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ANTHROPOMETRY AND BIOMECHANICS
Theory and Application

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PREFACE

Assessment of the physical dimensions of the human body and application of this knowledge to the design of tools, equipment, and work are certainly among the oldest arts and sciences. It would be an easy task if all anthropometric dimensions, of all people, would follow a general rule. Thus, philosophers and artists embedded their ideas about the most aesthetic proportions into ideal schemes of perfect proportions. "Golden sections" were developed in ancient India, China, Egypt, and Greece, and more recently by Leonardo DaVinci, or Albrecht Durer. However, such canons are fictive since actual human dimensions and proportions vary greatly among individuals.

The different physical appearances often have been associated with mental, physiological and behavioral characteristics of the individuals. Hypocrates (about 460-377 BC) taught that there are four temperaments (actually, body fluids) represented by four body types. The psychiatrist Ernst Kretchmer (1888-1964) proposed that three typical somatotypes (pyknic, athletic, aesthenic) could reflect human character traits. Since the 1940's, W. H. Sheldon and his coworkers devised a system of three body physiques (endo-, meso-, ectomorphic). The classification was originally qualitative, and only recently has been developed to include actual measurements.

Today's engineers assess human dimensions and physical capabilities in physical units, and use these measurements to design hand tools, work stations, equipment, and work tasks to fit human dimensions and capabilities. Thus, "Engineering Anthropometry is the application of scientific physical measurement methods to human subjects for the development of engineering design requirements". (Modified from Roebuck, Kroemer, and Thompson 1975*). Hence, engineering anthropometry is one of the backbones of "Ergonomics", or "Human Factors", which study human characteristics for the appropriate design of the living and work environment.

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*Roebuck, J.A. Kroemer, K. H. E., and Thomson, W. G., Engineering Anthropometry Methods. New York, NY: Wiley, 1975.

A separate branch of applied anthropometry developed in the late 1900's. Body structures, kinetics and kinematics of the human body, the mechanics of the musculo-skeletal system, etc. were specifically investigated. This field of scientific endeavor, now called "Biomechanics", was defined by Roebuck et al. as the interdisciplinary science comprising mainly anthropometry, mechanics, physiology, and engineering studying mechanical structure and behavior of biological materials. It concerns primarily the dimensions, composition, and mass properties of the body segments, the nature of joints linking the body segments and their mobility; the mechanical reactions of the body to force fields, vibrations, and impacts; the voluntary actions of the body in bringing about controlled movements, and applying forces, torques, energy and power to external objects like controls, tools, and other equipment.

Relations between engineering anthropometry and biomechanics are so close that it is difficult and probably useless to draw demarkation lines between them. Knowledge about the physical characteristics of the body is obviously basic to each, and designing the man-made environment from tools to tasks so as to suit human dimensions and to meet human capabilities is the common desired result.

This, in fact, outlines the purposes of this symposium.

In recent years, considerable development has taken place in the surveying and collection of anthropometric data. Methodological advances have been achieved in anthropometric techniques. New functional studies have been made in the areas of reach, muscle strength, lifting, etc. There has been a great increase in the use of such data by engineers, architects, and industrial designers. Comprehensive computer-aided design techniques have been developed for work space design using data based on anthropometry and on the simulation of human movement patterns and complex work tasks.

Accordingly, this conference aimed

- to review the current status of anthropometric and biomechanical data
- to consolidate the theoretical and methodological advances in anthropometric and biomechanical studies
- to evaluate the role of computer-assisted techniques in the acquisition, presentation, and application of biomechanical and anthropometric data
- to provide a source book, by way of publishing comprehensive proceedings, for use by researchers and practitioners alike.

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CONTENTS

Opening Address

POSTURAL RESEARCH - THE NEXT CHALLENGE TO ANTHROPOMETRICS AND BIOMECHANICS

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POSTURAL EFFORTS ARE STATIC EFFORTS

Postural efforts are associated with static contractions of the muscles. In static efforts the muscles remain in a state of heightened tension with force exerted over an extended period. This type of work resembles an electromagnet, which has a steady consumption of energy while it is supporting a given weight.

Static effort compresses blood vessels and reduces blood irrigation of the muscles. Therefore, the statically loaded muscle has a decreased supply of sugar and oxygen, while waste products (lactic acid, carbon dioxide and others) are accumulated. These waste products are causing the acute localized fatigue in the statically loaded muscles; tiredness, pains and even cramps are the symptoms of excessive static load.

EXAMPLES OF POSTURAL EFFORTS

Our bodies must often perform static efforts during everyday life, but the most common static load is required by some long-lasting postures.

Thus, when standing a whole series of muscle groups in the legs, hips, in the back and neck are strained for long periods. Thanks to those static efforts, we can keep selected parts of our bodies in any desired attitude.

Postural efforts are high in the following situations:

- Bending the back either forwards or sideways.
- Holding extended arms forwards or sideways.
- Standing in one place for long periods.
- Putting body weight on one leg while other leg operates a pedal.
- Bending head and neck forwards or backwards for long periods.

These postural efforts are considerably increased when the inadequate posture is associated with holding or manipulating weights.

MEDICAL ASPECTS OF POSTURAL EFFORTS

Postural efforts lead to an increased energy consumption and to a raised heart-rate; thus longer rest periods are necessary.

But postural efforts do not only decrease performance and productivity, in the long run they also affect well-being and health. In fact, if postural efforts are repeated daily over a long period, more or less permanent aches will appear in the limbs concerned, and may involve not only the muscles but also the joints, tendons and other tissues. Long-lasting postural efforts can lead to deterioration of joints, ligaments, tendons and other parts of the connective tissue.

Several field studies as well as general experience show that postural efforts are associated with an increased risk of:

- Inflammation of the joints.
- Inflammation of the tendon-sheaths.
- Inflammation of the attachment-points of tendons.
- Symptoms of chronic degeneration of the joints in the form of chronic arthroses.
- Painful induration of the muscles.
- Disc troubles.

Persistent pains in the overloaded tissues appear particularly among older operatives.

We can assume the following relationships between postural efforts and risks of pains or diseases:

Postures	Risks of pains or diseases
standing in one place	feet and legs, varicoses
sitting erect without back-support	extensor muscles of the back
seat too high	knees, neck
seat too low	shoulders and upper arms
trunk curved forwards when sitting or standing	lumbar region; deterioration of intervertebral discs
head inclined forwards	neck, deterioration of intervertebral discs.

ERGONOMIC PRINCIPLES TO AVOID POSTURAL EFFORTS

A major objective in the design and layout of jobs, work-places, machines and tools should be to minimize static efforts due to inadequate postures. To reach this objective, two principles must be taken in consideration:

- All work-place dimensions (including tools) should be suited to the body-size of the operator; thus postural efforts can be minimized.

- Postures must be adopted which will allow for as many muscles as possible to contribute; thus the muscles will be most efficient and most skillful.

These principles require the application of Anthropometrics and of Biomechanics; they are essential for the assessment of

- adequate working heights
- comfortable head positions
- adequate vertical and horizontal grasping space
- adequate operating space for the legs
- comfortable hand grips, knobs and other controls.

NEW POSTURAL PROBLEMS : NEW CHALLENGES

It is estimated that three quarters of all operatives in industrial countries have sedentary jobs. The main problem of the sitting posture involves the spine and the muscles of the back which are not merely not relaxed but considerably strained in various ways.

Orthopaedic research showed that the sitting posture is increasing the pressure inside the discs which means that this posture is associated with an increased wear of discs and spine. This result is confirmed by many field studies showing a high incidence of back aches in operators with sedentary jobs. Orthopaedic and ergonomic research come to the same conclusion: Work seats require a high backrest, slightly concave to the front at the top end and distinctly convex in the lumbar region.

Another aspect of modern production technology are the constrained body postures which appear in many "man - machine" work-places. A relatively fixed visual distance, fixed positions of the hands operating keyboards or controls are the main reasons of constrained postures involving postural efforts of the neck, shoulders, arms, and hands. Work on Visual Display Units or on other business machines is a widespread example of the present problem of constrained postures.

At those work-places constrained postural efforts are added to the adverse effects of the sitting posture and are often associated with increased visual loads. These are some of the new challenges to Anthropometrics and to Biomechanics - to develop the proper design of such man - machine systems in order to fit the essential work-place dimensions to the body size as well as to the involved body functions. However, the main objective remains the same:

"Fitting the working conditions to the man".

Session I
Data Acquisition Methods

FUNDAMENTALS OF ANTHROPOMETRIC SURVEY MEASUREMENT TECHNIQUES

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INTRODUCTION

In the modern technologically based society there is increased recognition of the basic importance of human population dimensional measures. This is reflected in the observation that some 85% of the major anthropometric studies world-wide have been completed during the past 20 years. The emphasis on military population studies has resulted in models for the increasing number of civilian-based surveys. But as the need for population surveys increases, new techniques and methods must be developed to increase the accuracy, quality and quantity of measures, and the means to quickly reduce and interpret these data. Bioanthropologists have greatly benefited from the technical contributions of other disciplines, particularly that of bioengineering, biostatistics, and biophysics. In reviewing recent technological advances and some current survey problems, this paper presents a brief overview of the state-of-the-art of anthropometric survey techniques and methods.

SAMPLING STRATEGIES

One of the first problems any anthropometric study comes up against involves the decision of how big a sample is necessary and how does one go about obtaining it? This is crucial because not only will it effect the cost of the study (and therefore whether it is even feasible to do) but the validity of the results. There probably is no single answer which will fit all cases. The decision on which of several alternatives will provide a statistically acceptable sample usually depends upon a number of factors and may involve some compromises.

The most recent and extensive sample representative of the civilian non-institutionalized population of the U.S. (HANES) was based on a nationwide probability sample of 28,043 individuals (although much less were actually measured for particular measures) selected to be examined in 65 different primary sampling units[1]. But at the other end of the scale, using the statistical basis for selection by matching on one variable (intervals of statures), after Churchill[2], only 28 males were considered statistically representative of the 1967 USAF population[3]. Similarly, ten females were considered to be representative of U.S. female truck and bus drivers[4].

Various random sampling plans have been devised for most anthropometric surveys, but all fall short of being truly random in the statistical sense. Churchill and McConville[5] have also utilized a "quasi-quotas" method of sample population matching, and "microcosm" samples based upon either of two methods, one of which is to select a sample which matches the population statistics for these variables. In the automotive industry one technique used a pool of premeasured co-workers, with selection for particular workspace studies based upon matching predetermined population variables. This latter technique provided a readily accessible pool of subjects at minimal cost. In a large-scale national survey the sampling strategy may become very complex and expensive when it is necessary to consider multiple factors of age, sex, race, geographic-political, socio-economic, rural or urban, and other demographic considerations.

Another question the researcher must resolve is how many measurements to take? This has varied greatly in current surveys and depends upon the purpose of the study - is it to design garments for an entire population - or to determine inside grip dimensions of six olympic pole vault contenders? Generally, "captive" subjects, such as those comprising military populations allow taking a large number of measures per individual. Thus some 189 measures were obtain in the 1967 USAF study, and 177 in the 1977 study of U.S. Army women.

However, much fewer measures have usually been taken on "voluntary" subjects for several reasons. In the 1962 HES U.S. adult population study only 18 measures (12 linear) were taken, partly because of limited time available per subject and also because anthropometry was only a small part of the study. We have found that about 20 minutes and 40 measurements is the time span most subjects tolerate in reasonable humor.

In dealing with infants and younger children, however, even less time may be tolerated. Yet often such younger populations also require numerous measurements. Stoudt[6] concluded that 196 measurements comprised a comprehensive list desirable for design of child restraint systems, with 44 the minimal number needed for the construction of manikin and mathematical models. Subsequently Young et al.[7] determined that 96 measurements were needed for three and six year old masterbody dummy forms. Similarly, in the design of wearing apparel at least 160 measurements may be required.

A method adopted in our recent national anthropometric surveys[8,9] of some 8,154 infants and children for the U.S. Consumer Product Safety Commission offered one solution to the problem of how to obtain more data when only 15-20 minutes per child was available. The strategy used was to obtain 22 basic core measurements on all subjects, plus 20-23 additional measures on each subject, from one of three groups (consisting of shape, linkage, or head, face and hand measurements) computer randomly selected on every third subject. The key factor in this approach was to select core measurements that correlate highly with all measurements in the other three groups. This provides a means of statistically checking the representativeness and comparability of the non-core populations.

MEASUREMENT TECHNIQUES

Although the traditional methods of static anthropometry using the tools of classic morphological osteology are still employed, there have been a number of new techniques developed with varying success and acceptance. Some of these will be detailed in subsequent papers in this session.

Standard Anthropometry

Most studies are based upon use of the standard anthropometer to obtain linear measures, the sliding and spreading calipers for smaller dimensions of the head, face, and extremities, and a steel tape for body girths. These basic tools have been supplemented in many studies by additional fixtures to obtain various functional measures such as types of reach. Skinfold (fat) calipers have been used to a much lesser extent and usually in nutritional or somatotype oriented studies. Those studies primarily concerned with seated workspace relationships often utilize specially designed fixtures with sliding measurement devices. In the hands of an experienced anthropometrist these basic tools are effective and have provided the bulk of the available data to date. Yet such tools could be said to represent 19th century technology, and present many limitations.

Stereophotogrammetry

Photographic techniques have long held promise, but the path has been littered with miscarriages. Some systems, such as the 1957 Photo-Metric system used in an Air Force study, have not had further development. More recently stereophotogrammetry (stereographic or stereometric anthropometry) techniques have been used in a number of experimental studies, but with inconclusive results. Techniques evolved from advances in cartographic aerial photography are attractive at first blush. An increasing number of stereometric sensors are used to locate three dimensional spatial coordinates of points distributed over the body surface, and appear particularly useful for studying body volume, mass distribution, body density, surface area or even 4-D spatio-temporal measurements. However such studies have not yet proven to be useful in large-scale anthropometric surveys, and involve expensive and time-consuming methodology. One major problem with stereophotometric techniques is that in order to obtain linear measures, surface marks must be placed at various body landmarks so that desired measures can accurately be determined from the photos.

Three-Dimensional Systems Anthropometry

Another method of measuring the body in three-dimensional relationships involves "systems anthropometry"[10] in which human body position and mobility are described in a 3-D frame of reference based on a precise description of body links and joint articulation[3,10]. Still in an experimental stage, this approach is aimed at understanding the complex variability of body position and mobility in order to develop a mechanical model for computer simulations and articulated dummy surrogates.

Computerized Automated Anthropometry

Advances in computer technology have led to several attempts in the past to directly couple instrumentation with automated data capabilities. A successful state-of-the-art system has been developed at the University of Michigan and used in two nationwide anthropometric studies[8,9].

To obtain body segment lengths, GPM Swiss standard anthropometers and calipers were modified to provide electrical readout of length by means of a 10-turn potentiometer. In addition, a means of standardizing measurements on soft tissue is provided by a miniature pressure transducer in the plexiglass blade. This allows simultaneous recording of both length and pressure. To measure body circumferences a girth device was designed which also provides an electrical readout to the computer upon command. Two portable center-of-gravity devices, one for infants, and the other for larger children and adults, consist of platforms supported by three precisely calibrated load cells.

Measurements from these devices go directly to the NOVA minicomputer system through a 12-bit A/D converter. The system also includes two magnetic tape drives for data storage and a keyboard, terminal, and a TV display unit.

The data collection process is controlled by a computer program called MAP (Michigan Anthropometric Processor), which contains routines for calibrating equipment, sensing which measuring device is being used, editing and storing data on magnetic tape, sequencing through the measurements and demographic questions, and informing the anthropometrist when a measurement value seems inaccurate in relation to the subject's age, stature, or weight. This program also allows the measurer to skip forward or back to a specific measurement, lists all data for review at the end of each subject, and selects on a rotating basis, the particular measurement set for each subject. This computerized equipment was transported by maxi-vans to 104 locations around the U.S., selected in accordance with a random sampling plan based upon 74 primary sampling units maintained by the Survey Research Center of the University of Michigan Institute for Social Research. The initial study obtained 41 measurements on 4,027 individuals to age 12. In a second study 87 measures on 4,127 subjects to age 19, were taken. For each of 16 age groups, the sample size, mean, standard deviation, 5th, 50th and 95th percentile for each of the measurements taken, for males, females and combined sexes were reported.

A major advantage of the protable computerized automated anthropometry system over traditional methods is that numerous sources of measurement and recording error are eliminated. Data recording, storage, reduction, and analysis is rapidly and accurately accomplished. The major disadvantage is that such a system is still expensive in comparison to the traditional equipment. Nevertheless, the Michigan Automated Anthropometic System now represents the state-of-the-art in anthropometry, and provides the first practical and portable computerized means of instanteously obtaining center-of-gravity measurements.

CONCLUSIONS

Anthropometric population surveys are increasing on a world-wide basis with recognition of the basic role such data play in human factors and workspace design, garment and automotive design, and other product related design and regulation decisions. The solutions to fundamental problems in determining a representative sample size, number and definition of measures required, sampling strategy (including sex, age, race, socio-economic, politico-geographic, rural-urban and other factors), and data handling vary with the nature of the study. Review of new directions and technologies strongly indicate that while traditional techniques will probably continue to be the basis for most studies the state-of-the-art-has progressed far beyond this.

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EVOLUTION OF THE TECHNIQUES OF DATA COLLECTING AND PROCESSING IN BIOMETRY

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Traditional techniques of anthropometric measurements and the usual way of processing these data do not supply people in charge of biometry and biomechanics with adequate information.

The notion of morphology involves the description of human body geometry: dimensions, surfaces, volumes, masses, inertial properties, as well as the location in space of relative positions of anatomical structures in movement.

These facts have led biometricians and engineers to develop methods of measuring the human body in three-dimensional space.

The biostereometric methods developed in our laboratory are complementary in various respects.

In particular, we commonly use anthropostereometry, i.e., stereometry with direct measurement of the human body and automatic data collecting and processing.

We are also developing different types of biostereometric measurements: opto-electronic (laser) or ultrasonic, and in certain cases, photogrammetric methods with stereorestitution. The three-dimensional data thus collected are processed in large data filing computers (data bank) and on interactive visual displays. This method is of great help in finding solutions to problems in biometry and ergonomy.

RESULTS OF LARGE-SCALE ANTHROPOMETRIC SURVEYS

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INTRODUCTION

Large-scale anthropometric surveys have a long tradition in Europe. There are various reasons for this: In most countries there is an obligatory military service for all young men, there is a uniform school system run by the state and there are or have been mass organizations for children, young and older people which provide plenty of opportunities to conduct large scale surveys. A certain stability of the social structure and in comparison to the USA a low level of migration in these countries assure that the data obtained by such surveys remain valid for quite a number of years. Furthermore, a reliable system of registration of all persons and all migrations enables the researcher to prepare proper quota samples regarding regional and social data which could be of importance for the anthropometric results.

PRECONDITIONS

When reporting on the results of large-scale surveys we suppose that

- the anthropometric method in a particular survey is fully standardized:
  Vague indication of measurement methods such as "according to Martin" or "according to Hertzberg" is not sufficiently precise; especially in the case of large-scale surveys it is necessary to state exactly what was measured and how the measurement

was carried out. Comparative studies (e.g. Piquet, 1954) have shown that sitting height depends to a considerable extent on whether someone is sitting on the floor, on a low stool, on a seat whose height from the floor corresponds exactly to calf length or whether his legs are swinging freely with total or partial support under the thighs. This is because the sitting position determines the curvature of the spine, which in turn affects the sitting height. This means that not only the act of measurement but also the measurement conditions must be described.

the researchers are well trained in the anthropometric program:
Particularly in the case of large-scale anthropometric surveys negligence may often be observed with reference to this point. Showing an undergraduate or any other assistant the measurement technique and then letting him copy the measuring process is not enough; the researcher must be familiar with the anatomical assumptions and conditions to which the measurement has to be adjusted. Many anthropologists have made the unsatisfactory discovery that a researcher who was supposedly competent in the field "improved" in the course of a large-scale survey, and that the greater precision of later results made them incomparable with earlier ones. Where measurement work is carried out by technical assistants with no knowledge of the basic principles of anatomy and biomechanics, the measurements taken in the course of a long-term anthropometric investigation may be found to deviate increasingly from the original purpose, as the measuring process itself means nothing to an assistant who is not aware of the anatomical background.

there has been an anthropometric test program to assure that the results of all researchers can be reproduced and are comparable:
This kind of test program should not be on too short-term a basis in order to ensure the reliability of the data to be worked with (cf. Lewin et al. 1969).

the sample for the survey is based on a proper statistical knowledge of the population so that it can be considered statistically representative, at least in regional and social respects:
This requirement is not realizable for the populations of many countries owing to statistical knowledge that is inadequate for a biometric survey. However, an effort should at least be made to provide

a reasonable estimate for the survey sample.

MEASURING INSTRUMENTS

Ever since the beginnings of anthropometry there have been attempts to improve the range of measuring instruments. Up to the 1930's there was hardly a well-known anthropologist who had not invented at least one instrument. In practical work over the years this considerable quantity of measuring utensils has been reduced to a basic minimum composed of an anthropometer, a few calipers and a tape measure, and most large-scale anthropometric surveys have been carried out with just these tools.

More recently various attempts have been made to "modernize" the range of instruments. This mainly involves the use of fairly traditional apparatus equipped with an electronic reading and data processing mechanism; repeated efforts have also been directed towards the optical registration of body measurements without having to touch the people concerned.

The first of these methods has the advantage of minimizing mistakes in reading off and in data processing. It does, however, have important disadvantages: This modernized apparatus is more complicated to use because the electronic measuring units attached to the traditional instruments make them heavy and also because it needs a cable connection to the computer. The exactness of the measurements only equals that of more traditional instruments when the equipment is used by an experienced researcher. As, however, these new instruments were primarily developed for surveys, which generally employ less well-trained researchers, the instruments themselves can be the cause of inexact measurements.

Furthermore, these modern devices are less inconspicuous and less easily manipulated that the older type of apparatus, with which measurements could easily be taken in public, in offices and under various conditions. The apparatus that is connected to an EDP system requires a special working area and organizational and technical preparation for the investigation, which can prove to be a considerable hindrance in large-scale surveys.

Attempts to measure humans by stereophotographic methods have been made for over ten years now. First efforts involved marking points of the body in order to be able to identify them from photographs. This method was found to be too complicated; in the time it took to mark the points, a trained anthropologist had already measured them. Current trials aim to do without manipulation of any kind and simply to carry out the entire measuring process by optical methods.

This procedure has been found advantageous on a number of counts. It is not suited, however, to all purposes, because photographic methods only account for the exterior body or clothing outline without taking the variable degree of compressability of soft body parts into consideration, which is very important for all practical purposes. The external trunk outline of a naked, stout and elderly adult does not permit any serious statements about his body form, as permanent skeletal features, that may not be altered at short notice to meet the demands of diet or fashion, cannot be captured photographically. The width of the pelvic girdle remains constant in all body positions. The shape of the abdomen, on the other hand, differs for the same person naked and standing, clothed and standing, or seated. This type of difference can easily be measured by properly defined traditional investigation methods but not by optical registration of the exterior. This is why I do not believe that current optimism with reference to optical measurement methods is justified. At the present time there is no measurement method that can compete with "classical" anthropometric methods with regard to exactitude, ease of reproduction, flexibility, adaptability for different situations and also with regard to cost.

RESULTS

Data obtained in a large-scale survey serve three main purposes:

1. If a clearly defined region forms the basis for the sample, the results provide an overview which can be used for general planning purposes, i.e. safety regulations, standards, legislative and also marketing purposes.

2. Information gathered in such a survey is usually not intended to serve only one purpose but to provide information for a number of current and future questions. On the other hand, the amount of informa-

tion permits the integration of special findings in a complete biological system.

3. The considerable amount of information gathered further allows the combination of anthropometric data and so provides a great depth of information:

Anthropometric data can be clearly differentiated by sex, age and type of profession with respect to physical strain, social class, and regional origin. It is for instance known that the process of ageing as far as anthropometry is concerned depends on physical training, social conditions and regional origin. These influences can cumulate and thus influence the possibilities for practical application of the measurements.

If we only consider 2 sexes, 3 age groups, 3 social strata and 2 regional groupings, then we already have 36 subgroups before we have started to deal with the measurements. If we then only combine two or three basic measurements we will have so many groups that only a very great data base can satisfy the requirements (Jürgens e.a. 1975, Moroney & Smith 1972, Daniels & Churchill 1952).

Every ergonomist knows that normally we cannot use measurements of the "average man" (arithmetic mean), but it is necessary for the design of products and human environment to consider certain limits, for instance the 5th and 95th percentile or, for safety regulations, the first and 99th percentile of the respective population. Very often, however, this knowledge is applied only to the total body height, so that the differentiation into percentiles is limited to this measurement only. One "expects" a person of the 5th body height percentile to have also arms and legs and all other measurements in this percentile range. Here again we detect the concept of the average man and practical measurements demonstrate that it is as inapplicable as before.

Large-scale anthropometric surveys made by the textile industry have already demonstrated that in reality different lengths of arms and legs as well as a broad range of circumferences of the trunk can be combined with the same body height; this knowledge was the basis for the different sizes of clothing. It is impossible to find these combinations of measurements theoretically or with certain statistical procedures;

here large-scale surveys must be the basis.

Here the point should be made that large-scale anthropometric surveys not only provide a general picture of the measurement combination occuring in a given population, but also provide information about the frequency of occurrence and statistical distribution of these combinations and about which combinations occur so frequently that it is economically viable to produce a special clothing size to fit them. Data from large-scale surveys is needed to identify these characteristic combinations and to reduce the number of sizes required to an economic prospect.

Similar problems to those of the textile industry can also be found in the automobile industry. Normally the interior of a car is designed for persons of certain body proportions, and again the total body height is considered to be the indicator, though this measurement is of no direct use for the design. It would make more sense to take the sitting height as a basis for the design, or other body measurements which are directly needed. As we use an unfit indicator we can only compensate for all the shortcomings caused by this by providing excessively numerous complicated mechanisms to adjust the seats, the wheel and pedals.

A typical example of the concept of the "average man" is reflected in the automobile industry in the mechanism to adjust the driving seat in a variety of vehicles: in many cases it is only possible to move the seat forward on a sloping track, because it is assumed that people who have such short legs that they must move the seat forward also have a short trunk and consequently need to sit higher in order to see out. This corresponds to the concept of the "average man". People with short legs but a long trunk are at just as much of a disadvantage as those with a short trunk and long legs. For both of these groups of people it would be more sensible to be able to adjust the height of the seat and its position relative to the pedals independently. The question of how often such deviation from average measurements may be found in a population can once again only be answered by means of a large-scale survey.

Large-scale surveys give us an opportunity to compare the morphology of different populations and thus give us an idea of their metric differences. Here the differences in body proportions and the metric relations of the different parts of the body are of importance, not the body height. This type of comparison prompts the question of the extent to which it makes sense to adapt one thing to all populations of the world by special adjustment provisions. Perhaps it would be better from the economical and technical point of view to divide mankind into two groups and serve them with two sizes of the product, whether it be a car or something else. Here from the metrical point of view a northern and a southern type of man would have to be considered.

CONCLUSION

Provided the necessary technical preconditions are fulfilled, it is obvious that large-scale anthropometric surveys can serve three main purposes which can not be properly dealt with otherwise:

- they give us a basic knowledge of a population which enables us to draw representative samples and also to integrate the metric data obtained from these samples into the framework of the whole biological system,
- they provide us with data suitable for planning and standardization purposes,
- they enable us to study the combination of body measurements and their variation.

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THE HUMAN MACHINE IN THREE DIMENSIONS: IMPLICATIONS FOR MEASUREMENT AND ANALYSIS

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INTRODUCTION

Scientists and laymen have a favorite analogy: the human body as machine. In this context, machine is "...a structure consisting of a framework and various fixed and moving parts, for doing some kind of work" (Webster's New World Dictionary, 1974). The human skeletal system is the "framework", while the neuromuscular system generates forces and controls movements for performing work. Modeled as a machine, the body's skeletal linkage system acts as mechanical levers (Tichauer, 1978). Dempster (1955) defined skeletal links as straight-line distances between joint centers of rotation; for computer simulations, his interpretation suggests a stick-man model as a reasonable, straight-forward approximation. Unlike present-day machinery, however, there is poor "quality control" in the linkage system of our human machines; that is, the length of the links varies among individuals with respect to body size and even in the same individual with respect to position. Thus, the potential range of variation in body position and mobility may be maximized by behavioral and cultural variables (Maule and Weiner, 1975). Consequently, anthropometrists measuring the body are concerned with standardization of instruments, landmarks, and body configuration. These three technical areas have largely determined the parametric definition of the human machine in current models.

In describing the human machine quantitatively, traditional anthropometry has made one-dimensional, scalar measurements of the body in one of two positions: standing or sitting. A clear understanding of variability in body size has been obtained from one-dimensional data (Robinette, Churchill, and McConville, 1979; Robinette and Churchill, 1979) and has been successfully applied to problems of body size (i.e., link-length for fixed positions). However, in frequent attempts to use these same types of data for design problems of the dynamic human body; i.e., position and movement, inaccuracies result.

This paper will provide an introduction to three-dimensional anthropometry in order that its terminology and concepts be clearly understood. Following definition and discussion, two examples will be given of the way in which three-dimensional anthropometric data describe body posture and joint kinetics.

THREE-DIMENSIONAL ANTHROPOMETRY

The basic variable in three-dimensional anthropometry is a location vector, its value determined with a mathematical frame of reference, such as a Cartesian coordinate axis system. Within such a framework, measurements of the body are made by locating points with a mechanical, electro-mechanical, or optical system from which three-dimensional coordinates can be derived. The data, therefore, are x-, y-, and z-coordinates in a fixed axis system located in relation to an environment, such as a laboratory, automobile, chair, etc. Three-dimensional anthropometry is the measurement of points on the human body in a well-defined vector space. Within the context of an investigation these points are either random targets closely spaced for a good estimate of body volume (Herron, 1976) or functional pointmarks that represent specific anatomical landmarks, for an accurate measure of body position and mobility (Reynolds and Hubbard, 1980). Only the latter approach will be described in the present paper.

Traditionally, anthropometric landmarks have provided repeatable endpoints of a measurement that represented an anatomical or clearance dimension. A pointmark is, on the other hand, a targeted point on a landmark. The location of a pointmark defines a vector in three-dimensional space and anatomical or clearance dimensions are calculated as point-to-point distances between two pointmarks. Because they can be measured with the body in any position, the use of pointmarks is a substantive addition to the science of anthropometry. With three pointmarks on each body link, an anatomical frame of reference (Reynolds and Hubbard, 1980) can be defined which will specify completely the spatial relationships between body links: the standardized posture required in traditional anthropometry has thus been superseded. If the same three pointmarks on each body segment are measured in different positions, the relative change in position can be used to describe the motion characteristics of a joint (Marcus, 1980). Therefore, three-dimensional anthropometry may be considered an appropriate method of describing the body as an open-link system whose posture is variable but quantifiable.

Posture may be described quantitatively either as a set of pointmark vectors for a given workspace or, more completely, as a set of anatomical coordinate frames whose relative positions are defined in three-dimensional space. Following are two examples: 1) a sample of living subjects seated in a hard seat and 2) the hip and sacroiliac kinematics of one unembalmed cadaver. In both examples, the basic data set consists of three-dimensional coordinate locations of pointmark vectors: the foundation for a three-dimenional systems approach to the human machine is established.

THREE-DIMENSIONAL SEATED POSTURE

Although Europeans (Åkerbloom, 1948; Grandjean, 1969) have studied seated posture extensively, most research investigations have encountered difficulty in quantifying the position of the body in various postures. In fact, a single posture has often been standardized when anthropometric data on the seated position are desired.

Past investigations of body posture have utilized graphical (Corlett, et al., 1979) or verbal (Branton and Grayson, 1967) methodologies. One of the most highly systematized methods of describing body position was developed in the field of dance where labanotation (Hutchinson, 1970) has been programmed (Smoliar and Tracton, 1978). A more elaborate system was perhaps developed by Roebuck (1968) for evaluating spacesuit mobility; however, none of these techniques for describing posture provide the capability of spatially relating the human machine to the geometry of the working environment. In order to quantify posture accurately so that it has a geometric basis, three-dimensional anthropometry shows promise as a potentially useful technique. Thus, extremely precise codification of the human machine may contribute to the solution of its "breakdown" problems.

In 1972, a set of three-dimensional anthropometric data was collected on 281 subjects in a Federal Aviation Administration-sponsored study of female flight attendant trainees (Snow, et al., 1975). The subjects were measured in a hard-seat with a mechanical, three-dimensional anthropometer (as shown in Figure 1). The origin of the axis system is at the right edge of the seat back/pan intersection, with axes oriented relative to the gravity vector. In a right-handed orthogonal axis system, the x-axis is positive anteriorly, the y-axis is positive left laterally, and the z-axis is positive upwards. (These directions are given relative to the subject seated in the hard-seat.)

Each subject was asked to sit as if she were in a commercial aircraft seat. The anthropometrist then attempted to align her mid-sagittal plane coincident with the midline of the chair; no other comments about or corrections to her posture were made. Eleven pointmarks were measured on each subject: vertex, left ectocanthus, left neck-shoulder junction, right acromion, suprasternale, left acromion, left iliocristale, left iliospinale, left trochanterion, left maximum lateral thigh point, and left maximum superior thigh clearance point. Posture was not standardized: a

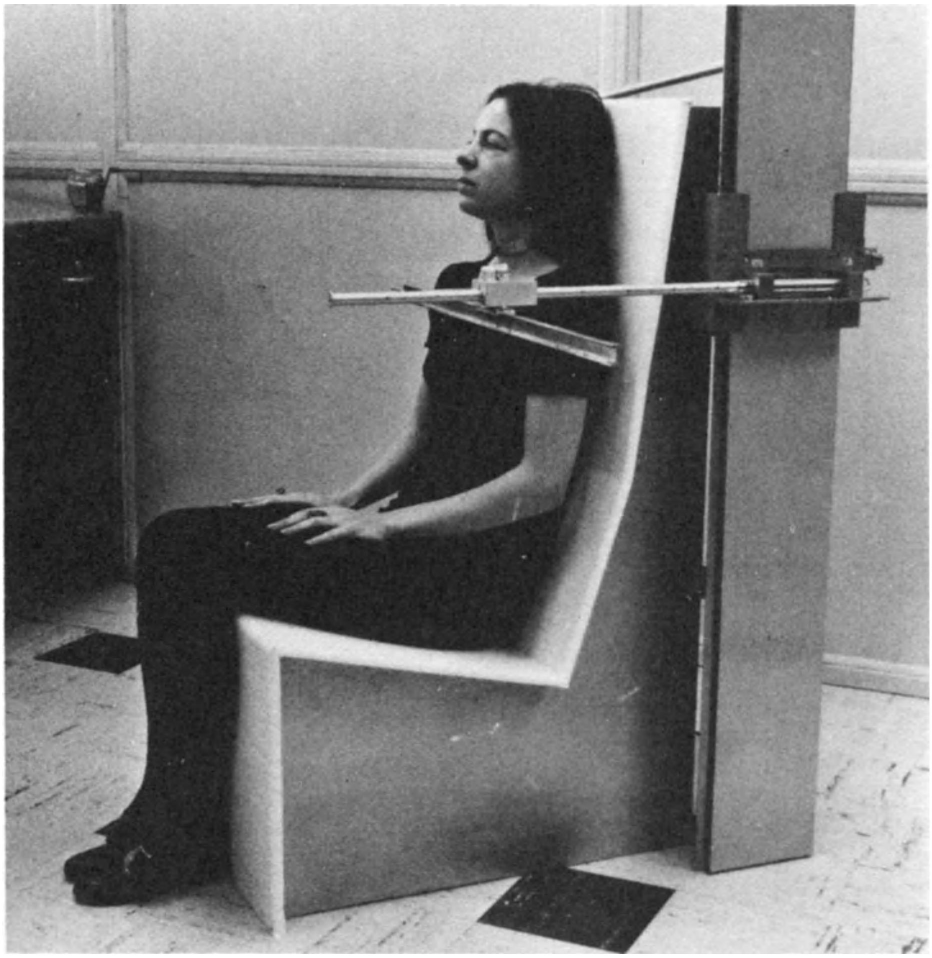

Figure 1. Subject seated in hard-seat with three-dimensional anthropometer attached.

goal of the study was to investigate this "real-world" variability since, in reality, air passengers sit differently. An additional goal of the research was to test the hypothesis that three-dimensional data could measure variability due to differences in posture and body size, and that these differences could be described with appropriate data analysis procedures.

Differences in body position, due to subject location in the hard-seat, were reduced by re-defining an axis system origin independent of the hard-seat axis system origin. All cases with data missing were removed. Average x-, y-, and z-coordinates for each subject were calculated according to the following formula:

$$X_c = \frac{1}{n_x} \sum_{i=1}^{n_x} X_i$$

Thus, a new centroidal vector (X_c, Y_c, Z_c) was located in three-dimensional space for each subject. To remove the positioning effect, each subject's variable dataset was transformed into the new coordinate axis system, thus changing the origin to an anthropometrically comparable location.

Variability in the data was now reduced to differences in body size and posture. To determine if subjects assumed different postures, the data were clustered using the Michigan Interactive Data Analysis program at The University of Michigan Computing Center. Based upon the average Euclidean distance between the x- and z-coordinates for vertex and ectocanthus pointmarks, the clustering algorithm established two groups. Because it lies in the frontal plane and describes lateral body stability, which should be independent of body position, the y-coordinate was not used. Thus, within the range of possible postures in the hard-seat, a "slouched" and "erect" posture were identified in the three-dimensional data.

The two-dimensional location of each pointmark in the two clusters has been plotted in Figure 2 which depicts the sagittal projection (XZ-plane) of the average values. The sagittal projection illustrates that the subjects have been divided into: 1) a "slouched" posture (Δ) with the head (vertex and ectocanthus) positioned away from the chair back and the pelvis (iliocristale and iliospinale) rotated back toward the chair; 2) an "erect" posture (o) with the head positioned back towards the chair and the pelvis rotated forward. The projection illustrates that those individuals with a "slouched" posture are taller with respect to the chair than those individuals with an "erect" posture.

Body posture has always been difficult to describe quantitatively. The basic problem results from the very complex human machine; that is, the open-chain linkage system has, by a conservative estimate, approximately 44 degrees of freedom, the sum of the degrees of freedom for each of the major joints of a body represented in typical computer man-models. Therefore, the variety of postures which an individual may assume and the variety of postures which a group of individuals may assume are, for all practical purposes, infinite. The foregoing example has however, demonstrated that 3-D anthropometry can quantify, with great precision, specific body positions within a sample group of body postures.

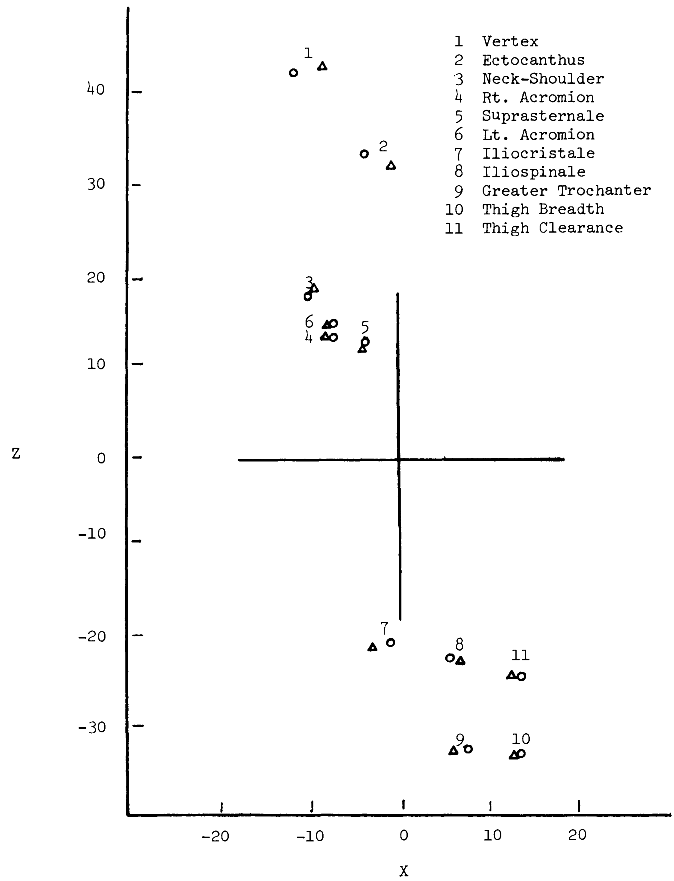

Figure 2. Two-dimensional plot of average values in centimeters for eleven pointmarks in the x-z plane (Δ = "slouched" posture; o = "erect" posture).

THREE-DIMENSIONAL RELATIVE MOTION OF THE SKELETAL SYSTEM

The human machine moves by relative displacements of the skeletal linkage system. That is, motion of one link can be described relative to a fixed link by measuring in three-dimensional space the location of the moving link in two positions. When motion parameters of the skeletal linkage system are determined in three-dimensional space, an accurate model of body position and mobility can be developed. The assumptions involved in restricting the model to motions of the skeletal linkage system are as follows:

--the skeleton provides the primary basis of human body position;

--the skeleton provides the primary leverage system for muscle action;

--the skeleton defines the geometric shape of a joint within which joint mobility is constrained;

--the skeleton defines basic body size.

Within this conceptual framework, three-dimensional data have been obtained to investigate the kinematic properties of the human machine as a three-dimensional system composed of links connected at joints each with six degrees of freedom. A stereo-radiographic technique has been developed in the Systems Anthropometry Laboratory at Michigan State University to measure the three-dimensional locations of anatomical pointmarks on the skeletal linkage system. Current research in the Laboratory is focused on relative motions among the skeletal segments of the lumbar/pelvic/femur linkage system. Relative movement between the sacrum, hip bone and femur and their absolute position with respect to an inertial axis system have been obtained from an unembalmed cadaver, held in a standing position while the thigh was moved through paths of motion. A pair of stereo-radiographs was obtained of the pelvic/femur links for each discrete position along the paths of motion, beginning from the anatomical position and ending when the body became unstable in its upright-supporting harness. Pointmarks targeted on the film were digitized and outputted to a program that calculated the three-dimensional coordinates of each target relative to an inertial axis system, which is visible on each film.

Relative motion among the bones can be described by an angle about and a displacement along a single axis (Suh and Radcliffe, 1978). The instantaneous screw axis is defined by a translation "s" along the axis, a rotation "ϕ" about the axis, and direction cosines, "U_x, U_y, U_z" of the axis. Data in Tables 1 and 2 describe three screw axes for relative motion at the hip and sacroiliac joints. Each of the three bones was targeted with three pointmarks and an axis system calculated for each of the three bony segments. The left hip bone was mathematically held fixed in space and the data analyzed for relative motion of the femur (Table 1) and sacrum (Table 2).

These data provide limited evidence that the pelvis is not a rigid body: the sacrum appears to move as a function of femoral movement, although its motion is, for practical purposes, only rotation. Thus, for hip abduction, the sacrum rotates primarily in the x-y plane of the hip bone axis system; for hip abduction, primarily, in the x-z plane; and for hip flexion, primarily, in the y-z plane.

The screw axes in Tables 1 and 2 have been located relative to an anatomical frame of reference. Anatomical axes systems constitute a change from traditional biomechanical engineering approaches since they are relative frames of reference based upon measured data. When an axis system is defined with measured data, errors in mensuration become evident and important. The effect of errors in the definition of an anatomically-based coordinate axis system has been investigated by Robbins (1977) and Marcus (1980). Robbins stated

TABLE 1
Screw Axis Analysis for Hip Motion

Motion	s(cm)	ϕ (deg)	u_x	u_y	u_z
Abduction	-.07	24.0	.949	-.265	.171
Abducto-flexion	-.46	44.5	.742	-.407	.532
Flexion	1.44	55.6	.951	-.309	0.0

TABLE 2
Screw Axis Analysis for Sacroiliac Motion

Motion	s(cm)	ϕ (deg)	u_x	u_y	u_z
Abduction	.03	1.23	-.148	-.346	.926
Abducto-flexion	.13	1.20	.339	.917	0.22
Flexion	0.0	2.33	.985	.080	-.147

that the data can be no more accurate than the definition of the axis system itself and that the axis system definition should be based on pointmarks as far apart as possible on the same rigid body. Marcus showed that the origin of the anatomical axis system should be equidistant from all of the pointmarks used to define it. Such requirements are not easily met; and the methods of determining an anatomical frame of reference which meets these stringent criteria is still under investigation.

DISCUSSION AND CONCLUSION

The two illustrations of three-dimensional anthropometry describing postures of living subjects and three-dimensional kinematics of hip and sacroiliac motion demonstrate a basis for three-dimensional measurements and analyses of the human machine. Incorporated in all these data is a basic problem in the identification of pointmarks. Engineers have often accused anthropometrists of having "magic fingers;" and at present a substitute for careful palpatory location of pointmarks derived from comparative morphological anatomy does not seem to exist.

Pointmarks and their identification must be carefully investigated since they contribute to errors in data analysis: the absolute position and mobility of the body in three-dimensional space can only be as accurately defined as the pointmarks are accurately located. Population studies are possible only when variability in pointmark definition between subjects is minimized. All three-dimensional data analysis is made with algorithms that react sensitively to errors because the analysis uses mathematical calculations that propagate and often magnify error. As a result, procedures must be developed that contain error in the raw data and minimize error propagation in the data analysis.

Despite the two examples presented here that show a clear advance in information obtained with three-dimensional, over two-dimensional, anthropometry, a current need remains to develop accurate and cost efficient means of three-dimensional measurements and analysis. With the advent of the digital computer, models have proliferated both for civilian and military applications, but the advances in modeling technique have often been made without concurrent advances in anthropometric databases. This trend clearly needs to be eliminated if we are to progress toward accurate predictive models of the human machine.

Three-dimensional anthropometry presents both basic and applied investigators with a tool for measuring geometric properties of the human body for dynamic models. These data are essential to the ergonomic maintenance, repair, and replacement of productive capacity for our human machine.

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AN ANTHROPOMETRIC DATA BANK: ITS HIDDEN DIMENSIONS

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The U.S. Air Force's anthropometric data bank was initiated in 1973 by Mr. C. E. Clauser as a facility designed to incorporate in comparable format the raw data from available anthropometric surveys so that they could be recalled and reanalyzed for specific purposes as needed. Such a repository would assure that individual anthropometric survey data would remain available at a single location even though the principal investigator or sponsoring agency no longer had an interest in its maintenance. However, the data bank was envisioned not just as a repository containing data from a variety of sources but as a facility in which such data would be processed and cast in comparable format so that it would be recalled and analyzed for design purposes using a series of standard computer routines. Over the years, the data bank has expanded steadily and today it constitutes a unique source of such data.

The current holdings of the Air Force Aerospace Medical Research Laboratory's (AFAMRL) Anthropometric Data Bank includes 34 separate surveys (Table 1). While the initial emphasis was on military data, any large-scale survey is a candidate for inclusion. Of the 34 surveys currently included, approximately one third are for U.S. male military groups; approximately one tenth are for U.S. female military; one third are for foreign male military; and the remainder are for U.S. civilian populations. Altogether, the data bank contains information obtained from over 100,000 subjects; approximately 300 variables are represented. These survey data have been acquired through the good offices of the responsible principal investigator or sponsoring agency who recognize the desirability of

Table 1. Current resources of the AFAMRL Anthropometric Data Bank.

