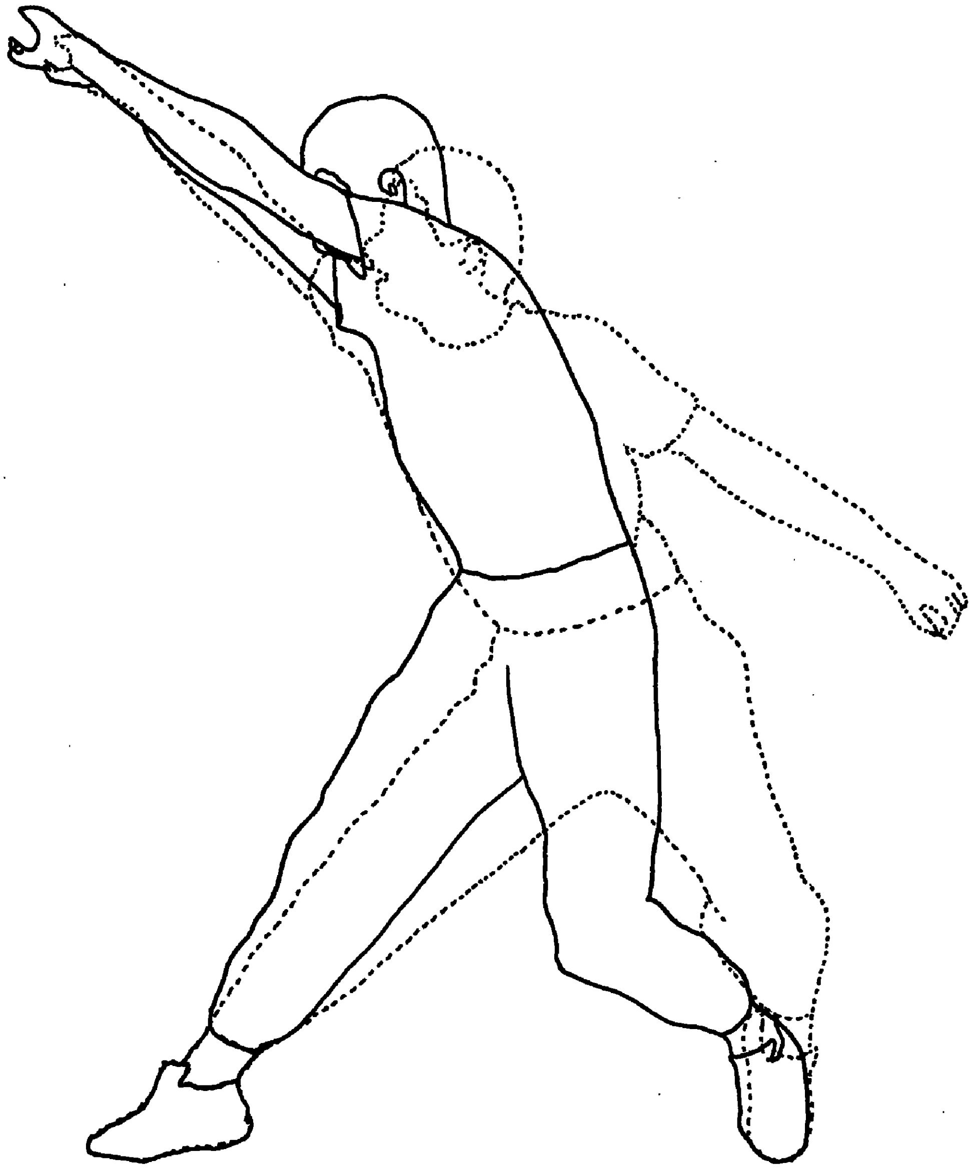

Figure 5. Tracings from photographic records of one subject showing the change in freestyle posture permitted by releasing one hand from the bar during a maximal exertion directed in the pull/press quadrant of the PSD. Bar height = 1·75 m. (See text for further details.)

The main conclusions emanating from the study were:

(1) Sex differences in static one-handed maximum voluntary exertions varied substantially according to the direction of exertion and bar height. This served to illustrate the complex interactions occurring between the underlying variables (e.g., body weight, posture and the sex differences in strength of the muscle groups involved).
(2) Considerable strength advantages (in a given direction) may be gained by employing components of deviated forces during one-handed exertions at 1·75 m. Relatively little benefit may be obtained by using these deviated forces at 1·0 m.
(3) It was more common to find two-handed strengths exceeding one-handed strengths at the 1·0 m bar height. There were, however, a number of directions at both 1·0 and 1·75 m bar heights where one-handed strengths approached, and even exceeded, two-handed strengths.

When considering the current strength data, it should be kept in mind that the values given are for ideal conditions. This assumes posture is unrestricted by work space and force output is essentially unaffected by conditions at the foot and hand interfaces. While such conditions are unrealistic for a typical working environment, the data provide a starting point for estimating the effects of environmental factors on one-handed exertions.

Finally, due to the widely differing postures available, use of the strength data in biomechanical models of strength (e.g., Garg and Chaffin 1975) is problematic unless detailed anthropometric and postural analysis is performed. Nevertheless, data from the present experiment may enhance the reliability of such models in areas of interpolation where there have previously been few data.

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