Survey Date	Survey	Sample Size	Vari-ables
	U.S. Military Populations: MEN		
1950	U.S. Air Force Pilots	4,000	146
1959	U.S. Army Aviators	500	46
1964	U.S. Navy Aviators	1,529	98
1965	U.S. Air Force Ground Personnel	3,869	161
1966	U.S. Army Ground Personnel	6,682	73
1966	U.S. Navy Enlisted	4,095	73
1966	U.S. Marines Enlisted	2,008	73
1967	U.S. Air Force Flyers	2,420	189
1970	U.S. Army Flyers	1,482	88
	U.S. Military Populations: WOMEN		
1946	U.S. Women's Army Corps	7,563	65
1968	U.S. Air Force Women	1,905	139
1977	U.S. Army Women	1,331	151
	U.S. Adult Civilian Populations: MEN		
1961	Air Traffic Controllers	678	65
1962	Health Examination Survey (HES)	3,091	18
1974	Law Enforcement Officers	2,989	23
1975	Health & Nutrition Examination Survey (HANES)	6,563	11
	U.S. Adult Civilian Populations: WOMEN		
1962	Health Examination Survey (HES)	3,581	18
1971	Airline Stewardesses	423	73
1975	Health & Nutrition Examination Survey (HANES)	10,123	11
	Foreign Military Populations: MEN		
1960	Turkish Armed Forces	912	151
1961	Greek Armed Forces	1,071	151
1961	Italian Armed Forces	1,342	151
1961	Korean Military Flyers	264	132
1964	Vietnamese Military Forces	2,129	51
1967	German Air Force	1,466	152
1969	Iranian Military	9,414	74
1970	Latin-American Armed Forces	1,985	76
1970	Royal Air Force Aircrew	2,000	64
1972	Royal Air Force Head Study	500	46
1972	Royal Australian Air Force	482	18
1973	*French Military	1,272†	118†
1974	Royal New Zealand Air Force Aircrew	238	63
1974	Canadian Military Forces	565	33
1977	Australian Personnel	2,945	32

* In process of inclusion; † not final.

the anthropometric data bank concept. Two new surveys, the Australian Armed Forces (1977) and the French Military (1973), have, for example, been received this past year. The first has already been incorporated into the data bank and the second is being processed for inclusion. We anticipate two to three new acquisitions during the coming year.

Upon receipt, the data are treated in the same manner as the data we have developed in our own surveys. It is inevitable, however unfortunate, that any large collection of anthropometric data will contain an unknown number of errors. While the sources of such mistakes are many, their chief cause is human fallibility. In the 1967 U.S. Air Force anthropometric survey, for example, 2,420 flight crewmen were measured for 190 variables--an awesome total of 459,800 measurements. It requires but a momentary mental distraction during any of the measuring or data processing steps to cause an error to slip into the recorded material.

It is critical, therefore, to introduce methods for checking and evaluating anthropometric data to provide some degree of assurance that errors are identified and reduced to a minimum. This is accomplished at increasingly more sophisticated levels with the aid of a high-speed computer which can rapidly check and evaluate vast numbers of numerical observations in a systematic fashion.

The two editing programs commonly used were developed by Edmund Churchill of the Anthropology Research Project under contract to the Air Force Aerospace Medical Research Laboratory and, when used together, effect a "coarse" and "fine" sifting of the data. The XVAL (eXtreme VALues) routine scans for gross errors by sorting out the ten highest and ten lowest values from a given group for examination. As can be seen on Table 2, each variable is listed with the 10 lowest and 10 highest values printed out with their associated subject numbers, followed by the sample mean, standard deviation, and coefficient of variation. The statistics Veta I and Veta II, measures of skewedness and peakedness, respectively, are also computed and are particularly sensitive to atypical distributions. A suspect value for stature on Table 2 is flagged by arrows, as is its associated Veta II value. The estimated mean and estimated standard deviation are recomputed after elimination of the 10 largest and 10 smallest values for comparison.

The EDIT (EDITing) program is used to test each data point for each subject by comparing the measured value with a predicted value obtained from regression equations and flagging those which exceed set limits. This program is designed to single out from a mass of normally distributed data those values which appear to be abnormal or aberrant when judged in terms of other data for the same subject. The program's procedure is based on the computation of multiple regression equations for estimating a given variable in terms of a

Table 2. Excerpt from sample XVAL program.

	3 GRIP STRENGTH VALUE	SBJCT	4 STATURE VALUE	SBJCT	5 CERVICALE HEIGHT VALUE	SBJCT	6 ACROMION HEIGHT VALUE	SBJCT
1ST SMALLEST	41.0	154	→1389.0←	82	1347.0	145	1278.0	145
2ND SMALLEST	42.0	177	1602.0	145	1392.0	173	1329.0	60
3RD SMALLEST	42.0	135	1643.0	173	1400.0	60	1329.0	35
4TH SMALLEST	42.0	92	1644.0	35	1401.0	35	1335.0	95
5TH SMALLEST	43.0	126	1646.0	93	1405.0	95	1337.0	173
6TH SMALLEST	44.0	165	1650.0	60	1407.0	93	1349.0	36
7TH SMALLEST	44.0	80	1651.0	95	1414.0	36	1351.0	93
8TH SMALLEST	44.0	67	1657.0	36	1417.0	165	1356.0	103
9TH SMALLEST	45.0	94	1672.0	103	1417.0	80	1356.0	80
XTH SMALLEST	45.0	93	1676.0	80	1420.0	103	1363.0	119
******								
XTH LARGEST	66.0	43	1875.0	108	1619.0	133	1544.0	43
9TH LARGEST	67.0	38	1881.0	120	1621.0	120	1545.0	172
8TH LARGEST	67.0	104	1882.0	44	1622.0	108	1547.0	109
7TH LARGEST	68.0	109	1886.0	83	1623.0	157	1551.0	89
6TH LARGEST	68.0	112	1892.0	157	1624.0	83	1553.0	108
5TH LARGEST	68.0	122	1899.0	43	1630.0	140	1566.0	140
4TH LARGEST	70.0	57	1906.0	140	1631.0	44	1579.0	44
3RD LARGEST	70.0	81	1913.0	102	1669.0	20	1585.0	102
2ND LARGEST	71.0	98	1923.0	31	1675.0	31	1607.0	20
1ST LARGEST	73.0	106	1956.0	20	1675.0	102	1607.0	31
THE MEAN VALUE	55.17		1769.28		1516.54		1451.22	
STD. DEVIATION	6.70		72.21		60.80		59.34	
COEF/VARIATION	12.15		4.08		4.01		4.09	
''TOP''	.33		.41		.28		.35	
''BOT''	.19		1.44		.37		.47	
VETA ONE	.22		-.74		.25		.14	
VETA TWO	2.67		→7.08←		3.01		3.03	
(N-20)-AVG EST	55.04		1770.39		1515.93		1450.88	
(N-20)-S.D.EST	6.83		66.83		60.52		59.15	
PCT DIFF/MEANS	2.		-2.		1.		1.	
PCT DIF/ST DVS	-2.		8.		0.		0.	
SIZE OF SAMPLE	146		148		148		148	

pair of related variables, followed by a comparison of the "actual" values with their regression estimates. When the differences between these values exceed a preassigned criterion (expressed in terms of the regression equation's standard error of estimate), the program reports this fact, together with a variety of relevant information. For example, we may establish an editing combination of stature, cervicale height and tragion height. Each variable will be estimated from a multiple regression equation calculated from the other two variables. When the estimated value deviates from the recorded value by the equivalent of, say, 3.5 standard errors of estimate, the discrepant values are printed out along with additional information regarding that particular subject. While either the XVAL or EDIT program can be used without the other, they have been developed as complementary procedures and are far more effective when combined than they are when used separately.

The methods and computer routines developed for this process have been described in complete detail in Editing Procedure for Anthropometric Survey Data, an AMRL technical report, prepared by Kikta and Churchill (1978). The point we wish to make here is that, prior to inclusion into the data bank, all data receive a comparable level of scrutiny using identical procedures. Once the data have been examined, basic statistical outputs are prepared. These include the standard descriptive statistics for each variable: mean, standard deviation, the coefficient of variation, measures of skewness and kurtosis and the percentile values. There are a number of ways to calculate percentile values and each survey may have been reported using a slightly different method of computation. We recompute the percentile values in a standard manner to enhance comparison between percentile values among the surveys.

A data bank computer tape is then prepared. The format of the tapes has been established to make them as self-contained as possible. Each tape includes a brief history of the survey; the name of any appropriate publications describing the survey; coding for non-numerical values, variable names, ranges and working constants, the data, and the formats and constants needed to read and use the tapes. The tape format has been described by Churchill et al. (1977).

Periodically, the data from the data bank are sorted by measurement and tabulated in a data book. While these books have not been published, they are similar in form to the tables we published in the National Aeronautics and Space Administration (NASA) Anthropometric Source Book, Volume II (1978). Such a tabulation permits the rapid scanning of the descriptive statistics for a variable of interest for all the surveys in which this variable was measured. It often requires a considerable effort to identify how the measurement was made and when it is comparable in measuring technique with other variables so labeled. Chest girth or circumference, for instance, can be measured at several levels but even when taken at the same level can be measured at maximum inspiration or expiration or at mid-point of shallow respiration. Therefore, in the data book, a measurement such as this may be listed in any one of several places.

Only after the survey data have been completely processed does the survey become incorporated into the data bank.

A valuable adjunct to the anthropometric data bank has been the development of numerous computer programs designed to analyze the data for specific purposes. These programs range from those used in the preparation and format of simple descriptive statistics, through single, multiple and stepwise correlations and regressions, to uni- and bivariate sizing analyses. Additional programs are available to display the data in a variety of ways. Such graphics include single and double bivariate tables, regression bands, bivariate ellipses, and others (Table 3 and Figure 1). As the data are identically formatted, the programs can be used for any survey by changing a few header cards. These programs have been written or adapted specifically for anthropometric data but can be used with other data sets such as moments of inertia or strength scores with but minor modifications.

While the analysis of the survey data is normally directed toward a population or subpopulation represented by that particular survey, it is also possible to combine and manipulate data for application to populations which have not been measured. In a recent study we were interested in preparing a sizing analysis for Navy women's clothing. No anthropometric data exist for U.S. Navy women, but recent data were available for both U.S. Air Force women (Clauser et al., 1972) and U.S. Army women (Churchill et al., 1977). A comparison of the data from these two surveys indicated a remarkable degree of similarity in terms of both mean values as well as in their variance. Approximately 45 clothing dimensions were determined to have been measured by similar techniques thus making it possible to pool the data. In this manner, we were essentially able to double the overall sample size and increase the number of subjects in each size category for the analysis. Such an increase in sample size is particularly important at the ends of the distribution of the sizing

Table 3. A sample bivariate frequency table (1967 USAF)

BUTTOCK-KNEE LGTH(IN)	SITTING HEIGHT(IN)										
	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0	40.0	41.0	TOTAL
27.5					1		1				2
27.0					4	4	3	1			12
26.5						6	8	9			23
26.0			1	1	4	17	17	9	2		51
25.5			3	6	13	36	33	19	7	1	118
25.0			2	10	58	71	46	34	6	1	228
24.5			5	27	79	133	71	36	6		357
24.0			12	41	119	137	86	28	7		430
23.5		1	14	58	152	144	69	14			452
23.0		4	9	70	127	94	38	12	1	1	356
22.5	1	2	9	45	77	45	27	4			210
22.0		1	8	35	52	20	9	1			126
21.5			8	14	8	7					37
21.0			3	2	5	1					11
20.5			1	2	4						7
TOTAL	1	8	75	311	703	715	408	167	29	3	2420

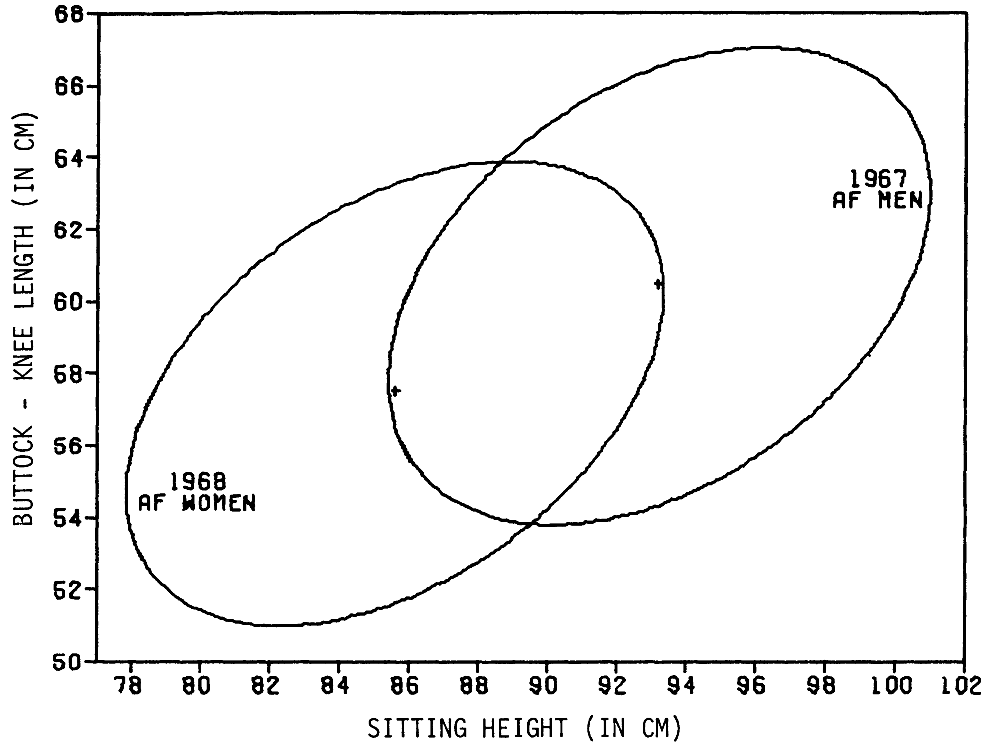

Fig. 4. A 95% probability ellipse.

dimensions. The results of this analysis have been reported in McConville et al. (1979).

In another recent study, we were concerned with the size and proportions of individuals at the two tails of the height-weight distribution. By definition, these subsets were individuals less than the 10th percentile value or greater than the 90th percentile in both stature and weight. By combining data from samples, we were able to make the subsets sufficiently large to provide confidence in the results. Again, the organization of the AFAMRL data bank makes such studies, if not simple, at least feasible.

The broadly based anthropometric data secured from military populations which now exist in functional form in the AFAMRL data bank can be successfully applied to a great number of nonmilitary design problems. By drawing samples from the data bank matched to specific body size characteristics of the civilian population, as revealed by the Health Examination Survey and the Health and Nutrition Examination Survey, the distribution of values of various anthropometric variables required to solve many ergonomic problems can be reliably determined. In addition, with but limited data on most civilian design samples, regression techniques permit us to estimate with known levels of confidence the distribution of values for most body size variables of interest.

We are now in the process of just such an analysis for nuclear power control room operators and maintenance personnel. A questionnaire survey for age, height and weight of such personnel has been completed. From these data we shall develop from the AFAMRL data bank matched samples for analysis. We plan to validate the results of this analysis by the conduct of a mini-survey of this group during the coming year.

The AFAMRL anthropometric data bank as presently constituted, then, provides a comprehensive and reliable data base for the continuing analysis and understanding of body size variability. While its users, to date, have been largely from military organizations and government agencies, such as NASA, National Highway Traffic and Safety Administration (NHTSA), and Federal Aviation Administration (FAA), we believe that this facility, with continuous development and expansion has unlimited potential as a valuable resource for designers and engineers in the civilian sector as well.

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Session II
Anthropometric Data Bases

PRESENT AND FUTURE NEEDS FOR ANTHROPOMETRIC DATA BASES

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1. INTRODUCTION

Different populations differ anthropometrically. Although it is a simple matter to determine whether or not such differences are statistically significant, what we really wish to know is whether or not these differences are of practical significance for human factors applications. While for some design problems relatively small differences in a single body dimension or physical characteristic may be critical, in other design areas much larger anthropometric differences may be easily accommodated with little or no difficulty. The questions to be answered then, are which specific measurements are needed, and on which populations or sub-populations. These decisions must be based upon a thorough assessment of all likely uses to which the anthropometric data might be put.

Many of the specific needs for anthropometric data in human factors engineering are based on past and present experience, and can be explicitly defined. In response to these needs, many data have been obtained, and are currently available on selected populations. Some of these groups have been described anthropometrically in great detail, while others have been described much less completely. Still other populations are virtually unknown anthropometrically. Clearly, the latter two categories need a more complete anthropometric description of those measurements known to be most useful for the solution of basic design problems in human factors engineering. In addition, consideration must be given to the advisability of obtaining and presenting more detailed data on any population to deal with any more specific, and perhaps unusual, design needs, that might be peculiar to that group. Finally, it is necessary to anticipate future needs for all populations based upon both changing design requirements for various kinds of equipment or environments, as well as upon the biological changes known to occur over time in individuals and populations, e.g. secular changes.

Given, first of all, the known range of anthropometric variability of human populations, and secondly, the very diverse range of human factors design areas to which anthropometric data are currently applied, or potentially could be applied, it can be seen that our anthropometric data base will need to be quite extensive both in terms of populations represented, and individual measurements presented.

In order properly to evaluate our present and future needs for an anthropometric data base, it will be useful, first of all, to have some understanding of why different populations differ anthropometrically. This will enable us to ensure that all of those factors known to cause variability in human physical characteristics have been adequately accounted for in the data selection process. Once these factors are known, we can determine which specific populations, subpopulations, or specialized subgroups need to be represented in our data base. The next step is to determine which kinds of anthropometric data should be included, e.g. static, dynamic, biomechanical, etc., followed by the selection of individual dimensions and measurements. Finally, we will need to determine the best means of obtaining these data, as well as the most effective means of presenting the data for optimal utilization.

It should be emphasized, however, that what might be considered as even a minimal, ideal, anthropometric data base may by no means coincide with existing data, and as we project for future needs, additional elements of complexity and uncertainty are added. Further, decisions as to the inclusions to or exclusions from such a data base could vary widely depending upon the interests of those making the determinations. What is needed is an objective view of the problem that would encompass all, or at least most, of the more basic, fundamental needs of users of anthropometric data, plus as many of the more specialized, even though sometimes obscure, needs as it may be practicable also to include.

2. SOURCES OF ANTHROPOMETRIC DIFFERENTIATION

Many different factors contribute to anthropometric variability. Some of the more important of these are biological in nature and intrinsic to the individual, while others are primarily environmental and can thus be considered as extrinsic. Still other factors relate to the procedures used in obtaining and processing the data. Each of these variables contribute to a greater or lesser extent to the anthropometric characteristics of the individual, and ultimately to the anthropometric distinctiveness of different populations.

Of the biological variables affecting human physical characteristics, some of the more important are genetic in nature. These include sex, always a factor influencing physical differentiation. Taking the United States as an example, we find that on the average men are about 13 cm taller and 13 kg heavier than women (Stoudt et al., 1965; Abraham et al., 1979). Other body dimensions tend to vary correspondingly, with men almost always having the larger absolute measurements. Exceptions are hip breadths and circumferences, and thigh circumferences, where women have the larger average measurements. Body proportions also vary by sex. Men have arms and legs not only absolutely longer than women, but also longer relative to stature and sitting height (Damon et al., 1966).

Anthropometric distinctiveness can also result from the common genetic backgrounds possessed by members of the same race, ethnic group, national population, or geographic region or subregion. World-wide, the variability of anthropometrically distinct groups is great indeed. Looking at international differences, when "large" populations i.e., North Americans or Northwest Europeans are compared with "small" populations, i.e., Southeast Asians, average stature and weight differences can be the order of 14 cm and 27 kg. If 95th percentile Americans were compared with 5th percentile Southeast Asians, the differences become much more extreme, or very roughly double the above values. (Churchill et al., 1971; White, 1964). Other ethnic or geographic differences are less extreme but still often of considerable practical significance.

Age is also one of the more obvious factors that differentiates people in terms of body size. The year-to-year changes that take place as part of the growth and development process are reasonably well documented, at least as far as a few basic anthropometric indicators and other selected dimensions are concerned. See, for example, Snyder et al., (1975) and Hamill et al., (1977). Where children must be accommodated by a given design as well as adults, anthropometric variability can easily result in a two-fold difference-or more. Age changes less well known are those that take place in adults during the normal aging process, more especially the sometimes rather marked changes in body size and capabilities that occur during senescence (Friedlander et al., 1977; Damon and Stoudt, 1963).

Another basic biological variable, though also clearly influenced in part by environmental factors, is the health of the individual, as affected by diet, physical activity and medical care. Malnutrition, undernutrition, and overnutrion change body size in obvious ways. Dieting or "weight-watching", and overeating can produce significant anthropometric changes in short time periods. Physical activity and exercise, or the lack of it, produce changes in weight and measurements involving muscle tissue and fat. The presence or absence, type and quality, of medical care during infectious and chronic disease is also reflected in human morphology. Again, the physically handicapped present distinct anthropometric subgroups.

Environmental variables affecting human body size and capabilities can be classified as either primarily physical or socio-cultural. The former includes climate and altitude, and the effects of gravity and weightlessness. As an example, stature typically increases by a full 5 cm in the weightlessness of space flight, almost all of the change taking place in the trunk and neck caused by a lengthening of the spinal column (Thornton, 1978). As for the socio-cultural environment, various aspects have repeatedly been shown to be associated with anthropometric differentiation. Occupation is one of the more obvious; civilians differ from the military, and within each of these major groups, specific occupations may differ from each other. Other factors include social status, economic status, and educational level, though clearly, complex interrelationships exist between many of these socio-cultural variables. For a more detailed overview of the biological and environmental factors affecting human body size, see Annis (1978).

In terms of future, as opposed to present, needs for an anthropometric data base, special attention must be paid to the secular increases in body size that have been documented on a world-wide basis in recent years. Most current estimates for stature increases in the United States range from about 0.8 to 1.3 cm per decade (Stoudt, 1979), though some estimates based on military populations are lower. As stature increases, so do most other body dimensions. Although there is some indication that this increase may be ending, at least among more socio-economically favored groups, this does mean that present day anthropometric data may not necessarily accurately describe future generations, thus necessitating remeasurement of the same population over different time periods.

A final area to be considered in assessing anthropometric differentiation between populations relates to the procedures and techniques used to obtain this information. An initial question concerns sampling and subject selection, i.e., who gets included in, or excluded from, whether by intent or chance, any measured population. Truly random samples are difficult to obtain. All subjects must, after all, be volunteers. However, attention to the proper stratification of subjects based on consideration of the variables described above can produce reasonably representative samples. Where this is not done, random variation among small groups, or bias in subject selection, can result in anthropometrically distinct subgroups drawn from the same parent population.

Finally, the measuring techniques employed, the measuring instruments, the body position of the subjects, and the presence or absence of clothing or personal equipment can result in very significant anthropometric differences between groups. As but one example, while subjects have traditionally been measured unclothed for purposes of biological research and comparability between studies, special requirements for workspace design may necessitate the measurement of fully clothed and equipped subjects. As an alternative, specially determined increments or decrements for clothing and equipment can be added to, or subtracted from, nude body dimensions. Such issues raise the question of comparability of data between studies, and will sometimes restrict the applicability of given sets of data to only those special conditions under which they were taken. While there is reasonable standardization between most static anthropometric surveys, sources of potential differences must always be carefully examined. For other, more specialized studies, especially of dynamic or functional anthropometry, the possibilities of study uniqueness or lack of comparability are considerably greater.

In summary, the number and complexity of the factors described above, as well as their potential interactions, all contribute in different ways and in different magnitudes to anthropometric variability between populations. As a result, each of these distinct populations may require anthropometric description for human factors engineering purposes.

3. WHICH POPULATIONS NEED ANTHROPOMETRIC DESCRIPTION?

With a knowledge of those factors that either cause or are associated with differences in the physical characteristics of populations, it is possible to determine in advance which human groups are most likely to require detailed anthropometric description for the varied purposes of human factors engineering.

First of all, the above noted racial, and geographic differences make it incumbent upon us to have a wide representation from all areas of the world including individual countries as well as regional or ethnic groups within those countries.

Secondly, for all of the above populations, males and females must be described separately, though in some cases it may be desirable to have combined, general population data, as for example, for all vehicle drivers, or all users of a given product. In general, at the present time, females are less adequately described than are males.

Age differences are also obvious and would require a full representation in any anthropometric data base, though decisions must be made as to which age subgroups are required. Ideally children and adolescents should be measured at one year intervals, since between the ages of 1 and 16 years children gain very roughly 5-7 cm and 2-3 kg a year (Stoudt, et al., 1960), thus making each yearly age group anthropometrically distinct, though there is, of course, much overlap between the groups.

Adults must also be represented, both as a single group, and by at least 10 year age subgroups. The latter is desirable because of the changes in body size that take place as part of the normal aging process, e.g. increases in weight, followed by a decrease, accompanied by a small but consistent decline in height and many height-related dimensions (Stoudt et al., 1965). It is also most important that the elderly be represented. These may be arbitrarily, though conveniently, defined as those above 65 years of age. The sometimes very marked and significant changes that take place in body form as a result of senescence make it desirable to have this population represented by 5 year age subgroups. At present the elderly are very imperfectly described in terms of their physical characteristics and capabilities. In view of their very special needs, and of the fact that they are becoming an increasingly larger (numerically) proportion of our population, it is clear that they require our special attention.

Differences, sometimes substantial, between the body sizes of people in different occupations have been long noted, both in conventional wisdom and by scientific measurement. Truck drivers differ from policemen, laboratory workers from manual laborers, stewardesses from secretaries, etc. (Damon et al., 1966; Annis, 1978). Such differences may sometimes result from the self-selection of certain physical types into a given occupation, and/or sometimes from the causal effects of the occupation itself. Regardless of the cause, where such differences are found to be of practical significance for workspace or equipment design purposes, each occupational group will require separate, anthropometric coverage.

One broad, basic, occupational differentiation that is of very special importance, is that between civilians and the military. Civilians, almost universally, are much less well known anthropometrically than the military. For this reason it has sometimes been convenient to assume that military populations can be equated with civilians for anthropometric purposes. Military population, however, are selected groups, sometimes highly so. They are healthier than civilians and are generally in much better physical condition. In addition the upper and lower extremes of body size are eliminated. Their age range is substantially lower than that of adult civilians. All of these factors are associated with body size, with the result that military groups are consistently taller and larger, though usually lower in weight and weight-related dimensions per unit of height. For example, U.S. Air Force males are fully 4.1 cm taller but only 3.5 kg heavier than U.S. civilian males. And U.S. Air Force females are 2.1 cm taller, but 5.7 kg lighter than U.S. civilian females. (Churchill et al., 1977; Clauser et al., 1972; Stoudt et al., 1965). Clearly, we are dealing with very distinct populations, each with their own special characteristics and requirements. Much more and much better anthropometric data are needed on worldwide civilian populations.

Among civilians one distinct series of people requires special consideration. These are the physically handicapped, though the very wide variety of types of handicap make this group an especially challenging one to describe and deal with, whether from the point of view of prosthetics, or of the design of, or accomodation for, special equipment for their use.

Some of these above groups are currently described anthropometrically--though with varying degrees of completeness. Others are virtually unknown. The current state of the art in the availability of applied anthropometric data has been reviewed in two recent publications, one by White (1978) who has reviewed U.S. and worldwide sources of anthropometric data and included 105 references in his bibliography, and an annoted bibliography of 236 references in the field of applied anthropometry and biomechanics compiled by Laubach and his associates (1978) for the National Aeronautics and Space Administration.

4. WHICH MEASUREMENTS ARE NEEDED?

Applied anthropometric surveys are generally intended to obtain a series of measurements on some selected population which will have application to the solution of existing or envisioned design problems. The kinds of anthropometric data gathered in different surveys may therefore differ widely depending upon the intent of each study.

Traditionally, anthropometric data have been largely limited to the so-called static, or anatomic measurements of the human body, specifically heights, lengths, breadths, depths, circumferences and arcs, measured in either the standing and/or seated position. One recent source lists over 275 distinct static measurements. See Churchill et al., (1977). More recently, however, additional kinds of measurements have come to be included, such as dynamic measurements of human body movement, including arm and leg reaches, inertial properties of the human body and its segments, muscle strength, ranges of joint motion, and speed and accuracy of motion. All of these can properly be considered as falling under anthropometry, "the measurement of the human body and its parts and functional capacities." As such, the concept of an anthropometric data base must be expanded to include these additional types of information on human physical characteristics.

It is important to note that all measurements should be taken in surveys whose subject selection criteria and measuring techniques are either well standardized, or at least explicitly defined. Data from different studies should, insofar as possible, always be comparable, or where this is not the case, the reasons for the lack of comparability must be specified. One example of an existing, operational, anthropometric data base containing a variety of different measurements on different populations is that compiled by the U.S. Air Force's Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, Ohio. As of the beginning of 1980 this data bank contained anthropometric information from some 35 different studies of adults. These surveys include a preponderance of military populations, both U.S. and foreign, though with some representation from U.S. civilian populations. Both males and females are included. The numbers of anthropometric variables represented range from a few dozen in some studies to as many as 190 in a single U.S. Air Force study. The number of subjects measured ranges from a few hundred to as many as 25,000 in an older U.S. Army survey (Churchill et al., 1977).

5. METHODS OF OBTAINING AND PRESENTING THE DATA

Anthropometric data have traditionally been obtained through surveys--actual measurements taken on the human body with anthropometers, calipers, or other mechanical, or sometimes photographic, devices. Such data have usually been presented for applied purposes in terms of basic descriptive statistics, the mean and standard deviation, and a range of selected percentiles between perhaps the 1st and 99th. Additional statistics might include standard errors, measures of symmetry and kurtosis, coefficients of variation and coefficients of correlation.

Churchill has suggested, and rightly so, that massive surveys of thousands of subjects should no longer be necessary to obtain the needed anthropometric data. Rather, with the proper use of sampling and data gathering strategies, acceptable levels of accuracy can be obtained from random samples of 350, and from matched samples of many fewer subjects (Churchill, 1976). For the future it will also be important to have some means of predicting the value of any specific dimension or variable, when that dimension or variable is not available in directly measured form. Put most simply, such prediction methods would involve extrapolations or interpolation from existing measured, correlated, body dimensions or characteristics. Examples might be the prediction of: 1) sitting heights or eye heights from stature; 2) body lengths from other body lengths, breadth from other breadths, etc.; 3) changes in body dimensions with increasing or decreasing age; 4) female body dimensions from male body dimensions within the same population--given knowledge of certain basic relationships between male and female data. Or, more generally, the prediction of a battery of measurements for a given population from data describing more extensively measured, related populations, again where certain basic common dimensions and characteristics are known from each subgroup.

The success of such a process, as measured by the accuracy of the predicted dimensions, will depend upon the quantity and quality of the anthropometric data available, as well as upon a knowledge of the specific mechanism of action of each of the relevant variables affecting human morphology and function. An effective base should therefore contain as much detailed information on as many different kinds of human populations as is possible. In some cases, special limited surveys may be necessary to complete or fill in gaps in the anthropometric spectrum.

Finally, and most importantly, in dealing with anthropometric methods, attention should be directed to improving and/or developing new techniques for describing the human body, including, for example, three dimensional anthropometry, stereophotogrammetry, ultrasound, and holography. The latter approach especially, shows great promise for obtaining, storing, and processing a virtually limitless amount of retrievable information describing the human body, though a considerable amount of developmental work needs to be done before any such system could be operational.

6. CONCLUSION

The existing, overall, worldwide, anthropometric data base, though clearly adequate for some specialized purposes on some specialized populations, needs to be expanded to meet additional present needs, as well as an anticipated expansion of future needs. More anthropometric and biomechanical information is needed on a variety of different general populations, and specialized sub-populations. Mathematical modelling and the prediction of data from existing measurements should play an increasingly important role in the future, as will the development of new data gathering techniques.

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ANTHROPOMETRIC AND BIOMECHANICAL DATA ACQUISITION AND APPLICATION TO REHABILITATION ENGINEERING

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INTRODUCTION

It can be stated without fear of contradiction that, in the United States, severely disabled people have not been able to take their rightful place in American society. Opportunities in the vocational, educational, transportation and independent living areas have simply not been available to the severely physically disabled population. In 1972, a research effort was initiated in Wichita, Kansas, under the joint auspices of the Cerebral Palsy Research Foundation of Kansas, Inc., and the College of Engineering, Wichita State University, to attempt to correct this situation. In the researchers' minds, it is necessary to integrate a wide variety of programs into a service delivery system in order to respond to the needs of severely handicapped people to create a total life-style. A person's life should not be considered as a series of independent needs but as an integrated hierarchy of human aspirations.

In order to implement this research, it became necessary to quantify measures of the physical capabilities of handicapped persons. There is a dirth of anthropometric and biomechanical data related to handicapped people. The handicapped population served by this research effort is primarily cerebral palsied persons and those individuals who have suffered brain damage either through trauma or congenitally. It became painfully clear during the initial stages of the research that some sort of objective means of determining the residual capability of handicapped persons was needed. To respond to this need, the research project developed an apparatus called the AMI (Available Motions Inventory). It is designed to determine, in objective rather than subjective terms, the physical capability of handicapped persons in order that they may be productive in vocational, educational, transportation, and independent living environments.

The purpose of this paper is to expand on this theme to acquaint the reader with the Available Motions Inventory apparatus. It should be realized that the research project is a pragmatic one. The results of the research are applied on an everyday basis to the problems confronting handicapped people. The basis of the research is to place "real, live, flesh and blood human beings" on the job, in the classroom, or in their own apartment. Therefore, the research is not theoretical but is practical and has application to a wide variety of barriers limiting the alternatives of handicapped persons. In many cases, it is felt that the research has theoretical implications, i.e., the study of the therapeutic effect of work. However, prior to the present time, the researchers have been more involved with the development of service delivery systems for severely handicapped people rather than theoretical laboratory investigation.

METHODS

Rationale

It is fairly common practice for broad classifications established by medical diagnosis to be carried over into rehabilitation and job placement efforts. It is immediately obvious that these categories provide a qualitative description of the physical disability. These descriptions are useful in the medical and therapeutic treatment where there is a need to identify the pathology or disability for purposes of correction. In finding employment for the handicapped, however, a quantitative measure of a person's physical capabilities is essential. This is the basis for the Available Motions Inventory (AMI) as developed at Wichita State University by what is now designated as the Rehabilitation Engineering Center under the sponsorship of the Cerebral Palsy Research Foundation of Kansas.

The Available Motions Inventory samples a variety of physical tasks which are typically required in performing jobs in an industrial setting.

Limiting evaluation items to industrially related tasks is not meant to preclude expansion of the system to other job areas. Naturally, some overlap of tasks will occur so that many of the industrially related evaluative devices as presently developed will serve for other job areas as well.

Evaluation Hardware

The devices which have been devised to evaluate a client's physical capabilities fall into two main categories: controls and assembly. The names given to the controls and assembly categories are not meant to imply that the information yielded by the devices in these categories applies exclusively to machine control or to assembly-job capabilities respectively. The information provided

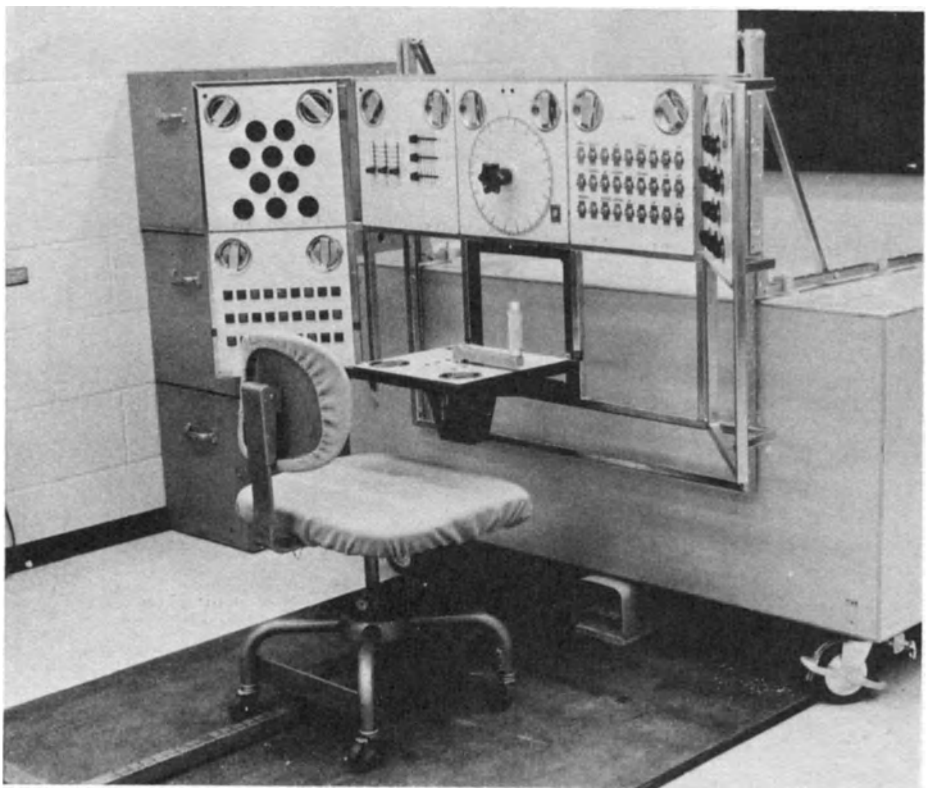

FIGURE 1. AMI Device

by either can have significance for both production and assembly types of industrial jobs. A modular design was adopted for these devices as shown in Figure 1. This concept allows for ready testing at various positions relative to the client. The modules were fabricated to permit evaluation of capability in using one or more machine controls. The controls included on the modules were selected on the basis that they constitute a representative sample of typical machine controls found in industry. The base of each module is a one foot square aluminum panel. The machine control is on the front face of the plate and the mechanical and electronic hardware used in measuring the client's response is in the rear.

Capability Evaluation

The client's capability to perform industrial tasks is evaluated by the analysis of scores recorded on seventy-one subtests. These are divided into six groups to facilitate record keeping and data processing. A listing of these groups and their subtests are as follows:

Switches:	Slide, Rotary, Detent, Toggle, Pushbutton
Settings:	Crank, Balance Crank, Handknob
Rate:	Crank, Balance Crank, Handknob, Footpedal
Strength:	Pinch, Grip, Applied Torque, Applied Force
Assembly:	Plates, Spacers, Flat Washers, Lock Washers, Hex Nuts, Grommets, Positioning, Bolts, Drill
Reaction:	Hand

A brief description of experimental procedures is given below.

Equipment Set-Up and Data Acquisition

A. Record by checking the appropriate box whether the client is ambulatory or is confined to a wheelchair.

B. Popliteal height

1. Seat the client in any standard chair so that the client's lower legs are perpendicular to the floor with several inches clearance between the back of the lower leg and the front lip of the chair. The feet should be placed flat on the floor and the client should be asked to sit erect.

2. Measure and record the client's left and right popliteal height. If the client's lower legs are significantly different lengths, measure and record the longer of the two. Make a note on the Record in the case of significantly different lengths.

3. Place the test chair or client's wheelchair centered laterally in front of the AMI frame. If an adjustable height chair is available, adjust the seat height (front edge) equal to or slightly less than popliteal height.

C. Seated elbow height

1. With the subject sitting erectly in chair or wheelchair, measure and record the right seated elbow height. For this measurement, the arm is flexed at the elbow to 90° and is positioned so that the upper arm is perpendicular to the floor. The distance to be measured is the distance from the floor to the lower surface of the ulna at the elbow joint.

2. Repeat for left elbow height.

D. Determine and record the client's preferred hand. This may be done by observation during the test if the client is unable to respond to such a question. If the client shows no preference, enter "NONE" in the appropriate space.

Reach

A. Horizontal functional reach

1. Set the vertical position of the AMI frame so that the top surface of the horizontal frame is equal to or slightly above the average of the two measured elbow heights. (If the left and right elbow heights are different by more than two inches, different AMI frame height adjustments must be made for all subsequent left and right handed measurements.)

Instrumentation

The data acquisition scheme for the AMI is divided into two main categories. Data for pinch, grip, switch settings, dial settings, and pushbutton operation is obtained by visual observation of the pinch and grip guages and by visual observation of the dial and switch settings.

Data for the tests involving the measurement of torque utilize strain guages with appropriate electronic instrumentation which converts the strain to voltage which is read by means of a digital voltmeter.

Data involving the counting of either rotations or hits and misses as in the case of the drill simulator is obtained by means of electronic counters. In the case of the rotation counter, the scheme also includes a ten-second clock which is connected such that once the handwheel is moved such that a single pulse is obtained from the photo-interrupter, a ten-second period is begun. The display unit will then indicate the number of revolutions of the handwheel that takes place within ten seconds of the initial interrupter pulse. Timing of intervals required to achieve switch settings, dial settings, and assembly tasks is performed by the evaluator's observation of the activity and use of a standard stop-watch.

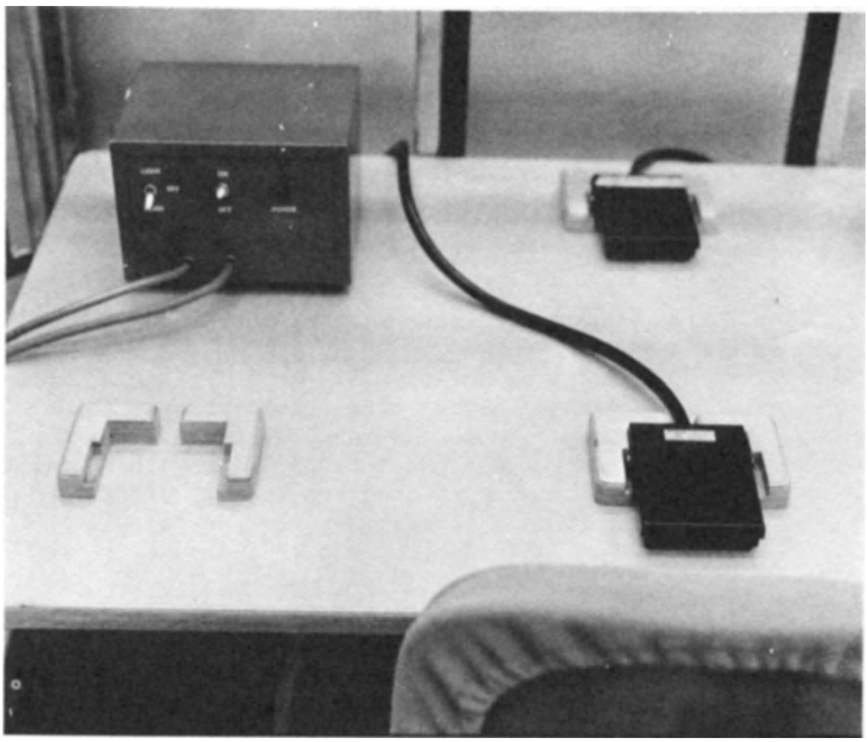

FIGURE 2. Reaction Reach Timing Device

Timing of an individual's reaction time and time required to reach a given distance supplements the timed items of the Available Motions Inventory; it is particularly useful in analyzing the activities required to achieve the assembly items.

The test client's hand rests on a pedal switch. The client is directed to respond to an auditory stimulus, a buzzer, by releasing the pedal switch, reaching to a similar switch and depressing the second switch. Time required to release the first switch as well as the time required to reach the second switch and depress it are measured electronically in decimal seconds. These measured increments of time are called reaction time and reach time, respectively.

Motions started from a position directly in front of the seated client reaching to the side and a more remote position directly in front are timed with each hand as well as these same positions in reverse order. The former items sample extension movements; the latter items sample flexion movements. These two classes of neuromuscular activity may be distinctively different in a handicapped person.

Data evaluation involves the comparison of the test client's mean score on each subtest with a set of standard data. The standard data is the mean score achieved by a group of thirty able-bodied persons on the various subtests. This provides a direct comparison of the individual test client to a standard score. Standard deviation refers to the variability of performance achieved by the client on repeated trials of a subtest. Z-score refers to the number of standard deviations difference between the client's mean score and the standard's mean score. A positive Z-score indicates performance better than the standards group. A Z-score ranging from -3.00 to zero would indicate that the client could perform that class of tasks with no engineering modifications to the work environment. Negative Z-scores larger than -3.00 would indicate that a client could not perform such tasks without engineering adaptive devices. See Appendix for samples of computer printouts.

RESULTS AND CONCLUSTIONS

The AMI evaluation has been applied to the adaptation and placement of approximately 100 clients. Both actual results of placements and studies to verify the AMI have indicated that it is, in fact, a useful tool for that which it was designed. An example of one of the studies involved the ranking of the expected efficiency of ten clients based upon the motion order analysis of a one-handed box folding operation. When the ten clients were actually assigned the task, eight of the ten predicted ranks were correct. The two in error were not significantly misranked.

AMI results were the sole basis for handicapped employee placement and adaptation for a production line producing license tags for the State of Kansas. This production line involved ten severely physically disabled employees. The minimum production rate acceptable exceeded 1500 units per day. All placements and adaptations were successful with the exception of one individual due to emotional rather than physical problems.

AVAILABLE MOTIONS INVENTORY

NAME:
CLIENT#: 1021
DATE OF BIRTH: 09-18-58
SEX: MALE
DATE OF PROCEDURE: 08-05-80
SET UP: WHEELCHAIR

POPLITEAL HEIGHT:	52.0
SEATED ELBOW HEIGHT: (LEFT)	68.8
SEATED ELBOW HEIGHT: (RIGHT)	71.2
HORIZONTAL FUNCTIONAL REACH: (LEFT)	26.0
HORIZONTAL FUNCTIONAL REACH: (RIGHT)	26.0

GROUP	SUBTESTS	LEFT HAND MEAN	LEFT HAND Z-SCORES	STANDARDS	RIGHT HAND MEAN	RIGHT HAND Z-SCORES
SWITCHES				ACT-PER-MIN		
CLH	SLIDE	16.667	-1.994	46.8620	16.129	-2.030
CLH	ROTARY	18.315	-3.443	42.7510	19.608	-3.261
CLH	DETENT	17.730	-4.485	44.2600	14.493	-5.033
CLH	TOGGLE	50.847	-2.372	107.3320	61.224	-1.936
CLH	PUSHBTN	57.692	-2.858	121.4400	65.217	-2.521
SLH	SLIDE	28.571	-1.522	51.0430	20.000	-2.102
SLH	PUSHBTN	44.118	-3.329	117.2030	53.571	-2.899
CLV	SLIDE	18.182	-2.522	53.4910	30.303	-1.656
CLV	ROTARY	17.182	-3.071	51.0540	17.045	-3.083
CLV	DETENT	11.494	-3.967	52.6970	17.007	-3.436
CLV	TOGGLE	43.478	-3.963	118.0720	63.830	-2.882
CLV	PUSHBTN	41.667	-3.394	116.7560	45.455	-3.223
CUV	SLIDE	27.778	-1.940	61.5700	20.000	-2.386
CUV	ROTARY	21.368	-2.029	53.3360	23.810	-1.874
CUV	DETENT	15.873	-3.059	52.9280	18.727	-2.823
CUV	TOGGLE	56.604	-3.643	121.8320	71.429	-2.815
CUV	PUSHBTN	53.571	-2.902	130.4560	60.000	-2.661
SUV	ROTARY	24.155	-3.785	52.9140	24.155	-3.785
SUV	DETENT	17.007	-4.307	52.6130	12.626	-4.837
SUV	TOGGLE	50.00	-4.014	120.4530	42.857	-4.421
SETTINGS				ACT-PER-MIN		
CLH	CRANK	19.391	-1.249	36.2470	22.046	-1.052
CLH	BAL CRK	9.081	-1.649	28.9120	10.249	-1.552
CLH	HANDKNOB	7.654	-3.292	35.9080	18.287	-2.053
SLH	BAL CRK	5.148	-1.994	26.9230	10.229	-1.529
SLH	HANDKNOB	8.175	-2.531	36.1900	17.813	-1.660
CLV	CRANK	10.017	-1.956	34.1130	18.003	-1.308
CLV	BAL CRK	15.112	-0.987	31.0410	18.383	-0.784
CLV	HANDKNOB	14.506	-2.125	38.2940	25.926	-1.105

GROUP	SUBTESTS	MEAN	Z-SCORES	STANDARDS	MEAN	Z-SCORES
	CUV CRANK	21.296	-0.801	33.6470	11.739	-1.105
	CUV BAL CRK	9.613	-1.640	27.8570	17.569	-0.925
	CUV HANDKNOB	13.064	-2.237	41.2870	18.981	-1.768
	SUV CRANK	13.131	-1.304	32.7850	17.551	-1.011
	SUV HANDKNOB	14.696	-1.489	40.9940	19.665	-1.208
RATE				ACT-PER-MIN		
	CLH CRANK	54.000	-2.982	167.3990	66.000	-2.666
	CLH BAL CRK	66.000	-3.582	184.5590	81.000	-3.129
	CLH HANDKNOB	9.000	-2.428	62.5190	15.000	-2.156
	SLH BAL CRK	63.000	-2.980	184.2590	60.000	-3.054
	SLH HANDKNOB	9.000	-2.466	63.6590	15.000	-2.195
	CLV CRANK	78.000	-3.344	201.9590	90.000	-3.020
	CLV BAL CRK	72.000	-3.254	191.1590	96.000	-2.598
	CLV HANDKNOB	12.000	-3.588	64.7390	12.000	-3.588
	CUV CRANK	72.000	-2.941	177.9590	66.000	-3.913
	CUV HANDKNOB	9.000	-2.976	60.5390	12.000	-2.802
	SUV CRANK	69.000	-3.677	188.6390	84.000	-3.216
	SUV HANDKNOB	9.000	-3.500	71.0990	9.000	-3.500
	FOOTSWITCH	0.000	-10.000	195.4870	0.000	-10.000
STRENGTH				POUNDS		
	PINCH	18.250	-0.886	24.2250	17.250	-1.035
	GRIP	32.000	-2.088	84.6190	53.500	-1.235
	ATQ SLP	0.000	-10.000	126.2040	32.432	-2.174
	ATQ PRO	97.625	-0.868	162.2260	103.583	-0.788
	AFV UP	37.710	-0.476	46.7310	29.006	-0.935
	AFV DOWN	13.876	-2.098	47.3180	22.697	-1.544
	AFL LATL	14.402	-1.412	39.2870	16.271	-1.306
	AFL MEDL	9.728	-1.533	45.5730	25.734	-0.848
	AFT PUSH	21.704	-1.608	61.7170	23.456	-1.538
	AFT PULL	46.764	-0.992	72.1960	51.613	-0.803
ASSEMBLY				ACT-PER-MIN		
	PLATES	11.494	-3.287	28.3840	9.868	-3.604
	SPACERS	13.228	-6.042	38.1570	14.245	-5.795
	FLAT WASHERS	13.228	-4.997	37.9980	19.380	-3.756
	LOCK WASHERS	13.123	-5.055	29.0870	14.124	-4.738
	HEX NUTS	6.859	-4.483	20.4900	8.418	-3.970
	GROMMETS	14.245	-4.016	30.0710	15.723	-3.641
	POSITIONING	3.704	-3.258	8.0370	4.352	-2.771
	BOLTS	3.978	-4.439	19.3240	4.386	-4.321
	DRILL	24.217	-3.972	67.4170	39.308	-2.584
REACTION				ACT-PER-MIN		
	LATERAL R	72.727	-1.617	277.8711	184.615	-0.735
	TRANSVERSE R	80.537	-1.540	217.1660	80.537	-1.540
	LATERAL M	36.331	-1.966	255.3670	108.108	-1.712
	TRANSVERSE M	82.192	-1.254	251.5830	93.750	-1.169
	REACTN TIME	84.507	-2.187	131.1080	85.562	-2.137

It has been determined that results of the AMI have been useful in selecting jobs that handicapped clients could perform with the minimum adaptation. In addition, AMI results provide insight into the most appropriate adaptive devices and the extent to which a client must be adapted in order to perform industrial tasks with the required productivity.

The AMI is the most effective technique in measuring the gross and fine motor abilities of the severely physically handicapped; hence it is most effective in job design and modification.

Upon comparing all the tests used for evaluating physically handicapped clients the advantages of the AMI over work samples become apparent. These are given below:

1. The AMI takes a much lesser amount of processing time as compared to work sample testing, e.g., the testing time for the AMI is three to four hours (on an average) versus six to seven days for work sample tests. This shorter testing time reduces instruction costs and client fatigue.

2. From the very outset, the AMI has been designed for the severely physically handicapped, i.e., the various task parameters have been selected keeping physical disabilities (especially cerebral palsied individuals) in mind. The "work sample" tests were mainly designed for the mentally handicapped or for the less severely physically handicapped, and have been recently adapted for the severely physically disabled. In fact these tests have been normed on mentally or slightly physically handicapped population, thus making a comparative analysis invalid.

3. The administrator of the other tests has to be very experienced in order to rate his clients. A scale of three or five points (used in a number of work sample tests) is inadequate. For severely physically handicapped individuals with large variances a larger scale (a spread of ten points) is almost a must for appropriate representation. Also, the scale mentioned is subjective.

   In the case of the AMI, the administrator has to be experienced only in the logistics of experimentation (the procedure and equipment are pre-determined and standardized). The results are computed and interpreted thereafter. The scale is objective and hence more reliable.

4. The AMI comprises work samples and anthropometric data. This has the advantage of standardized information in small building blocks. The anthropometric data can be interpreted as needed. It can be used to predict performance in a large number of industrial jobs (the smaller the building blocks the more flexible and accurate the various combinations).

5. In the case of work samples, the actual job comprises a number of tasks with varied complexities. If an individual does poorly in any one of these tasks his score may drop below acceptable limits, even though the other tasks were performed well. Thus, the individual is considered incapable of performing the work samples, and subsequently a particular job, even though a minor modification would have corrected the error.

With the AMI, the anthropometric data is analyzed before job compatibility is evaluated. If performance in a particular mode is low, that is duly considered in job design modification.

One aspect of future research will be devoted to the classification of the tests which provide the greatest predictive capability relating to individual efficiency (or relate to the client in general), the work space layout and the particular task to be performed. Considerable advantage would be derived from test variables that were so classified.

ANTHROPOMETRY OF MENTALLY AND PHYSICALLY HANDICAPPED PERSONS EMPLOYED IN PRODUCTIVE OCCUPATIONS

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INTRODUCTION

Physically and mentally handicapped persons are being increasingly employed in the organized industrial sectors. A number of factors are responsible for this situation. On one hand, the governmental requirement on equal employment opportunities is opening the doors for handicapped persons to be productively employed. On the other hand, the management is also beginning to realize that handicapped workers form a very stable and highly motivated employee group. It is also claimed by social work professionals that the productive occupation by itself results in a certain therapeutic effect and hence the "main streaming" must be considered desirable to the individual. The end result of all this is the lessened responsibility of the society in general to care for these persons by institutionilizing them.

DESCRIPTION OF THE STUDY

The industrial engineering department at The University of Texas at Arlington has been involved in a project of providing engineering and technical services to Goodwill Industries of Dallas and Easter Seal Sheltered Workshops of Fort Worth with the support of Texas Rehabilitation Commission. One part of the project concerns making recommendations for ergonomically acceptable workstations, tools, equipment, job design etc. The anthropometric and biomechanics data needed to make such recommendations was found to be scarcely available in the literature. Therefore a study was initiated to collect such data. This paper describes the part of the study dealing with selected anthropometric measurements.

Table I. STATISTICAL SUMMARY OF SELECTED ANTHROPOMETRIC MEASUREMENTS

		MALE N = 26		FEMALE N = 33	
		$\bar{X}$	σ	$\bar{X}$	σ
1. Age	yrs.	32.46	14.87	33.60	12.57
2. Weight	kgs.	73.31	15.21	63.74	16.82
3. Height	cms.	169.73	8.08	159.00	8.17
4. Acromiale Height, Rt.	cms.	140.93	7.87	131.54	7.92
5. Iliocristale Height, Rt.	cms.	102.40	7.46	96.79	6.72
6. Tibiale Height, Rt.	cms.	43.20	3.35	39.53	3.17
7. Hip Breadth	cms.	34.83	3.21	35.74	4.32
8. Popliteal Height, Rt.	cms.	44.13	3.18	39.74	2.95
9. Sitting Height	cms.	87.05	3.99	83.78	3.86
10. Sitting Shoulder Ht., Rt.	cms.	58.61	3.60	56.25	3.35
11. Sitting Knee Height, Rt.	cms.	54.56	2.91	49.86	3.41
12. Acro.-Elbow Length, Rt.	cms.	36.35	2.60	33.70	2.72
13. Forearm Length, Rt.	cms.	47.30	2.80	42.96	2.68
14. Hand Length, Rt.	cms.	18.31	1.29	17.22	1.38
15. Thumb Tip Reach, Rt.	cms.	66.43	3.91	61.19	4.63

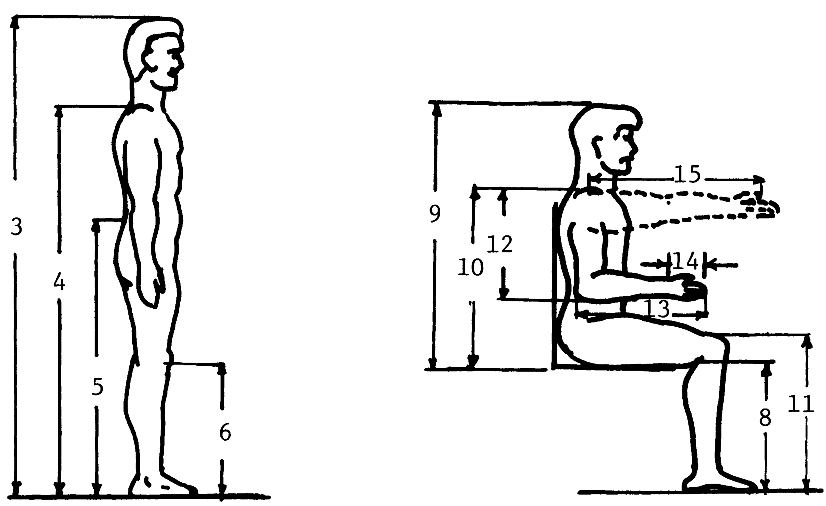

Figure 1. Diagrams representing the anthropometric measurements as numbered in the table above.

The study covered more than 80 subjects of various types of handicaps. A total of 32 different body size measurements and age and sex information were obtained. Body size measurements were obtained on right side as well as left side of the individual as in a number of cases a pronounded difference could be observed. Not all the 32 measurements could be obtained in all cases due to practical difficulties associated with the specific handicaps; for example, no standing measurements were obtained on wheelchair bound persons. Table I presents the statistical summary of certain selected anthropometric dimensions of a group of 59 subjects. This group consisted of 26 males and 33 females on whom all the measurements were obtained. The measurements are represented in figure 1. The rehabilitation agencies classified 45 of the 59 subjects as primarily mentally handicapped and the others physically handicapped. The mentally handicapped persons also had mild to severe levels of physical handicaps. Mental handicaps included cases of mental retardation, mental illness, brain damage, etc. The physically handicapped individuals included cases of multiple sclerosis, deaf, stroke, advanced age, etc. Age wise, this sample consisted of 35 person of 30 years and younger and the rest over 30 years.

DISCUSSION

For various social, economic and legal reasons more and more of handicapped persons are offered employment in "sheltered" workshops and in regularly established jobs. However, very little is being done in terms of workstation redesign, task modifications, etc. so as to make the job fit the handicapped person. Thus the handicapped worker either survives on the job at a very low productive efficiency or quits and in the later case, is classified as "unemployable". Workstation designs and task conditions based on anthropometry and biomechanics of the handicapped worker is a prerequisite to properly evaluate the individual's vocational performance.

The anthropometry and biomechanics data needed by ergonomists in order to better design the workstation, the task, and the tools and so on is not necessarily the same as that needed by physical therapists and clinicians in their work. Most of whatever little data available in the extant literature is from practitioners in the above areas rather than from ergonomists.

Another point that needs to be given some thought is whether the 'standard' procedures and techniques normally followed in making anthropometric surveys of able bodied persons are suitable in the cases of handicapped persons also. Communicating even simple subjects with certain types of mentally handicapped person in itself is not an easy task. To make the handicapped person understand very specific instructions and cooperate during the measurement requires special skill on the part of the investigators. Palpilation of body reference points without upsetting the individual has not been found to be an easy task. Again, specialized measurement techniques need to be developed for certain types of handicapped individuals such as wheelchair bound persons.

It was also observed that in a number of cases there existed a pronounced difference between the right and left side measurements. Typically, victims of stroke, paralysis, multiple sclerosis, brain damage and similar conditions exhibited such tendencies. While the individual measurements clearly show this effect, the same is lost when the information on many individuals is pooled for statistical purposes.

Very similar and other difficulties may also be encountered during the collection of biomechanics information of the handicapped individuals. It is therefore felt that some modified approach for collection of anthropometric and biomechanics data of handicapped individuals needs to be developed. The approach may have to be tailor made for the specific investigation while maintaining certain common measurements for comparison purposes.

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PROGRESS AND PROSPECTS IN HUMAN BIOMETRY
EVOLUTION OF MEASUREMENT TECHNIQUES AND DATA HANDLING METHODS

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1. INTRODUCTION

Human biometry is concerned with morphological characteristics of the body, such as dimensions, masses, surfaces, volumes, inertial properties, etc., and the variations of these characteristics due to changes in the environment. Such changes occur through body growth and development, aging, seasonal biological rhythms, pathological conditions, nutritional conditions, and physical activities such as sports. Each of these conditions will affect morphology of the body, either in a so-called normal or pathological state.

Modern biometry goes beyond the context of medical or physiological conditions and considers new and artificial environments, as brought about by the design of equipment, or the effects of external conditions such as movements, shocks, vibration, weightlessness, and so forth. Such biomechanics require advances over the conventional measurement methods. Human body geometry must be described in three-dimensional space. Relations between dimensions and masses, such as characteristic inertial properties of the body and its segments, and the location of the centers of gravity must be described. These properties also show variability, depending on the posture of the body and the movement of body segments.

2. DESCRIPTION OF SPECIFIC STUDIES IN MORPHOLOGICAL BIOMETRY

The characteristics of the human body studies in morphological biometry are essentially associated with two basic characteristics: dimensions and masses.

These have long been a matter of concern, and a goal of study in physical anthropology since the measurement of the variability of human body dimensions was one of the "tools" used to classify and to compare various human groups. In recent decades, the relatively simple idea of measuring dimensions has been changed, and many other characteristics (such as masses, mobility, strength) have been incorporated to fulfill the needs of other disciplines, such as physiology, biomechanics, ergonomy, and human engineering. These sciences need information about characteristics of the human body as it varies intra- and interindividually, and under static and dynamic conditions. In contrast to the much simpler static case, in dynamic conditions physical characteristics change, often quickly, in time. Displacement and its time derivatives, speed and particularly acceleration, affect body characteristics under dynamic circumstances.

As Fig. 1 indicates, basic human body dimensions can be defined in terms of height, length, width, and depth. A combination of these dimensions leads to such characteristics as body surface and body volume.

A second group of intrinsic characteristics is derived from the assessment of body masses.

A combination of these two main groups of intrinsic data may be considered "elementary" as they define more complex characteristics, such as inertial properties and densities. Inertial properties, in turn, can be defined in terms of the position of the overall center of gravity, or the location of the centers of gravity of body segments; or with respect to the moments of inertia I_x, I_y, I_z with respect to axes passing through one or several centers of inertia (Fig. 2). Densities, either of the whole body or of its segments, are defined as the amount of mass per volume.

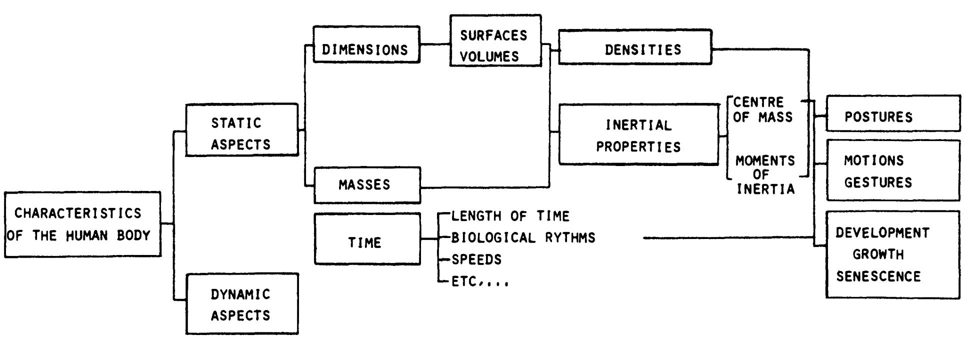


Figure 1. Variable data measured in biometry.

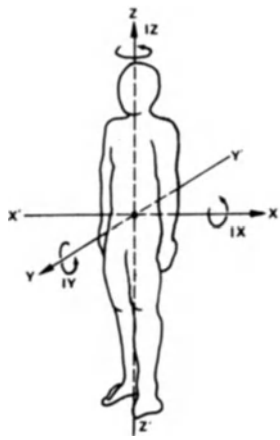


Figure 2. Principal axes of inertia in the human body.

The location of the segmentary elements is dependent on body posture, which hence must be considered both in static and dynamic biometry. If one introduces the factor time, the dynamic behavior of the human body is under study. Depending on the time scale, dynamic behavior may range from short-term studies of gesture and motion to long-term studies of the development, growth, and aging of the body.

3. METHODS OF STUDY DEVELOPED IN THE LABORATORY

Method of measurement and of data processing have been developed for each group of biometrical characteristics defined above (Fig. 3).

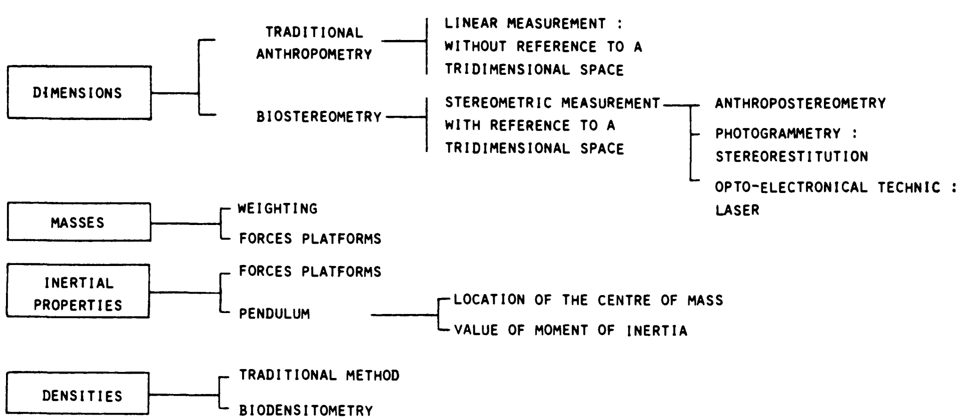


Figure 3. Laboratory studies and measurement methods.

They include:

- dimensions,
- masses and forces,
- inertial properties.

3.1. Measurement of Human Body Dimensions

Methods of measurement of the human body evolved as provoked by the distinct concerns of physical anthropology, and by the needs of other sciences, such as anatomy, biomechanics, physiology, and ergonomics. One main feature of this evolution is the need of defining dimensions according to references in three-dimensional space.

3.1.1. Traditional anthropometry provides a more or less exhaustive collection of linear dimensions, i.e., direct measurement

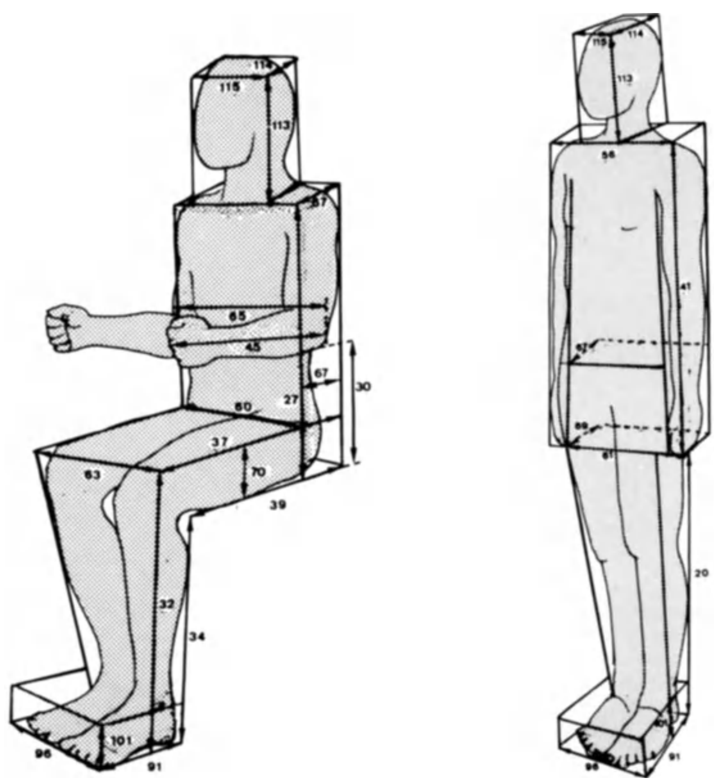


Figure 4. Measurements permitting the definition of the geometry of the seated or standing subject.

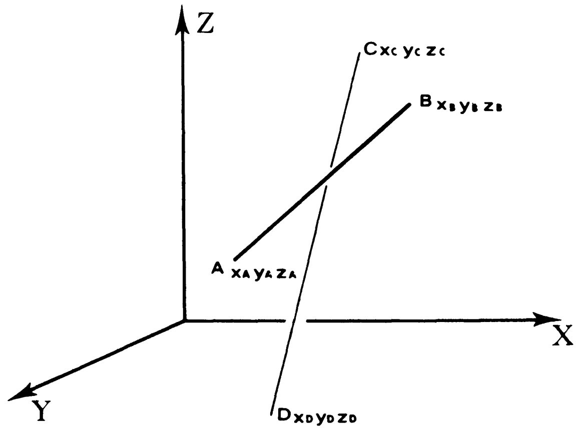


Figure 5. Identification and localization of anatomical points in space, determining the segmentary length.

of distances between anatomical points, or between points and reference surfaces (floor, wall) or perimeters or angles.

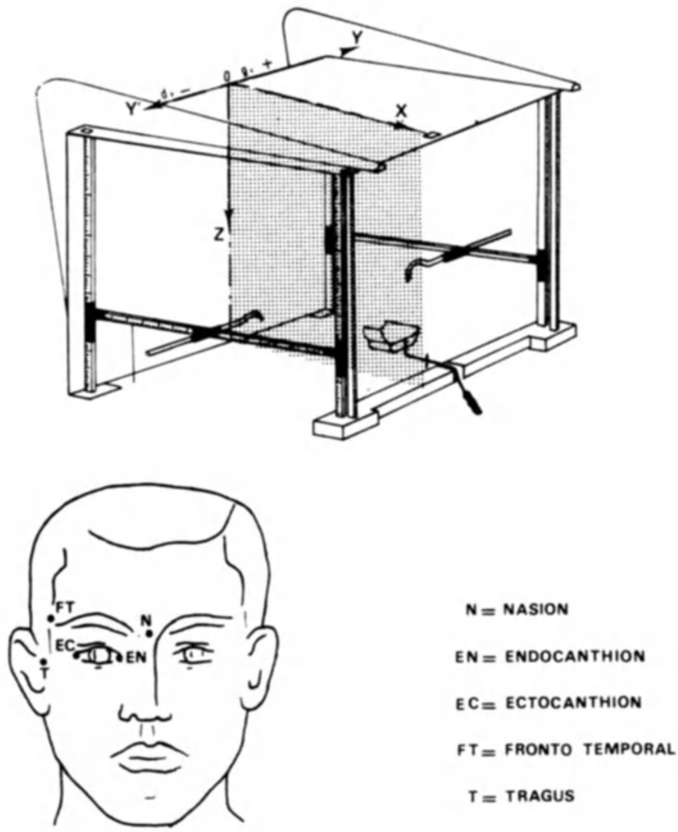
From these data, the geometry and composition of the human body can be restored by combining heights, lengths, widths, thicknesses, angles, and perimeters (Fig. 4).

3.1.2. Biostereometry stands out as a very significant step in the measurement of the human body. It not only gives values of the distances between anatomical points, as does classical anthropometry, but it also describes, with the greatest precision, the spatial location of segmentary elements of the human body with respect to a trirectangular reference system.

Each anatomical point which should be taken into account is identified by its coordinates X,Y,Z (Fig. 5). Thus, with the help of analytical geometry, one can calculate distances from point to point, from point to segment, from point to plane, distances between planes, angles of segments or planes, etc.

From these very general principles of biostereometry, we shall consider here only three technical solutions:

- direct biostereometry with an anthropostereometer,
- photographic biostereometry with photogrammetry or orthogonal systems of photography,
- biostereometry with opto-electronic equipment: laser telemetry and optical sensor.



n=150	RIGHT SIDE						LEFT SIDE				
DISTANCES mm	m	σ	v	mini	maxi	test "t"	m	σ	v	mini	maxi
N – EN	25.33	2.75	10.87	15.81	33.89	NS	25.25	2.73	10.82	19.26	31.92
EN – EC	27.82	2.38	8.54	21.18	33.41	NS	27.97	2.15	7.67	21.96	33.40
N – EC	53.14	3.38	6.37	45.49	60.74	NS	53.22	3.11	5.85	44.88	60.24
N – FT	60.86	5.25	8.63	46.61	71.62	NS	61.02	4.36	7.15	52.24	72.52
N – T	122.03	5.24	4.30	106.22	134.67	NS	122.12	4.84	3.97	100.84	133.99

Figure 6. Anthropostereometer and example of results.

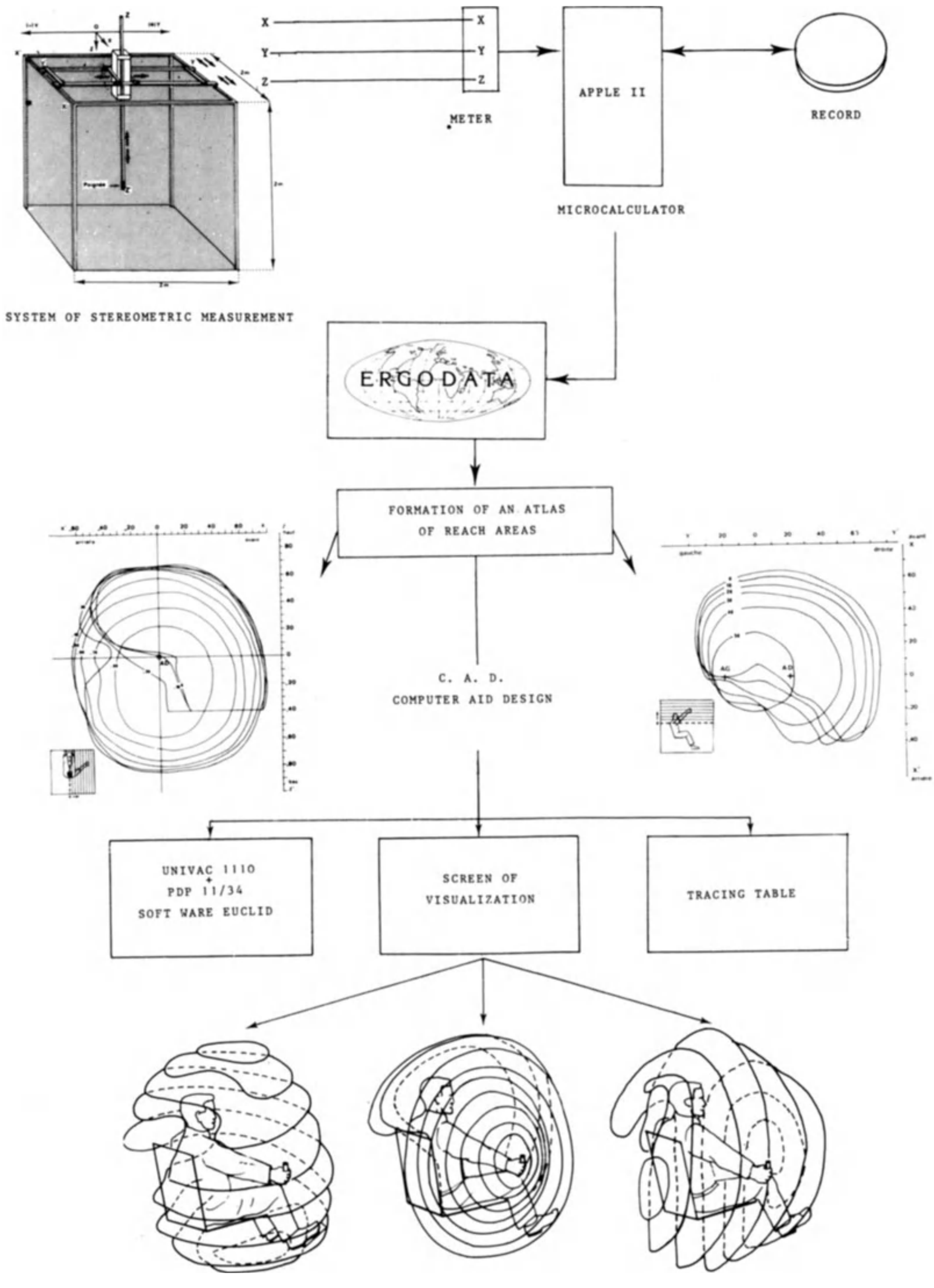


Figure 7. Use of three-dimensional data for research area description.

Direct biostereometry or anthropostereometry: Developed in the laboratory and still being improved, it allows an automatic assessment of coordinates. In this system (Fig. 6), X,Y,Z coordinates of anatomical points are simultaneously assessed by mean of rods in contact with a landmark. The reference space is determined by the apparatus itself.

Whatever the orientation and the functional position of the subject and the segmentary elements (head, face, arm, hand, lower limb, etc.), they are perfectly located during the experiment in space. It is obvious that such a method becomes valuable for the design of equipment and for the simulation of an operator's post of activity or workplace. In this context, the elements of the person (anatomical points) and the elements of the system (commands) are calculated according to a common reference system (Fig. 7). In this technique, biostereometric data are directly measured with an electronic sensor and numerized in a microcomputer (Apple II).

Indirect biostereometry with photography: The acquisition of biostereometric data is no longer made directly from the object, but from photographic or cinematographic pictures of this object.

Photogrammetry is one technique which is. presently highly developed and which gives very precise information (Fig. 8).

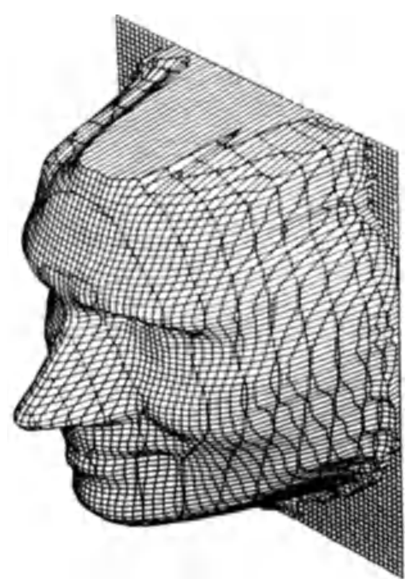


Figure 8. Example of three-dimensional photogrammetric restitution (from Duncan, Foort, and Mair).

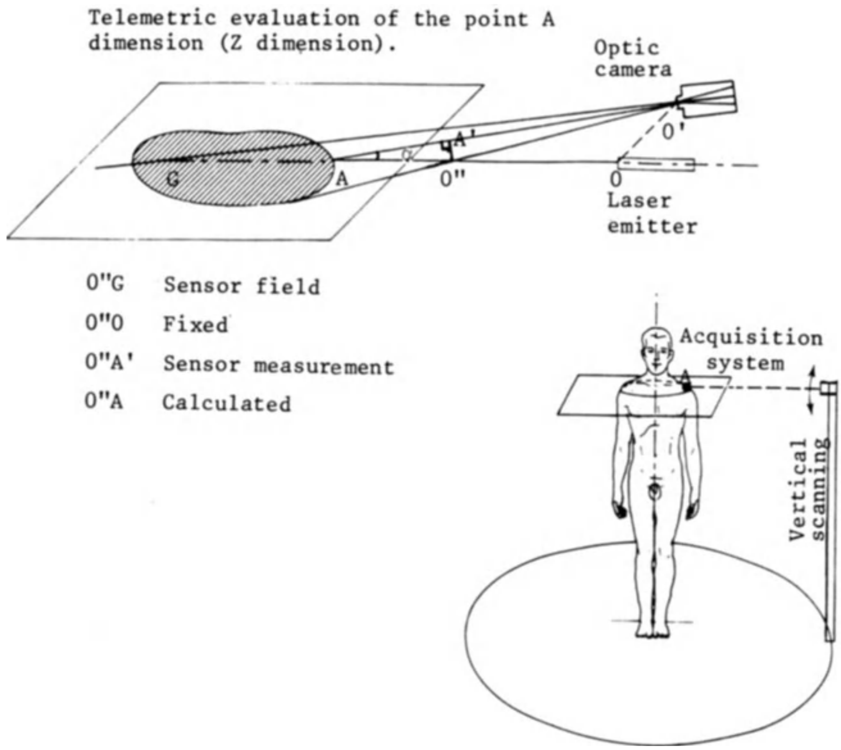


Figure 9. Principle of body measurement with a telemetry laser.

Unfortunately it requires the use of complex data collecting and processing systems, which hinders its general acceptance in the field of biostereometry. For example, this technique for dynamic biometry requires facilities to "chop" a gesture by stroboscopic effects.

In the study of motions, the use of a cinematographic system with movie cameras in orthogonal planes makes it possible to draw the trajectory of anatomical points in space.

Biostereometry with opto-electronic techniques, telemetry by laser and optical sensors: This method (Fig. 9) is a great improvement in the technique of biometric characteristics measurement because it makes it possible to locate any point of an object in space by the location of the light spot of the laser beam on a *matrix of diodes* of the camera. The third coordinate, Z, which measures the distance between points on the object and the camera-laser system, is obtained by telemetric measurement. The great advantage of this technique is that no human operator has to intervene: coordinates X,Y,Z of the object are automatically measured and processed by means of computer equipment.

DIFFERENT TECHNIQUES	TYPE OF MEASUREMENT	TIME OF ACQUISITION	
- TRADITIONAL ANTHROPOMETRY	LINEAR MEASUREMENT	60 TO 120 MEASUREMENTS BY SUBJECT PER HOUR	MANUAL HANDLING WITHOUT REFERENCE TO A 3-D SPACE.
- ANTHROPOSTEREOMETRY :			
. DIRECT MEASUREMENT	3 - D	100 TO 300 POINTS BY SUBJECT PER HOUR	WITH REFERENCE TO A 3-D SPACE. MANUAL HANDLING DETERMINATION OF VOLUMES OF ACTIVITY.
. AUTOMATISED MEASUREMENT .	3 - D	100 TO 1000 POINTS BY SUBJECT PER HOUR	AUTOMATICAL DATA PROCESSING.
- PHOTOGRAMMETRY :	3 - D	PHOTOGRAPHIES 1 TO 2 MN. BY SUBJECT ∞ OF POINTS.	DETERMINATION OF SURFACES, VOLUMES DATA PROCESSING THROUGH AN OPERATOR.
- OPTO-ELECTRONICAL TECHNIQUES			
. LASER	3 - D	30000 POINTS IN 5 SEC. BY SUBJECT.	AUTOMATICAL DATA PROCESSING

Figure 10. Evolution of measurement techniques in biometry.

Figure 10 summarizes the characteristics of the various measurement techniques.

3.1.3. Morphology and "time factor." The concept of studies in human morphology must be dynamic: anthropometric description of the body at a given moment does not take into account the variability of the living body.

Time and duration appear inseparable from morphology. During short duration we analyze moments and gestures, and over long duration, we note growth, development, and biological rhythms.

In this last case, the use of measurement techniques of the human body in three-dimensional space considerably enriches our knowledge of dynamic aspects in growth.

With time we consider a new notion of movement and progressive structuration of anatomic elements in space. It makes it possible, for example, to assess quantitatively in children harmonious or pathologic frequency of postures in orthopedics.

3.2. Methods of Measurement of Masses and Forces

The measurement of masses and effects of accelerations on masses of the human body is performed with well-known methods in biometry and biomechanics.

Under static conditions, when the only acceleration on the human body is the pull of gravity, weight is measured.

In contrast, during motion "g" acceleration is not the only factor: either by its own action, or in response to external force fields or impulses, the human body reacts and generates forces.

These forces are different from the simple weight value $Weight \doteq M \cdot g$ in the static condition. Measurement of dynamic forces can be performed with a force platform, which indicates the forces transmitted to the body in three directions (Fig. 12 and 13).

3.3. Biometric Measurement of Inertial Properties of the Human Body

The compound pendulum is one of the most precise tools to determine inertial properties of the human body in a static position.

It allows us to measure accurately the values of inertial moments I in relation to the X,Y,Z axes passing through the center of mass G of the human body, according to the elementary relation

$$T = 2\pi \sqrt{\frac{I}{mg.d}} \quad (1)$$

where T is the period of the pendulum, I the moment of inertia of the pendulum, mg the weight of the pendulum, and d the distance from

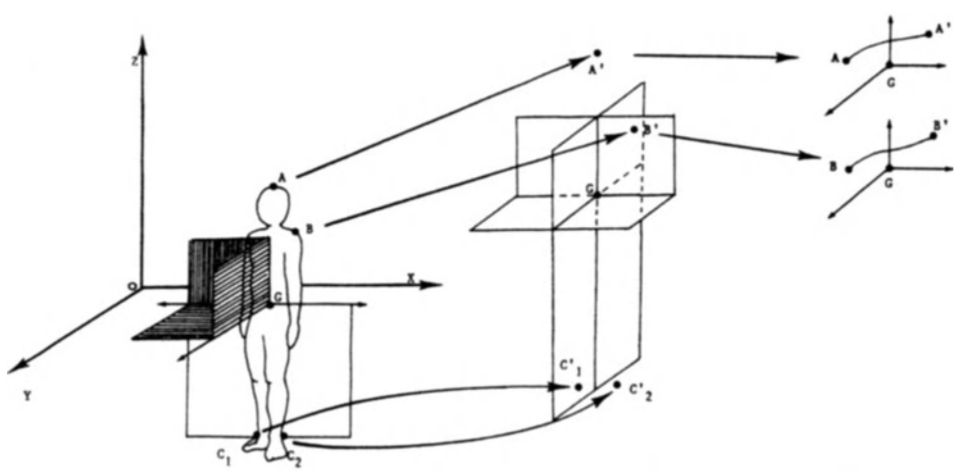


Figure 11. Biostereometry and measurement of segmentary element displacement in a three-dimensional space, over time.

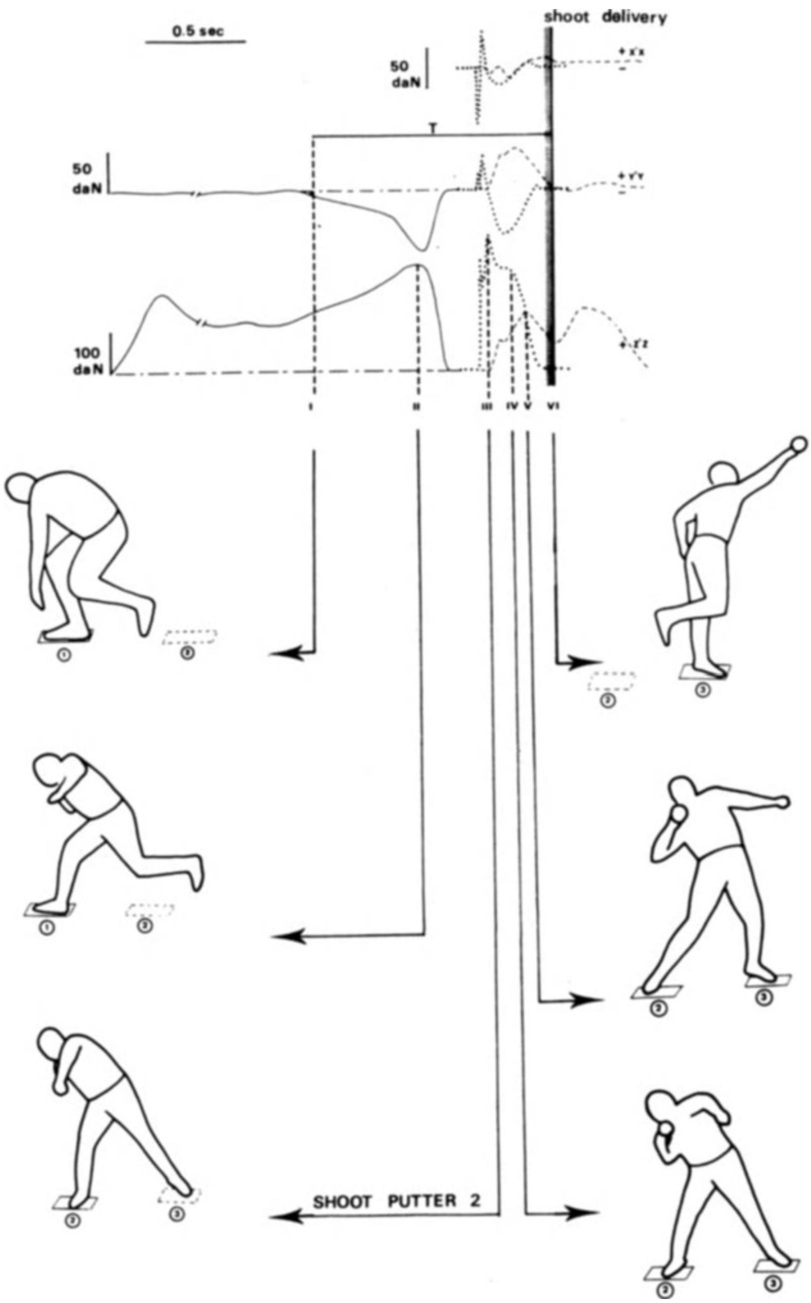


Figure 12. Relation between characteristic events of forces and typical postures.

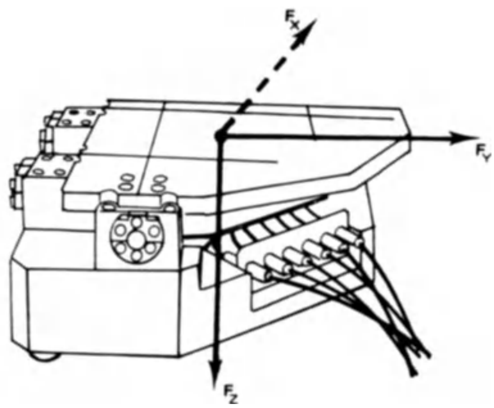


Figure 13. Force platform with six components.

G, the center of gravity, to the axis of oscillation. Usually, measurements of the inertial properties of the human body are done by the double oscillation method application of the Huygens theorem.

The location of the center of mass itself, given by the measurement of the oscillation period of the pendulum and the masses (man + pendulum), is defined according to its location in a trirectangular reference system. Anatomical points are located in the same reference system (Figure 14).

4. DATA PROCESSING AND HANDLING

Individual data gathered by the above-mentioned techniques are generally presented as

- linear dimensions: heights, lengths, widths, perimeters,
- segmentary or global values of surfaces or volumes,
- listings of coordinates X,Y,Z,
- masses and weights,
- inertial properties.

In the first stage, this information is stored in the data bank "ERGODATA." The raw basic individual data are then mathematically transformed into values of biometric characteristics: thus, the coordinates X,Y,Z of anatomical points are transformed into values of lengths, perimeters, angles, surfaces, volumes, or anatomical elements.

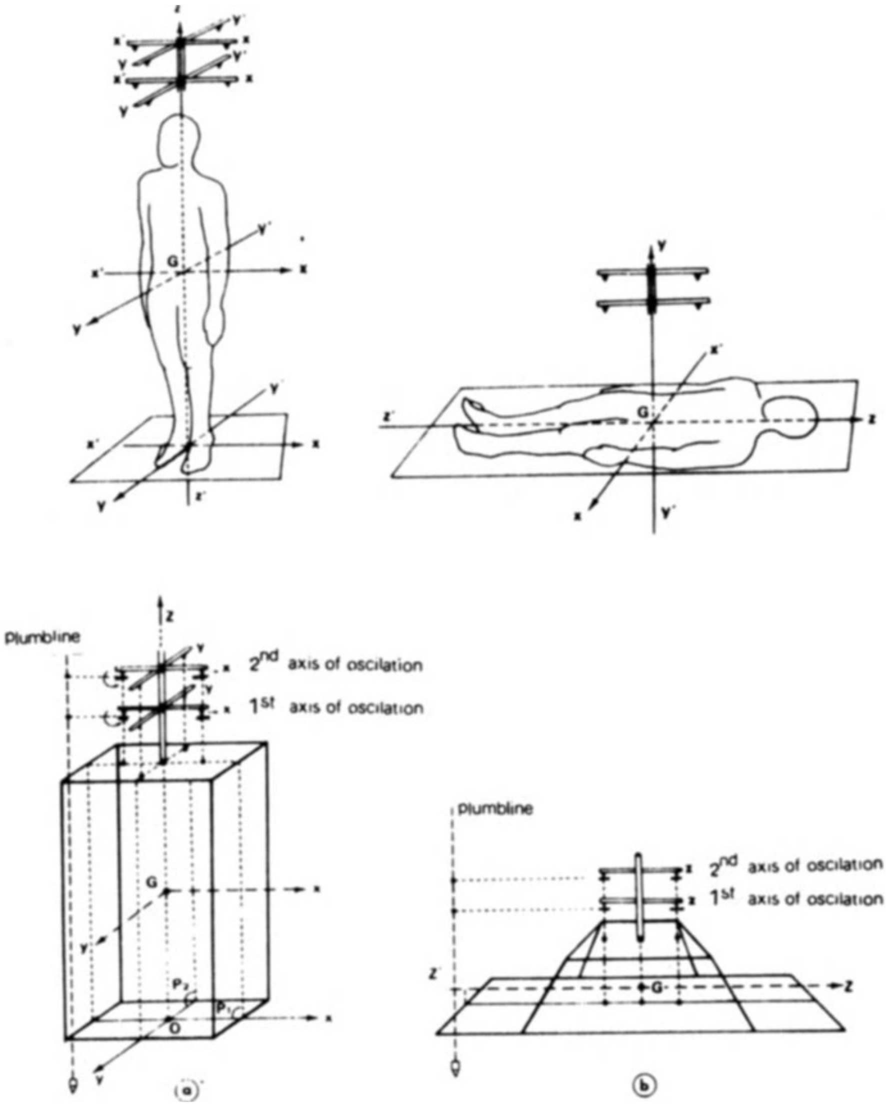


Figure 14. General scheme of the frames related to three-dimensional space.

RESULTS EXPRESSED IN : *Kg.m²* : *for the moments of inertia.* *cm* : *for the positions of the center of gravity G.*			Moments of inertia			Position height of the center of gravity G.		
N° of subject	*Weight*	*Stature*	I_x	I_y	I_z	H_G	L_x	L_y
Statistical characteristics m	69.09	175.32	11.51	12.38	1.12	96.49	15.09	8.83
σ	9.60	6.72	1.99	2.03	0.29	4.25	1.31	0.62
V	13.89	3.88	17.28	16.39	26.09	4.40	8.71	6.99
Mini.	55	162	8.67	9.09	0.73	86.9	13.4	7.6
Maxi.	88	184	14.48	14.90	1.77	101.1	17.7	9.7
Amplitude of variation.	33	22	5.81	5.81	1.04	14.3	4.3	2.1

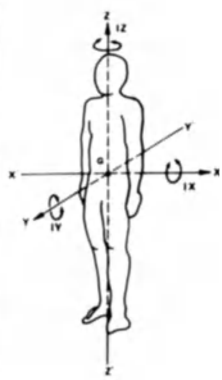


Figure 15. Examples of results obtained by measurement of inertial characteristics with the pendulum method.

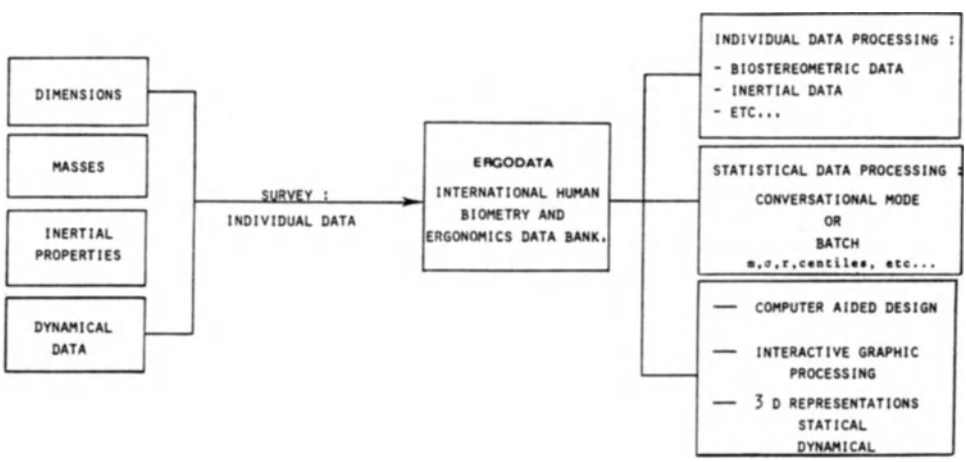


Figure 16. Biometric data processing.

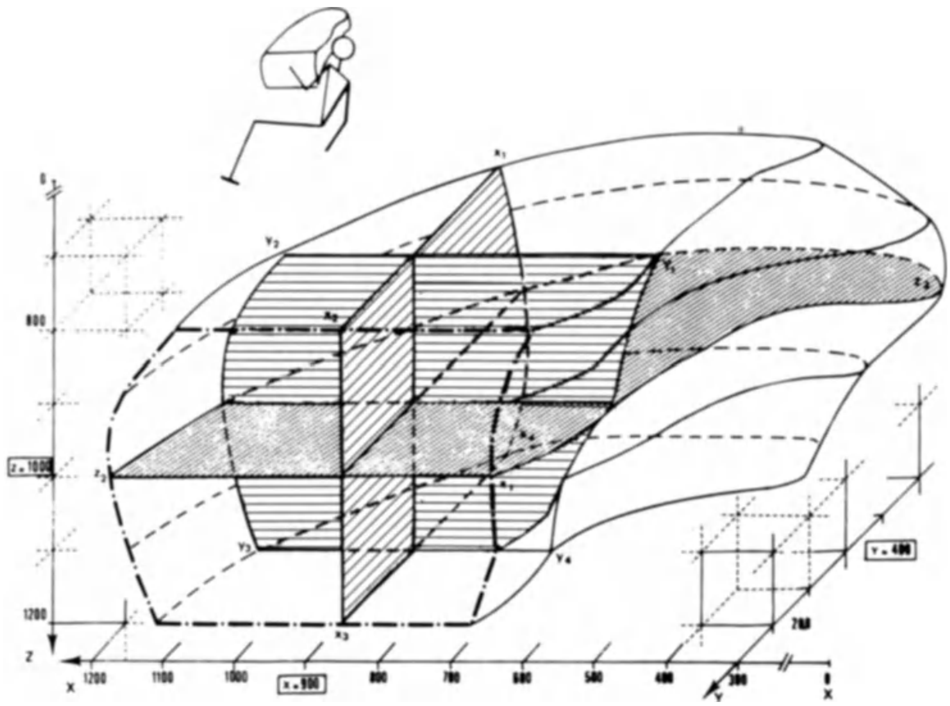


Figure 17. Functional reach zone (partial representation). Functional reach area through one transverse, one frontal, and one sagittal plane:

transverse $(2_1, z_2, z_3)$: Z = 1000
frontal $(x_1, x_2, x_3, x_4,)$: X = 900
sagittal (y_1, y_2, y_3, y_4): Y = 400

The experimental values of mass and oscillation period of the pendulum are also transformed, into values of inertial moments and positions of the center of mass.

In the second stage, this biometric and biomechanical information may be treated statistically as required in the given case.

In other words, results of a survey data stored in ERGODATA can be handled individually, but they can also be used for the creation of samples (thanks to the conversational mode) in association with other data or other surveys stored in the bank.

Finally, computer-aided design can be performed on the basis of the biometric data.

Biometric data, linear dimensions, three-dimensional coordinates of anatomical points, and intersegmentary angular data are put into the computer for graphic processing. Specific software makes it possible to create models of the human body or of the man-machine system which can be varied in time and space. This is an interesting technique for system design in ergonomy, functional anatomy, and biomechanics either in static or in dynamic situations.

5. CONCLUSION

This presentation provides a brief overview of the evolution of methods and techniques, from traditional anthropometry to optoelectronics, including the sophisticated tools that the computer places at our disposal for scientific data processing.

Concepts of new systems and equipment, often to be used in very particular and constraining situations, e.g., in aerospace or submarine activities, rehabilitation, robotics, etc., require the consideration of numerous biological data and of particular physical characteristics of the human body: dimensions, masses, volumes, inertial properties, etc.

This evolution of methods and concepts parallels the growing requirement for more and more precise information about people.

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Session III
Models of Anthropometric Data

BIOMECHANICAL COMPUTER MODELING FOR THE DESIGN AND EVALUATION OF WORK STATIONS

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INTRODUCTION

Biomechanical Computer Modeling is becoming an effective tool for the design and evaluation of work stations. Computer models allow complex analyses to be performed quickly and economically, to enhance the performance of operators of new systems. The possibility of performing large quantities of complex analyses, however, makes possible large quantities of undecipherable (and often undiscoverable) errors. The computer does not eliminate any potential for error which exists for manual analysis.

One of the more popular traditional tools of the crewstation designer is the three-dimensional mock-up. In performing biomechanical analyses with a mock-up, the major problem is selecting subjects with the desired body-size characteristics. Subjects are not uniformly proportional, so that when a group of subjects is selected to meet one desired critical dimension, other relevant dimensions can fluctuate widely. This is illustrated by Table 1, which compares important design related dimensions on four individuals selected from the 1967 Survey of USAF Rated Flying Personnel. These four individuals were selected as having a 5th percentile height (167.2 cm), that is, 5 percent of the sample population were that height or shorter, while 95 percent were that height or taller. Table 1 shows the percentiles of other key dimensions that are not close to the 5th percentile. Subject A with his 0.5 percentile thumb reach and 20th percentile sitting height says "I can see out the window very well, but I cannot reach some of the hand controls." Subject D says, "I can reach all the hand and foot operated controls, but the windows are too high for me." Such occurrences have caused erroneous evaluations and crewstation configurations which do not accommodate the required range of user population.

Table 1. Design Related Dimensions on Four USAF Flyers Having 5th Percentile Stature (Percentile of 67 USAF Flyers)

Subj.	Height (Stature)	Sitting Height	Thumb -Tip Reach	Buttock -Knee Length	Knee Height Sitting
A	5	20	0.5	3	6
B	5	38	2	16	2
C	5	0.5	24	62	10
D	5	0.05	74	48	55

COMPUTER MODELING AS A SOLUTION TO CREWSTATION DESIGN

Computer graphics permit the construction and manipulation of three-dimensional models of crewstations for design and evaluation. There are several advantages to computer aided design. Unlike mock-ups, there is no physical hardware which requires time and money to build and to modify. Computer models exist as arrays of numbers which are quickly and easily changed. Computer models may be displayed on CRT terminals or plotted to any scale on high resolution plotters. By adding a variable geometry representation of a human operator to the model, biomechanical analyses of the operator's interaction with the crewstation are possible.

Biomechanical computer models have application to many crewstation problems: physical size accommodation, visual field accommodation, reach accommodation, dynamic response to acceleration, and strength assessment.

Physical size accommodation refers to the fit of the operator in the seat, head or helmet clearance, knee clearance, shin clearance, etc. An example of this type of model is the COMBIMAN (COMputerized BIomechanical MAN-model) (McDaniel, 1976; Evans, 1978). The USAF's COMBIMAN model is a three-dimensional variable geometry man-model and crewstation which may be reconfigured using interactive graphic techniques. The man-model may be sized by entering relevant anthropometric dimensions, or from anthropometric survey data using percentiles or algorithms. The model and crewstation are displayed on a CRT for interactive manipulation or plotted to scale for future reference and measurement.

Visual field accommodation refers to evaluating the visual restrictions of the operator. In the COMBIMAN model, the line-of-sight angle to displays, windows, controls, landing fields or other objects are computed and mapped on a two-dimensional visibility plot. Since the man-model is variable in size and can be moved about in the crewstation, such visibility plots give a realistic analysis of what the operator actually sees when in the crewstation.

Reach accommodation refers to modeling the operator's ability to reach to and operate hand and foot controls. The COMBIMAN model accomplishes this by comparing the reach ability of individuals of critical size characteristics. Strength is an important factor in reach analysis. For major manual controls, ability to touch a control does not always mean the operator has enough strength to move it.

Response to acceleration refers to the high G loading due to aircraft maneuvering and impact acceleration due to ejection, parachute opening, and crash situations. An example of a model that performs these analyses is the USAF's ATB (Articulated Total Body) model (Kaleps, 1978). This model divides the operator's body into 15 mass segments for dynamic analysis of the body's response to acceleration.

PROBLEMS WITH BIOMECHANICAL MODELING

The problems of using computer simulations for crewstation design and evaluation arise from inadequacies in the data bases being modeled, forgetting assumptions made in the modeling process, inappropriate use of the computer model, failure to verify analysis, and failure to validate the model.

Traditionally, computers and computer analysis has enjoyed a technological mystique which gave them an inherent face validity. Now that computers are becoming commonplace, the almost supernatural aura of computers is waning. For the newer aspects of computer usage, (such as graphics, interactive graphics, and color graphics) the technological reverence remains strong. These new computer technologies are valuable tools, but are also tools which are costly and difficult to develop. In some cases, the model is never related to a specific data base, but becomes a graphics magic show, with all the proper shapes, but no substance.

Models of biomechanical data bases cannot be used in the same manner as traditional manual analyses. When performing design or evaluation analyses by traditional means, the human engineer examines the problem, and then selects the research data base which is most relevant to the problem. Since all design and evaluation problems are unique, the selected data base may be different for each application.

Computer modelers, however, usually strive to solve a generic problem area, rather than a single design problem, because the computer's efficiency lies in repetition. So then, which data base does one select for the computer model? The answer is certainly not all, and most frequently, not even two data bases can be simultaneously accommodated in a single model. No two anthropometric surveys contain the same set of dimensions. Even dimensions with the same name may have been measured using different references. For reach data bases, variability of clothing and restraint preclude any useful combination. In strength studies, there is broad variance in measuring technique, as well as definition of variables. In summary, the biomechanical data bases cannot be readily combined in a single model, The existing data bases were collected for purposes other than generic computer modeling.

The need for simplifying assumptions in computer modeling is a practical reality, but they constitute limitations in accuracy. Since these limitations do not affect all computations equally, it is difficult to apply them to the confidence limits. Most often, the assumptions are ignored, or lost in the shuffle.

Statistics books teach us that the error increases as the predicted value moves away from the center of the modeled distribution, and increases non-linearly, until beyond the upper and lower ranges of the data, the potential for error is so large, that the model is worthless. Since no biomechanical data base covers all situations, the computer model based on that data is likewise limited. To use the model outside the region of the modeled data is contrary to good engineering practices.

Because of the complexity of computer models, it occasionally happens that a combination of input variables interact in such a way as to produce erroneous results. Frequently, the results are so far from expected as to be obvious. However, sometimes the results are only slightly off, and are not readily detectable. It is recommended that manual checks or measures be made on any applied analysis.

SOLUTIONS TO BIOMECHANICAL MODELING PROBLEMS

The problems stated above make computer modeling difficult, but not impossible, if the model maker is prepared to embark upon a software development program which may require 5 to 10 times the original estimates for funds and duration, and the development of the necessary biomechanical data bases from scratch. The COMBIMAN model, being developed by the USAF Aerospace Medical Research Laboratory, is scheduled for completion next year, which will be a 10-year development program. Except for the anthropometric data bases, all other biomechanical data bases will have been developed to satisfy requirements of this computer model.

A major study in progress at AMRL seeks to improve the anthropometry and reach data bases by measuring the effects of clothing and restraints (harness) on the reach mobility of aircrewmembers. In this study, reach capability is measured for all combinations of flight clothing (baseline, summer flying suit, winter flying suit, underarm flotation device, jacket) and restraint (no restraint, lap belt restraint, and shoulder harness with varying amounts of slack.) The spatial location of the major body joint centers will be measured, in addition to the maximum extension reach envelope for pushbutton, rotary, and handle type controls.

Two studies of strength and endurance are nearing completion at AMRL. For the general crewstation, male and female subjects exert their maximum force against a handle in a seated workplace. There are 76 handle locations and 6 directions of force for each of the 76 locations.

For the pilot's crewstation, male and female subjects exert their maximum strength and endurance on aileron, elevator, rudder, collective, brakes, and ejection controls. In all of these studies, detailed anthropometric measures allow evaluation of control position and strength as a function of body size, as well as absolute force. The force that one can apply on a control is a function of the location of the control and the direction of force required.

In summary, the majority of biomechanical data bases were not gathered for the purpose of computer modeling. They have neither the number of variables nor the proper definition of variables for computer modeling. The first task in any modeling effort should be the selection or development of a valid data base. Not only does this increase the accuracy and utility of the model, but it also simplifies the model development.

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USER NEEDS IN COMPUTERISED MAN MODELS

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INTRODUCTION

Models have long been used as part of the design process and they have advantages of cost and speed over other methods both for strategic and operational decision making. Greater computer availability and lower cost means that computer modelling is increasingly likely to be used by designers. Every model is an abstraction and the key to successful modelling appears to be to include in the model only those factors which are relevant to the decision to be made. On the other hand commonality of needs between problems means that some model attributes are useful for the solution of a range of problems. Is it possible to determine which attributes should be included in computerised anthropometric and biomechanical man models for, (i) designers of workstations wishing to use CAD methods, and (ii) ergonomists who wish to use a man model as a framework for ergonomic data collection.

The needs of designers are examined in the light of potential applications and practical experience of using the SAMMIE system (Bonney et al, 1979; Case and Porter, 1980). The needs of ergonomists are more speculative and are examined from the gains that would accrue from using an agreed model framework.

MAN MODELS: GENERAL DISCUSSION

Human Factors information can be computerised either as a predictive model or as data - raw or summarised. An obvious approach is to use a predictive man model. The reasons for this include:

The necessity to represent the man model geometrically because of the interactions with the workplace model.

Predictive models can be combined with flesh algorithms, strength algorithms, etc. in order to represent the man model in working situations, rather than the artificial situations of data collection. Evaluative algorithms can be used for example to test reach, joint constraints, interference with the workplace etc.

However, it is necessary to compromise the natural wish to model all attributes of man because:

Most applications do not need a detailed model.

A detailed man model would take so long to manipulate and display that it could not be used as an interactive tool.

Except for some specific populations (mostly military) comprehensive data is not available or has large gaps in it.

Even with good data there are problems with generalising the recorded actions into predictive rules.

Thus the natural and straightforward modelling approach needs to be modified to exclude attributes which are unimportant for the problems to be solved, or for which appropriate data is unavailable. However even the ideal man model still needs the skill and experience of the designer and an interactive design system is essential for most applications. The ergonomics literature abounds with data derived from limited studies of special occupations, different age groups, different applications and different equipment. There is a need to be able to draw on this data. Hence the practical way forward appears to be that systems and designers will use geometric models and current available data together within the same computer system.

However there are dangers associated with using models and data within the same system:

Contradictions could arise between the model and the data. e.g. the eyepoint implicit in the model could differ from that explicit in the data. What does the designer then do?

Data has an inherent lack of flexibility and is likely to be applications specific. There may thus be difficulty in using it except for the purposes for which it was collected. Although this is true also of a mathematical model at least the effect, e.g. of scaling the model, will be consistent. The danger is that one accepts this consistency as reality.

Nevertheless the designer can recognise this and learn to use the tool effectively. On the other hand where a designer does not use computer aided design these inconsistencies are likely to be present but unrecognised.

The requirement in the longer run is an agreed data collection framework which can match the needs of generalised model building with 'ad hoc' data collection. It is appealing to ask whether a geometric model could provide such a framework. If so, this would provide a consistent database and would also improve the predictive ability of the model itself.

MAN MODELS FOR WORK STATION DESIGN

A man model, whatever its attributes, is useless as an evaluative tool unless it can be linked with a system of work station design which is sufficiently comprehensive and responsive to meet the designer's needs. Furthermore, because the real operator becomes part of the real work station, the man model must be constructed, and be capable of manipulation, as part of the work station model. Once one satisfies these two requirements, even a trivial man model can be useful.

If we have a flexible work place modelling system then what attributes should be built into the man model? Looking first at the general attributes, the need for a good response for interactive working requires that the model has to be an idealisation. Another practical limitation to model complexity is the designer's skill of using computer aided design. However with improved skill and training more complex models could be used.

Possible Man Models

Let us examine how specific man models could be used to evaluate specific aspects of work station suitability. This will then allow us to determine, conceptually at least, the incremental value (in an evaluative sense) of each additional man model attribute. Thus the simplest man model for evaluating operator vision would be a point representing the eyepoint of the operator. The simplest model for checking whether there was room for a standing man in the workplace would be a box and the simplest man model for reach evaluation would be a stickman with joint constraints.

There is greater difficulty in producing clear cut answers to more complex evaluations. Questions such as does the task lead to discomfort or is the task safe, require the designer to state his equipment assessment criteria and leads to a rapid escalation in the complexity of the man model.

Man model requirements can be looked at from two viewpoints, namely, the problems which can be solved by specific man model attributes and conversely the attributes needed to solve specific problems. In practical terms a skilled designer can make effective use of a less sophisticated man model by calling on his own design skills and knowledge even if neither stored data nor formal evaluations are available as part of the system, whereas a sophisticated man model still needs the designer's skill. It appears that interactive computing allows the designer and CAD system to develop a symbiotic relationship. This suggests that the most effective short term man model development should be in response to the needs of good designers solving specific problems.

MODELS FOR ANTHROPOMETRIC DATA COLLECTION

Many man models owe a great deal to Dempster's (1955) original approach. As this has stood the test of time might it form the basis for a more general approach to data collection? Might it be possible to adopt the strategy that data was collected on a consistent basis so that even small samples could add to the available knowledge? Let us examine how that might be done.

The problems of anthropometric data collection have been well versed. The principle ones are the population selection, sample size, the presentation of information in an unambiguous manner, and the application of the collected data to real problems. Frequently the problem is tackled from the point of view of methodology rather than applicability. Emphasis has been placed on measuring techniques and statistical analysis whereas insufficient consideration has been given to the eventual use of such data. An added problem is that designers, the eventual users of data, are rarely in a position to initiate surveys due to lack of resources, expertise, or the immediacy of the design problem.

The presented information is the interface between the data collector and the designer, and is of two kinds. The first kind is application specific data which does not seem to have a great future as the infinite variety of working situations for which data is required defies all attempts at collecting the data.

The second kind of data relates to basic human features such as limb lengths, maximum torques which can be attained at joints, etc. This parametric data is not application specific and to be applied it would become part of a data base which could either be transformed into the required application data, or, more relevantly, converted into a predictive computer model which would be useful for problem solving.

It is clear then that the interface between the designer and the collector of data should be placed at the point of basic data. This places a requirement on the designer to have available methods for processing the basic data into a usable form, and a requirement on the data collector to adhere to a rigidly defined database. There are signs of database systems developing (e.g. Coblentz). The difficulty is in defining a sufficiently general data base and then educating users and ergonomists to adhere to its constraints. However if this could be done then there is the possibility of obtaining a steadily improving database which could form the basis of determining national and international standards.

CONCLUSIONS

This rather philosophical paper has advocated a set of ground rules for producing a satisfactory man model which integrates the needs of computer aided designers and ergonomists. The model should be:

- embedded in an adequate workplace modelling system.
- usable at several levels of complexity.
- usable in conjunction with currently available data.
- capable of improvement by adding further attributes.

In addition it has been suggested that:

- a data collection proposal should be formulated.
- data should be collected according to an agreed database format
- the database should, from time to time, be analysed to produce agreed predictive rules.
- these predictive rules could form the basis of agreed national and international standards.

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SOME COMPUTATIONAL PROBLEMS IN DEVELOPING COMPUTERIZED MAN-MODELS

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INTRODUCTION

Anthropometric data may be presented in a variety of forms, with probably the most common being tabular format. This includes percentile and summary statistical listings and regression equations. This form provides quick, easy reference but unfortunately this is not always the most useful presentation for solving three-dimensional design problems. Design problems need anthropometric data presented in the context of human-form models, incorporating human movement as well as static anthropometry. This type of design requirement by the United States Air Force led to the development of the 3-D COMBIMAN (COMputerized BIomechanical MAN-model) model.

The engineering application of the COMBIMAN model was in design and evaluation of air-crew station geometry. The goal was for a versatile, easy to manipulate, highly accurate man-model. The Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson Air Force Base, Ohio set out to achieve this goal using in-house computers and interactive graphics capabilities to reduce the anthropometric survey data to a graphic form which would facilitate its use by engineers and human factors specialists.

The AMRL has both American and foreign military and civilian surveys representing over 90,000 individuals available for use in its own data bank. Over 46,000 individuals are contained in the military surveys alone. This data is available in tabular, regression, and raw data form. Unfortunately, up to now, most of the surveys, both military and civilian, have been geared toward clothing applications, and not toward man-modelling. Consequently, many of the vital breadth and depth dimensions have not be included. Another problem encountered among surveys has been the lack of common variables. The basic height-weight dimensions are present, but surveys contain different arm-reach or clearance-related dimensions, or chose to adopt different measuring techniques when acquiring the data. The final problem with the surveys is common to all tabular data -- it is only two-dimensional and gives little indication of the relative placement of dimensions into 3-dimensional human form.

MAN-MODEL DEVELOPMENT

The COMBIMAN model development started with the AMRL data bank surveys, in particular the 1967 U.S. Air Force Rated Flying Personnel Survey, and with the link system research conducted by AMRL personnel. There were two reasons for using the 1967 survey: 1) it dealt with the Air Force population under investigation, and 2) it contained the most complete set of relevant dimensions for generating the link system and enfleshment parameters.

The current link system consists of 35 links, originating at the Seat Reference Point (SRP). Three of these links are zero-length links, used only to align distal links in space. One is located at SRP and the others are at the right and left shoulder joints. The lengths of the remaining 32 links are calculated at program run-time from 12 external surface dimensions. The dimensions are listed in Table I.A. It should be noted that the model has been defined with three hand links. This accommodates the various types of hand reaches possible, i.e., fingertip, functional, and grip-center. All three hand links originate at the wrist.

Table I: Anthropometry Used in Man-Model Development

A Required Surface Dimensions (link & enfleshment dimensions)	B Mass and Length Related Dimensions
Weight	Weight
Sitting Height	Bideltoid Breadth
Acromion Height, Sitting	Hip Breadth, Sitting
Knee Height, Sitting	Chest Depth
Buttock-Knee Length	
Shoulder-Elbow Length	Sitting Height
Biacromial Length	Eye Height, Sitting
Hip Breadth	Knee Height, Sitting
Chest Depth	Buttock-Knee Length
Foot Length	Elbow-Grip Length
Hand Length	Thumb-Tip Reach
Elbow-Wrist Length	

The validation phase of the COMBIMAN link system and enfleshment procedures consisted of: 1) the collection of necessary surface dimensions from a statistically selected sample of subjects from the 1967 USAF survey, 2) inputting their values in the interactive graphics program to define the man-model (see Section, 2.2.12, Evans, 1978), and 3) the adjustment of link length and ellipsoid semi-axes length equations to reflect a greater accuracy in the anthropometric approximation of the model. Subjects were selected with respect to either their sitting-height or weight. Computed man-model dimensions were compared to the subjects' actual dimensions and modifications were made to the scalar multiplier or ellipsoid axes calculations based on residual statistics to minimize the sums of square residuals for surface dimensions.

USER INTERACTION

All man-model link and enfleshment dimensions are calculated in terms of the 12 surface dimensions stated in Table I.A. It is not always practical to expect a user to have values available for all 12 dimensions. To provide the user with greater flexibility, while still obtaining an accurately proportioned model, sets of mass- and length-related variables were defined for model redimensioning. These sets of variables are shown in Table I.B. The user selects one variable from each category, and defines a value, either in absolute units or as a percentile of the survey population. Multiple regression equations are used to calculate the complete set of surface dimensions required for man-model generation. Combinations of values supplied by the user are checked to assure a reasonably proportioned model.

Features of the model useful in designing and evaluating work places are reach-to-a-point and reach envelope generation, visibility plot generation, and model redimensioning.

Reach envelope and reach to a point use the same model repositioning algorithm. The reach envelope procedure reapplies the algorithm for a sufficient number of points to define a 3-D reach envelope for the given model posture, size, restraint, and reach-type, while the reach to a point is performed only once. Reaches may involve one or both hands or feet. Restraints limit upper body movement to arm-only, arm-plus-shoulder-only, or full torso above the L5/S1 joint. Reach type refers to the hand link involved in upper-body reaches, i.e., grip-center, functional, or fingertip reach.

Visibility plots map the visual field of a given workplace against the current head and eye position of the model. Superimposed on the plots are limits of visual fixation and peripheral visions.

The internal link lengths are related to the surface dimensions by a predefined and validated scalar multiplier. While more complex relationships could be developed to accommodate the variability at the ends of the prediction range, the scalar relationships have been adequate for the requirements of the model thus far.

The links are positioned using Euler-type transformation angles; each link's position is determined with respect to the proximal link in the chain. Links are added sequentially, starting at SRP. Each link has its own local 3-D coordinate system, fixed to its proximal end. This construction technique places realistic limitations on the range of movement of each joint and permits the repositioning of a distal link by movement of a proximal link. This allows each link to move with up to six degrees of freedom with respect to the external coordinate system (see, McDaniel, 1976). A more detailed description of the link-system geometry is contained in Bates, et al., (1973).

Various enfleshment strategies were considered but the approach adopted was to position 3-D ellipsoids about selected joint centers and connect adjacent ellipsoids with tangent lines, thus outlining the model's form. Since the ellipsoid center was not always at the joint center of rotation, ellipsoid center offsets with respect to the joint center were also calculated. The overall objectives of enfleshment were to achieve realistic human form, and to obtain calculated external dimensions equivalent to the original surface dimensions used to generate the model internal link-lengths.

The size and shape of an ellipsoid is defined by the dimensions of the semi-axes lengths. These dimensions are based on body surface and mass dimensions. The semi-axes dimensions for each joint correspond to the height, width, and breadth surface dimensions at that joint. All ellipsoid axes are parallel to the axes of the link system of coordinates. Adjusting the size and offset of the ellipsoids provides a realistic contour of highly flexible joints at any degree of joint flexion or extension.

While the model exists in three dimensions, it is projected onto a two-dimensional user-defined viewplane on the cathode ray tube (CRT) screen. The ellipsoids surrounding the joints are also projected onto the screen as 2-dimensional ellipses. The man-model can be rotated and magnified or reduced within the viewing area; any such manipulation will also change the shape and size of the shadow of a given ellipsoid on the CRT screen. A fast and efficient algorithm was developed to assure uniform joint enfleshment regardless of the man-model posture or position with respect to the viewing plane. The algorithm finds the analytic or closed form expression for the elliptical contours for the required viewing plane, and then generates points along each of these contours for the CRT display.

CONCLUSIONS

While the redimensioning capability of the model has been validated, the repositioning capability has not. This is primarily due to a severe lack of suitable joint mobility and reach capability data. An experiment is underway within the AMRL to obtain the required joint mobility and reach capability data for both clothed and unclothed subjects in various restraint conditions. Previously, all model dimensions have been for unclothed subjects, primarily because of the severe lack or anthropometric and reach data on clothed subjects. Once available, clothing will be used in the calculation of ellipoid semi-axes lengths, enlarging the outer contour of the model. It will also be used in the joint mobility constraints providing more realistic ranges of movement over a greater set of real-world conditions.

The link between SRP and the Mid-Hip joint ties the model to the workplace. At the present time, the characteristics of this link are not fully defined, due to a severe lack of data on pelvic geometry and seat compressibility. Hopefully, in the near future data will be available to further refine this critical link and more accurately define the model's interaction with seat and restraint systems.

The limitations of the model are largely due to insufficient data currently available for man-modelling purposes. The model has been designed so that new data, as it becomes available, can be incorporated in a relatively straightforward manner. Enhancements scheduled for the near future include validated reach and joint mobility data, clothing and personal protective equipment data, and an expanded set of anthropometric surveys to include both male and female data. Future areas for consideration include the incorporation of human strength data and fatigue data.

This model represents only one of many approaches to designing and implementing a computerized man-model. Each approach has its advantages and disadvantages. The common requirement of all approaches is data - anthropometric and biomechanical. The faster this data can be obtained for the purpose of man-modelling and the more standardized and reliable its format, the easier it will be to develop human-form models for the specialists who need them so desperately.

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EMPIRICAL MODELS OF INDIVIDUALS AND POPULATION MAXIMUM REACH CAPABILITY

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INTRODUCTION

The evaluation of reach requirements has traditionally been an important aspect of the design process under those conditions where extreme reach distances may be required. Extreme reach distances arise due to several considerations including: (1) physical constraints such as shoulder harnesses and seat belts restrict human movement; (2) engineering and safety design criteria may conflict with reach criteria giving rise to large reach distances; and (3) human reach capabilities may be limited by an individual's handicaps.

Applications for maximum reach estimation procedures include the evaluation of workplace designs, automobile interiors and cockpit interiors. The analytical techniques used in these applications are based either on biomechanical or empirical models. The biomechanical approach offers maximum flexibility in determining the effects of task requirements, body posture and seating constraints on maximum reach capabilities. However, biomechanical models are complex in comparison with empirical models and require access to substantial computer software for efficient utilization. Empirical maximum reach procedures are readily available to the practitioner as graphical representations of maximum reach contours (Kennedy, 1978) and may be compared directly with the reach requirements for a particular task. However, body posture and seat design may be restricted to a small range of configurations. Thus, empirical models must be derived for a variety of postural, environment and population configurations to be of practical use.

LIMITATIONS OF EMPIRICAL MODELS

Although current analysis procedures utilizing maximum reach contours have proved useful, several important limitations are evident. First, and perhaps foremost, maximum reach contours are available for a very limited set of environmental, postural and population configurations. One important consideration which hinders the development of additional maximum reach contours is the lack of efficient data analysis procedures.

Secondly, current procedures for estimating population percentiles allow for only a single reach point. Thus, the derivation of population percentiles is not feasible for several sequential reach points. The use of available procedures for estimating population percentiles may result in serious errors. For example, error arises for restrained airplane pilots since a tall person may have 95th percentile right hand reach capabilities in the right lateral reach region, whereas a small person may have 95th percentile right hand reach capabilities in the left lateral reach regions.

Thirdly, available reach analysis procedures do not allow for the evaluation of a particular individual's reach capability. The time required for analysis of each individual prohibits this type of evaluation. Thus, current methods do not facilitate analysis of the match between the reach capabilities of a particular individual and the reach requirements of a particular job design.

DEVELOPMENT OF EMPIRICAL MAXIMUM REACH MODELS

Extending the power and flexibility of reach analysis procedures requires the development of efficient data analysis techniques. The basic requirement of a maximum reach model is that the model should be capable of describing a maximum reach data set which is approximately spherical in shape.

An investigation of several classes of models indicates that cartesian models are unacceptable due to severe estimation bias whereas spherical models provide an acceptable estimate of the maximum reach sphere (Boydstun, et al., 1979a). Therefore, a spherical class of models is selected for the development of maximum reach models. The form of the model may be described as:

$$r(\theta,\phi) = \sum_{\ell=1}^{n} c_i \, f_i(\theta,\phi) \qquad \text{(Eq. 1)}$$

where: (1) c_i are the least squares parameter estimates; (2) n is the number of parameters; (3) $f_i(\theta,\phi)$ are polynomials in cosine and sine of θ and ϕ; (4) θ and ϕ are horizontal and vertical reach angles; and (5) r is the maximum reach distance.

MAXIMUM REACH MODELS FOR THE SEATED AND CONSTRAINED FEMALE AIRPLANE PILOT

The derivation of individual maximum reach models is based upon data provided by Kennedy (1976). Given the form of the model (spherical harmonics), a particular model must be selected. That is, the appropriate number of parameters must be selected based on several criteria, including: (1) model parsimony; (2) percent variance accounted for (R^2); and (3) model bias, as reflected through prediction error.

A second order (nine parameter) spherical harmonic model was chosen based on these considerations (Boydstun, et al., 1979b). The model yields an average R^2 value of 0.820 for 29 female subjects. Minimum and maximum R^2 values are 0.687 and 0.880, respectively. Residual plots reveal several areas of model bias, including (1) prediction errors near the feet result from missing data in this region; and (2) prediction errors to the rear of the subject result from both missing data and from differing arm postures (supine or prone) confounded with a north to south data collection procedure. Increasing the number of model parameters does not substantially increase R^2 values or decrease model bias.

The development of a general individual model for the female pilot data is motivated by the desire to provide a maximum reach model based on a reduced set of data. The reduced data set selected for the general individual model includes maximum reach measurements on the RIGHT, LEFT, FRONT, BACK and NORTH coordinate axes with origin at seat reference point. The resulting model has the form:

$$c_i = \sum_{j=1}^{m_k} b_j f_j(\text{RIGHT, LEFT, FRONT, BACK, NORTH}) \quad i=1,\ldots,9 \qquad \text{(Eq. 2)}$$

where: (1) c_i is a spherical harmonic coefficient of Equation 1; (2) b_j is a least squares parameter estimate; (3) f_j is a stepwise regression entry of first order, second order and first order interactions of the independent variables; and (4) m_k is the number of significant ($p < .10$) coefficients (Boydstun and Kessel, 1980). The average R^2 values for the general individual model is 0.801 as compared with 0.820 for the individual model. Thus, the decrease in model quality is negligible although a validation study is appropriate.

MAXIMUM REACH MODELS FOR HANDICAPPED PERSONS IN WHEELCHAIRS

The deviation of individual maximum reach models is based on a study of 4 male and 2 female subjects (Boydstun, et al., 1980). The individual right hand models yielded an average R^2 of 0.92 with minimum and maximum values of 0.79 and 0.97, respectively. The individual left hand models yielded an average R^2 of 0.92 with minimum and maximum values of 0.80 and 0.97 respectively.

General individual models were derived for right and left hand reach based on anthropometric measures. The models have the form:

$$c_i = \sum_{j=1}^{m_k} b_j f_j \text{ (SITTING HEIGHT, SHOULDER HEIGHT, SHOULDER BREADTH, ARM LENGTH)}$$

where ARM LENGTH corresponds to either the right or left arm length including the hand. The models yielded average R^2 values of 0.86 and 0.85 for the right and left hands, respectively. The average decrease in R^2 values in comparison with the optimal least squares models is 0.06 and 0.07 for the right and left hands, respectively.

A general model based upon a reduced data set (Equation 2) with origin at seat reference point yielded an average R^2 of 0.90 and 0.91 for the right and left, respectively. The average decrease in R^2 values in comparison to the optimal least squares model is 0.02 and 0.01 for the right and left hands, respectively.

DISCUSSION

The maximum reach models extend the capabilities of present analysis procedures to include sequential reach analysis for a particular individual. Thus computer aided procedures may be used in job analysis to compare individual reach capabilities with job requirements. Individual reach predictions may be derived by collecting a complete maximum reach data set and deriving an individual model or by using the general individual models. Derivation of an individual model will be required for many job analyses since available general individual models are limited to seated pilot and handicapped reach configurations. Additional general models should be derived for other configurations including work bench operations, standing postures, etc.

The time required to derive individual models is substantially reduced by the spherical harmonics technique. Data collection time is typically less than two hours and analysis time is negligible. Thus the development of general individual models is greatly facilitated.

The models also provide the capability of providing population estimates for sequential reach points. This may be accomplished either with simulation techniques for a sample of individuals or with a general anthropometric model based on available anthropometric population data. Additional general models must be derived to realize this potential.

Finally, it should be noted that validation studies should be performed before using the general models in applications, particularly for the handicapped reach data due to the small sample size.

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ISSUES IN THE STATISTICAL MODELING OF ANTHROPOMETRIC DATA FOR WORKPLACE DESIGN

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The use of equations to represent the physical characteristics of humans dates almost from the beginning of multivariate statistics. Although equations based on anthropometric data were used during the early 30's (see Rao, 1952), these dealt principally with such applications as skull classification and involved extremely limited data sets. Prior to 1940, there was only a limited understanding of the need for multivariate data and virtually no awareness of its potential uses in design. The extensive experience with operator crewstations obtained during World War II identified vividly the need for more effective use of anthropometry in military systems and pointed out the importance of systematic attention to operator size diversity in workplace layout. Although the necessity for multivariate measures for this purpose was well defined by the early 1950's (Daniels, 1952), the computational machinery of that period imposed significant limitations on the techniques that could be employed. Despite the basic work of Dempster (1955), these limitations constrained any serious development of statistical models and the focus was necessarily on specifications, standards and design guidelines using univariate and bivariate data distributions.

By the middle 1960's, as computer technology advanced, realistic multivariate models for workplace design became feasible, and a period of rapid development followed. The work of Ryan (1971) and others under the JANAIR project culminated in the BOEMAN link-model and later in its close relative, the Crewstation Geometry Evaluator (CGE) (Katz, 1972). Although CGE/BOEMAN is still a powerful and relatively complete reach/interference analysis technique, even at its inception it was somewhat obsolescent in its batch input and output and off-line graphics. As developments in real-time computation and interactive graphics continued, a number of more modern models were undertaken, based in varying degrees on the Dempster (1955) link system and the original BOEMAN. The COMBIMAN (McDaniel, 1976; Evans, 1978), SAMMIE (Bonney et al., 1976), CAPE (Bittner, 1975), CAR-I (Edwards, et al., 1976), CAR-II (Harris, 1980) and the PLAID system (Lewis, 1979) are all user-interactive computer models for determining the anthropometric feasibility of a workspace layout. Although they share common ancestries, these models also reflect some distinct differences in design philosophy and intended usage. These differences are significant in highlighting an apparent paradox in the building of anthropometric models. Up to a point, broadened capability within a model enhances both its efficiency and its usefulness to a designer; as more and more features are added beyond those required for intended applications, the potential for decrements in model performance and problems in user acceptance increases concomitantly. Configuring or revising a workplace design model demands some attention to the causes and resolutions of this paradox.

The powerful hardware/software/graphics systems of the last decade have continually expanded the spectrum of capabilities and special features which can be incorporated into anthropometric models. A model developer with access to sophisticated equipment and elegant new algorithmic solutions may have extreme difficulty in remembering that not all these capabilities and features may be appropriate to his specific purposes. Each option in a computer model adds to core requirements, increases setup time and places an additional load on the model user in learning input procedures and ouput interpretation; timeliness of results is particularly affected by input/output complexity. Unnecessary or seldom-needed options inflate the costs and difficulties of model development, use and modification. There is thus a series of tradeoffs to be performed in determining the specific mix of characteristics of a model intended for routine use as a tool in workplace design. The purpose of this paper is to make these tradeoffs more explicit by defining issues to be considered in evaluating the need for model features and by exploring major options available to developers and users of workplace design methods.

GENERAL ISSUES

Deciding how to configure an anthropometric modeling system involves resolution of three related basic issues: 1) Who are the model users? 2) How general or specific are the intended applications? 3) What degree of complexity is required to perform these applications?

The question of the characteristics of intended users is critical to resolving other issues of specificity and complexity. A model targeted toward its own developers poses very different problems from one to be used by engineers not versed in anthropometric subtleties. A major problem with BOEMAN/CGE is the extraordinary difficulty encountered by the inexperienced user in coping with its complex setup and interpretive requirements. CAR, at the other extreme, achieves high user acceptance through simplified input and deliberate exclusion of otherwise desirable features. Focusing on modelers and anthropometric specialists as users allows increased sophistication and accuracy at the risk of decreased breadth of application.

The generality of a model, the number of distinct analyses accomplished within a single computer routine, strongly influences both convenience of use and the overall cost of application. For example, a model which does conventional reach analyses, carries out algorithmic checks for physical and visual interference and performs strength analyses, will require more data, more time to setup and run, and must generally be applied later in a development cycle than a model which focuses on one of these analyses alone. There are multiple application points and different aspects of design for which models can be useful. For each of these applications, tradeoffs can be made considering the user, the need for timely output, and cost factors in deciding whether and how to combine analyses.

The same types of tradeoffs apply in decisions about model complexities. A major determinant of complexity is the accuracy required by a given application. Simple models, using fewer parameters and less refined approximative techniques, may be valuable in early design to detect gross deficiencies, but insufficiently precise for full-scale evaluation as design evolves. The CAR model, for example, retains the CGE link-man,but aims at "quick and easy" reach analysis, eliminating graphics, reach interference checks and several other features. By such selective simplification, setup time for initial reach analyses was reduced to about 10 percent of that for CGE, with costs for comparable evaluations at about 1 percent of previous requirements. CAR thus provides a convenient and inexpensive alternative to more complex routines when time and cost are important. Such explicit trades between convenience, capability and cost can be made for other features and are useful resolutions to complexity.

Given that the developer has defined the requirements for his modeling system and evolved a consistent philosophy for its general structure, an additional series of questions about the details of model content will arise. The need for each of a number of specific model features and the method of implementing these features should be systematically examined within the framework of the modeling structure.

SPECIFIC FEATURES AND OPTIONS

Specified Percentile vs. Percentage Accommodation. BOEMAN/CGE and the majority of its successors perform reach and interference analyses on a link-man of some fixed percentile on each link; in some (i.e., COMBIMAN) the user may specify different percentiles for each link. A distinct alternative to this approach is the concept of "percentage accommodation" defined by Moroney and Smith (1972), introduced as a modeling feature by Bittner (1975) in CAPE and implemented in both CAR models (Edwards, et al., 1976; Harris, et al., 1980). The focus of percentage accommodation is the use of Monte Carlo methods to generate "random" link-men from a specified operator population, evaluating each for compatibility with a crewstation geometry and estimating the percentage of the population able to use the proposed layout. Such a procedure is particularly useful in quantifying the impact of crewstation layout deficiencies and in comparing a design to a target percentage. It is less powerful in detecting problems for individuals with severe mismatches between link dimension percentiles, since such individuals occur with low frequency in the population and are thus rarely drawn in the sample. Assessing the accommodation of "unlikely" operators is a strong point of properly utilized user-specified percentile models. Because of these differences in focus, the sequential use of both types of model is strongly recommended. CAR-II, described in Zachary (1979) and documented in Harris, et al. (1980), adds a specified percentile option to the percentage accommodation approach.

Enfleshed vs. Stick Models. Enfleshment, the construction of a "body" around the link-man, is highly desirable for models which carry out interference checks, evaluation of escape envelopes, or other analyses which examine volume overlap between the operator and the crewstation. The use of an enfleshed figure is of little or no value in reach distance assessment, visual interference checks or other distance-based evaluations. Current models vary in extent and method of enfleshment from the stick models of CAR and CAPE to the highly realistic COMBIMAN and BIOMAN (Frisch, 1978). Enfleshment entails a high computational overhead; whether it is used within a model and the detail with which it is accomplished should be critically evaluated for each application. It is important that enfleshment capability match, but not materially exceed, defined requirements.

Clothed vs. Unclothed Operators. Operators who wear heavy or restrictive protective clothing show dramatic changes in reach envelopes due to shifts in link pivot locations and reductions in joint mobility (Gregoire, 1977). Models intended for classes of applications which require special clothing or equipment should provide options which reflect these changes and differentiate, if necessary, between heavy and light protective clothing. Implications of clothing for accommodation are further defined by Harris, et al. (1980).

Graphics Requirements. On-line graphics drawings of an operator within a crewstation can be used by a skilled designer for subtle detection and diagnosis of interference problems. Graphics can provide clear documentation of difficulties once they are detected, and enhance the credibility of findings to a customer not experienced in anthropometry. It should be noted, however, that graphics are not critical for many routine analyses (i.e., reach distance) and the use of graphics for these analyses often requires considerable experience. Further, the complexity of on-line graphics is often the major factor in the cost of developing and operating a modeling system, particularly when combined with detailed enfleshment. Tradeoffs for graphics use can thus be critical in satisfying model requirements. The transportability of models between computers and access by field users are significantly constrained by graphics systems. When time and cost are important, models without graphics or with off-line graphics should be considered, followed if necessary by interactive graphics analyses in later design stages.

Seated vs. Freestanding Operator. Most existing models were developed for evaluation of workplaces with seated operators, and link-men are constructed from either a seat reference point or a design-eye point. SAMMIE, developed for industrial applications, uses a foot-anchored reference system, thus accommodating standing operators. Although there are minor problems in translation across the three reference systems, algorithms can be modified to allow evaluation options for standing or seated operators, with accommodation for both fixed and adjustable seats and fixed/adjustable foot controls (see Zachary, 1979). These options should be considered for all reach/interference models.

Male/Female Differences. Current models literally use a link "man." Transformation of measurements to link values is done with link/measurement ratios and measurement intercorrelations based solely on male populations. Similarly, joint mobility limits are derived entirely on the basis of male data. Since women differ on numerous skeletal and muscular features, the extent to which these parameters can be generalized to female populations is not well understood. Ketcham-Weidl and Bittner (1976) found reasonable results from CAPE when correlations based on males were used with female measurements for Monte Carlo simulations. Hosler and Morrow (1980) concluded that size differences between male and female populations in seated crewstations are far less important for accommodation than are differences in strength. Although female-specific parameters must eventually be obtained and incorporated for proper validity, these findings suggest that current models may offer at least reasonable approximations of female accommodation using male-derived model structures.

Strength Models. The question of whether an operator can generate sufficient force to operate a control or actuate an ejection seat is a major concern in workplace modeling. The issue is not whether the modeling of such a capability is ultimately required; it is rather its inclusion in a general computer model vs. development of a separate strength model. Even the restricted case of force exertion for a seated operator is complex, with major interactions between key variables that must be included to achieve acceptable accuracy. Ayoub et al. (1979) summarize data on strength requirements and Bittner and Ayoub (1979) describe a structure for modeling force exertion tasks. The tradeoff is the convenience of all analysis within a single model against the computational overhead and input complexity of supporting a strength model on occasions when only reach or interference analyses are desired.

Extended Seat Back Angle/High Acceleration Cockpits. Most current models presuppose a seat back angle for a seated operator between 0 and about 30 degrees. When the angle materially exceeds this range, existing linkage systems and joint mobility data are of uncertain accuracy. Articulated seats and seats which recline to or near the horizontal such as the PALE tilting seat (Von Beckh, 1972) ar the High Acceleration Cockpit (Mattes and Roberts, 1975) can not be properly evaluated for accommodation by existing link-man models, since additional links in the torso would be required to manage articulation. To be effective on future fighter/attack aircraft crewstations, models must address and satisfy this requirement.

Gravity/Acceleration. Data used by most workplace models assumes a one-G environment. Changes expected in reach and force exertion under zero-G conditions are under study by NASA (1978). Movements of body segments under forces of acceleration/deceleration are addressed by such efforts as BIOMAN (Frisch, 1978) and the Articulated Total Body model (Kaleps, 1978). Realistic response of a link-figure to acceleration is a key part of modeling ejection envelope clearance and involves heavy computational load. These analyses should be performed separately from conventional workplace modeling, although common data files and shared graphics structures for the two model classes are both feasible and economical.

CONCLUSIONS AND RECOMMENDATIONS

The issues and options discussed above define an immensely complex series of decisions and alternatives to be considered when constructing or modifying a statistical model. There are two basic approaches to resolving these decisions. The first incorporates all required features and capabilities in a single model for general use in all aspects of workplace design. Sufficient experience in using workplace models is available to suggest a reexamination of the single general model as an ultimate goal and to prompt a deliberate movement toward a second approach, a series of special-purpose models tailored to specific design problems.

There are numerous advantages to the use of less complex special models for initial problem detection and diagnosis. Such models are relatively inexpensive to develop and operate, have simple input and output, give quick turnaround time on analyses and can be used by the broadest possible user community with few concerns about transportability. The emphasis in these models is on cost, convenience and speed, for applications in early design stages.

Once initial problems of accommodation are identified, it is of value to move to more refined models of greater accuracy for in-depth followup of problems. These models will have a heavier focus on precision and accuracy and can utilize special features not required or practical in the design screening models; analyses are performed in greater detail and require the involvement of anthropometric specialists to interpret and to make best use of model outputs. The procedure of preliminary screening of workplaces followed by in-depth resolution of problem areas is cost effective, makes good use of anthropometric and engineering design skills and provides a level of accuracy appropriate to needs at each stage of analysis. Serious consideration in future model development should be given to this concept of sequential application of such special-purpose models.

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Session IV
Maximum Voluntary Exertion Data

OVERVIEW OF METHODS TO ASSESS VOLUNTARY EXERTIONS

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1. INTRODUCTION

A variety of methodologies have been utilized in attempts to measure muscle strength. These methods can be grouped according to two types of strengths which are tested. These are static and dynamic strengths. Dynamic strength is defined by Neilson and Jensen (1972) as "... the ability to apply force through the range of motion." The resistance which isotonic muscle contractions can overcome can be used as an index of muscle strength. Static strength has been defined as the maximal force muscle can exert isometrically in a single voluntary effort. All strength can be classified under these two classifications.

2. DYNAMIC STRENGTH

Fleishman (1964) has developed a series of 30 tests designed to measure what may be called maximum dynamic strength. Some of these tests involve moving or supporting the weight of the body repeatedly during a specified period of time; such as pull-ups, pushups, rope climb, sit-ups, and leg lifts. In other tests (softball throw, vertical jump, standing broad jump) subjects performed the exercise for a specified number of trials and their best score is recorded. A third procedure requires subjects to perform the exercise for as long as possible. Tests using this method include the bent arm hand, leg raiser, and hold half push up. Bavard, Cozens, and Hagman (1949), Larson and Yocom (1957), and Matthews (1973) discuss test batteries that contain a number of tests quite similar to those described by Fleishman, Neilson and Jensen (1972) also describe a number of dynamic strength tests similar to those described by Fleishman. In addition, they present somewhat less strenuous versions of these tests to suit the needs of females.

These tests may be worthwhile in that they are easy to administer, require little equipment, and can be completed in two minutes. Their disadvantages lie in the facts that no partial credit is awarded and a relatively small sample of the body's muscle groups are tested. It should be noted that some investigators may not consider some of the tests described above as valid measures of strength, but rather measures of endurance.

Other measurements of dynamic strength has been made using a different approach than that reported by Fleishman. Such technique has been reported by several investigators. Such techniques have been reported by Doss and Karpovich (1965) which measures muscle strength during isotonic movements, both concentric and eccentric. Asmussen et al. (1965) reported similar measurements.

3. EQUIPMENT USED TO MEASURE DYNAMIC STRENGTH

The measurements similar to those proposed by Fleishman do not require any equipment, however, specific equipment has been developed for some meausrements. Such equipment is the Kelso-Hellebrandt ergograph (Hellebrandt, 1948) which measures a series of repetitive movements and not a simple maximum effort.

Another apparatus used to measure dynamic strength is reported by Asmussen, et al. (1965). They constructed a dynamometer that measured the force exerted by the elbow flexors and the extensors. The apparatus measured the subject's strength as he either pulled the handle towards him or resisted the pull of the handle as the piston drew it away from him, however speed of contraction was not controlled.

A more sophisticated commercial apparatus is the Cybex dynamometer, capable of measuring static and dynamic strength. Although the apparatus was not developed specifically for this purpose, it can be used for measuring strength (currently being used and assessed at Texas Tech University Laboratories). The apparatus uses a hydralic system and can provide the work done using a work integrator.

4. STATIC STRENGTH

Other than the definition given by Kroemer for static strength, Neilson and Jensen define it as "... the ability to apply force at a particular position without moving through the range of motion (1972). Static strength has also been defined as the capacity to produce torque or force by a maximal voluntary isometric muscular exertion. It is the most used measurement for human strength. Differences have been reported in the literature between Static and dynamic strength. At the same time, high correlation has been reported between the two measures by some investigators (Asmussen et al. 1965).

5. EQUIPMENT USED TO MEASURE DYNAMIC STRENGTH

A variety of instruments have been developed to measure static strength. The manuometer (Matthews, 1973) is a spring device used to measure static strength of the finger flexors. Spring type devices such as the tensiometer are considered inexpensive means of measuring static strength. In 1949 Newman introduced a hydraulic myometer. The cybex is one of the latest hydraulic type apparatus in use.

Strain gauges are often used in present day studies of strength (Wasserman, et al. 1974). The strain gauge is fixed in a circular steel ring or an L-shaped bar. The amount of force that is being applied is determined by amplification and the use of appropriate recording system. Recent equipment have utilized load cells to measure human strength with digital readout capabilities. Some of these have also capabilities for averaging and holding maximum values.

6. TESTING PROCEDURES

STATIC	DYNAMIC
(I) Protocol for Measurement	
(1) A maximum steady exertion for a total of 3 seconds should be performed.	(1) A maximum steady state range of movement at a given speed should be completed.
(2) The strength score should be taken as the mean or maximum score during the 3 seconds.	(2) The strength score is a continuous position dependent value. Values at different angular position (or similar other identifiers) should be reported.

(3) N/A

(3) Speeds are normally varied to establish the functional relationship between dynamic strength and speed of movement.

(II) Subjects

(1) Subjects should be screened prior to selection (can be a function of the purpose).

(2) Subject is usually instructed not to jerk, but to increase exertion to maximum during a 4 or 5 second period.

(2) Subject usually instructed to jerk but "pick up" the instrument and apply maximum force during the prescribed movement range.

(3) Provide qualitative feedback to the subject about their general performance. Elicit any comments about any problems he/she may have experienced.

(4) Rewards and/or competitive incentives change levels of motivation and hence bias the strength scores.

(5) Rest periods should be provided. These rest periods should not be less than 2 minutes.

(III) EXPERIMENTAL CONDITIONS

(1) Describe the segment of the body involved (or the muscles involved). Describe the movement (flexion, extension, abduction, ..., etc.).

(2) With interest in space activities, the level of gravity should be also described.

(3) Body posture assumed should be described. Is the subject sitting, standing, prone, supine, ..., etc.

(4) If the subject is strapped, the experimentor should describe it.

(5) The device or equipment used should be fully described with particular reference to how the coupling between the subject and the device is accomplished.

(6) Special attention should be given to the moment arm through which the force is applied. It's length should be reported.

(7) If strength is measured in units of force, then this vector should be described in terms of direction and magnitude. If it is measured in units of torque, then direction, magnitude and moment arm should be given.

(IV) <u>SUBJECT IDENTIFIERS</u>

(1) The sample size, the population it represents and how the sample was stratified should be reported.

(2) If any screening of subjects was made, the criterion or criteria used for screening should be reported.

(3) Sex and age of the subject, height and weight, or other characteristics of interest for the study (body build, lean body mass, ethnic origin, ... etc.) should be reported.

(4) Any training received relating to strength prior to testing should be discussed.

(V) <u>DATA PRESENTATION</u>

(1) Generally, the mean and standard deviation are reported. Median and mode occasionally reported. Fifth, 50th, and 95th percentiles are occasionally reported.

(2) The underlying distribution should be reported if known. If assumed normal, this should also be identified. Skewness should be also reported.

(3) Minimum and maximum values should also be reported.

7. VARIABLES AFFECTING STRENGTH MEASUREMENTS

One procedure involved in strength testing which varies among tests is the manner in which the subject's representative score is determined. Some investigators select the best score while others use the average of several trials. Berger and Sweney (1965) and McCraw and Talbert (1952) report that reliability coefficents change if best scores are correlated rather than average scores. Henry (1967) and Jones (1972) dispute this, however. Test batteries vary in that some call for a standard testing order while others utilize a random testing order.

Another procedure involved in strength testing is the instructions given to subjects concerning how to exert maximal force. Kroemer (1970) points out that although few studies describe such instructions, they can affect the outcome of strength tests. Kroemer told subjects to exert force in one of three ways: exert and hold maximal force for five seconds; apply gradually increasing force until maximum is reached; apply maximal force suddenly, twice. These three methods of applying force resulted in distinctly different force curves. Further, Kroemer (1979) has found that subjects who are instructed to build up force rapidly achieve higher peak strength scores than subjects who are instructed to build up force slowly.

A number of other factors have been found to affect strength scores. Among these are the subject's motivation (Berger 1967; Johnson and Neilson, 1967); the position of the body (Williams and Stutzman, 1959); environmental stimuli (Ikai and Steinhaus, 1961); and anthropometric characteristics of the subjects (Clarke, 1957). Cladwell, et al. (1974) has developed a standard procedure for testing static muscle in order to reduce variation caused by these factors.

In conclusion, there are several problems which must be addressed. These are: (1) a standardized procedure for dynamic strength, further refinements for the procedures for static strength. (2) Comparison between static and dynamic strength. This is particularly important to establish the usefulness of each and their more appropriate applications. (3) To obtain data for specialized occupational population in addition to female data. Therefore, more effort should be given to provide these data. (4) To develop a program to evaluate the equipment designed particularly for training, but used for strength testing to determine its usefullness and hopefully establish some specification for human strength measurement equipment.

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POSTURAL CONSIDERATIONS IN MAXIMUM VOLUNTARY EXERTION

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This paper is concerned with maximal manual exertions in the sagittal plane while standing; the whole body is therefore involved. Body weight and a choice of posture in which weight can be used to advantage constitute one factor governing exertion. Its effect is analogous to the force that a log of wood, leaning against a handle, would exert in the Dead Axis (Fig.1), perpendicular to the line between the handle and the ground support. In the 'dead weight' analogy, the force depends only upon the weight of the log and where its mass is centred relative to the ground support and the handle. Muscular capacity constitutes a second factor in exertion, which also depends upon posture; an analogy is the force that a Jack-in-a-Box exerts. The force is in the Live Axis (Fig. 1) which is the line between the centre of pressure at the ground and the handle. Although ded-weight and Jack-in-a-Box effects both operate in exertion, they cannot be readily separated. The log of wood retains its shape by virtue of tensions and compressions in its fibres. Man retains his posture by means of tensions in muscles and ligaments and by compressions within the skeleton. Man's muscles are required both to retain the posture and to create the 'Jack-in-a-Box' forces.

If we measure the vertical or horizontal force-components in maximal static lifts and pulls respectively, with various placements of the hands and feet (together)(Fig. 2), we may calculate the Dead-Weight Fractions of the variance of strength which are accounted for by variances of weight and height in the population (Pheasant, 1977). Nearly 70% of the variance is accounted for when the measurement is close to the Dead axis, but only 20% when it is close to the Live axis. It is clear that forces in the Dead axis counterbalance the action of body weight about the centre of foot pressure, while any force can exist in the Live axis without disturbing the equilibrium.

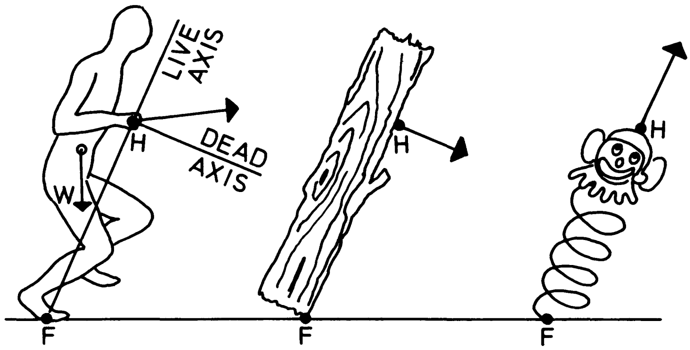


Fig. 1. Left: Manual force in exertion, showing Live & Dead axes.
Centre: Dead-weight analogy of exertion in Dead axis.
Right: Jack-in-a-Box analogy of exertion in the Live axis.

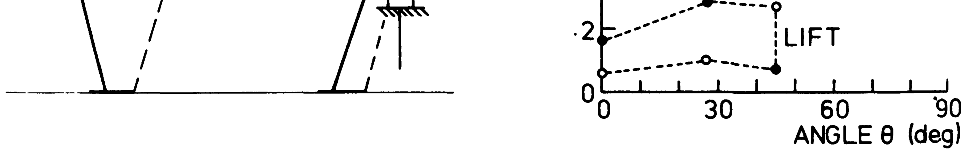


Fig. 2. Left: Measurements of the horizontal component of a pull and its angle to the hand-toe line, or the vertical component of a lift and its angle, for various placements of the hands and feet.
Right: The Dead-Weight Fractions (DWF) as a function of the angle between the measured exertion and the hand-toe line for 9 different static lifts and pulls.

In the general case of exertion in any direction, the man in Fig. 3 is exerting a force which has components of LIFT and PUSH (PRESS & PULL if negative), and also a torque TWIST. The torque may be important if the hands are separated in the sagittal plane, but were negligible in the experiments for which results are presented. The experimental rig incorporates a bar handle, fitted with force transducers to measure the manual forces. The LIFT and PUSH components of force generate signals which drive an X-Y recorder; deflections from the centre of the chart therefore represent the force vector. The chart (Fig. 3) is called a Postural Stability Diagram (PSD). Since static exertion is represented, the scales around the edge of the diagram may be used to consider the forces at the feet which accompany the manual forces.

By encouraging the subject to exert forces in all directions, allowing rest pauses to avoid fatigue, a record is obtained (Fig. 4) whose envelope contains all possible force vectors. The radius of the envelope is measured in 36 directions, 10 degrees apart, around the clock. Means and standard deviations of the 36 force vectors for a group of subjects are then calculated. Interpolations at other angles are satisfactorily obtained by means of a periodic cubic spline function, with the exception of the 10 degree intervals in which the function predicts a maximum of minimum. In these intervals, the interpolation is weighted in the ratio 4:1 in favour of linear interpolation.

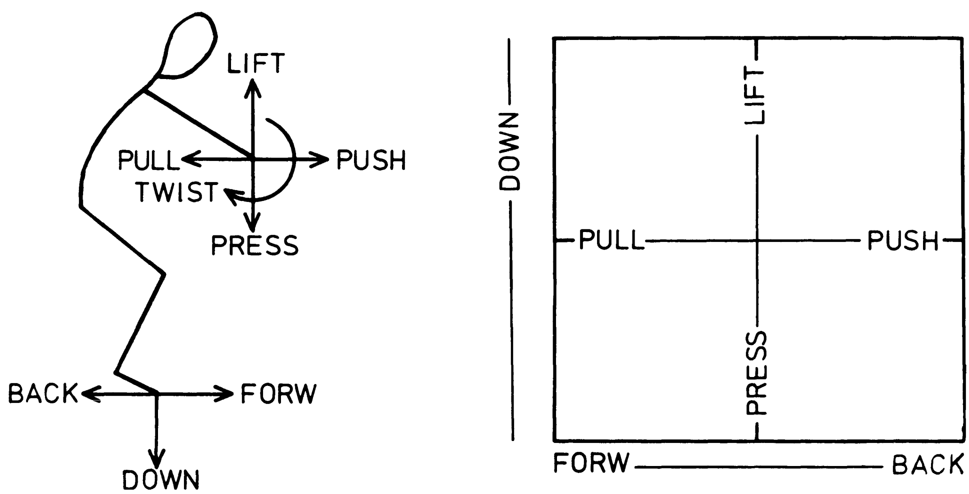


Fig. 3. Forces that man may exert on the environment and the Postural Stability Diagram on which they are represented.

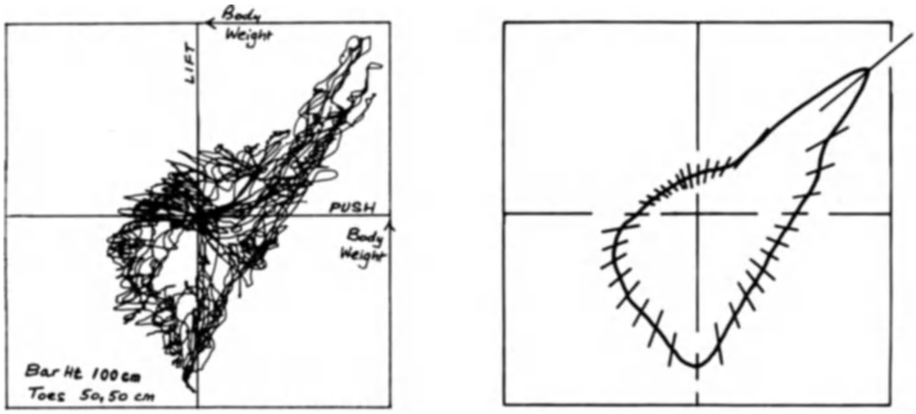


Fig. 4. Left: Experimental PSD record (hand height 1m, toes 0.5m to rear. Right: Means ± 1 sd, 10 males, same conditions. The envelope is based on a periodic cubic spline function.

If we consider the static balance of the man in Fig. 5, by taking moments about the centre of foot pressure, we obtain the Equation of Static Exertion (ESE):

$$\text{LIFT}/W = (h/b).\text{PUSH}/W \; -(a/b) \; -(\text{TWIST}/b.W)$$

This simple equation is given a special name because it links some important quantities, namely the LIFT and PUSH components of force at the hands, the weight of the body, the centre of pressure at the feet and the position of the centre of gravity. The ESE can be represented as a line on the PSD (see Fig.5). The slope of the line is the slope of the Live axis. The intercept on the base of the PSD (LIFT/W= -1) equals the horizontal distance of the centre of gravity from the handle as a fraction of handle height. The perpendicular distance of the line from the origin represents the Dead-weight force. The Jack-in-a-Box effect is to generate forces whose vector heads are varying distances along the line. At any instant, static exertion is made according to a particular ESE. If a required force is not on the line, the slope and/or the intercept must be altered to accommodate the vector. The slope is altered by changing the centre of pressure within the foot base. The intercept is altered by moving the centre of gravity of the body. The ESE states what combinations of LIFT and PUSH are possible in a given posture and manner of support. It does not, of course, say what actual force can be generated, because that is a matter of choice if it is sub-maximal, and subject to physiological constraints, not merely the laws of statics when maximal.

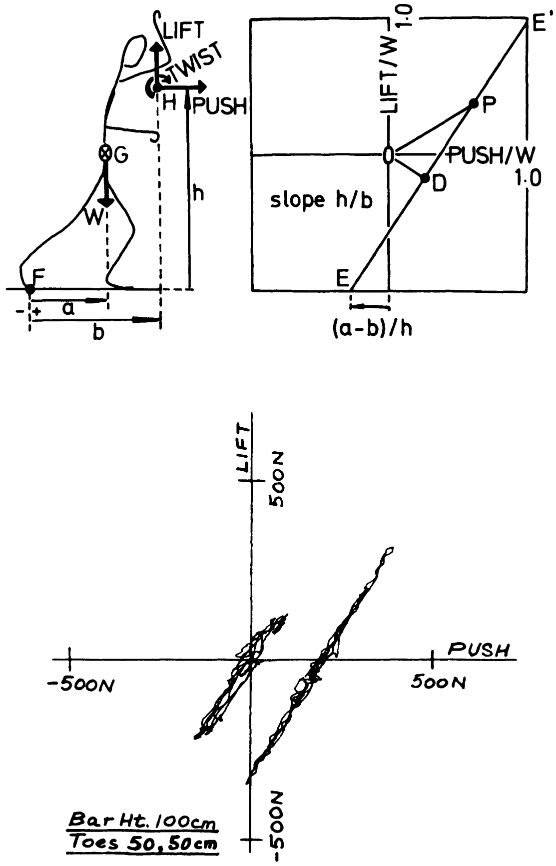


Fig. 5. Top left: Diagram illustrating the quantities which appear in the Equation of Static Exertion.
Top Right: The ESE plotted as line EE' on the PSD. Vectors OD and DP may be recognised as the dead-weight and Jack-in-a-Box components of the manual force vector.
Bottom: ESEs observed experimentally with a subject standing on his metatarsal heads. Lines obtained in two postures which differed by virtue of a shift of the subject's centre of gravity (a-b), but the hand and foot centroids (h/b) did not alter.

The experimental record in Fig. 5 shows that the ESE is operative. The subject maintained a fixed posture and stood on the heads of his metatarsals, while trying to exert forces in as many directions as possible. He then shifted his weight and repeated the exercise. The Live axis was the same for both postures so that the records obtained both had the same slope. The effect of shifting the centre of gravity was to change the intercept of the line which contained the heads of the vectors.

Studies of manual exertion have been mainly devoted to lifting tasks, although horizontal pushing and pulling have also received some attention. In contrast, very little data is available concerning the general case of exertion in any direction. If they were, the information could be used in the design and analysis of tasks. A framework for the application of PSDs to task design was outlined by Grieve (1979 a, b). Consideration has so far been given to analysis in the sagittal plane. Our experiments are designed to provide an appropriate data base in PSD form. The merit of the diagram is that other statements besides strength can be made on it. These include task demands and environmental constraints such as floor friction; superposition of the statements allows the task designer or safety engineer to consider how satisfactory a match exists between the operator and the environment.

Fig. 6 contains 12 PSDs which show the mean forces that can be exerted relative to body weight, in a variety of foot and hand placements. The columns, left to right, refer to hand placements of head, waist and shin height. The rows, top to bottom, refer to feet together with shoe-toes under the bar, with one foot 50cm to the rear, both feet together 50cm behind the bar, and finally with one foot at 50cm and the other 100cm behind the bar. The force in any particular direction is systematically affected by both foot and hand placement; this fact suggests why the information is relevant to task design. For example, we see in Manoeuvre 2 (hands at head height, toes 50 cm behind the bar) that subjects have an ability to exert themselves in the Live axis and also to press downwards, but they are otherwise quite weak. In contrast, the subjects in Manoeuvre 5 (hands at shin height, toes beneath the bar) have considerable strength in all directions in which a LIFT component is involved.

By means of a large balance board, the limiting anterior and posterior locations of the centre of gravity were determined for each combination of foot and hand placement. Limiting ESEs apply when the centre of pressure at the feet is at the anterior limit of the foot base while the centre of gravity is at its posterior limit, and vice versa. The extreme lines (average slopes and intercepts) are drawn on the PSDs in Fig. 6. The limiting lines come close to, or touch, the force vector envelopes in many cases. It is concluded that the limiting combination of anterior foot

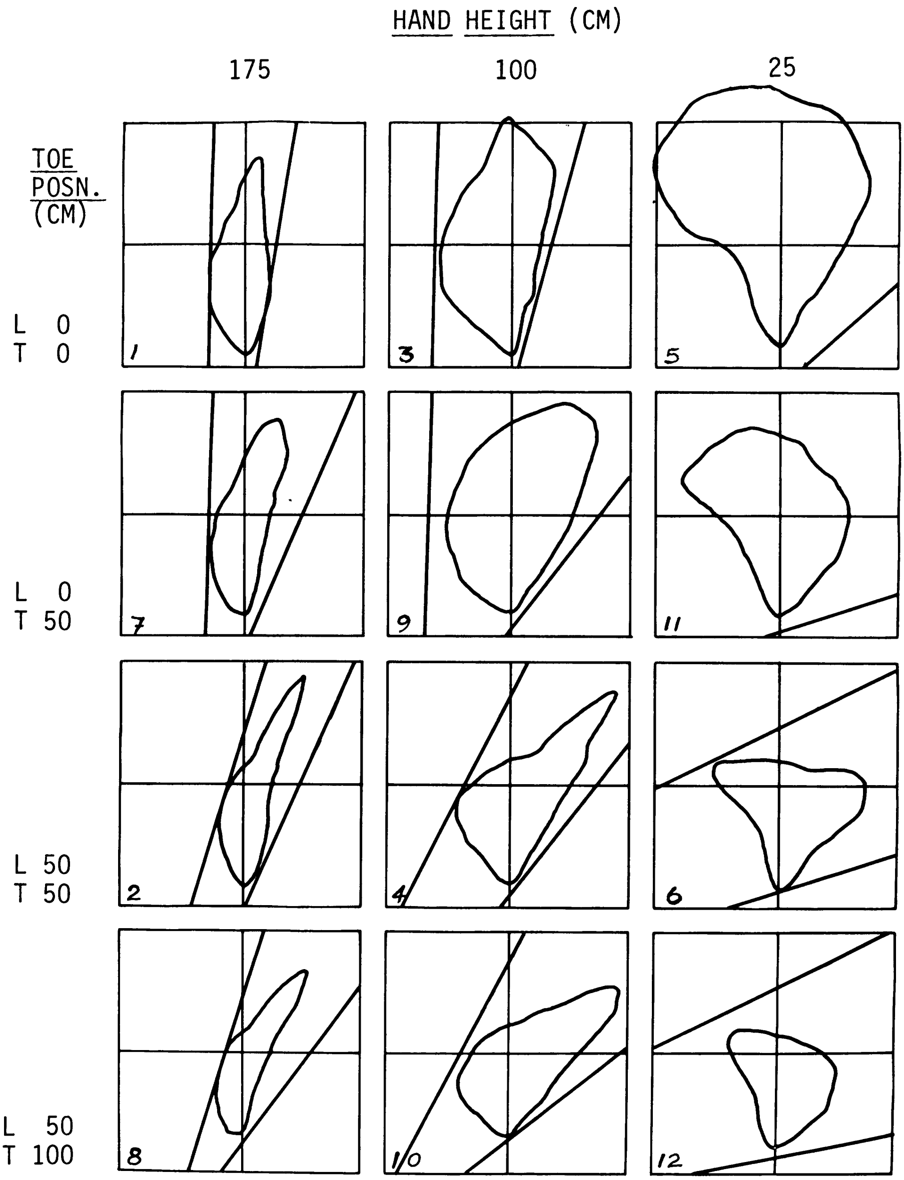


Fig. 6. Mean PSDs obtained with males, for various heights of handle and various horizontal placements of the toes of the shoes (lead L and trail T) behind the bar. Ten subjects were measured in manoeuvres 1-6, of whom five were measured in manoeuvres 7-12.

support and posterior mass centroid is used. On the other hand, a trailing heel is not commonly used in combination with the anterior mass centroid, probably because its use would require an unacceptable degree of dorsiflexion of the ankle. Exertions in most directions are not apparently limited by the foot base and the distribution of weight; physiological explanations must be sought in most cases.

As more data is acquired, the present research should result in a descriptive model of exertion in which interpolative algorithms provide statements about static forces in any combinations of foot and hand placements and any direction of exertion. The predictions will be based purely upon observations of whole-body exertions. They will not require a set of assumptions about the properties of joints in the articular chain and will avoid lengthy iterative searches for optima which are features of some current synthetic models. The initial drawback clearly lies in the amount of experimental data required for confident prediction. Practical applications require a knowledge of space requirements as well as strength; recent experiments, with Miss Tendall and Mr. Livesley as collaborators, combine photogrammetry with force measurement. Figure 7 shows stick-men in postures associated with 8 directions of exertion which are based on computed averages of 10 subjects. The demands of maximal manual exertions upon the principal articulations are therefore calculable and are the subject of a current search for rules governing the optimisation of exertion and posture. The process is therefore the inverse of the synthetic approach, with the expectation that common ground for direct comparisons will emerge.

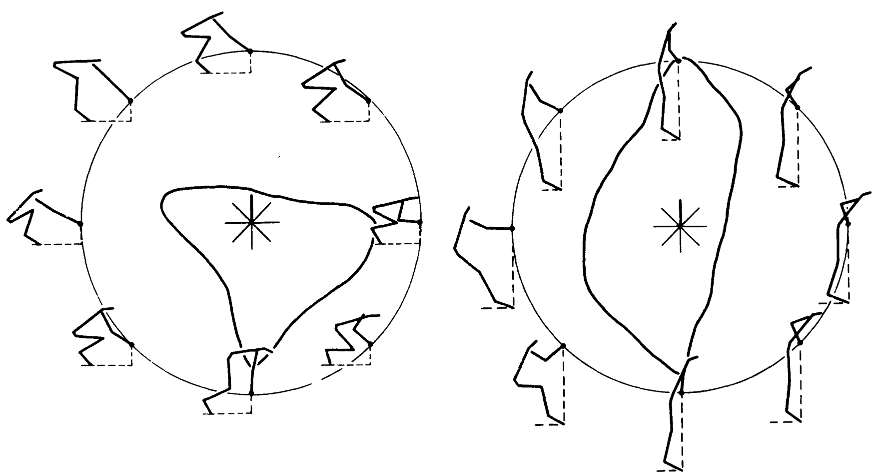
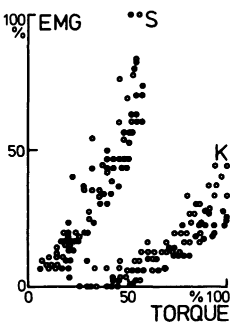


Fig. 7. Computer-averaged postures based on photogrammetry of 10 men exerting maximal forces in eight directions.

It appears to be an untested assumption that the behavior of the musculature acting across an articulation, in particular the maximum torque that can be generated, will be predictable from the same function of angle and other subject parameters during a whole body-exertion, as that observed during an isolated test of that articulation in which stabilisation and restraint of the body is provided. In addition, a subject engaged in sagittal exertion may often be observed to adopt postures which involve rotation of the hip and abduction of the shoulder from the anatomical position. Such changes imply that muscles operate at different lengths and mechanical advantages to those that would apply to postural adjustment confined to the sagittal plane.

The presence of bi- or multi-articular muscles introduces a further complication, which in theory at least, must be incorporated into a realistic synthetic model. To take one example, consider the mechanisms for exerting a plantarflexor torque about the ankle. In the extreme of dorsiflexion, tension in ligaments of the joint, coupled with compression of the articular surfaces will create a torque. A resting muscle, by virtue of its connective tissue, will exert tension if stretched sufficiently. In the case of gastrocnemius muscle, because of its femoral attachment,



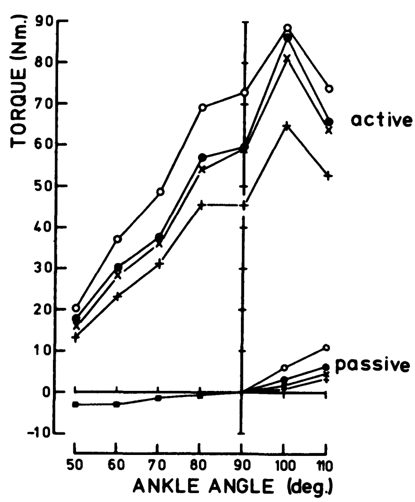


Fig. 8. Left: Plantarflexor torques at rest and in maximal exertion as a function of ankle posture. Knee at 0(o), 45(•), 90(χ) and 135 (+) degrees of flexion.

Fig. 9. Right: Surface EMG of erector spinae as a function of mid-lumbar extensor torque during upright pulling at shoulder height (S) and stooped pulling at knee height (K). Filled and open circles represent two subjects.

the degree of stretch is a function of knee as well as ankle posture. Fig. 8 shows that the passive torque at the ankle, when no electrical activity can be detected on the calf, is a function of knee posture (Pheasant, 1977). This effect may be attributed to tension in gastrocnemius muscle. Active ankle torque is also a function of knee angle, again because gastrocnemius is involved, but arising from the length dependence of tension in its active muscle fibres rather than its connective tissue stroma.

The documented case of the lady who lifted a motor car away from her son who was crushed underneath, but crushed some of her vertebrae in the process, suggests that the intrinsic strength of the musculature may sometimes be greater than that normally released by nervous activity. A more mundane experiment on the back muscles gave results (with similar findings for forearm supinators and ankle plantar-flexors, Grieve & Pheasant, 1976), which lend support to the idea of neural limitations. From estimates of the weights of body parts, a recording of the posture and a measurement of the manual force, the amplitude of the rectified and smoothed electromyogram from mid-lumbar erector spinae may be plotted against the calculated torque acting about the lumbar vertebral column. When the back is in an erect posture (Fig. 9), the muscles are relatively short and weak. During increasing voluntary effort a limit is reached in which further increase of EMG causes little or no increase of torque. It may be assumed that the muscles are fully activated and their intrinsic capacity is being used. With a flexed back, with relatively long and strong erector spinae, the approach to maximum effort terminates abruptly with no suggestion that further electrical activity would not produce further torque. This is strong evidence that further effort is limited, not by intrinsic muscle properties, but by neural inhibition, possible because potentially injurious stressed have been created somewhere within the body. Such phenomena emphasize the importance of comparing the predicted performance and articular loadings in synthetic models with observed performance in exertion.

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STANDARDIZED STRENGTH TESTING METHODS FOR POPULATION DESCRIPTIONS

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Over the last two decades, a substantial number of strength measurements have been gathered on a variety of populations from Olympic athletes to industrial laborers to infant toddlers. The primary intent of these data has been to develop guidelines for engineering design, to evaluate training and conditioning programs, and to determine potential risk of musculoskeletal injury for those engaged in manual materials handling.

CRITERIA FOR STRENGTH MEASUREMENT

There are many different ways to evaluate strength. In evaluating any method or technique it is important to agree on the criteria for measurement. The measurement should be 1) safe, 2) reliable, 3) quantitative, 4) practical, 5) predictive. For instance, a strength test which sets a specific goal for the subject may be unsafe for an overly motivated subject. Likewise, repeatability of the test result outside laboratory conditions, minimizing observer bias, simplicity in instruction, administration time and hardware requirements are all important. The last criterion is the most important while the most difficult to meet. Is the sample measurement predictive of future performance, capability or risk?

Two methods which at present appear to best meet some subset of these criteria and have been reported most extensively in the literature are isometric tests and psychophysical tests. The specific protocols recommended are described in detail by Chaffin (1975) and Snook (1978). Essentially, with the psychophysical approach the subject actually performs a lift, push, pull, carry activity and regulates the force exerted by adding or subtracting weight to the object handled. In contrast, with isometric exertions there is no movement and strength measured as the average force exerted during the middle 3 seconds of a 5-second exertion. Of course, both methods are actually psychophysical and neither represent physiological capacity.

INDUSTRIAL POPULATIONS

The most extensive results using the psychophysical approach with industrial populations in the U.S. have been summarized by Snook (1978) and Ayoub (1978). The most extensive data on isometric strength for U.S. industrial worker populations is reported by Chaffin, et al., (1977) and Keyserling, et al., (1978).

In the latter studies, 10 gross postures were used as shown in Figure 1. A total of 1239 workers in rubber, aluminum, steel, and electronic component processing industries were tested with the results shown in Table 1.

Attempts to predict these isometric strengths with regression models based personal attributes of gender, height, body weight, and sex have failed, in general, to explain more than 1/3 of the population variance. This precludes the use of population stereotypes in predicting an individual's strength. As a group, however,

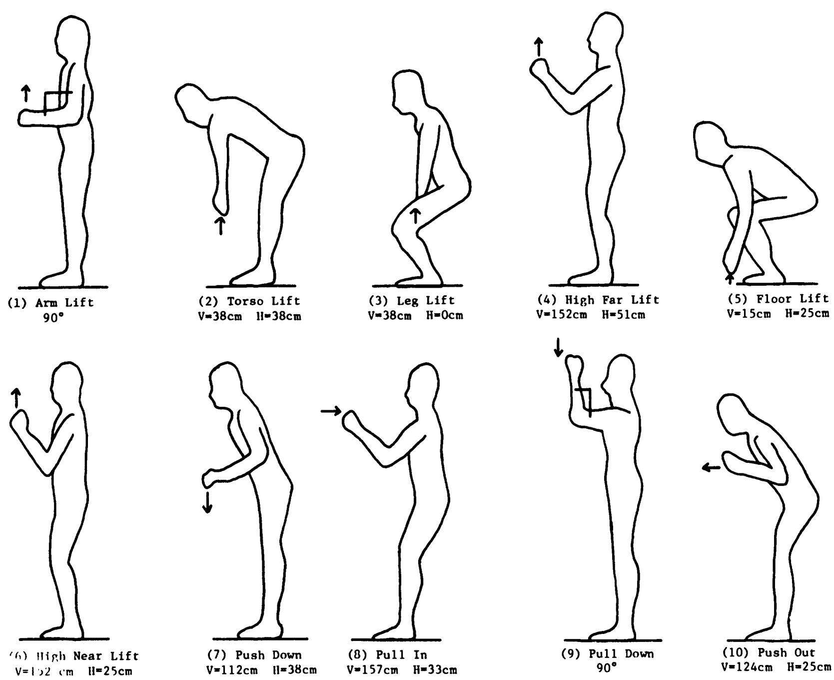

Figure 1: Strength Test Postures

Table 1: Maximal Voluntary Isometric Strength (kilograms)

TEST	ASSUMED DISTRIBUTION	SAMPLE SIZE	COEFF. OF VARIATION	MALES POPULATION PERCENTILE 10	25	50	75	90	SAMPLE SIZE	COEFF. OF VARIATION	FEMALES POPULATION PERCENTILE 10	25	50	75	90
1. Arm Lift	Normal	1052	.07	23	31	39	48	56	187	.08	9	15	22	28	34
2. Torso Lift	Log Normal	1052	.09	26	34	45	60	77	187	.10	13	17	24	33	44
3. Leg Lift	Normal	638	---	49	69	91	114	134	133	---	15	27	40	53	64
4. High Far Lift	Log Normal	309	.09	16	19	23	28	34	35	.12	9	11	13	16	19
5. Floor Lift	Normal	309	.08	59	74	91	108	123	35	.08	32	44	56	69	80
6. High Near Lift	Normal	309	.08	35	44	55	66	76	35	.11	16	22	29	36	42
7. Push Down	Log Normal	309	.08	34	39	44	51	58	35	.10	26	29	33	38	43
8. Pull In	Log Normal	309	.07	24	27	32	37	43	35	.10	19	22	25	29	33
9. Pull Down	Normal	309	.05	49	55	62	69	75	35	.04	32	39	46	53	60
10. Push Out	Log Normal	309	.08	23	27	31	37	42	35	.11	17	19	22	25	29

it is apparent that females are weaker than males, taller and heavier workers are strongest, and body weight is detrimental to strength with increasing age.

USE OF STANDARD TESTS TO PREDICT STRENGTH

Given that anthropologic measures are limited in their ability to explain strength differences between people, an alternative approach is to develop a set of standard tests which can predict strength in an arbitrary posture. Modeling the intercorrelations of these 10 gross posture tests allowed another 1/3 of the population variance to be explained. However, none of these strengths is a consistent predictor of performance on other tests as shown in Table 2. This raises serious questions concerning the use of standard (gross) tests to predict strengths in alternate postures. Further, more isolated muscle function tests such as grip strength, abdominal strength, etc., should give even poorer regression predictions, (Laubach, 1976).

The resolution of this problem requires either that 1) strength assessments be finely tuned to specific job simulations or improved biomechanical models be developed to extrapolate isolated function tests.

USE OF ISOMETRIC STRENGTH TO PREDICT PSYCHOPHYSICAL STRENGTH

Gross isometric strength measurements do appear to be correlated with more dynamic psychophysical strength especially with lifting

Table 2: Regression Equations to Identify Standard Strengths

Strength	Regression Equation	R^2	Std. Error
Arm Lift	Y = 17.6 + .225HF + .0939F + .257PLD + .139HN - 3.69S - .000954HxW	.578	6.24
Torso Lift	Y = -9.08 + .866HF + .0963F + .150HN + .00110HxW + .241AxS	.501	11.2
Leg Lift	Not tested	---	---
High Far Lift	Y = -2.94 + .0786F + .122AR + .163T + .000484HxW - .00120WxAxS	.602	4.87
Floor Lift	Y = 1.05 + 1.07HF + .365PSD + .775AR + .296HN	.569	17.5
High Near Lift	Y = -54.3 + .125F + .478AR + .155T + .523PO + .323H	.598	11.1
Push Down	Y = -17.7 + .0714F + .134PI + .252PLD + .231PO + .177H	.451	7.31
Pull In	Y = .656 + .106PSD + .0797T + .275PO + .000992HxW	.453	6.14
Pull Down	Y = 55.7 + .159PSD + .238AR + .0806HN - .330H + .00294HxW - .243WxS + .00277HxAxS	.698	6.33
Push Out	Y = 1.27 + .140PSD + .220PI + .157HN + .101W	.482	5.78

Legend: AR = Arm Lift HF = High Far Lift HN = High Near Lift PI = Pull In PO = Push Out
T = Torso Lift F = Floor Lift PSD = Push Down PLD = Pull Down H = Height
W = Weight A = Age S = Gender

tasks. Ciriellio (1978) found significant correlations of .56, .64, and .78 between isometric arm, torso, and leg strengths (postures 1-3 in Figure 1) and dynamic lift capacity between the floor and knuckle height for 14 industrial men.

A similar study at the Center for Ergonomics showed comparable results. Six subjects performed four trials with each of 3 different sized tote boxes (25, 50, 75cm), with and without handles, psychophysically and isometrically. The isometric tests were also varied to include freedom for posture selection and freedom for angle of lift. Correlations of .82, .84, and .79 were found between the isometric arm, torso, leg strengths and psychophysical strength.

The highest correlation (.87) was observed when the subject was permitted to elect the posture and lift angle of choice when simulating the lifting act in an isometric test. The lowest correlation (.74) between isometric and psychophysical strength was observed when the subject was required to isometrically lift vertically.

It is interesting to note that while the constraint to isometrically lift vertical showed a somewhat lower correlation (not significant), the prediction of psychophysical strength was less biased, as shown in Figures 2 and 3. For the unconstrained free posture and lift angle, the demonstrated isometric tests were roughly twice the psychophysical weights lifted. This confirms the belief that unconstrained isometric tests overestimate

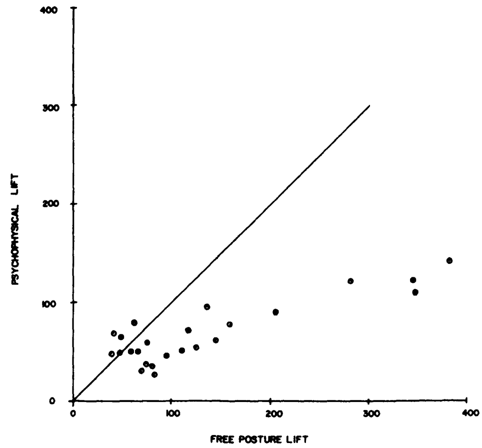

Figure 2: Comparison of Psychophysical & Free Posture Lifts

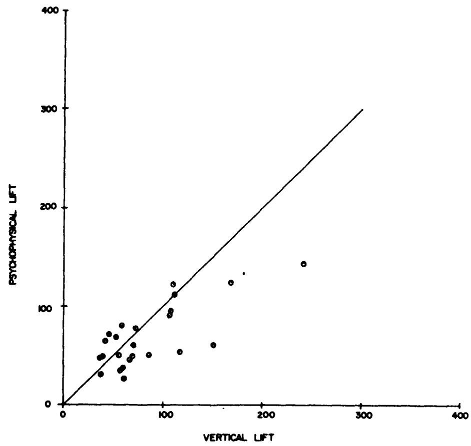

Figure 3: Comparison of Psychophysical & Vertical Lifts

psychophysical capacity. In this case, the artificial isometric constraint to lift vertically reduces most of the bias in prediction.

From a practical and predictive fidelity point of view however, both methods underpredict capability. In the earlier study (Chaffin, et al., 1977) it was noted that 44% of the population could not exceed their most stressful job strength requirements during isometric tests. It should be noted, however, that excessive musculoskeletal injury experience was the factor which motivated that study in the first place.

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EVALUATION OF CONTROLLED STATIC EXERTIONS IN VARIOUS MUSCLE GROUPS

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Abstract

The definition and description of static muscular exertions is a problem encountered in the attempt to create realistic and applicable mathematical models of the human body characteristics. When asked for a maximal effort, the human subject may present less than genuine maximal voluntary exertions (due to various motivational factors). Therefore these inaccurate inputs may account for some of the wide variability of results and the inability of many mathematical models to describe accurately the biomechanical situation.

Previous research has investigated the maximal and submaximal strength characteristics of elbow flexion (Marras 1978, Marras and Kroemer 1979). This was accomplished by investigating the parameters of the cognative feedback and control process one experiences during a contraction. The present research extends the scope of the research to other muscle groups.

Cognative Control

In order to exhibit a given strength score at a dynamometer, the subject contracts the muscles involved in a definite manner. Thus, the strength score to be exhibited determines an "executive program" in the cerebral and cerebellar parts of the central nervous system, CNS. According to this program, impulses are sent from the CNS to the muscles along the efferent pathways (Kroemer 1979).

While the muscle bundles involved contract, feedback about the contraction status is provided along several afferent pathways.

In the model, they are simplified into three different control loops. The direct feedback stems from the Golgi tendon and spindle organs of the primary active muscles. Secondary feedback originates at these sensors in other muscles, used to determine the relative insertions and relative origin of the primary muscles, depending upon which part is fixed. The third feedback is external, in such that it provides information about the score actually exerted at the dynamometer primarily through vision (such as seeing a pointer on an instrument) or audition (such as through the voice of the experimenter, or sounds of the recording device).

The strength of contraction of a bundle of muscles is regulated by two classes of coding, triggered by signals along the efferent pathways. Depending upon the threshold requirements of the contraction to be effected, two types of alpha-motor neurons are excited to initiate the contraction of extrafusal fibers. For low threshold exertions, small alpha-motor neurons are stimulated first which activate slow twitch fibers. For stronger exertions, more such motor units are activated. For high threshold exertions, larger alpha-motor neurons for the triggering of fast twitch fibers are also recruited. Thus, one method of regulating strength exertion consists of "recruitment coding" regarding the activation of the type and number of muscle fibers to be involved.

A second method to regulate the muscle strength exertion is through "rate coding." Here signals of increasingly higher frequency speed up the firing rate of the motor units with increasing tension.

According to this model, the regulation of a strength exertion requires a coordination of a complex feedforward and feedback system. If external feedback is excluded, a closed loop system is established that works as follows: depending upon the desired strength output, a stereotypical executive program is called up in the central nervous system. For low level (submaximal) muscle contraction, a delicate balance between recruitment and rate coding must be maintained rerequiring extensive feedback about the actual status of contraction. For a maximal exertion, both rate and recruitment coding are used from the onset to the fullest extent, with feedback required only regarding whether or not full muscular contraction is being executed.

The cognative control of the balance between coding systems appears to be highly individualized between subjects with respect to time (Marras 1978, Marras & Kroemer 1979). Therefore, the time required (strength buildup) for one to achieve muscle control for portions of one's strength exertions is expected to be linearly correlated with the portion of strength one is attempting to exert. This was the first hypothesis tested.

In addition, the experimental hypothesis can also be applied to the phase of maintained force exertion as required by the experimental regimen (Caldwell et al. 1974). Following earlier reports in the literature (Beck and Hettinger 1956; Laurig, Rohmert, and Zipp 1975; Rohmert and Sieber 1960) more variability during the phase of maintained force exertion should be expected at submaximum levels than at maximum levels. Accordingly the second hypothesis was that maximal strength exertions can be repeated by subjects without external feedback with less variability than submaximal exertions. This was tested in terms of variability analysis of a repeated measure design.

The Experiment

Twenty males and twenty females of college age were tested throughout their range of strength. The muscle groups tested were those involved in elbow flexion (EF), leg flexion (LF), leg extension (LE), and finger flexion (FF). Each subject was asked to repeatedly exert 25%, 50%, 75%, and 100% of his strength (in a controlled manner) for each muscle group.

Each subject's percent difference from his/her exertion level average for each exertion was used as input into the variability analysis to test the hypothesis that increased variability in repeated trials occurs with lower exertion levels. This analysis was performed for all subjects collectively and for male subjects and female subjects separately, for each type of exertion.

Each strength exertion was analyzed at the peak portion of the strength exertion curve and at the maintained level. Furthermore, the percentage of strength exerted was calculated as a function of each subject's 100% average and as a function of the greatest exertion. The variability analyses for these different data treatments are summarized in Table 1. If a variability trend existed, it was the reverse of that predicted by previous researchers. In general, the maintained portion of the strength exerted curve produced more

Table I - Summary of Significant Differences in Variability of Muscle Groups ($p \leq .01$)

Muscle Group	100% Average Based: Maintained	100% Average Based: Peak	Maximum Based: Maintained	Maximum Based: Peak
LF	*	*	*	*
LE	$\underline{*}$ $\underline{\dagger}$	$\underline{*}$ $\underline{\dagger}$	$\underline{*}$ $\underline{\dagger}$	$\underline{*}$ $\underline{\dagger}$
EF	$\underline{*}$ $\underline{\dagger}$		* $\underline{\dagger}$	*
FF	$\underline{*}$ $\underline{\dagger}$ $\underline{\nabla}$		$\underline{*}$ $\underline{\dagger}$ $\underline{\nabla}$	$\underline{*}$ ∇

* = group significance   † = female group significance

∇ = male group significance   _ = Trend of more variability as strength level increases significant variability results than the peak portion of the exertion curve regardless of how the percentage of strength was defined. Finger flexion produced the greatest significant difference in variability at requested levels. This may be due to a higher degree of tuning of the finger muscles.

The group summary of correlation coefficients of slope versus the percentage of strength for LF, LE, EF, and FF is presented in Table II. The table contains two group correlation coefficients for each exertion (along with the confidence limits): one related to the percentage of strength in the maintained portion of the exertion, the other to the peak portion of the exertion. The correlation coefficients between slope and maintained force were practically the same whether average maintained force or maximal maintained force were used as base values for the calculation of percentages. The same held true for the correlation between slope and peak percentages.

The correlation coefficients for the maintained and peak portions of the exertion seemed to follow each other rather closely. All group correlation coefficients were significant, supporting the hypothesis of the individual relationship between strength buildup and the portion of strength exerted.

The trend in these analyses seems to indicate that the more finely tuned the muscle group tested, the higher the correlation coefficient: arms and fingers are preferred for accurate tasks, whereas legs are generally employed when power is needed.

In summary, the experiments indicate the following:

1. Experimental hypothesis regarding the tradeoff between coding system controls appear acceptable on the basis of analysis of the data.

Table II - Group Average of Correlation Coefficients (converted from z scores) Between Buildup Time and Percentage of Strength

Muscle Group	$\bar{r}$ Maintained	95% Confidence Limit	$\bar{r}$ Peak	95% Confidence Limit
LF	0.790	$.635<\rho_{LF}<.884$	0.790	$.635<\rho_{LF}<.884$
LE	0.810	$.665<\rho_{LE}<.895$	0.785	$.625<\rho_{LE}<.880$
EF	0.850	$.735<\rho_{EF}<.920$	0.870	$.765<\rho_{EF}<.928$
FF	0.835	$.710<\rho_{FF}<.910$	0.860	$.750<\rho_{FF}<.923$

All group $\bar{r}$ are significant ($p < .01$)

2. The traditional notion that the level of strength exertion can be identified by the variability of repeated exertions can no longer be maintained. This study refutes again the assumption that larger variability should be expected at lower levels of strength capability exertion and that minimal variability should be expected at maximal levels.
3. This study confirms earlier findings by the authors that the speed of strength formation is related to the portion of avaliable muscle strength exerted. High correlation coefficients were found between the onset slope and the percentage of individual force exerted. This relation promises to provide a technique to ascertain whether or not a subject performs at the maximum possible strength level. Furthermore, it might provide a technique to assess at what actual level of strength capability the exertion takes place.

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ON-SITE MAXIMUM VOLUNTARY EXERTION MEASUREMENTS AND JOB EVALUATION

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INTRODUCTION

In recent years, measurements of muscular isometric maximal voluntary contraction (MVC) became popular with those involved in estimating capacity for physical work. One such example is the recently designed versatile unit for use by the U.S. Armed Forces Examination and Entrance Station (Knapik et al., 1979), which allows MVC measurements of the back extensors, arm-shoulder (upper extremities), flexors and knee-ankle extensors (lower extremities).

More specific approach was taken by investigators in Europe (Paulsen and Jorgensen, 1971; Pedersen and Staffeldt, 1972), and in the USA (Chaffin et al., 1976) who sought to measure the muscle groups crucial to manual material handling (MMH). The motivation behind these studies was the epidemic of muscular-skeletal, predominantly back injuries, which was found to be highly correlated with MMH (ILO, 1962; Magora and Taustein, 1969; Chaffin and Park, 1973). While the European investigators limited their measurements to the back extensors, the USA group designed a device to closely simulate lifting posture while measuring: knee extensors, back extensors, and elbow flexors. These devices met the major objectives for field measurements. That is, they were portable, sturdy, and easy to administer for rapid measurements of large numbers of people. Independent of these developments, we got involved with similar needs to devise a unit for use in on-site measurements of the MVC of workers in industry. We tried, as best possible, to isolate the muscle groups measured by applying the test to individual joints (Kamon and Goldfuss, 1978; Yates et al., 1980). This presentation is concerned with the use of our unit in three plants involved with production of steel, paper, and chemicals.

OBJECTIVES

In the circles of industrial management there is on the one hand apprehension in regard with the need to accommodate the Equal Employment Opportunity (EEO) requirement, and on the other hand, a growing awareness that a conflict exists between the demand of many tasks and the worker's physical capacity. It could very well be that the first leads to the second, but it seems that the awareness of the man-job conflict prevailed because of the recent increase in workman compensation costs. Whichever the reason, we were asked by management to conduct strength measurements of regular, as well as newly hired workers, hoping that the information will provide the basis for the following objectives, set in the priorities as seen by management: (1) screen workers; (2) pretrain unfit workers; and (3) make the necessary job modification to, at least partially, eliminate the man-job conflict.

METHODS

In order to meet these objectives, we took the following steps: (1) sought the tasks considered physically demanding in each industry; (2) analyzed the selected tasks for the biomechanical stresses involved; (3) measured, on as large a sample as possible, the lever arms and the Maximal Voluntary Contraction (MVC) of the muscles around the joints considered crucial to adequately perform the tasks in question. The quantified biomechanical stress of each task was then compared to plant population distribution of the measured MVC.

Task Analysis. Because of limited funds, which is more common than unrestricted funding, the biomechanical tasks analysis was performed using the simplest means possible. That is, one observer analyzed each task in terms of crucial static postures. If resistance to forces were involved, the observer measured them using a dynometer.

Since the man-machine constrains defines in most cases arm-back positions, the posture was judged for the lever arms around the following three joints: lower back, shoulder, and elbow. This is shown in Figure 1. Notice that the lower back included lever arms for the load handled and for the upper body. To simplify the analysis, the observer judged the posture as one of the following three trunk angles: 25°, 60°, and 90°.

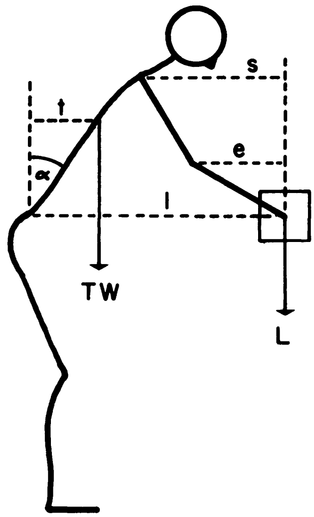

Fig. 1. Lever arms used for postural demand of the different tasks

The lever arms for each of the three observed angles were determined on the basis of the 50 percentile of the available anthropological dimensions (Diffrient, Tilley and Bardagjy, 1974). An example of the lever arms used for a standard male is shown in Table 1.

Table 1. The lever arms between the lower back and upper body center of gravity (UBÇG), and between the joints and the load, for three trunk angles assumed for different tasks

Angle°	Lower Back to UBCG	Lower Back to Load	Shoulder to Load	Elbow to Load
25	8	23	2.5	11
60	17	44	5.0	22
90	20	51	5.8	26

The two values: (1) the lever arm according to the observed posture; and (2) the measured forces resisted during the performance of the task were used to derive the torques as a cause for biomechanical stress. Examples will be shown in the results section.

Measurements of Maximal Voluntary Contraction and Torques

The strength testing device used was described before (Kamon and Goldfuss, 1978; Yates et al., 1980). Briefly, a dynamometer or a load cell was secured to the base of the unit and was linked to the tested subject via cable and nonstretchable belt. A potentiometer attached to the dynamometer's dial transferred the registered force to an electronic unit which was designed to integrate the force over three seconds after rejecting the first second of pull on the dynamometer. The average force was then displayed on a digital readout. The apparatus could either be wheeled or folded and carried to the working site. The workers were measured in pairs. The MVC for each group of muscles was tried twice with one minute rest between trials. The best trial was taken as the worker's MVC. Then the worker rested while his colleague was measured for the given joint. A series of tests on three or four joints for two workers lasted 20-30 minutes which management considered a reasonable short time for taking the worker off his work area.

Procedure. Each worker rested prior to onset of testing while his medical record was reviewed and blood pressure taken. Any past injury (particularly back problems) or measured high blood pressure (above 140/90 Torr) excluded the worker from the tests.

Back extensors MVC was measured similar to the technique described by Poulsen and Jorgensen (1971). However, in one plant, the physician considered the erect hyperextended back posture unacceptable for MVC. Therefore, the back extensor were tested in a 90° bent trunk. The subject was strapped to the load cell (on the base of the unit) through his shoulders in the same manner as in the erect posture. The MVC was performed with straight knees and the trunk at 90°.

Elbow flexion was conducted in a seated position with the shoulder and elbow joint kept at 90°. The shoulder flexion was measured either standing or sitting. The flexion MVC at 90° was conducted with the subject standing and pulling the strap which was attached to the upper arm as close as possible to the elbow. Two of the MVC taken were at angles expected during lifting: shoulder angle of 45° (low lift), and at 135° (lift above head). The strap was attached to the wrist and the pull was performed with the elbow fully extended either in a sitting position (135°

angle) or standing (45° angle) (see Yates et al., 1980).

Maximal static lift or maximal isometric lift (MIL) was part of the strength measurements in some plants. In the steel mill, it was done using a board connected by a cable from its center to the dynamometer. The board (60 x 50 cm) was grasped on the sides and was pulled at 50 cm above floor with the center of the board (line of pull) about 25 cm in front of the ankle. In the chemical plant a tray (50 x 40 x 12 cm) with recessed lips for grasping was used with a cable attachment from its center to the dynamometer.

Lever arms were measured as follows: for back, iliac crest to position of straps on shoulders; for shoulder, acromion to position of strap on upper arm or on wrist; for elbow, radial epicondyle to strap position on wrist.

Additional Strain Factors. Since some jobs included twisted trunk or repetitive lifting, a strain factor was added to the estimated total torque on the lower back. This gave a larger torque value equivalence due to the twisted posture or the repetitive exertion. The factors are summarized in Table 2.

Table 2. Strain factors in estimation of stress on lower back

Activity	Factor
Twist	1.1
Frequency of Lifting	
One per minute	1.1
Two to three per minute	1.2
Above three per minute	1.3

RESULTS AND DISCUSSION

Maximal Voluntary Contraction

A total of 1,100 men and 240 women were measured for Maximal Voluntary Contraction (MVC) in three plants: steel mill, paper mill, and chemical. For all practical purposes, the MVC values were similar for the workers of all three industries. Some other interesting observations were noticeable. A comparison between the two methods of measurements of back extensors MVC: erect (180°) with back slightly hyperextended and; bent trunk (90°), revealed no differences between the two methods (Table 3).

Table 3. Mean and standard deviation of maximal voluntary contraction (N) for back extension in the erect posture (slight hyperextension--180°) and in the forward flexed posture (90°)

Posture	Men (n=74)	Women (n=18)
180°	564 ± 121	373 ± 108
90°	599 ± 226	383 ± 206

Table 4. The mean maximal voluntary contraction for men employed under the different categories of the demands on the job

	Back Extension		Flexion Elbow	
Category	n	(N)	n	(N)
Very heavy	68	576 ± 191	56	274 ± 86
Heavy	173	590 ± 175	214	263 ± 85
Moderate	29	556 ± 189	23	271 ± 97
Light	19	544 ± 124	21	264 ± 78

In one plant, the MVC was compared to the category of the jobs, based on the amount of lifting the worker had to do (Kamon and Goldfuss, 1978). The values for each group are shown in Table 4. It can be seen that there are no differences between the groups although it was hoped that since each group included only workers tenured on their jobs, time selective process will be reflected in more strength for those on the heavier jobs. Such phenomena could help in future design of the jobs and training schedule in matching jobs with workers.

In two plants there were age-related differences in MVC for men. Although a regression analysis of MVC on age did not reveal a trend, when divided by age; below and above 35 years, the below 35 were significantly stronger than the above 35 worker (Table 5). The older group revealed 88% of the strength of the younger group. Table 5 also includes a sample of women from this plant (paper mill). Although women revealed age-related differences in strength similar to that shown for men, the sample was not large enough for statistical analysis. However, as expected, women showed about 40 to 60 percent of the MVC of the men.

Another observation was made by comparing new applicants to regular workers. An example of lever arms and torques are shown in Table 6 as measured on steel mill workers.

Table 5. Mean and standard deviation of maximal voluntary contraction (N) by age and sex

Age	n	Back Extension	Elbow Flexion	Shoulder Flexion (90°)	Isometric Lift
Men					
<35	410	594 ± 137	295 ± 59	275 ± 59	766 ± 177
>35	220	506 ± 147	255 ± 69	246 ± 49	678 ± 167
Women					
>35	157	378 ± 157	167 ± 54	129 ± 25*	405 ± 180*

*n=9

Table 6. Mean and standard deviation of the lever arms and torques from on-site measurements in a steel mill

	Regular Workers		Applicants	
	Lever Arm cm	Torque N·m	Lever Arm cm	Torque N·m
Back Extensors	40.4 ± 3.1	200 ± 54*	40.2 ± 2.53	213 ± 40
Shoulder Flexors (90°)	31.5 ± 1.8	82 ± 18	31.8 ± 2.0	84 ± 17
Elbow Flexors	26.4 ± 1.7	68 ± 13	26.5 ± 1.7	67 ± 13
Maximal Isometric Lift (MIL)	25.4 ± 1.6	186 ± 45*	25.4 ± 1.5	178 ± 38

*Significantly different from applicants ($p < 0.05$).

Since the lever arms did not differ in the two groups, the data shown for lever arm were pooled together. Maximal torques are shown separately for regular workers and for applicants. Notice the differences in the strength of back extensors and maximal isometric lift (MIL). The maximal torques of the two muscle groups contradict each other. While the applicantsrevealed stronger back extensors as compared to the regular workers, the regular workers revealed higher MIL. This phenomena indeed raise the question whether lift has more to it than individual muscle group strength. The difference in lift strength could have to do with technique which is earned with experience. Such an input to lifting is supported by the poor correlation between the MIL and the joint strength. The correlation coefficients were 0.59, 0.58 and 0.58 for MIL with respectively back, shoulder, and elbow MVC.

The correlation for the applicant was poorer than that for the regular workers.

Another interesting observation was the low coefficient of variance (20%) for the data obtained in the steel mill (Table 6) as compared to previous data (30%) from the paper mill (Kamon and Goldfuss, 1978). Since the paper mill involved four testers, while the steel mill data was collected by one person, the difference can be attributed to human testing procedures.

Comparison between Tasks and MVC

The torques derived from the directly measured MVC were compared to the assessed biomechanical stress of the tasks. For example, grinders were handling discs, 46 to 81 cm in diameter weighing 6 to 34 kg. Each disc was picked up from a pile and placed on the grinder, and after grinding picked up again and placed on another pile, at a rate of three per minute.

The observer found that the lifting involves trunk angles of 25 to 60° depending on the depletion level of the piled discs. Accordingly, handling 34 kg discs by an 80 kg person involved an estimated biomechanical stress of: 147 N·m for the held disc, 53 N·m for the stooped upper body, which totals to a biomechanical stress of 200 N·m.

Additional stress factors were given for different frequencies of lift, for a twisted posture and for carrying. Thus, a frequency of lifting three discs per minute carried a factor of 1.2. This increased the biomechanical stress to 200 x 1.2 = 240 N·m. This stress value for the back extensors was compared to the population MVC. The mean and standard deviation of the MVC (Table 6) indicated that with no consideration for repetition, the 200 N·m of the assessed stress is equal to the mean back extensors (MVC for regular workers, Table 6), and therefore the task is too demanding for half of the male workers. The stress factor due to repetitive lifting raised the equivalent back extensors stress to 240 N·m (Table 2), which statistically means that only 30% of the steel mill population were expected to, on the long run, safely perform the grinding job.

Such an analysis, using the z-score table was conducted for other combinations of load and tasks to determine the safety of the jobs for expected steel mill worker population. An example is summarized in Table 7. It can be seen that a varnishing job where an average man will stoop at 60° to handle weight of 15 kg is practically safe for only 72 percent of the prospective workers. Similarly, grinding a disc weighing 34 kg is safe for only 13 percent of the expected worker population.

Table 7. Analysis (z-score) for determination of men (body weight 80 kg) who can safely perform two jobs in the steel mill

Job	Weight Handled (kg)	Trunk Angle (°)	Stress Factors (ND)	Lower Back Stress (N·m)	Can Safely Perform Percentile
Varnish	34	25	1.4	143	85
	15	60	1.4	168	72
Grind	15	25	1.3	78	99
	15	60	1.3	156	79
	34	25	1.3	133	89
	34	60	1.3	161	13

Similar considerations were given to the shoulder and elbow joints. The estimated biomechanical stress and the measured MVC on sample workers were used to suggest for alteration in the system and for redesigning the work procedures of the highly demanding tasks.

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Session V
Models of Biomechanical Data

NEW PERSPECTIVES AND NEEDS IN BIOMECHANICAL MODELLING

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INTRODUCTION

Biomechanical modelling of the musculo-skeletal system of man has been and remains one of the challenging tasks in Bioengineering. The variety of systems ranging from the subcellular level to the whole body and the types of functions that can be modelled are almost limitless. In a review of models related to the biomechanics of impact, King and Chou (1976) discussed the availability and capability of gross-motion simulators and regional models of the head, spine and thorax published prior to 1975. This paper briefly updates this review and concentrates principally on biomechanical models of the non-impact type, involving the musculo-skeletal system; such as models of bones, joints and of the whole body or multiple body segments, including gait. Non-impact models of soft tissues, the cardiovascular system and hemodynamics, prosthetic devices, joint lubrication, thermodynamic events, and microscopic biological elements are excluded.

In reviewing the literature, over 100 models of the musculo-skeletal system have been identified without an exhaustive search. They cannot be individually referenced in this short paper but the list is available upon request.

AN UPDATE OF IMPACT MODELS

Since 1975, additional regional impact models of head, spine and femur have been proposed along with some activity involving 3-D gross motion simulators. A brief review of regional models is presented. There were at least 8 head impact models of which 4 were concerned with the brain injury resulting from angular acceleration of the head. Finite element modelling of head impact was found to be more realistic than models of spheres and ovals. Models of the spine were improved to include neuromuscular response. Head and neck models were popular and the effect of wearing helmets was also studied. A 3-D discrete parameter model of the spine has been formulated and exercised. A 2-D finite element model of the femur was developed to study its response to condylar impact.

ANALYTICAL RESPONSE OF INDIVIDUAL BONES TO LOAD

Scientific interest in osteomechanics dates back to the 17th century. However, engineering analysis of bone is a relatively recent phenomenon. Conventional beam theory was used to a limited degree to calculate stresses in long bones and was quickly replaced by finite element models. The femur, tibia and a lumbar vertebra have been modelled by this method.

Another area of bone modelling is concerned with the determination of in vivo elastic properties of long bones using vibration data. Models of the ulna and femur are available in the literature.

MODELS OF JOINTS

Internal forces and moments at a joint cannot be measured directly. The task of calculating these quantities is also no simple matter. The large number of muscles and ligaments involved usually render the problem indeterminate because there are more unknowns than equations. In dynamic models, the equations are generally non-linear. The simplest approach is to utilize EMG data or other justifications to reduce the numbers of unknowns. Alternatively, a minimum principle is used to generate the required number of equations for a unique solution. The popular objective functions used are minimum total muscular force and/or moment, minimum total mechanical energy or metabolic energy. It has been shown that the use of an optimization scheme is but a systematic form of the simple method of eliminating inactive muscles. For dynamic models, the differential equations are reduced to algebraic ones by electing to solve the so-called 'inverse dynamic problem'. This is accomplished by supplying the model with kinematic data, thus eliminating all derivatives.

The knee joint has been modelled by many investigators. The maximum force in the knee was estimated to be about 3 times body weight, using models which considered muscular action. Ligamentous models have also been formulated to study the role of the various knee ligaments in supporting this joint. There were several models of the hip joint which was analyzed as a statically determinate problem.

For the upper extremity, there were several models of the finger joint(s). These were designed to simulate tip pinch and other simple functions. It was estimated that the compression at the metacarpal joint was 7.5 to 8.8 times that of a unit pinch at the tip. Models of the elbow and shoulder have also been proposed.

The intervertebral joint was modelled by considering the disc and portions of the adjacent vertebral bodies as an axisymmetric cylindrical elastic structure, enclosing an incompressible fluid. Finite element modelling was used along with the assumptions that the disc was an orthotropic non-linearly elastic material. The role of the articular facets was not considered.

MODELS OF MULTIPLE BODY SEGMENTS AND THE WHOLE BODY

Four classes of models can be identified under this category. They are models of the lower limbs, including gait, of the spinal column or a spinal segment, of the thorax and of the whole-body, but not including gait.

There are at least 8 models of the lower limb of varying degrees of complexity to simulate human gait. As many as 31 muscles are involved and the problem was generally solved by an optimization scheme. A comprehensive model by Hatze (1976) is almost a fully voluntary simulation of a subject attempting to hit a target on the ground with his foot in the shortest possible time. A 2-D model was formulated using Lagrange's equations. The joint torques were divided into active and passive parts and an extensive model of the active torque was developed based on Hill's (1938) muscle model. Two control variables were identified and were determined by minimizing a time function. Models of gait involving the head, arms and torso along with the lower limb(s) are quite numerous. The general approach was to solve the redundant problem by means of an optimization procedure. Most of the cases were solved as an inverse dynamic problem.

At least 2 static models of the spine are available in the literature. A comprehensive structural model in 3-D was developed by Belytschko et al (1973). It can be used to study large displacements of the spine in lateral bending or buckling. There are also at least 2 finite element models of the thorax.

Whole-body models of human motion not involving gait have been proposed to simulate lifting of a weight, maneuvering in space by an astronaut, and swimming. These are usually multilink systems defined in 3-D space.

NEEDS IN BIOMECHANICAL MODELLING

There is a continuing need for good data on material properties of body tissues. As the models become more sophisticated, more of such data are required. Unfortunately, there is more glamor in producing models than in measuring material properties.

Finite element analysis is well-suited to biomechanical modelling because of the irregular geometries involved. However, nodal coordinate definition is still a tedious task and a versatility needs to be developed to permit rapid changes in size and shape without a complete respecification of coordinates.

Modelling of human activity will continue to be a challenge. Models of human gait have been studied exhaustively with no definitive conclusions regarding the best cost function to be used for the determination of muscle forces and joint moments. The use of optimal control theory and continued advancement in the simulation of voluntary muscle function are necessary to solve the gait problem. This may lead to extremely complex models, such as the complete musculo-skeletal model proposed by Hatze (1977). However, no alternatives are apparently available at this time. The ultimate aim is to create a mathematical robot which can not only walk and run but also lift weights and perform a variety of human tasks so that stresses and loads within the body can be studied.

Another vital need is the continued advance in the art of instrumentation and transducer development. The measurement of internal (muscle) forces and (joint) torques continue to defy the best scientific minds. The availability of miniaturized transducers and microcomputers will enable the imaginative bioengineer to gather real-world data from workers and athletes while they are performing their tasks. Such data are of value to modellers from the point of view of validation as well as the injection of realistic data into the models.

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THE DEVELOPMENT AND USE OF BIOMECHANICAL STRENGTH MODELS

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The general objective for the development and use of biomechanical strength models is to more accurately determine the amount of physical stress imposed on a person's musculoskeletal system by infrequent material handling tasks, i.e., each of which has a duration of less than five seconds and with a minimum of a minute between tasks. (Otherwise the limit of performance would not be a function of the mechanical characteristics of the skeletal muscle system, but instead of the physiological capacities of the supporting respiratory and cardiovascular systems). With increased identification of manual material handling related injuries, amounting up to 25% of industrial accidents (National Safety Council, 1974) and three billion dollars in medical expenses and lost wages per year (Chaffin and Ayoub, 1976), and with the growing concern for the health and safety of the worker, such as the OSHAct of 1970, the proper achievement of such an objective is becoming imperative.

The most basic concept involved in a mechanical analogy of the skeletal muscle system is that the skeletal muscles act at finite distances from the various bone articulations. Therefore, at each articulation, when a skeletal muscle contracts, it results in a reactive torque which must be capable of overcoming the resultant torque created by external and inertial forces at the same articulation. Earlier studies (Elkins, et al., 1951; Provins and Salter, 1955) examined elbow flexion activity and found a pronounced angles effect, with peak torques occurring at an included angle of 90°. Additionally, female subjects were found to produce half the male torques, while forearm rotation from a semi-prone position reduced the elbow torque another 10%.

An early planar model developed at the University of Michigan

(Chaffin, 1967) incorporated the above factors along with several vital assumptions: (1) the total strength of the arm is a function of the weakest muscle group's actions; (2) the ability to produce maximum torques at each articulation is independent of the activity level of an adjoining articulation; (3) the coefficient of variation of the strengths of a group of people within the same age group and sex is independent of sex, age and the hand and arm positions.

Predictions of the maximum torques that a person could produce at various joints is calculated by modifying maximum torques measured on, say, male college students according to the above factors. A second limit, in addition to the limiting muscle group, was introduced. This limit due to balance, defined a feasible geometric area in which an anthropometrically defined person must operate. Should he step out of this area, then balance cannot be maintained and the task cannot be performed.

The third assumption tried to answer the question confronting the job designer: what are the population strength norms for performing a given arm task? A first approximation can be made by referring to the variability of published laboratory studies (Hunsicker, 1955). However, considering the high variabilities found, a substantial need for pre-employment strength testing of industrial populations is indicated.

This early model was developed further by implementing additional features. Since back injuries occur frequently in industry and can result in considerable discomfort and expense, it was decided to include a section calculating spinal compressive forces, especially at the L_5/S_1 joint (Fisher, 1967). Much of the mechanics of the spine was based on previous studies of trunk stability (Morris, et al., 1961) and abdominal pressure reflexes (Davis and Troup, 1964). The relationships of leg position and muscle strengths of the hip extensor, knee extensor and plantar flexors were added by Burggraaf (1972). The model was expanded into a three-dimensional model by Schanne (1972) who used a three-camera photogrammetric method to test 18 subjects in 270 positions involving 20 different muscle groups. Prediction equations for muscle group strengths as a function of body configuration angles were developed via stepwise least-squares regression analysis. From these external loads could be converted to rotational torques and compared to the maximum torques produced by individual muscle actions, indicating the capability to handle the load.

Whereas the above model had concentrated on predicting joint torques in static situations, others have tried to implement the dynamic characteristics of motion such as acceleration, deceleration and moments of inertia into various models. Much of this is based on the early work of Plagenhoef (1963), who pioneered the methods of obtaining kinematic data from human motion. Pearson

(1961) expanded this into a dynamic analysis of the upper extremity, but only for planar motions. Ayoub (1978) developed a set of empirical models to determine the lifting capacity of individuals based upon the task variables of frequency of lifts, height of lifts, size and weight of loads handled and the individual characteristics of anthropometry and isometric strength data. In this case however, the dynamic aspects are only characterized as a frequency and not as true accelerations or decelerations. Much more has to be done before a truly dynamic three-dimensional, whole-body model is to be developed.

Presently, the University of Michigan Biomechanical Model is being valided with industrial population strength studies to adjust the laboratory obtained range-of-motion strength distributions. Eight different companies in six different industries involving

Table 1: Parameters of Industrial Strength Distributions

				MALES			FEMALES		
TEST	V	H	INDUSTRIES	N	$\bar{X}$	S	N	$\bar{X}$	S
Arm Lift	114	38	A,E,I,S,T	1276	383	125	234	214	93
Torso Lift	38	38	A,E,F,S,T	1141	480	205	246	271	125
Leg Lift	38	0	A,E,F,S,T	673	903	325	165	427	187
High Far Lift	152	51	A	309	236	71	35	133	36
Floor Lift	15	25	A	309	890	245	35	552	182
High Near Lift	152	25	A	309	543	156	35	280	102
Push Down	112	38	A	309	445	93	35	334	71
Pull In	157	33	A	309	320	80	35	254	53
Pull Down	112	38	A	309	605	102	35	449	107
Push Out	124	25	A	309	316	76	35	222	49
Push	102	36	T	54	338	196	27	236	76
Pull	152	33	T	54	525	156	27	338	98
Low Lift	46	38	I	170	320	125	20	214	71
High Lift	152	38	I	170	543	222	20	267	85
Pull	140	0	A,F,I,T	205	254	62	52	209	62
Push	140	64	A,F,I,T	205	418	178	52	276	120
Close In	69	8	A,F,T	35	1446	280	32	890	209
Low Close	23	25	A,F,T	35	681	142	32	565	173
Low Far	76	51	A,F,T	35	262	80	32	227	71
High Close	178	25	A,F,T	35	463	133	32	418	133

V = Vertical displacement of the hands from a point on the ground midway between the ankles (cm)
H = Horizontal displacement of the hands from a point on the ground, midway between the ankles (cm)
$\bar{X}$ = Mean of strength distributions (newtons)
S = Standard deviation (newtons)
Industries = A - Aluminum, E - Electric, F - Food, I - Insulation, S - Steel, T - Tire & rubber

1311 males and 266 females have been tested on 20 different tests as shown in Table 1. Using the model to predict male and female strength capabilities for the corresponding body postures and plotting these as a function of the mean measured strengths yields the relationship shown in Figure 1. Lifts are indicated by solid symbols, while pushes/pulls are indicated by open symbols. Predicted values can be expressed as .99 times the measured values. The linear relationship is significant at $p < .001$. As can be seen the model tends to overpredict slightly on lifts and to underpredict on pushes and pulls. The latter could be explained by the more dynamic nature of pushes or pulls, which is not accounted for in the model, the greater variability of postures used by workers in such tests and frictional characteristics of the shoe/floor interface. With in-

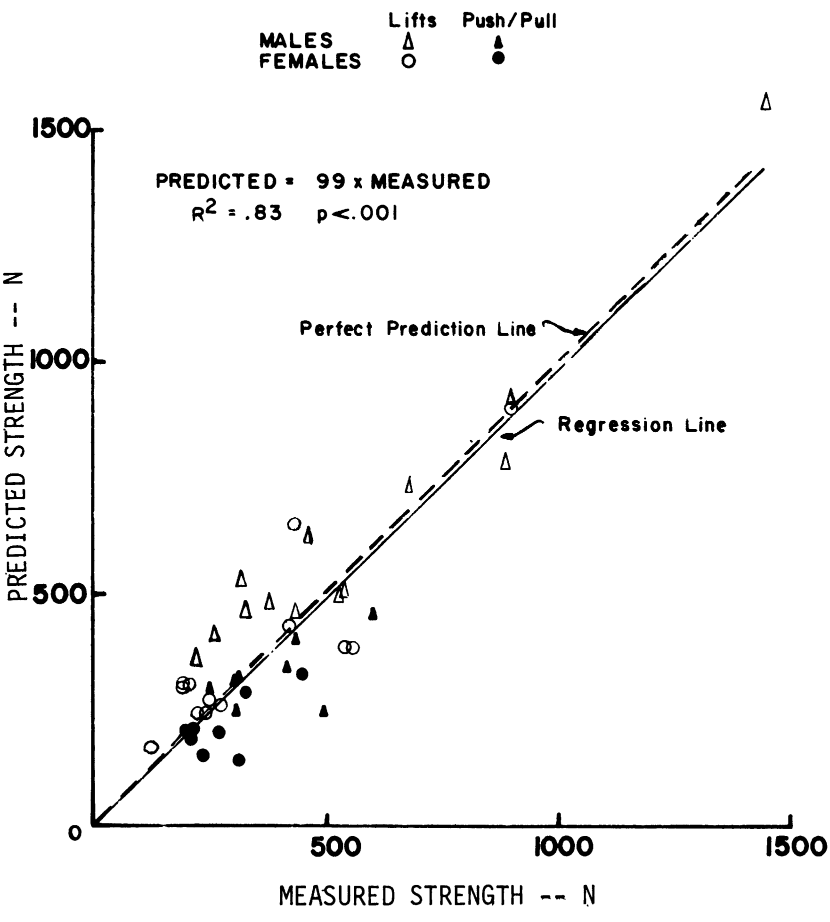

Figure 1: Predicted vs. Measured Strength

vestigations into these areas along with additional strength data for extreme postures, the model's predictive accuracy should become even better.

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THE VALIDITY OF BIOMECHANICAL MODELS OF VOLITIONAL ACTIVITIES

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INTRODUCTION

Knowledge of the load that acts on the different structures of the human spine in physical activities is needed to relate spine injuries to spine loads and to construct safe work places and work methods. No methods are presently available to directly measure these loads. Indirect methods, such as electromyographic recordings from trunk muscles, disc pressure measurements, and gastric pressure measurement have been used to that purpose. These methods are not entirely practical, however. They are partly difficult to perform, expensive and time consuming to analyse, and some are invasive and therefore suitable only under laboratory conditions.

Biomechanical model analysis can also be used to assess back loads. While external loads can often be calculated with reasonable accuracy, major assumptions must be made in these models to estimate the internal forces. Validation experiments are therefore required before the model can be used with confidence.

This paper describes a series of experiments in which the internal loads required to equilibrate the body in various well controlled and fully quantifiable static postures were analysed. These predictions were then tested through measurements of lumbar intradiscal pressure and of the myoelectric activity of several trunk muscles.

METHODS

To compute the loads on the lumbar spine the body is visualized as beeing divided by an imaginary cutting plane through the L3 level. A two stage calculation is then carried out; first the net reaction is computed, and then the internal forces estimated.

To calculate the net reaction a coordinate system was established, and the external loads acting on the upper body considered. These are loads applied to perform a task, and loads from body segment weights. They were obtained through measurements of any load held, and of mass center locations of the major body segments above the L3 level.

The net reaction, needed for equilibrium, is supplied by muscle contractions, connective tissue tensions, intraabdominal pressure, and spine motion segment resistances. These are forces internal to the trunk. Muscle contraction and spine compression forces were predicted from equilibrium considerations on a statically - determinate basis when possible. Trunk muscle groups were represented by a few single muscle equivalents, and antagonistic activity was assumed to be minimal. In situations that were statically indeterminate, linear programming techniques were used to estimate internal forces, using an objective function that minimized the compression on the lumbar spine.

The myoelectric activity was measured at eight locations on the back and four on the abdomen using surface electrodes. The signals were rectified and low pass filtered, and their RMS value determined.

The disc pressure was measured in the third lumbar disc using a pressure transducer attached to the tip of a needle.

This report is based on three different study series; two in which the muscle tension was predicted, and the myoelectric activity recorded; and one in which predictions of spine compression forces, and disc pressure measurements were also included.

MATERIAL

The studies were made on healthy volonteers 23-45 years old. Ten subjects were first studied while holding different weights in the right hand in ten different positions sitting at a table. In the second series the subjects held different weights in four different weights in four different sagittally symmetric standing postures, either upright or with the trunk flexed, and with the arms both close to and 35 cm away from the chest. Resisted flexion, extension, lateral bending and rotation were also studied. Similar experiments were then repeated in four subjects including measurements of disc pressure.

RESULTS

Good agreement was found between the predicted muscle contraction forces and the myoelectric signal levels (Figure 1), and between the predicted spine compression forces and the intradiscal pressure levels (Figure 2). This agreement prevailed over a force range of approximately 2500 N. It prevailed for both standing and seated activities, and for both light and heavy exertions.

DISCUSSION

The model was amply validated under the circumstances examined here. In spite of this caution is still needed when interpreting model estimates of forces internal to the trunk. It is still unknown what objective functions should be used to solve the statically - indeterminate problems that arise under different circumstances.

The model has not yet been tested under truly dynamic circumstances. The same principles can be used, however, adding the inertial forces and moments as external forces at the mass centers of the body segments. This, obviously, requires further computations.

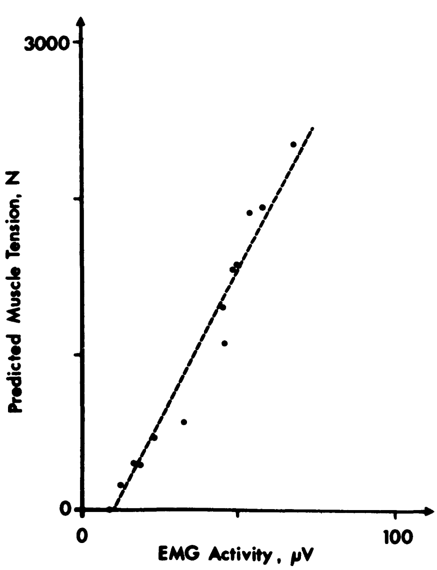

Figure 1

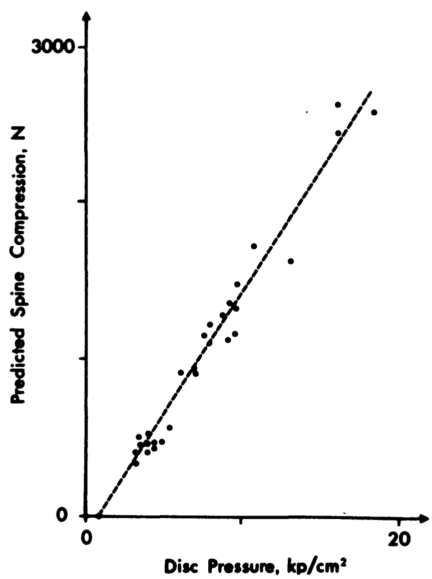

Figure 2

The validation experiments imply that reasonably accurate estimates of spine load can be made using simple approximative input data. This may be the reliable, quick, safe and inexpensive method long needed to assess spine loads at work and in research.

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DEVELOPMENT OF A BIOMECHANICAL HAND MODEL FOR STUDY OF MANUAL ACTIVITIES

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INTRODUCTION

Designing handles, tools, materials, and controls so that they can be used effectively without adverse health effects is of obvious importance. While existing hand size and strength data for some of the most common hand postures are of great value to designers of work equipment and activities, it is difficult to generalize such data from one posture to another. In addition, existing data do not identify stress concentrations that could have a pathological influence on the musculo-tendinous-osseous system. The following describes the development of a simple biomechanical strength model to overcome some of the inherent limitations of existing data.

DEVELOPMENT OF BIOMECHANICAL MODEL

As with any model, certain qualifications are required so that simplifying assumptions can be introduced. In this case the scope of consideration will be restricted to what Napier (1962), Landsmeer (1962) and Long, et al., (1970) have called power grip or handling. In such exertions high forces are produced on the volar surfaces of the hand and hand posture is constrained by the object being grasped.

The major force-producing muscles in power grip are the flexor digitorium profundus (FDP) and superficialis (FDS) located in the forearm. The FDP is recruited first to close the fist by flexing the metacarpal-phalangeal (MP), the proximal interphalangeal (PIP), and the distal interphalangeal (DIP) joints; the FDS then is recruited as necessary to flex the MP and PIP joints (Long, et al., 1970). Although there are 26 intrinsic muscles in the hand, their major action is flexing of the MP joint and extension of the PIP and DIP joints, particularly in low force precision type exertions (Landsmeer, 1962). Complex models describing the intrinsic muscles include many parameters that can only be assessed invasively (Chao, Opgrande, and Axmear, 1976; Thomas, Long, Landsmeer, 1968; Youm, et al., 1978). The following describes a simplified model suggested by Dempster (1961) in which the intrinsic muscles are neglected and the MP joint strength is considered as nonlimiting.

External load forces distributed over the palmar aspects of the fingers can be characterized as a single resultant force, $F_{\ell i}$, as shown in Figure 1a. Load moments produced about each of the joints, M_{ij}, oppose closing the fist. Closing of the fist also is opposed by passive moments, R_{ij}, due to deformation of joint tissues; however, these moments can be neglected where the joint is well within its range of motion. As joints approach the limits of their range of motion, passive forces become quite high and contribute significantly to the equilibrium with the muscles. Free body diagrams of the distal and proximal interphalangeal joints are shown in Figures 1b and 1c. The equation of static equilibrium at the DIP joint can be expressed to predict FDP muscle forces, $F_{\ell i}$, for each digit as shown in equation 1:

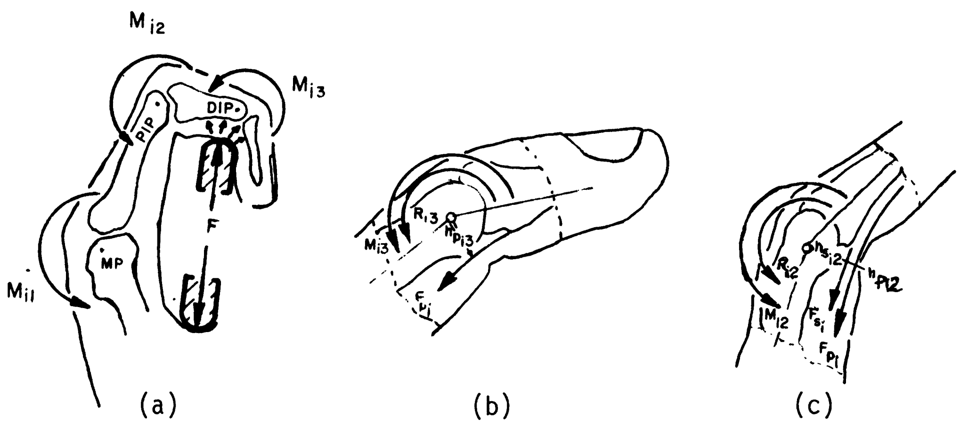

Figure 1: Free body diagram of the (a) external grip forces, (b) moments about the distal interphalangeal (DIP and (c) moments about the proximal interphalangeal (PIP) joint.

$$F_{p_i} = (M_{i3} + R_{i3})/h_{p_{i3}} \tag{1}$$

The tendon moment arms, $h_{p_{i3}}$, can be estimated from joint thickness as described by Armstrong and Chaffin (1976).

The equation of static equilibrium for the PIP joint then can be used to prodict the FDS muscle force, F_{s_i}, as shown in Equation 2:

$$F_{s_i} = (M_{i2} + R_{i2} - F_{pi} \cdot h_{p_{i2}})/h_{s_{i2}} \tag{2}$$

Thus, given the external load moments and tendon moment arms and neglecting the passive moments about the DIP joints, the FDP muscle forces can be computed for forceful exertions of the hand. Similarly, given the FDP force, load moments and tendon moment arms about the PIP joint, the residual FDS muscle force can be computed. If these computations are performed for maximum strength exertions, FDP and FDS strengths can be calculated. This strength information then can be used to compute hand strength for other hand postures.

APPLICATION TO STUDY OF STRENGTH AND POSTURE

To illustrate the application of the biomechanical model, a simple experiment in which muscle strengths are computed from strength measurements in one hand posture and used to predict strengths for another hand posture is described. Hand strengths were measured for a power grip position that corresponds to gripping a typical hand tool as shown in Figure 2a; this posture corresponds to that used in most standard measurements of grip strength. Such strength measurements do not reflect well the ability to perform exertions with the finger tips as is often required for lifting or pinching (see Figure 2b). Available strength data indicates that strength of the finger tips is only 15%-20% of the power grip strength (Swanson, et al., 1970). The following describes an experiment in which the biomechanical model will be used to predict finger tip strength from power grip strength measurements.

Six power grip strength measurements for one male subject were obtained with an adjustable grip dynometer. The subject was given several trials on preceding days to adjust the dynomometer to his preferred position. A top view of a free body diagram for the preferred power grip posture is shown in Figure 3a. Individual finger strengths were calculated according to the ratios of 0.25:0.34:0.26:0.16 as reported by Hazelton, et al. (1976). The load moment about the PIP joints were calculated as the product of the perpendicular distance between joint centers and the resultant load force for

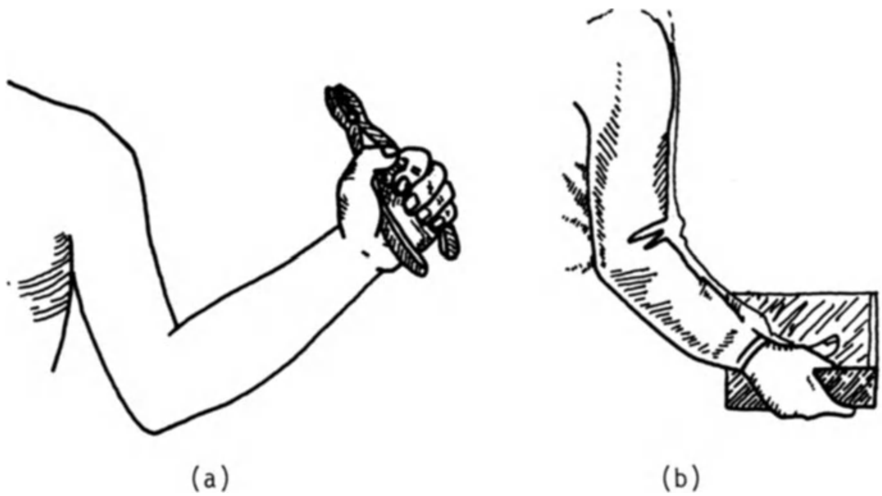

Figure 2: Hand tools can be embraced with the entire hand (a) while cartons and containers often can only be supported with the finger tips (b).

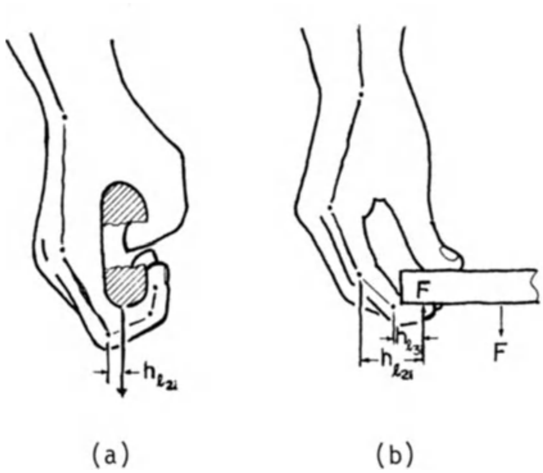

Figure 3: Depiction of resultant forces on fingers for (a) gripping and (b) pressing.

each digit. Unfortunately, the load moment about the distal interphalangeal joint, which is required for calculating the FDP muscle force, is not directly computable because it is not known how the load forces are distributed distal to the DIP joint. The muscle forces can be approximated if it is assumed that the load is equally distributed between the FDP and FDS, which is a reasonable assumption for a maximum exertion. It is then found that the equation of static equilibrium (Equation 2) for the muscle forces, tendon moment arms, and load forces can be reduced to the form shown in Equation 3:

$$F_{p_i} = F_{s_i} = (M_{i2} + R_{i2})/(h_{p_{i2}} + h_{s_{i2}}) \qquad (3)$$

Since the PIP joint is well within its range of motion, the passive moment at the PIP joint, R_{i2}, can be assumed to be zero; the equilibrium at the PIP joint will not be affected by the magnitude of R_{i3}.

The data for calculation for the average FDP and FDS strengths for each digit, F_{pi} and F_{si}, for six replications are summarized in Table I. Profundus strengths then were used to predict strengths that could be exerted with the distal phalanges in a pinch ro a press type exertion. The grip dynomometer was configured for the hand posture shown in Figure 3b. Predicted and measured strengths shown in Table II agree quite well for the second and fifth digits (0% error) but quite poorly for the 3rd digit (predicted 38% less than measured). Overall total finger strength is under-predicted by 15%; this approaches the range of within-subject variability.

Table I: Computation of FDP and FDS muscle moment arms (mm) and strength (kp) for each finger from grip strength measurement

Digit (i)	$h_{p_{3i}}$ [1]	$h_{p_{2i}}$ [1]	$h_{s_{2i}}$ [1]	F_{ℓ_i} [2]	$h_{\ell_{2i}}$ [3]	F_{p_i} [4]	F_{s_i} [4]
2	4.2	9.1	8.1	20.1	14.4	16.8	16.8
3	4.3	9.4	8.5	26.7	10.0	15.5	15.5
4	4.0	9.2	8.2	20.4	15.5	18.2	18.2
5	3.6	8.8	7.8	12.4	19.5	14.6	14.6
Total	---	---	---	79.3	---	65.1	65.1

1 - computed from Armstrong & Chaffin (1978)
2 - measured - see text
3 - measured from photographs
4 - calculated with equation 3

Table II: Prediction of maximum press strength (kp) with distal phalanx of each finger based on measurement of grip strength

Digit (i)	F_{p_i} [1]	$h_{\ell_{3i}}$ [2]	$F_{\ell_{3i}}$ [3]	$F_{\ell_{3i}}$ [2]	Δ%	$h_{\ell_{2i}}$ [2]	F_s [4]
2	16.8	10.7	6.6	6.6	0%	38.5	12.5
3	15.5	11.8	5.5	8.9	-38%	46.6	13.0
4	18.2	11.8	6.2	6.8	-6%	44.4	13.2
5	14.6	13.0	4.0	4.1	0%	36.7	2.3
Total	65.1	----	22.3	26.4	-15%	----	41.0

1 - calculated in Table I from equation 3
2 - measured (4 replications)
3 - predicted with equation 1
4 - predicted with equation 2

Some of the reasons for poor agreement between measured and predicted results include: 1) how the load was characterized, 2) how the load was assumed to be distributed between the FDS and FDP, and 3) contributions by the intrinsic muscles. Each of these areas needs additional research.

In addition to prediction of strength, the biomechanical model shows that designing handles so that the load is kept close to the second knuckle with maximum strength. The model also shows that people with large hands with correspondingly large muscle moment arms and who are able to wrap their fingers around the handles have a mechanical advantage over persons with small hands. Also, the model depicts four 2-dimensional fingers in series which better characterize the 3-dimensional capability of the hand than do existing 1-dimensional strength data. Areas of additional research for enhancement of biomechanical strength models for the hand include determination of: 1) digital link lengths, 2) joint angles for various link lengths and handle configurations and sizes, 3) external load distributions on the hand for various patterns of prehension, 4) muscle length strength data for the FDP and FDS and 5) limits of prediction for various hand postures.

APPLICATION TO THE STUDY OF CARPAL TUNNEL SYNDROME

Carpal tunnel syndrome is a median neuropathy inside the wrist. Histological analyses indicate that the neuropathy is related to mechanical insult (Neary, et al., 1975; Sunderland, 1976; Castelli, et al., 1980). The median nerve is confined within the carpal tunnel along with the extrinsic finger flexor tendons and the synovial membranes of the radial and ulnar bursa. Flexion or extension of the wrist will result in forceful contact and movement between the tendons and the volar and dorsal surfaces of the carpal tunnel (see Figure 4).

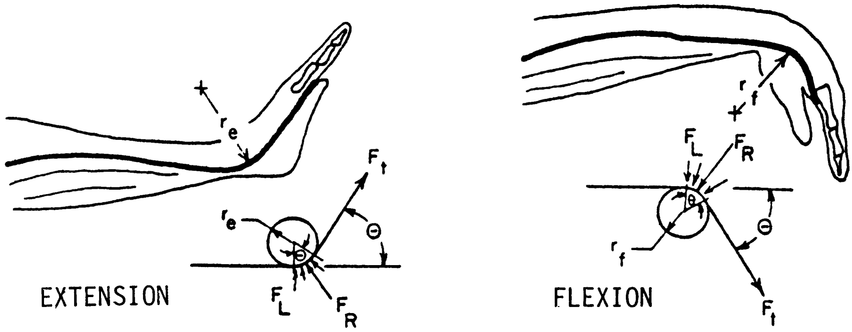

Figure 4: The extrinsic finger flexor tendons are supported by anatomical pulleys with radii r_f and r_e during flexion and extension of the wrist. Intrawrist forces, F_L and F_R are described by Equations (4) and 5). From Armstrong and Chaffin, 1979b.

The dorsal surfaces include the carpal bones and distal head of the radius; the volar surfaces include the flexor retinaculum and the median nerve. Thus, exertions of the hand with a flexed wrist would cause acute compression of the median nerve and explains why the so-called wrist flexion test results in acute symptoms of carpal tunnel syndrome (Phalen, 1966; Smith, et al., 1977).

The contact forces can be estimated if the tendons and adjacent structures are characterized as a low friction pulley-belt mechanism (Armstrong and Chaffin, 1979b). A uniform load distribution, F_L, normal to the contacting surfaces is related to tendon load, F_t, and the radius of the anatomical pulley, r:

$$F_L = F_t/r \qquad (4)$$

The resultant force, F_R, on the pulley structure is related to the tendon load and angle of contact between the tendon and pulley:

$$F_R = 2F_t \sin(\theta/2) \qquad (5)$$

From the above discussion of the biomechanical model and strength it can be seen that contact forces, and hence insult, will be greater for exertions with the finger tips, such as pinching, than for exertions of corresponding force but with a closed fist, such as grip. Although exertions with an extended wrist should not result in acute nerve compressions by the tendons as do exertions with a flexed wrist, in both cases the tendons and synovial membranes of the radial and ulnar bursa will be compressed. It has been reported that swelling due to aseptic tenosynovitis of the synovial membranes inside the carpal tunnel often is a cause of chronic nerve compression in persons with carpal tunnel syndrome (Phalen, 1966; Yamaguchi, et al., 1965). Repeated compression of the tendons and synovial membrane is a likely factor of tenosynovitis (Tichauer, 1966).

Lastly, it is predicted that stress concentrations will be from 15% to 25% greater in female hands with small radii of tendon curvature than in large male hands with large tendon curvature (Armstrong and Chaffin, 1979b). Although male and female differences in wrist size may be an important factor in the disporportionately high incidence of carpal tunnel syndrome in women, wrist size does not appear to be a useful predictor of the risk of developing occupational carpal tunnel syndrome (Armstrong and Chaffin, 1979a).

The arguments above help to explain the relationship between work with certain combinations of posture and force and carpal tunnel syndrome. Areas of future research should include development of dose-response models for repetitive trauma and the study of the other tendons and joints in the upper extremity.

SUMMARY

Biomechanical models of the hand have considerable potential for study of strength, handle size and shape, work posture, and repetitive trauma disorders. Areas for future development are identified for enhancement of model validity and utility.

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FACTOR ANALYTIC APPROACH TO BIOMECHANICAL MODELING[1]

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INTRODUCTION

As an aid in the analysis of motor behavior during the lifting of materials, biomechanical models have been used to study the effects of reactive forces and torques on the joints and links of the human body. In order to apply the mechanical laws of Newton to this type of research, an individual's segment lengths, centers of gravity and weight should be known. One of the first significant works on segmental centers was performed in 1889 by Braune and Fischer (1963) through their dissections of three cadavers. In 1955, Dempster extended this work by analyzing eight cadavers which resulted in better estimates of body dimensions. This research was further expanded by Clauser (1969), Plagenholf (1971) and El-Bassoussi (1974). Other authors (Donskoi, 1973; Zatsiorsky, 1973; Kirjonen, 1968) have applied multivariate statistics to develop their biomechanical models. The underlying principle used in their studies was that individual segment motion is a part of a phase of motion, and that the combination of all phases represent the total system of activity. Roozbazar (1973) emphasized the need for more multivariate analysis in his review of various approaches to biomechanical modeling due to the complexity of body movement. Finkelman and his associates (1977) recommended that multivariate analysis of variance be used in combination with univariate F tests. He claimed that multiple univariate analysis of variance tests applied to simultaneous multimodality measures often resulted in alpha error and loss of information due to the interdependence of dependent variables.

[1]The assistance and advice of Dr. M. M. Ayoub during this research effort is greatly appreciated.

For these reasons, the present investigation utilized factor analysis to extend El-Bassoussi's model (1974) involving non-repetitive short duration lifts in the sagittal plane. The result was a biomechanical model based upon clusters of motion in the floor-knuckle and knuckle-shoulder ranges of lift. These two regimens of motion are close analogs to industrial handling conditions in the sagittal plane; such as lifting a load from the floor to a table and from a table to a shelf. A separate analysis was conducted on each range of motion by studying fifteen dependent variables of segment accelerations electromyograms and forces at the feet. The resultant factor-variables were then utilized to compare lifting by male/female and trained/untrained individuals over time and weight within each regimen. The purpose of this paper is to outline the development, validation and utility of this factor analytic approach to further dynamic motion research.

METHOD

Eight male and eight female university students who were similar in age and anthropometric dimensions were used in this experiment. Age of the subjects ranged from 18 to 30 with a median of 25 years. Means and standard deviations, respectively, for the weight and height among the subjects were 62.4 kgs., 2.2 kgs. and 172 cms, 2.8 cms. Segment lengths were also controlled with the highest standard deviation among the links being 1.6 cms.

Initially all sixteen subjects were considered inexperienced and untrained. An inexperienced/untrained lifter is operationally defined in this experiment as one who did not participate in a regular physical fitness program or exercise routine, use weights, or have a job which involved manual handling of materials. From this sample, four males and four females were selected for the training program while the other eight subjects served as the control group. The experiment also involved separating these sixteen subjects into two equal groups of male/female and trained/ untrained individuals (experimental and validation) for replication purposes. Each of the subjects were observed under all treatment conditions of weight (10, 25, 40 pounds), time (0-.25, .26-.50, .51-.75, .76-1.00, 1.01-1.25 second intervals), measure (pre and post training), and lift regimens (floor-knuckle, knuckle-shoulder). After completion of the training program, the trained and untrained subjects were again measured, approximately a two week interval. Although data for both replication groups were collected separately, the two training programs and time intervals between measurement periods were similar. In all, there were six independent variables and 960 cases per lift for each of the 15 dependent variables. A case represented the combination of the following levels within each independent variable on two trials and 16 subjects: sex-2, program-2, group-2 (between subject variables); weight-3, time-5, measure-2 (within subject variables).

The training program consisted of two males and two females in each replication group lifting 10, 25, and 40 pound weights in floor to knuckle and knuckle to shoulder lift regimens for fourteen practice periods. During each session, subjects in the training program lifted each weight by regimen approximately six to eight times. This totaled to approximately 42 lifts per subject per session. The goal of the program was to improve technique rather than to have muscular development. There was never any attempt to stress, fatigue or motivate the subject to complete more work than he or she wanted to do or was capable of doing. The program attempted to: (1) improve coordination between and rhythm within body segments, (2) decrease biomechanical stress, (3) increase movement efficiency and economy, and (4) stress a lifting method (National Safety Council, 1974) which relied upon balance, initial thrust and low moments upon the body. By emphasizing these rules repeatedly, it was assumed that each trained subject would optimize his performance through repetitive trial and error motion.

Data collection entailed the use of stroboscopic photography, force platform and electromyogram (EMG) methodologies. The equipment consisted of a still camera, lights and a rotating disc with equally spaced apertures for photography; a force plate and dynagraph for force recordings; integrating preamplifier and miniature surface electrodes (½" diameter) for electromyograms; and weights and barbell. The resulting photographic negatives of the experimental lifts provided angular displacement-time data from the lighted movements of the joints. Angular displacements were found by measuring the angles between each joint's segments (El-Bassoussi, 1974). The floor-knuckle lift had six angular displacements (0, .25, .5, .75, 1.0, 1.25 seconds) for the ankle, knee, hip and shoulder joints, while the knuckle-shoulder lift collected data on the ankle, hip, shoulder and elbow joints. In order to simplify the dynamic analysis of the data, the following assumptions were made:

1. The human body is composed of rigid links.
2. These links are joined at articulation points or joints.
3. The lower arm and hand, because they remain aligned during motion, were considered as one link in the analysis. The same was true of the arm during the floor-knuckle lift and leg during knuckle-shoulder lift, since the upper and lower portions of these appendages moved similarly.
4. The density and geometrical shape of a segment remained uniform throughout the lift.
5. Rotation occurred only about the sagittal plane.
6. Segmental motion was considered circular and the radius of rotation was constant.
7. Displacement between the joints and their connecting links was negligible.

8. The ankle remained fixed in one position throughout a lift.

The displacement - time relationship of Slote-Stone (1963) was used next in the calculations. This equation is:

$$\text{Angular Displacement (time i)} = \frac{Dmax}{2\pi}\left(\frac{2\pi t_i}{T} - \sin\frac{2\pi t_i}{T}\right)$$

where; Dmax = maximum angular displacement, radians
T = total displacement time, seconds
t_i = incremental time, seconds

Instantaneous angular displacement is seen in this equation as being of equal increments of total displacement in radians. These increments of displacement are determined from the relationship between the incremental time period to total time of movement. The total time used in the analysis of each segment was the difference between start and end of motion or 1.25 seconds. The advantages of having fixed time intervals and a total time limitation in the study were that the problems associated with the analysis of continuous data was avoided, while all of the pertinent information was included and numerical handling was facilitated. The first and second derivatives with respect to time of the angular displacement equation are angular velocity and angular acceleration. These values determined linear acceleration for each segment. Also important in these calculations is the determination of each segment's weight from percentages of actual body weight and center of gravity from percentages of actual segment length. These transformation values can be found in Plagenholf (1971). The results of this effort in each lift regimen were: (1) accelerations in the z and x axes for each segment analyzed, and (2) inertial forces at the hands in the z and x axes. The z and x axes (Thomas, 1972) represent, respectively, vertical (up/down) and horizontal (forward/backward) movement with positive acceleration being in the direction of motion.

Integrated electromyograms in arbitrary units for each incremental time period were collected on two muscles: medial deltoid and rectus femoris, quadriceps. The main functions of these muscles are that of shoulder abduction (deltoid) , and knee extension and hip flexion (quadriceps). During the experiment, muscular activity was measured by placing both sets of probes in the center of the muscle on the right side of the body. Tracings of these electrode attachments were made during the first measurement period so that placement during the second period would be standardized. Two curves were determined, unstressed (relaxed) and stressed (lifting) conditions. The unstressed baselines were subtracted from the stressed muscular outputs in order to correct for measurement error, heart rate and muscular tension. Lastly, a dynagraph and force platform were used to record force changes at the feet: frontal (forward/backward), lateral (left/right), and vertical (up/down). Data output was in terms of peak variations of positive and negative forces for each time interval above and below a zero baseline.

The last topic of discussion in this section is the experimental procedure. Prior to the placing of electrodes, the subject was allowed a familarization or warm-up period of 15 minutes, which involved calisthenics and the lifting of 10, 25, and 40 lb. weight loads. Each individual was then connected with electrodes and positioned on the force platform. During the experiment, each person performed three lifts with each weight in each regimen. There was a total of 18 lifts per subject. The first lift was a practice one, while data were collected on the second and third lifts. The sequence of weight lifted by one subject was randomly selected, and maintained across both regimens.

RESULTS

Factor analysis was performed separately for each lift regimen on the 15 dependent variables involving acceleration patterns in the x and z axes, forces at the feet in three axes, and two electromyograms. Inertial forces at the hands in the x and z axes were not included in these analyses, but were studied during the validation phase of this experiment. The conceptual model for factor analysis utilized in this study treated the testing conditions (dependent variables) as variables, the time segments and independent variables as cases, and people as constants. In this approach, the resultant factors were clusters of variables as they covary over time. The principal axis method was conducted to maximize the amount of variance shared commonly among the factors. Factoring was halted when the eigenvalue slipped below 1.0. Accordingly, two factors explained 58% of the variance for the floor to knuckle lift, and three factors explained 53% of the variance for the kunckle to shoulder lift. Varimax rotation was performed so that each variable loaded mainly on only one factor. In this way, factorial interpretation is as simple as possible. Table 1 contains the results of the statistical rotation with the variable loadings outlined by factor. A factor loading is similar to a correlation coefficient. The square of the loading indicates the amount of variance explained by a variable on a factor. The sum of the squares in any column gives the total amount of variance by a factor, while the average of these squared loadings depicts the proportion of total variance. The sum of squared loadings in a row (h^2) shows the proportion of variance by a variable on all of the factors. The higher the h^2, the more common variance a variable shares with the other variables (Nunnally, 1967).

Table 1 indicates that most of the variance is explained by the acceleration data. In the floor-knuckle lift, factor I was represented by movement in the x axis, while factor II was defined by changes in the z axis. Factor III in the knuckle-shoulder regimen stood for x axis movement. Trunk/upper arm/leg and lower arm/hand

TABLE 1
FACTOR MATRIX AND LOADINGS FOR FLOOR-KNUCKLE AND KNUCKLE-SHOULDER LIFTS OF THE COMBINED SAMPLE

VARIABLES	FLOOR-KNUCKLE LIFT FACTORS			KNUCKLE-SHOULDER LIFT FACTORS			
	I	II	h^2*	III	IV	V	h^2*
Rectus Femoris	.20	.11	.05	.09	.00	.00	.01
Medial Deltoid	.08	-.02	.01	.20	.02	.01	.04
Frontal Force	-.34	-.22	.16	.21	-.06	.24	.11
Lateral Force	.29	.03	.09	-.16	-.22	.28	.15
Vertical Force	.78	-.04	.61	.22	-.09	.53	.34
Leg - X Axis	-	-	-	.70	-.06	.06	.50
Lower Leg - X	.76	.42	.75	-	-	-	-
Upper Leg - X	-.73	-.19	.57	-	-	-	-
Trunk - X	.46	-.60	.57	.94	.03	.11	.89
Arm - X	.94	-.20	.92	-	-	-	-
Upper Arm - X	-	-	-	.88	.08	.06	.78
Lower Arm - X	-	-	-	.91	-.03	.08	.84
Hand - X	.96	-.04	.92	.63	-.13	.18	.45
Leg - Z Axis	-	-	-	.00	.75	-.03	.56
Lower Leg - Z	-.23	.67	.50	-	-	-	-
Upper Leg - Z	-.10	.84	.72	-	-	-	-
Trunk - Z	.29	.95	.99	.02	.93	-.09	.87
Arm - Z	.45	.85	.93	-	-	-	-
Upper Arm - Z	-	-	-	-.13	.80	.25	.72
Lower Arm - Z	-	-	-	.02	.38	.89	.93
Hand - Z	.53	.77	.87	.07	.11	.90	.83
Total Variance	.31	.27	.58	.24	.15	.14	.53

*h^2 = common variance explained by variable

movements in the z axis, respectively, defined factors IV and V. Although the electromyogram and force platform variables did not contribute heavily to the factor structure, many of the factor loadings were significant at .20 and above. Quadriceps and deltoid muscles loaded, respectively, on the x axis of the floor-knuckle and knuckle-shoulder lifts. This was as expected since these lifts coincided closely with each muscle's specific function. Vertical force explained most of the variance of the platform variables within the factor structure. These significant loadings demonstrated some concurrent validation between the different sources of data collection and analysis.

Validation of this factor variable model was performed by comparing the factor structure of both the experimental and validation samples. The factor scores for each person from either the experimental or validation group were correlated with the scores from the combined data set. The comparability of the factors were judged by the size of the relationships (Nunnally, 1967). Factor scores are similar to a multiple linear regression model by utilizing the loadings as beta weights which are multiplied by the case's standard score on each variable. The following results indicated a high similarity between both factor structures: I = .751, II = .911, III = .360, IV = .685, V = .915. Validity of the Slote and Stone equations was also important since the development of the present model depended upon the determination of angular velocities and accelerations for each body segment. Validation procedures were performed using the Kolmogorov-Smirnov goodness-of-fit test. Results indicated that there were similar distributions in both lift regimens for (1) observed and predicted (Slote and Stone) angular displacements on all of the segments over time, and (2) the resultant forces in the x and z axes from both the feet (platform) and hands (film). Multiple regression was also used which demonstrated that there were significant relationships between inertial forces at the hands (film) and forces at the feet (platform). The average multiple correlation for the four regression analyses was .467.

DISCUSSION

A valid biomechanical model utilizing factor analysis was developed for non-repetitive, short duration tasks in the sagittal plane during floor-knuckle and knuckle-shoulder lifts. The factor analytic procedure was performed in order to determine similarities or clusters among the variables, to erect a structure or classification model to ease the burden of analysis and interpretation, to increase experimental power and validity, and to act as a screening device for testing the aggregate effects of each variable. The utility and extension of this methodology to future experimental studies could be demonstrated by the combination of factor analysis with analysis of variance in this research effort. Fifteen dependent variables in each regimen were collapsed to five dependent factor-variables. Factor scores from these analyses were then studied at four different statistical levels. Analysis of variance, simple main effects, and Tukey multiple comparisons helped to determine significant main and simple main effects. In this way, large amounts of information were efficiently and effectively studied through the clustering and screening of the data. T-tests were then used to evaluate the impact of significant independent variables on each of the 15 dependent measures within each factor by studying the initial (non-factored) values. This last effort completed the computations by isolating the critical components of motion in order that inferences could be stated. Throughout these statistical tests, the alpha probability level was made smaller as the level of testing changed in order to minimize the occurrence of a Type I error.

The purpose of the paper, which is to explain the development, validation and utility of the factor analytic approach, has been accomplished in preceding paragraphs. A logical summation to this discussion would be to outline the conclusions regarding male/female and trained/untrained lifting differences in the data:

(1) Males had higher accelerations and decelerations than females during the floor-knuckle lift.

(2) Males relied more on back and arm strength, while women used more leg and back motion to supplement strength differences during the knuckle-shoulder lift.

(3) Male movements approximated the trained condition while female lifts were similar to the untrained sample in both lifts.

(4) Trained individuals demonstrated more efficient and coordinated lifts by having similar patterns of acceleration with, but significantly higher deceleration patterns from, the untrained condition during both lifts.

(5) Training programs should be considered in the industrial environment, if women are expected to lift moderately heavy loads because of their lower physical fitness and coordination when compared to men. This last conclusion was supported by another study (Shannon, 1980) which conducted a critical incident technique of strain/sprain/overexertion injuries in the industrial environment.

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Session VI
Applications I

WORKSPACE EVALUATION AND DESIGN: USAF DRAWING BOARD MANIKINS AND THE DEVELOPMENT OF COCKPIT GEOMETRY DESIGN GUIDES

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1. USAF DRAWING BOARD MANIKINS

One of the more recent design tools developed from anthropometric data is the series of USAF Two-Dimensional Drawing Board Manikins.[1] They were designed by the author primarily for use in the design and evaluation of seated work and crew stations, although with the use of appropriate limb parts they are of essentially equal usefullness in standing workstation design. Fifth, 50th, and 95th percentile male manikins were designed in accordance with the anthropometry of the USAF rated pilots projected to the 1980-90 time period. The procedures used in making these projections are included in Churchill and McConville (1976). A plan for the 5th percentile male manikin is illustrated in figure 1. A 5th percentile female manikin was designed primarily after the current USAF anthropometric data on women from Clauser, et al (1972). An abbreviated list of body-size data after which the manikins were designed is found in table 1.

Considerable additional anthropometric data were used to establish the overall sizes and mobility of the manikins. Several dimensions derived from Snyder, et al (1972), were used to establish the relationships between and the mobility limits of the major segments of the torso. The centers of rotation of the head, neck, and torso correspond to the atlanto-occipital joint, the interspaces between the 7th cervical and 1st thoracic vertebrae, 8th and 9th thoracic vertebrae, 3rd and 4th lumbar vertebrae, and the hip joint. Joint range data for the limbs were taken from Barter, et al (1957).

Information regarding the position of the base of the heart (aortic)

[1]USAF Patent 4,026,041, May 31, 1977.

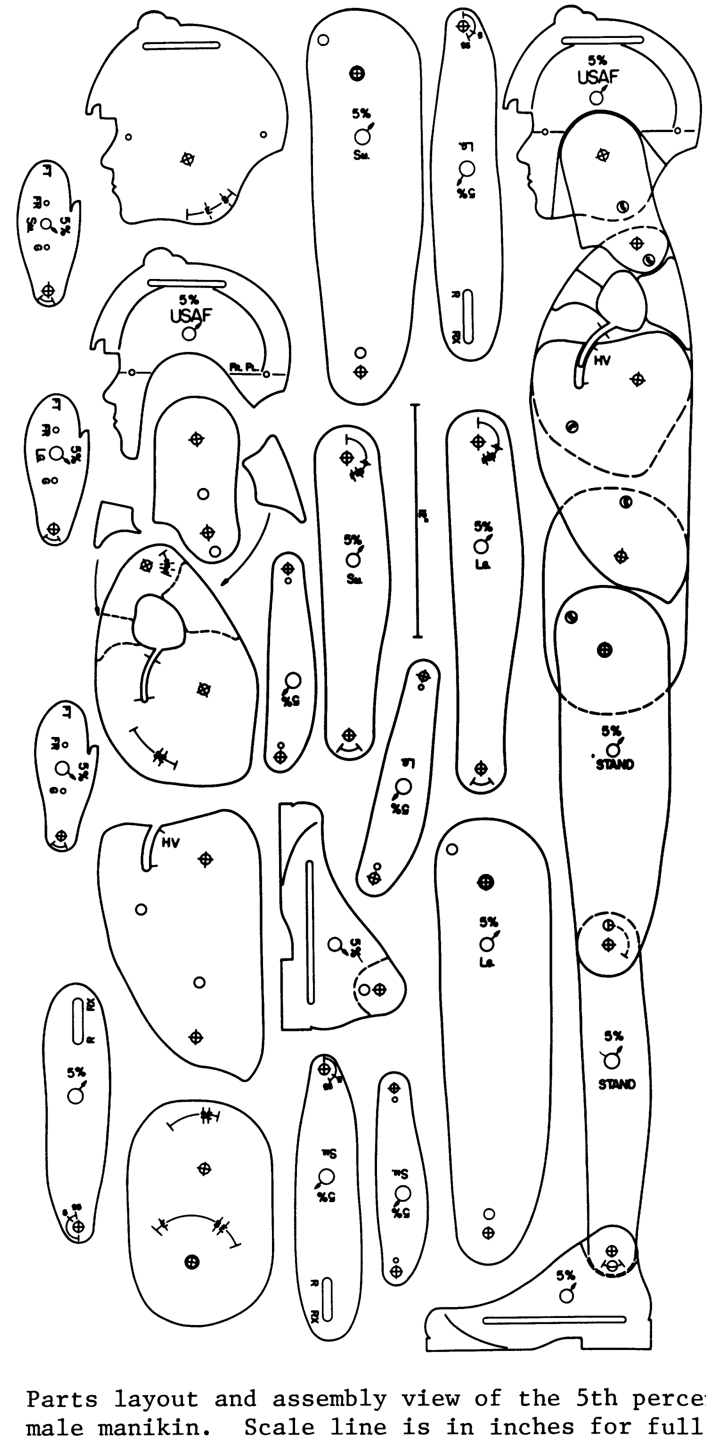


Figure 1. Parts layout and assembly view of the 5th percentile USAF male manikin. Scale line is in inches for full scale.

TABLE 1. Anthropometric data after which the USAF manikins were designed - an abbreviated list.

DIMENSION[1] (All values in centimeters)	AF WOMEN 1968	USAF MALE, RATED OFFICERS 1980-1990 ESTIMATES		
	5TH%	5TH%	50TH%	95TH%
Stature	152.4	168.2	178.4	188.6
Sitting Height	80.4	88.5	93.6	99.0
Eye Height (Sitting)	68.7	76.4	81.3	86.5
Thumb-Tip Reach[2]	71.0	78.0	86.0	93.0
Thumb-Tip Reach, Extended	76.0	82.9	90.1	97.7
Forearm-Hand Length	40.0[3]	44.6[4]	47.9[4]	51.2[4]
Elbow-Grip Length	29.6[3]	32.8	35.4	38.1
Hand Length	16.9	17.9	19.2	20.6
Buttock-Knee Length[5]	51.3	54.1	60.8	67.6
Knee Height[5]	44.5	49.9	56.1	62.4

[1] Unless otherwise indicated, female data are from Clauser, et al (1972). Male data were projected from Grunhofer and Kroh (1975).
[2] From Kennedy (1978).
[3] From Churchill, et al (1977).
[4] From Hertzberg, et al (1954).
[5] For seated work stations - most-used values.

valves) was taken from Eycleshymer and Schoemaker (1911). Tracking the position of the base of the heart is accounted for by using overlapping arcuate slots and engraved indices on the overlapping parts of the upper torso. The position of the valves can, therefore, be estimated as the torso flexes and extends. By tracking the positions of the eye and aortic valves, changes in tolerance to $+G_x$ and $_z$ accelerations can be appreciated.

Located close to the center of rotation of the manikin segments are adjustment holes and indices indicating ranges of motion. Near the centers of rotation within the head, neck and torso, the letters "E" (Erect) and "S" (Slump) are engraved. Adjacent segments may be aligned such that the adjustment holes will overlay indices so lettered. When all are overlaying "E", the head, neck, torso, and thigh are in the erect, seated (or standing) position - when overlaying "S", a typical slumped orientation of the torso is achieved.

Additional upper and lower limbs were designed to allow the user to consider variability in body proportions as well as in body size. Using regression equations based on Eye Height, Sitting, and Weight, and an appropriate factor of the Standard Error of the Estimate, the ranges of limb lengths that can be expected to be associated with the various percentile torso sizes, i.e., 5th, 50th, and 95th percentiles, were determined. The ranges necessary to include the central 90 percent were calculated and alternate limbs were designed accordingly. In practice, the small limbs associated with the 5th percentile torso usually see more use than the others. As will be seen later, however, special design situations require the use of other body-limb combinations to represent the extremes of capability and, therefore, accommodation. To facilitate the use of the manikins for standing work stations, a lower limb of appropriate length was designed. When this limb is in use, the floor-to dimensions such as Eye Height (Standing) and others are not as accurate as when these landmarks are considered in the erect seated position.

2. COCKPIT GEOMETRY DESIGN GUIDES

Cockpit geometry design guides have the general appearance of the familiar U.S. Department of Defense Military Standards 33574, -5, and -6, which specify the basic cockpit geometries of stick and wheel controlled, fixed wing aircraft and helicopters, and the USAF Design Handbook 2-2, "Crew Stations and Passenger Accommodations". They differ from these documents, however, in that they permit a great deal more flexibility in design. These military standards specify single values for the seat back angle, seat angle, vertical seat adjustability and the location and movement envelopes of the throttle, control stick, and rudder pedals. They strongly imply, by their lack of any alternative guidance, that aircraft of the same generic type must all meet the same standard geometric requirements. The design guides, however, have been developed specifically to portray ranges of acceptable dimensions and relationships. They also will make available more extensive anthropometric and geometric data not found in military standards and handbooks. It is hoped that they will provide the much needed anthropometric data base to permit flexibility in cockpit design.

There are several critical elements basic to any aircraft cockpit geometry design guide. They are: (1) back angle, (2) seat angle and, (3) in the ejection cockpit, the angle of the path along which vertical seat adjustability is achieved, and (4) also in the ejection cockpit, the angle of ejection (the ejection clearance line). The range of body size accommodation is always 5th to 95th percentile for Eye Height, Sitting, although 1st to 99th for this dimension is easily achieved. The ranges of accommodation for all other body dimensions is 1st to 99th percentile, minimum. To achieve these ranges of accommodation, the USAF 5th to 95th percentile male drawing board manikins were used, along with their alternate limbs. Since hard mock-ups and live subjects were not used to verify the dimensions, the recommended values must be perceived, as their name implies, to be Guides.

In the brief space of this paper, only selected guides for an ejection type cockpit can be presented. Figure 2 portrays geometric information for cockpits with a 15° seat-back and 10° seat combination and in which vertical seat adjustability and ejection are parallel to the back. Adequate adjustability for 5th to 95th percentile accommodation to Eye Height, Sitting can be obtained with 4.6 cm movement parallel to the back, above and below NSRP: 6.6 cm above and below NSRP will accommodate 1st to 99th percentile for this body dimension.

To help guide the placement of hand operated controllers in the forward direction, the guide contains information showing the relationship between minimum reach capability and the minimum space needed for fore and aft ejection clearance. Obviously, in an ejection-seat cockpit, it is necessary that hand operated controls in front of the pilot be located beyond the ejection clearance line. This requirement is crucial in attempting to achieve accommodation to large ranges of hand reach and Buttock-Knee Length. Back angle and direction of seat adjustment play critical roles in achieving useful, reachable space forward of the ejection clearance line.

Another important consideration is the range of lower leg (shank) lengths. These values, expressed as arcs originating from expected knee centers, determine the maximum thrust of the foot in the forward direction. It is in this manner that the position of full forward throw of the rudder from its full forward (99th percentile leg) and full aft (1st percentile leg) adjustments. The throw and adjustability dimensions can be developed from these data. For the purpose of comparison, all examples of possible rudder location, throw, and travel in this short paper, are along a horizontal line at NSRP level. This should not be taken as a recommendation. A wide variety of approaches to provide rudder-travel and throw can be derived.

Several other useful data points are included. They include range of eye positions, catapault/ejection eye position, position of the base of the heart, the highest expected knee position during full rudder thrust with the opposite leg, position of the knee of the large pilot and clearance needed for safe ejection, minimum head clearance under the canopy, and others. Although not illustrated in this paper, dimensional information has been developed to provide the designer with several alternatives for locating the maximum full pitch down--full left aileron control stick position: ranges of reference points for the throttle, sidearm control, and forearm rests: a selection of fixed sidestick orientations so as to be centered in the range of forearm pronation-supination: and reach contours in front of the pilot.

Figure 3 portrays similar information regarding another 15° back angle--10° seat geometry in which, to achieve vertical seat adjustment, the seat is moved forward and upward along an angle established so as to achieve equivalent reach capability for the 1st to 99th percentile range. Using this procedure to obtain vertical adjustability, the smaller pilot is moved upward and forward. This is entirely logical from a human factors standpoint since the smaller pilot should be located higher and farther forward in the cockpit to achieve equivalent general accommodation as the larger pilot.

The up and forward seat adjustment introduces an interesting and instructive seat of design considerations. Referring again to figure 2, vertical seat adjustability is upward and aft, parallel to the seat back. When in the full up seat position, the pilot with a short torso and with arms shorter than usual--less than 1st percentile--as expected, will represent the minimal reach capability that must be accommodated. With up and forward seat adjustability, a pilot with different body and limb proportions produces minimal reach capability. The seat adjustability angle and length portrayed in figure 3 are such

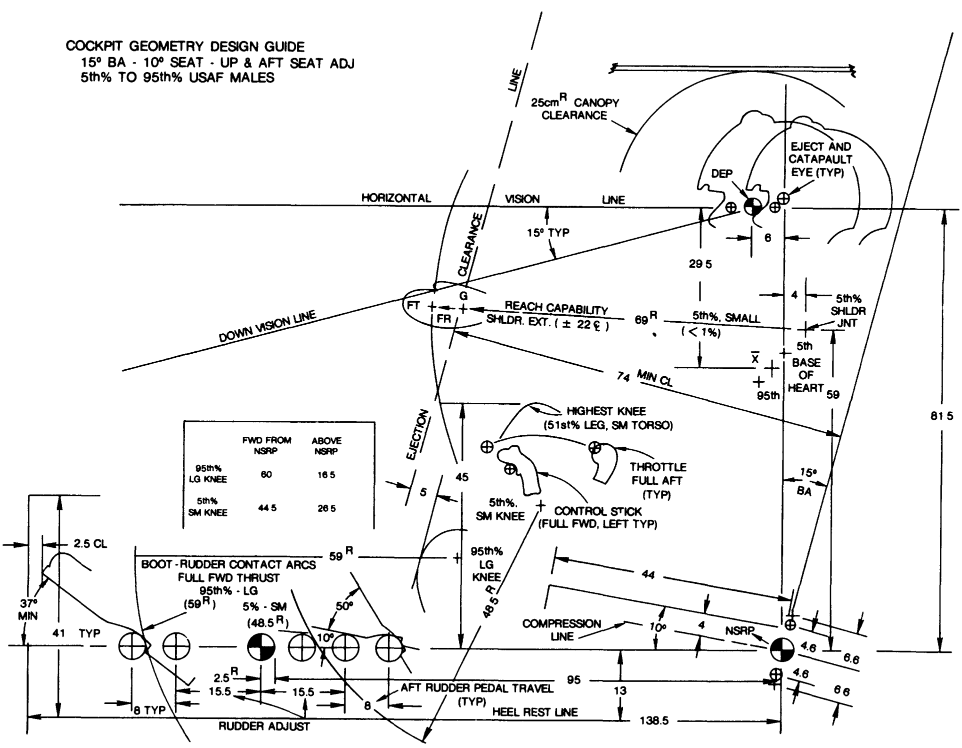
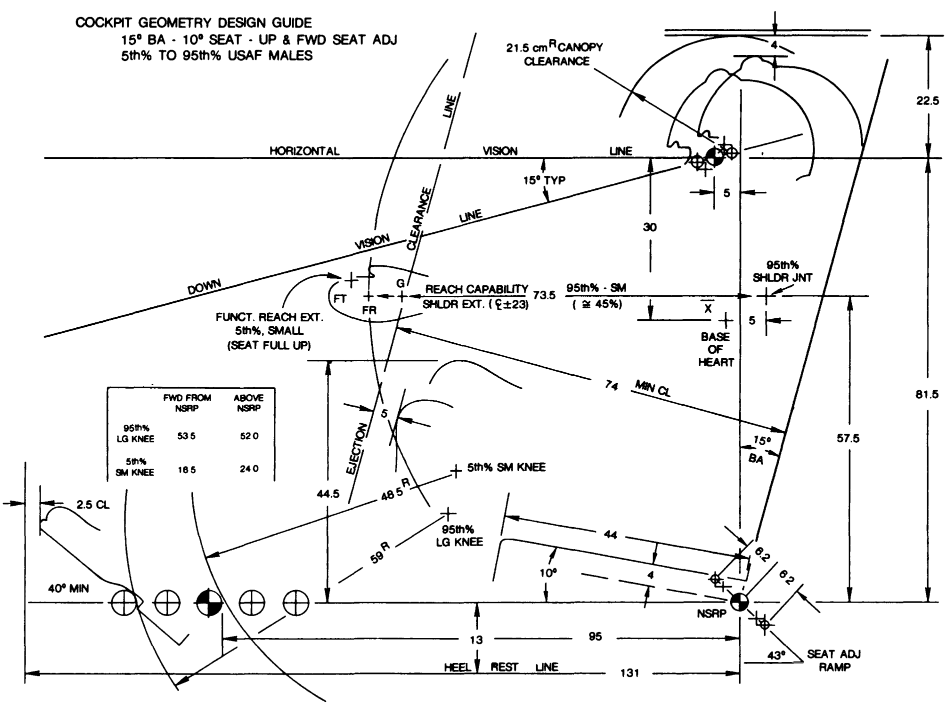


Figure 2. Cockpit geometry design guide for ejection-type cockpit with 15° back angle, 10° seat, and seat adjustability and ejection parallel to the seat back.

that the pilot with a long torso and relatively short arms--45th percentile minimum--will have the least reach capability forward. This body proportion, then, unexpectedly produces the minimum reach capability from the recommended seat position. Although this direction of seat adjustment appears to result in a slight enlargement of the accessible space forward of the ejection clearance line, another problem is created, that of assuring adequate knee clearance during ejection.

If there could be certainty that all pilots would adjust to the horizontal vision line, no problems related to safe knee clearance during ejection would be anticipated. However, since pilots often adjust themselves as high as possible, the probability of a clearance problem must be considered. This probability is increased if and when the pilot with a large torso and a large Buttock Knee Length raises the seat up and forward. In an attempt to control the maximum to which the larger pilots can raise the seat upward and forward, a minimal



	FWD FROM NSRP	ABOVE NSRP
95th% LG KNEE	53.5	52.0
5th% SM KNEE	18.5	24.0

Figure 3. Cockpit geometry design guide for ejection-type cockpit with 15° back angle, 10° seat, adjustability up and forward to achieve equivalent reach capability forward, and ejection parallel to the seat back.

canopy clearance is indicated--4 cm (approximately the thickness of the hand). It is unlikely that other, better procedures to control knee protrusion can be developed.

Another variant of the up and forward seat adjustment approach is found in figure 4. In this guide the seat is moved along a 71^0 angle for the purpose of achieving equivalent positioning of the pilots' eyes. An adjustment of 5.2 cm above and below NSRP will accommodate from 5th to 95th percentile Eye Height, Sitting--7.6 cm above and below NSRP will accommodate 1st to 99th. The seat adjustment angle and length are such that the body proportions that produce minimum reach capability are the small torso--short reach pilots--those that did so in the conventional up and aft seat travel portrayed in figure 2. The up-and-forward seat travel angle at which the change-over from small torso-short reach to large torso-short reach is between 43^0 (see figure 3) and 71^o (see figure 4). As can be seen in figure 4, the point to which the pilot with 95th percentile torso and

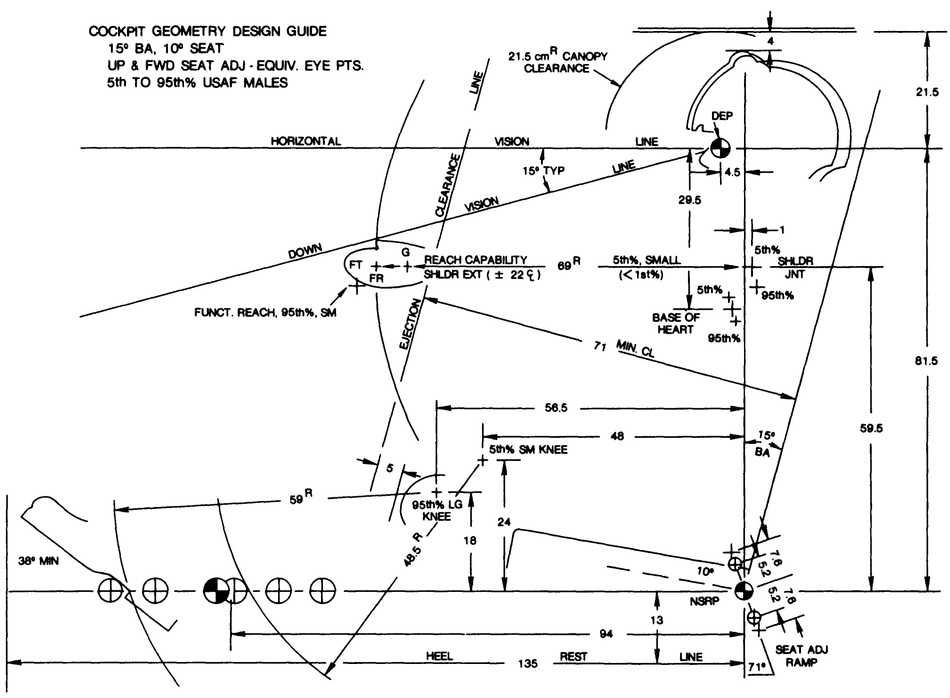


Figure 4. Cockpit geometry design guide for ejection-type cockpit with 15^o back angle, 10^o seat, seat adjustability up and forward to achieve common eye position, and ejection parallel to the seat back.

45th percentile reach can be expected to reach is further forward than that with a 55th percentile torso and 1st percentile reach. It appears that a small amount of additional space for manual control location is made available forward of the ejection line when using a 71^{o} seat travel line. Again, to limit the upward travel of the seat--for the primary purpose of controlling forward knee protrusion--a minimal head-canopy clearance might be required.

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SOMATOGRAPHY IN WORKSPACE DESIGN

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INTRODUCTION

The solution of ergonomic questions in systems design and evaluation is strongly dependent on the presentation of anthropometric data, which are formulated in various ways, mostly to meet the unique requirements of a particular design problem (compare GEDLICZKA, 1977). To fulfil the tasks of anthropometric design and evaluation of systems hardware more efficiently, techniques are needed which are valid to accommodate a wide range of subjects in all design spheres, integrate the various forms of data systematically, and in which the potential user's designing techniques are considered.

SPECIFICATIONS FOR A GEOMETRIC MAN-MODEL

In this paper it is dealt with a geometric man-model for ergonomic design and evaluation which may easily be applied by users with an engineering, ergonomic or medical background.

Such a method, which is a compromise between the complexity of man's anatomy and the need of practically applying anthropometric data, should meet the following requirements:

- A representation of the human body should be in accordance with anatomic and anthropometric principles.

- If a representation of the human body with specific

body dimensions is displayed in various postures, body dimensions and proportions must remain constant in all postures.
- Body dimensions should be derived from their frequency distribution in a population.
- The man-model has to be suitable and reliable both for anthropometric design and evaluation of proposed products and the redesign of already existing work places, consumer products, equipment etc.
- The man-model should enable to derive form and dimensions of systems hardware graphically, without resort to field and laboratory studies.
- The man-model has to exclude free hand graphic representation of the human body.
- The man-model has to be comprehensible to designers, respect their ways of thinking and their techniques.

EXISTING GEOMETRIC MAN-MODELS

If we look upon existing geometric man-models, we may say that the application of computer-models is, at present, too costly in small organisations, requires some skill, and is most efficient only for the continuous optimisation of a specific product, but inefficient in the case of a fast changing variety of design tasks.

In order to avoid free hand graphic representations of the human body, several types of drawing board manikins have been developed. They often have a restricted scope of application (e.g. seated operator) or data cannot be presented in a three-dimensional form. Another problem in the practical application of anthropometric data is that, on the one hand we do have sophisticated measuring methods to acquire anthropometric data of the human body in somewhat artificial postures, whereas on the other hand we know that these postures are only of limited relevance to the dimensions of a working person. Due to intraindividual and interindividual differences in work performance and its variation during the working time - and ergonomic design should enable those variations - the application of man-models in ergonomic design and evaluation is limited.

Being aware of these limitations we should not evaluate the different man-models in respect to anthropologic fidelity but consider the utility of simplifying the human body features for practical applications.

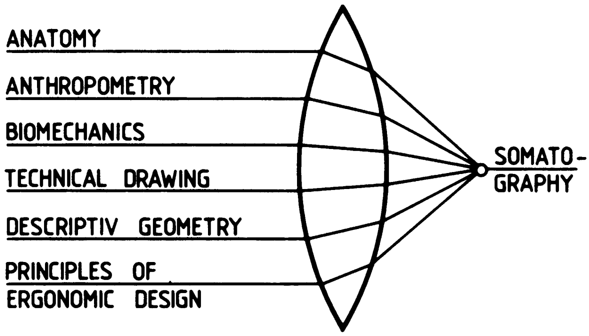

Fig. 1: Disciplinary Sources of Somatography

SOMATOGRAPHY

To meet the above postulated requirements for the presentation of anthropometric data suitable for ergonomic design and evaluation, Somatography has been continuously developed and applied in all design spheres over the past 20 years. Somatography is a graphic-constructive method of displaying scale models of the human body in clearly defined and reproducible body postures based on anatomic and anthropometric characteristics of the human body. In order to integrate technical and human data, Somatography draws upon anatomy, anthropometry, biomechanics, the principles of ergonomic design, the rules of technical drawing and descriptive and analytic geometry (Fig. 1). A scale model of the human body is derived by simplifications of the human body features.

- principles and simplifications of Somatography:

- The human skeletal system is represented by a kinematic model (Fig. 2).

  Instead of anatomical joints analogue technical joints (hinge, pivot, ball and socket joints) with clear, fixed, geometrical axes are defined.

  The elements of the skeleton are represented graphically by the lines connecting the joint centres.

  The spinal cord is replaced by a flexible rod of constant length formed by arcs of circles.

  The ranges of motion of the various joints of the skeletal model are assumed constant both for male and female.

Resulting positions of body segments are derived by superposing the elementary anatomical movements of the various joints (law of superposition).

- Any anatomically possible position of the body may be defined, identified and reproduced by the angular displacement of the limbs relative to each other.
- The body dimensions determined by skeletal and contour dimensions guarantee a complete and uninterrupted profile of the human body, consisting only of straight lines and arcs of circles thus excluding a free hand representation of the human body. Shoes and working clothes are included in the contour.
- The proportions of the body dimensions (ratio of dimensions in relation to the body height) are assumed constant for the whole range of body heights neglecting differences due to sex and age (15 - 65 years).
- To derive one body posture from another the rules of descriptive geometry may be used.
- The technique of drawing graphic representations of the human body conforms to the rules and standards of technical drawing.

body postures

In Somatography body dimensions are systematized in structural und functional dimensions. Structural (static) dimensions comprise skeletal dimensions, which define the distances between the joint centres of the body segments and contour dimensions, inseparably connected with the skeletal system, forming an uninterrupted profile of the human body in all three projection planes. Functional (dynamic) dimensions based on skeletal and contour dimensions define the spatial configuration of work places in respect to anthropometric traits of the users.

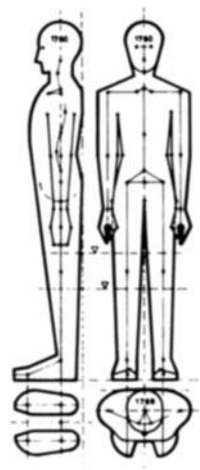

Fig. 2: Somatodrawing of the human body (standard posture) in side, front, top views

<u>system of body heights</u>

After having checked anthropometric data of different sources (Fig. 3), in Somatography a system of body heights for men and women was derived from a synthetic cumulative frequency distribution of body heights of a population (Fig. 4, JENIK, 1963). It contains minimal average and maximal body heights (5th, 50th, 95th percentile) as limits of individual stature ranges. The system of body heights covers dimensions between 1500 mm and 1900 mm (shoes included). The whole dimensional range of statures of 400 mm is distributed to three intervals, two comprising 130 mm and the last 140 mm of stature range. The stature range for women is 260 mm (2x130 mm) between the smallest woman (1500mm, 5th percentile) and the tallest (1760 mm, 95th percentile), the average woman being 1630 mm. So the body heights of average man and tallest woman and smallest man are assumed equal as well. By these simplifying assumptions the number of body heights relevant for design is reduced to four. Nearly all other systems of body dimensions do contain six statures: minimal average and maximal statures for both men and women (e.g. HELBIG and JÜRGENS, 1977). As the real differences are only millimeters, they may be neglected for the purpose of anthropometric design.

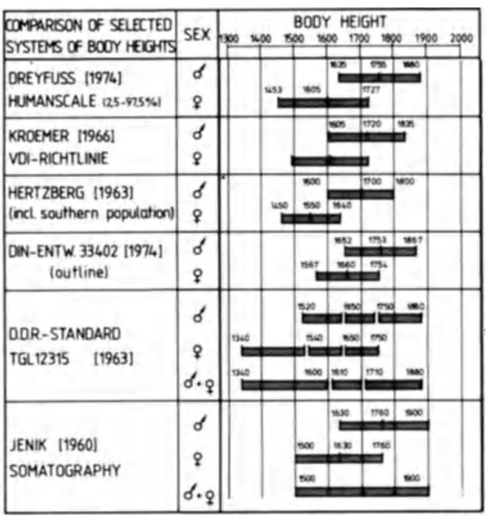

Fig. 3: Comparison of selected body heights

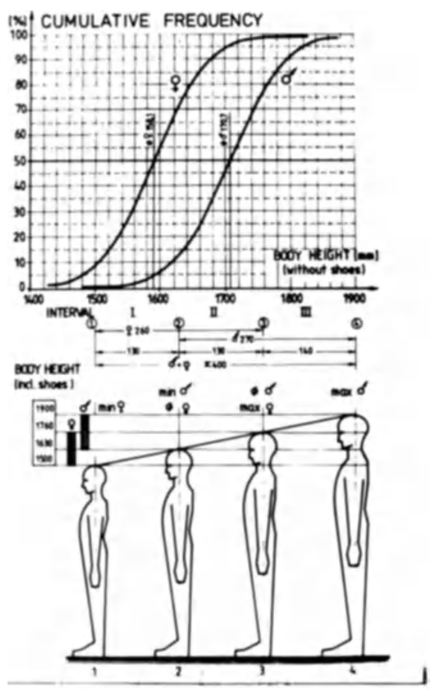

Fig. 4: Cumulative frequency distribution of body heights

construction of somatographic representations of the human body

To construct somatographic representations of the human body, manikins have been developed according to the principles mentioned above. Manikins for four body heights are available in scales 1:5, 1:10 for all three planes of projection (Fig. 2). Descriptive geometry is used to construct sophisticated body postures (e.g. if the body is turned in respect to the drawing plane, Fig. 5).

training of users in Somatography

An important point is how to train the users in applying geometric man-models in their everyday work of ergonomic evaluation and design. To teach Somatography special seminars are held twice a year in collaboration with the German REFA-Organisation. Additionally, seminars on ergonomic design including Somatography take place in the Volkswagen-Company. Up to now, about 500 engineers, industrial designers, plant lay-outers, work study practitioners, etc. have been trained. A Somatography manual is available for these seminars. Somatography is equally used in teaching industrial designers and engineers the methods and principles of ergonomics.

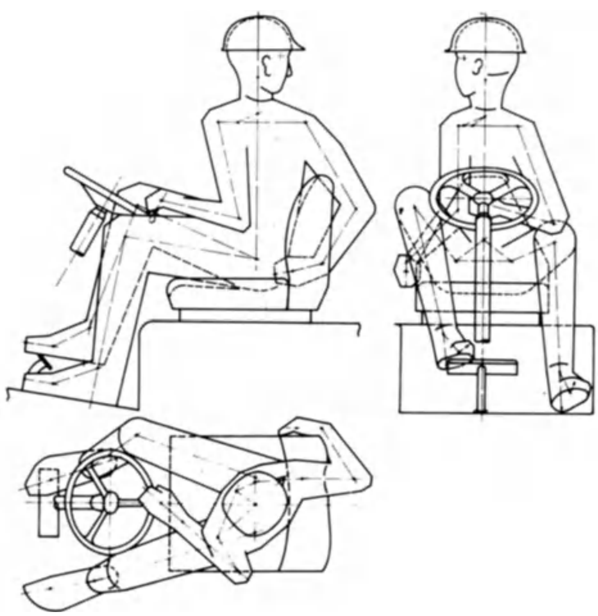

Fig. 5: Twisted body posture in a fork lift

application of Somatography

Somatography may be applied for evaluation and design of both existing systems (corrective ergonomics) and hypothetical systems (conceptive ergonomics). In the following the improvement of mining machinery by means of Somatography will be shown. In the somatographic analysis snapshots of the operator performing characteristic tasks are constructed in three projection planes (Fig. 6). To validate these drawings, photos or video documents might give additional information on the real performance behaviour of different operators.

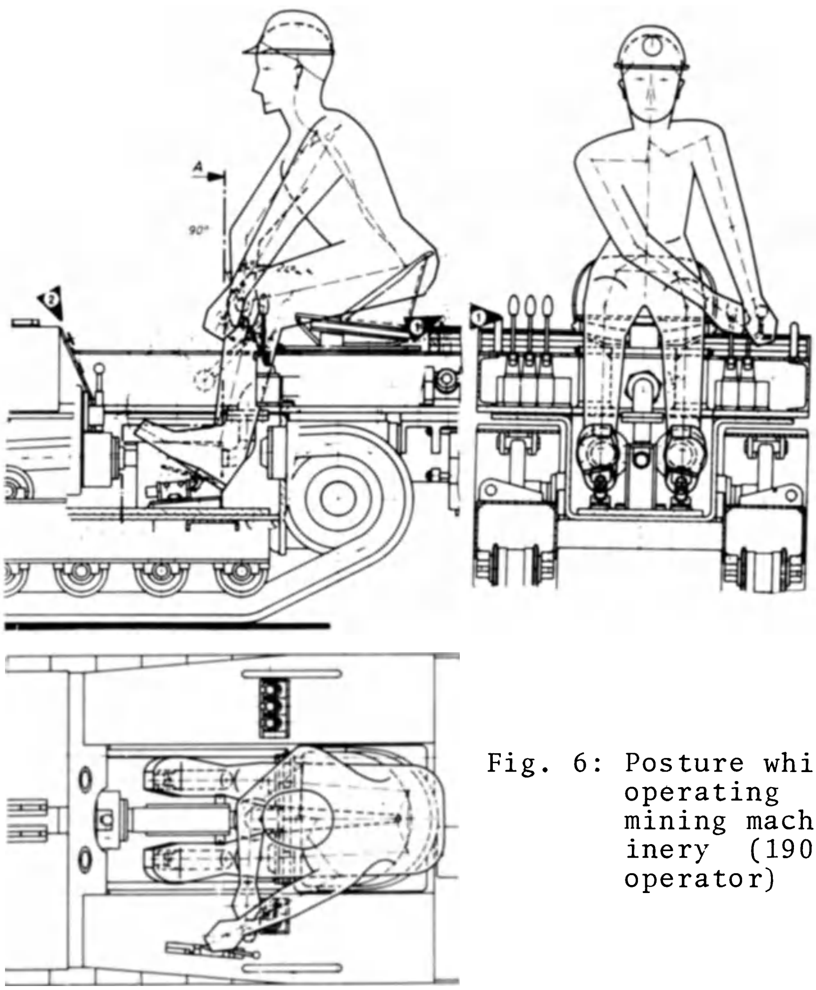

Fig. 6: Posture while operating mining machinery (1900mm operator)

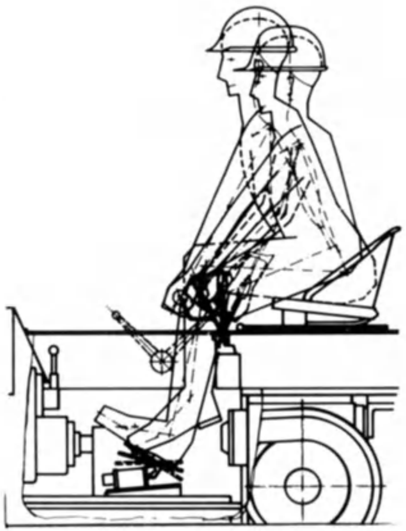

Fig. 7: Synopsis of different sized operators (old design)

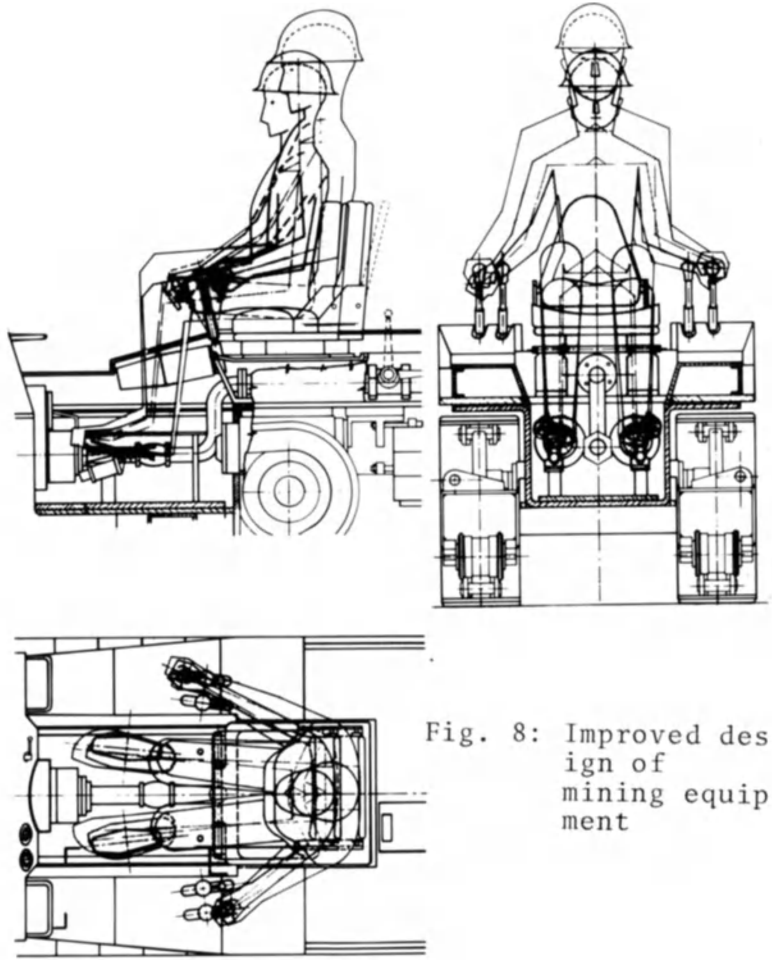

Fig. 8: Improved design of mining equipment

In Fig. 6 a critical task is shown, where the 1900 mm-operator cannot really sit and controls can only be reached in a bad posture. The bad location of the levers causes a twisted trunk, at the same time reducing the muscle forces available to apply the controls, while the operator has to look ahead. Contrary to the 1900 mm-person the 1760 mm-operator cannot reach the pedals while sitting nor can he sit while using the pedals: this is made evident by a synopsis of different-sized operators in one drawing (Fig. 7).

To develop an improved design the operator is drawn in the desired postures and the hardware around the operator is modified iteratively until the desired postures or sight geometry is achieved. Such an improved design is shown in Fig. 8 confronting different sized operators. A prototype is built without the intermediate stage of a mock-up. Physiological measurements showed a substantial decrease in heart rate and electrical activity of selected muscle groups (Fig. 9).

limitations and further development

Even though Somatography was developed to meet the needs of a wide range of ergonomic design and evaluation problems, the scope of this method is limited:

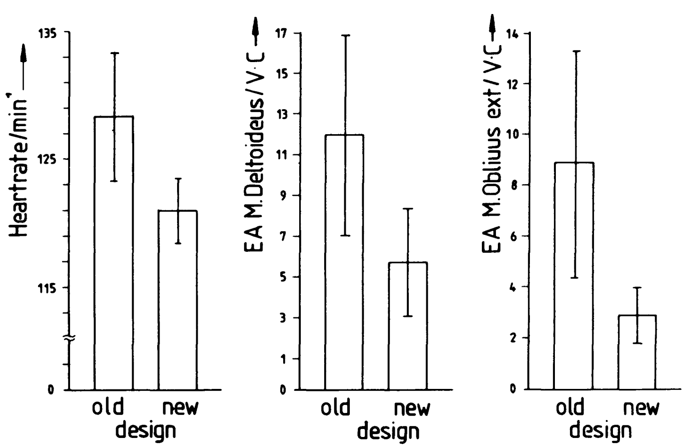

Fig. 9: Comparison of operators strain in old and new design

The human hand, due to its complexity, cannot be represented adequately by means of Somatography, thus the method cannot solve questions concerning hand grip design nor the design of shoes and clothing.
Because of surplus degrees of freedom an unequivocal body posture cannot be determined in all anatomically possible cases (e.g. with a given position of the hand centre and the shoulder-joint centre the position of the elbow joint centre cannot be defined clearly without additional conditions).
All anatomically possible postures may be graphically displayed by means of Somatography. Statements about stability of a posture or its physiological consequences - the dimension 'time' is not included - cannot be made in a geometrical system. Further research will be devoted to the integration of biomechanical and physiological parameters into Somatography.
A sequence of movements may be represented by somatographic drawings only in single characteristic positions.
Children under 15 years of age are not integrated in the dimensional system of Somatography.

Summarizing, the limitations of Somatography may be divided into two groups: First, all those being caused by a simplified representation of the anatomical facts in a geometrical system and, second, the limitations due to lacking biomechanical and physiological boundary conditions. Further research will deal with the first group of bounds and try to cope with the stability of body postures.

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A SYSTEMS APPROACH TO LONG TERM TASK SEATING DESIGN

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INTRODUCTION

This paper deals with what the author believes to be the two most critical factors necessary to ensure the design of ergonomically correct task seating. First, the contoured shapes and the overall dimensions of a task seating product can, and must, correspond to the full anthropometric range of the adult male/female use population. Second, user design management function must be a meaningful part of the product development process. It must function as a politically independent management tool to be reconciled with by the traditional product development management functions of marketing, engineering, and manufacturing.

Task seating, when referred to in this paper, is defined as a product designed for any seated function where the user, in order to perform effectively, is required to maintain a fixed task posture for periods that could exceed one hour. Five critical task seating functions are described in this paper. They include:

1. Production Typing
2. Factory/Clerical Repetitious Tasks
3. The Automobile Driver
4. The Performing Musician (seated)
5. The Air Traffic Controller

LONG TERM DISCOMFORT IS CAUSED BY CHAIRS THAT DON'T FIT THE USER

Although much has been written and researched about seating comfort, the most important factor that will eliminate long term discomfort in chair design is to design the seat and back shapes so they will fit the contours of the adult male/female user population.

A chair, like a pair of shoes, will cause discomfort and pain if not properly fitted to the user.

The critical areas in a chair where good fit is required include:

1. Location of the sacro-lumbar curve.
2. The side to side seat radius.
3. The side to side back radius.
4. The seat and back centerline profile.
5. The seat and back thigh centerline profile.
6. The depressions under the ischial tuberosities.
7. Seat height adjustment.
8. An effectively yielding fabric and upholstery treatment.

Ed Hertzberg, in his paper "The Human Buttocks in Sitting"[1] identified the specific pressure factors that cause discomfort from long term sitting. This author published a paper titled "Comfort, the Absence of Discomfort"[2], where seven of these pressure factors were presented in detail to the office furniture market. Hertzberg's paper reports the need to design a seat contour so that it tilts the pelvis forward thus creating a slight concavity in the lumbar area. This occurs naturally when humans assume a long term standing posture. The effect of pelvic inclination on the lumbar curve is discussed in most of the seating literature published in the past 30 years. Dr. K.H.E. Kroemer and Joan C. Robinette review European literature in their paper titled "Ergonomics in the Design of Office Furniture".[3] They report general agreement among Strasser, Akerblom, Leamann, Kroemer, Schoberth, Stier and Grandjean for the need to design a lumbar curve into chair back supports. Also, many of the pressure factors which cause long term discomfort emphasized by Hertzberg are referred to in this paper. "Fitting The Task To The Man" (1980 edition)[4], a book on Ergonomics authored by E. Grandjean, stresses the need for good lumbar support for task/worker seating.

FULL RANGE ANTHOPOMETRIC DATA DESCRIBING TASK SEATING CONTOURS

"Basic Design Measurements for Sitting"[5] is a very professional research study published in 1959 and authored by Dr. Clara A. Ridder. This body seating study was conducted at the University of Arkansas and was sponsored by the Arkansas State Department of Agriculture. In this study, Dr. Ridder has developed a set of fixed seat and back contours that represent a good fit in task seating ranging from the 5th percentile female to the 95th percentile male.

In 1973 the world's largest manufacturer of office furniture (Steelcase, Inc.)* developed a line of general office seating that

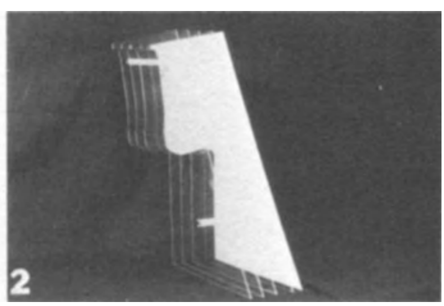
*Steelcase, Inc. is located in Grand Rapids, Michigan.

accurately incorporated the Ridder chair contours. (See Figure 1) These contours were pitched for an upright posture claimed by Dr. Ridder to accommodate the "dining, writing or game playing tasks". By 1978 over 300,000 general office chairs utilizing this unique anthropometric contour data had been sold to offices throughout the United States and Europe. Today this chair has probably sold to 1,000,000 users. The comfort acceptance of this chair line by such a large adult user population demonstrated the real world value of the dimensional data developed from the Arkansas study. This data is now being more accurately applied to new task chairs now available through U.S. office furniture manufacturers.

This Steelcase 430 chair is not an optimal task oriented chair design. It lacks elbow clearance at the back which is necessary for production typing, its seat depth and minimum seat height on some models exceeds the 5th percentile female limit. It has a tilt feature necessary for the relaxed posture but the back does not tilt independent of the seat. Nevertheless, the seat and back shapes of this unique general office product line have demonstrated excellent fit characteristics for a worldwide adult user population. In Dr. Grandjean's recent book "Fitting The Task To The Man" he comments that "Our profile for an easy chair is in good agreement with the recommendations of Ridder". This is one of the few references to the little known Arkansas study. Dr. Grandjean is probably the most prominent ergonomist in Europe today who is influential in applying human factors data to consumer and industrial products.

ANTHROPOMETRIC TASK SEATING TEMPLATES ARE NOW AVAILABLE

The development of a unique set of anthropometrically accurate task seating templates and upholstery detailing guidelines was completed for presentation at this seminar. (See Figure 2)



The contours developed for these templates accurately describe the 5th through 95th percentile range for body centerline, thigh centerline and three other seated body contours. These five contour lines define the critical seat and back shapes necessary for even weight distribution in task seating.

These templates reconcile the Arkansas/Ridder data with user input derived from some of today's users who have had long term task experience with the #430 Steelcase chair line. These chair templates can be used to guide in the design and development of new task seating. They can also be used to judge the anthropometric accuracy of the seat and back contours in existing products.

Of course, the interpretation of any dimensional user data into the design of task seating should be accomplished by skilled professional designers who understand the true needs of the specific users in critical task seating functions. Many of the so-called "task oriented" or "ergonomic" seating products on the market today are proclaimed by their manufacturers to meet "the needs" of the user. Very few of these, however, are designed to relieve the total 5th percentile through 95th percentile adult population from long term physiological discomfort. Many of these products accommodate only a portion of the range. Often only the 50th percentile male dimensions are incorporated.

GOOD "USER" DATA IN TASK SEATING CANNOT BE EFFECTIVELY APPLIED WITHOUT A "USER DESIGN MANAGEMENT FUNCTION"

As mentioned earlier, most companies have product development line functions that represent the three traditional product management areas; engineering (technology), marketing (point of sale), and manufacturing (producibility). Very few seating manufacturers in America have established product management functions that have line responsibility for incorporating "user needs requirements" during the product development process. Most human factors input to American seating products is at the discretion of product engineering. If the product engineering manager does not give this function a high priority, it does not get scheduled into the budget. How the user design line management function can be structured is described in the 1978 March/April issue of Industrial Design magazine. The article "Steelcase Design Emphasizes Furniture User Needs"[6] by Stephen MacDonald describes the "User Design" management responsibilities that were in effect during the time that the Arkansas (Ridder) data was effectively applied to a general office chair line.

USER DESIGNED TASK SEATING CAN SAVE MONEY AND LIVES

In 1974 a confidential office research study demonstrated that improved efficiency in a seven person word processing department could save $5,628 annually. This savings was accomplished by improving the work station arrangement. It is not unusual to expect that long term sitting discomfort could cause a 5 to 10 minute operator and machine time loss during a 2 hour working period.

Translated into 1974 dollars this would result in a $5,000 to $8,000 annual loss due to poorly designed task seating. This dollar loss becomes staggering when translated into 1980 dollars and multiplied times the many word processing groups and other key entry production typing functions in today's office world. It should be noted that most office typing chairs in America do not have full back support with elbow clearance nor do they have accurately dimensioned contoured seating that accommodates the full adult range.

In 1966 Grant McClellan's book "Safety on the Road"[7] reported that Senator Francis X. McCann and the Massachussetts Division of the American Automobile Association made a presentation to the Massachusetts legislature which included "recommendations for safer car design". The second item on their list stated a need for the "design of seats molded to a person's natural pressure distribution".

In a test conducted by this author, a #430 Steelcase chair was mounted in the driver's area of a VW van and driven 4000 miles. The longest continuous stretch lasted for two hours and approximately 120 miles over smooth highway. (See Figure 3)

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A subjective evaluation was made comparing this ergonomically designed office chair with the original standard van seat. The office chair, which gave significant back support to the driver compared to the standard seat, permitted freedom from any discomfort for the entire field test period. The standard seat would not permit freedom from discomfort after one hour of driving.

"Safety on the Road" also included 1965 accident statistics such as: "50,000 lives were lost, more than 4,000,000 people were injured, accidents that year cost over $10 billion, 40% of all fatal accidents involved a sober driver and of the 50,000 fatal accidents 20,000 occurred at night at speeds exceeding 70 miles per hour". If we can assume that distractions due to body pressure discomfort contributed to only 1% of 20,000 deaths, we can then say 200 people per year died as a result of poor driver seat design in the year 1965. Today the death rate on the highway has been reduced somewhat below the 1965 figure due in part to a lowered speed limit. However, in today's dollars all accidents would cost at least two times the 1965 figure, or $20 billion. If poor seat design contibuted to only .1% of this figure, the cost would be $20,000,000 annually!

In 1978, the Wenger Corporation, a music products manufacturer in Minnesota, developed the first posture oriented "music chair"[8] in America. Poor posture seating can effect an economic loss to the performing musician. This loss is associated with the cost of private lessons and the resulting inefficiency where the musician wastes practice time because of distractions due to discomfort in long term sitting and poor breathing posture. The serious loss is in potential earning power when the musician does not achieve a competitive level of physical control and musical quality in tone production. Most standard chairs force the musician to sit forward to avoid restrictive breathing caused by a 10^{o} to 15^{o} seat angle. (See Figure 4)

The contoured seat of a music posture chair eliminates sitting bone pressure by incorporating good weight distribution. The special contour tilts the pelvis forward for good spinal posture but lowers the thighs thus keeping the diaphragm free to facilitate good diaphragmatic breathing so essential to quality tone production. (See Figure 5)


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We are all aware of the critical tasks of the air traffic controller whose every judgement can determine the fate of hundreds of airline passengers each day. It is unthinkable that user design criteria would not be given top priority in this critical human operator function. Nevertheless, Walt Kleeman has reported concern based on a very interesting study[9] analyzing the seating products used by a cross section of air traffic controllers in America. This study cites cases in which user design considerations apparently did not take top priority.

One example in this study shows that seat heights will only accommodate 50% of the males and 5% of the females, thus creating the potential for serious discomfort during long term sitting in the majority of air traffic controllers' work stations. (See Figure 6) This condition is critical when related to the fact that at any given moment there are 100,000 people in airplanes in the sky.

A BRIEF ERGONOMIC ANALYSIS OF SOME TASK SEATING PRODUCTS CURRENTLY BEING PRODUCED

Two major United States office chair manufacturers and a major foreign manufacturer exporting to the United States are now producing both ergonomically and aesthetically designed task seating products that fit the 5th through the 95th percentile adult male and female users. These products have most of the features necessary for critical task seating requirements. They are also priced to represent a good value to the buyer and user. The American Seating "Bio Chair" which was industrial designed by Hugh Acton has the following features: (See Figure 7)

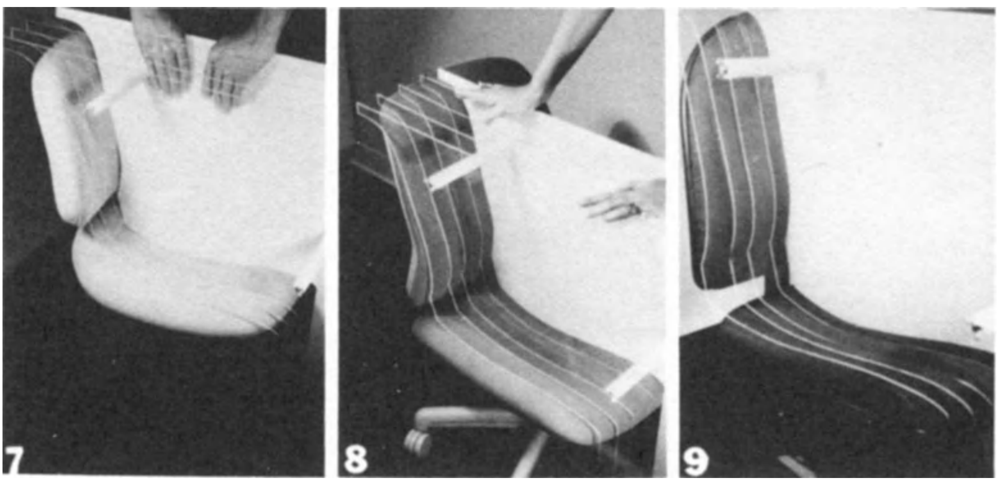
1. Good body fit contours.
2. An adjustable back angle.
3. An adjustable seat height (16" to 19").
4. An adjustable back height (32" to 35").
5. An unique horizontal swivel feature that yields to the operator's erratic reach activity at the work station.

This chair has a maximum back height of only 16" up from the seat. This is not adequate for leaning back into a rest posture, but since this chair does not have a full rest posture this does not create a serious problem. (American Seating Corp., Grand Rapids, Michigan)

The Steelcase ConCentrx Chair has the following features: (See Figure 8)

1. Good body fit contours.
2. Adjustable back tension with a free moving fore-and-aft task posture back feature.
3. An adjustable seat height (17" to 21").
4. One fixed task posture.
5. A full back height (17.5") with a full tilt back relaxed posture configuration.

The only questionable factor on this task chair is the low seat height position. 17" minimum should be 1" lower (or 16") in order to accommodate the low percentile female range. 21" is higher than is necessary for the 95th percentile popliteal height. However since the seat attitude of this chair can be shifted from 5 degrees to 8 degrees of tilt, this will help to relieve under thigh pressure for low percentile female operators.



The Stollgiroflex office chair imported from Switzerland and designed by Dr. Grandjean has the following features: (See Figure 9)

1. Good body fit contours.
2. Adjustable back height.
3. Adjustable seat height (16" to 20.8").
4. Adjustable back tension with a free moving fore-and-aft task posture back feature.
5. One fixed task posture.
6. Full tilt back relaxed posture configuration.

This chair is an ideal task chair. It is one of the first task seating imports sold in America. (International Furniture Industries Inc., New York U.S.A.)

Probably the most unique task seating product on the market today is the Wenger Music Chair, a non-adjustable stacking chair for the performing musician. (See Figure 5) This chair incorporates a seat pan shape that tilts the pelvis forward creating a proper sacro-lumbar spinal attitude, but the seat pan is designed with a slant to the thigh area that opens the diaphragm for good diaphragmatic breathing capability. This feature is patent pending. The overall chair is also tilted so that users may achieve good balance in the performing posture. The back does not support the performer - it simply guides him into a good upright posture. Flutists, french hornists, trombonists, cellists and violinists all require unique back postures that do not conform to a standard upright sacro-lumbar curve. The chair has no seat height adjustment, but it is available in three heights - 16", 17½" and 18½". This is the only posture chair produced in America today that is designed exclusively for the performing musician. It is manufactured by the Wenger Corporation of Owatonna, Minnesota. This chair differs from a non-musician's task chair in seat contour but its similarity in upright attitude to a good task seating product is apparent.

In completing the analysis portion of this paper I will cite one example where good body fit is not a feature of a product line that has been promoted and sold primarily for its implied ergonomic value. I have chosen to comment on only the operator model of this well known chair line since it is the one product in the line that might be purchased to be used in the critical task seating applications defined in this paper.

The "Ergon" operational chair produced by the Herman Miller Company, Zeeland, Michigan, does not compare well against the full range task seating templates. (See Figure 10) This chair has a lumbar curve but the concave upper back is too pronounced and it pushes the operator forward to a point where the back gives little or no support to the upper body. The back pivots and has a height adjustment feature that forces the upper back to be pushed forward even more since the back height adjustment mechanism moves the back upward in a curve and not a straight line. The contours in this chair do not conform to the 5th through the 95th percentile adult body size range. Even if they did, the rigid support under the foam is not shaped to fit the adult user in the compressed seated posture like the Steelcase, the Stollgiroflex and the American Seating posture chairs. When the foam is bottomed out on the Ergon Chair it loses its shape.

Although this chair, or other copies of it, may be acceptable for general office seating it is this author's opinion that it should not be specified for the critical long term task seating applications as defined in this paper.

SUMMARY

Long term discomfort, the result of poorly designed task seating products serving the business offices, factories, performing musicians, air traffic controllers, and automobile drivers in America, has caused many adverse effects. These conditions create unreasonable cost in death, pain and suffering, and loss of money. Responsible governments and industries throughout the world must clearly understand the necessary changes both in product design and in the product development management process that can eliminate this intollerable waste. Designers must work with accurate anthropometric data and management must incorporate a function responsible for the implementation of user design goals. Both are essential to the product development process if seating manufacturers are to be successful in the production of professional user-oriented long term task seating products.

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EVALUATION OF CHAIRS USED BY AIR TRAFFIC CONTROLLERS OF THE U.S. FEDERAL AVIATION ADMINISTRATION - IMPLICATIONS FOR DESIGN *

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In response to a request from the Federal Aviation Administration in 1978, the GSA-FSS National Furniture Center conducted a survey among FAA's 25,154 air traffic controllers to evaluate their chairs in use and to find out what the controllers want in a chair. 2,400 questionnaires were sent out to each tenth name and 1,967 useable replies were received. A partial summary of the results of that survey follows.

WHAT KIND OF CHAIRS DO THEY HAVE?

Their chairs adjust in several ways: seat height, which possibly can be adjusted with bare hands, but may also need a wrench; backrest height, which is adjusted the same way as seat height, but takes a different wrench; seat depth, which needs still another kind of wrench; armrest depth and armrest width, which need a wrench to remove the seat, a wrench to adjust and a wrench to reinstall for two possible positions; backrest tension, which is adjusted with a special key furnished with the chair (after removing the seat); and, the backrest pivot which adjusts automatically. The chair itself is a typical office swivel armchair on a four-prong base with casters.

Although the chairs are adjustable for back height (above), 53.1% of the sample didn't know it because they said that the chairs didn't have one. This points up the fact that complete instructions on the use of any adjustable chair must be given to the user <u>and</u>

*Note: This paper does not represent the official views or policies of the Federal Aviation Administration or the General Services Administration; the authors alone are responsible for its contents.

understood by the user.

HOW DO THEY USE THESE CHAIRS?

These chairs are task-intensive in that they are heavily used on three eight-hour shifts per day, seven days a week. 31.3% of the controllers spend 4 hours or less sitting during an eight-hour shift, 68.7% of them spend 5 to 8 hours sitting per shift and 15% of them spend 7 to 8 hours sitting per shift.

12.5% adjust their chairs at the start of their shifts, 41.2% find one that seems about right and 46.3% do neither nor do they adjust their chairs. Only 14.2% adjust their chairs during the day.

15.1% always use their backrests, 36.8% use them more than half the time, 30.4% use them about half the time, 17% use them less than half the time and only 0.7% never use them. Therefore, the controllers' chair must have a back; a stool wouldn't do.

HOW DO THEY FEEL ABOUT THEIR CHAIRS?

In answer to question 7, 32.3% find their chairs are unsatisfactory or barely satisfactory, 11.6% very satisfactory, 1.7% find them excellent and 54.4% find them satisfactory for a total of 67.7% favorable.

In answer to question 13, however, 4% are perfectly relaxed and 45.9% are very comfortable for a favorable total of 49.9%, while 39% are fairly uncomfortable, 8.5% are just plain uncomfortable, 1.9% feel acute discomfort and 0.7% feel pain for a negative majority of 50.1%; slightly more people are uncomfortable than are comfortable.

There may be a relationship between comfort and age. From age 15 through age 40 more people are uncomfortable than are comfortable, 53.8% to 46.2%. From age 41 through age 65, more people are comfortable, 56.8% to 43.2%. ($p<0.0008$)

Generally speaking, the percentage of people who are comfortable declines as the length of time spent sitting increases. From 1 to 5 hours the percentages are on the comfortable side, 61.9% being comfortable at 1 hours; this declines to 50.5% being comfortable after 5 hours. At 6 hours the majority shifts to 51.4% uncomfortable and increases to 64.3% uncomfortable at 8 hours. ($p<0.0014$)

WHAT DO THE CONTROLLERS WANT IN A CHAIR?

74.3% want the back upholstered with woven fabric and 25.7% want it upholstered with vinyl. 70.4% want the seat upholstered with woven fabric, 5.3% want vinyl on it and 21.7% want the seat upholstered in both woven fabric and vinyl; the rest showed no preference.

Fit/comfort was ranked first as a wanted chair attribute by 75.2% over safety, ability to adjust, durability, reparability, appearance and interface with other equipment in that order. Seat height adjustment was ranked first by 73.3% over other adjustments, back height, back tilt, seat depth, seat pitch, arm height, seat width and back width.

WHAT DO THE CONTROLLERS NEED IN A CHAIR?

Obviously, from the numbers and percentages of people who are uncomfortable, they need more comfort. While this study did not conclusively show that there is any definite factor causing discomfort, it is possible to speculate on likely causes of discomfort. Armrest height and a seat height adjustment deficiency are likely candidates.

Armrest height could be a factor is discomfort, especially since armrest height is not adjustable on the FAA chair; the weight of armrest height as a factor is discomfort is not known. While the case for seat height adjustment range deficiency is persuasive, it is not conclusive.

It is noteworthy that, as shown above, seat height adjustment ranked first among wanted adjustments and fit/comfort was the most wanted attribute.

RELATIONSHIP BETWEEN SEAT HEIGHT ADJUSTMENT AND POPITEAL HEIGHT

In a crosstabulation between stature and the answers to question 13 it was found that 63.2% of those between 5' (152.4 cm.) and 5'5" (165.1 cm.) are uncomfortable in contrast to the total sample showing 50.2% uncomfortable. A further breakdown indicates that 77.8% of those between 5' (152.4 cm.) and 5'2" (157.5 cm.) are uncomfortable and 60% of those between 5'3" (160 cm.) and 5'5" (165.1 cm.) are uncomfortable. ($p<0.0378$) In the stature range between 5' (152.4 cm.) and 5'5" (165.1 cm.) 66% of the males and 61.8% of the females are uncomfortable.

A 1968 study by Koremer and Robinette, further analyzed by Kleeman in 1972, indicates that the preferred range of seat heights should be between 13-2/3" (34.7 cm.) and 20-2/3" (52.5 cm.) for a stenographic or operator's chair; further data cited by Hertzberg in 1971 on the increasing stature of Americans might support an increase of the upper figure to about 21" (53.3 cm.).

The FAA controllers' chair has a seat height adjustment range of 17" (43.2 cm.) to 21" (53.3 cm.); therefore it was hypothesized that the concentration of discomfort in the above stature ranges might be related to the inability of the FAA chair to adjust below 17" (43.2 cm.) seat height.

Since the literature on seating comfort strongly suggests a strong relationship between popliteal height and the need for seat height adjustment (for fit, comfort and health, seat height should be slightly lower than popliteal height) and since this survey had not measured the popliteal heights of this sample, the U. S. Air Force Aerospace Medical Research Laboratory, Human Engineering Division, Workload and Ergonomics Branch was asked to furnish bivariate tables and regression equations from their Anthropometric Data Bank so that the range, medians and standard deviations of popliteal height of the sample might be approximated.

Clauser (1979) furnished material from the National Health Examination Survey of 1962 showing that among the Total Female population and Females Aged 25-40 a range of popliteal heights existed from 13.3" (33.7 cm.) to 18.4" (46.8 cm.) with a mean of 15.74" (40 cm.) and a standard deviation of 1" (2.5 cm.); 25% of these samples had popliteal heights of 15.1" (38.4 cm.) or less and 50% had popliteal heights of 15.8" (40 cm.) or less. Males in this same survey show a range of popliteal heights 14.8" (37.5 cm.) to 20.2" (51.2 cm.). 10% of these males had popliteal heights of 15.9" (40 cm.) or less. Based on this material, the present FAA chair (as to popliteal height) would comfortably fit a maximum of 50% of the men and 5% of the women in the general population, since the popliteal height for the 95th percentile woman is 17.4" (44.3 cm.) and the popliteal height for the 50th percentile man is also 17.4" (44.3 cm.). Even if shoe sole and heel heights were added, a substantial portion of the population would not be comfortably accommodated by the present FAA chair as to popliteal height related to seat height adjustments.

Further information from the AMRL Anthropometric Data Bank indicates that from limited samples in the stature ranges from 5' (152.4 cm.) to 5'5" (165.1 cm.), popliteal height for U. S. Air Force women is predicted to be from 15.3" (38.9 cm.)±0.5" (1.3 cm.) to 16.52" (41.7 cm.)±0.5" (1.3 cm.). For USAF men from 5' (152.4 cm.) to 5'5" (165.1 cm.) the prediction for popliteal height is from 14.2" (36.1 cm.)±0.5" (1.3 cm.) to 15.74" (40 cm.)±0.5" (1.3 cm.).

While other factors may be operating to produce the considerable discomfort shown by this survey, from the material above it can be postulated that a need for Kroemer and Robinette's (1968) suggested range of 13-2/3" (34.7 cm.) to 20-2/3" (52.5 cm.) may indeed exist, since in this survey, the range from 13-2/3" (34.7 cm.) to 17" (43.2 cm.) was not available to the users and measurably more discomfort was found in the lower stature ranges where this need for a lower seat height might be most acute. Much additional research and more comprehensive research is needed to establish the definitive parameters of seating comfort.

SUMMARY OF INFORMATION POSSIBLY IMPORTANT TO CHAIR DESIGNERS

1. Adjustments on the present FAA chair are difficult to use; easier adjustment devices should be considered. 2. Full information on how to use adjustments must be given to the users. 3. The controllers prefer a chair with upholstered arms and a back; a stool wouldn't be satisfactory. 4. With the substantial proportions of dissatisfaction and discomfort reported, an improved chair is needed. 5. Woven fabric is preferred as the upholstery material. 6. The controllers prefer that the back should tilt and that it should reach shoulder height. 7. The chair's fit/comfort is of first importance. 8. Some of the user's discomfort may be due to a lack of seat height adjustment range.

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BIOMECHANICAL AND ENGINEERING ANTHROPOMETRY CONSIDERATIONS FOR THE ASSESSMENT OF AMPUTEES' WORK PERFORMANCE

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1. INTRODUCTION

Working population in the contemporary industrial environment is composed of both impaired and unimpaired individuals. Industry and rehabilitation community deal with people who are fitted with prostheses to replace their natural arm or hand. The disciplines involved in rehabilitation have directed their efforts toward adapting the impaired individual to the normal environment, in the same way industry seeks to employ commonly used evaluation procedures to predict disabled employees' performance. Although there are few methods to evaluate performance of unimpaired workers, no particular method has been substantiated for the purpose of evaluating occupational performance of the upper limb impaired individual. This situation often results in misjudgments concerning the employability of such individuals. Evaluation of the effectiveness of arm and hand movements in industrial tasks has been the objectives of several engineering systems devised to aid in the estimation of time required for manual tasks and hand manipulations.[1] Techniques categorized as PMTS (Predetermined Motion Time Systems) analyze human motion patterns in terms of basic elements and provide data which can be used for performance time estimations under a variety of specific conditions. A question is whether and how PMTS can be applied to the evaluation and apriori performance analysis of amputees.

2. BIOMECHANICAL CONSIDERATIONS

Amputation of the arm radically changes the kinesiology of the upper extremity. Prehension is not complete, and a reduction in pronation and supination is a result of the absence of biological structures. This is inversely proportionate to the length of the residual forearm stump. Observing the prehension patterns naturally assumed by unimpaired individuals handling common objects used in everyday life, six types of grasp were classified, and the ability of hand turn was determined to be 170 degrees. In contrast, the artificial hand permits only one type of grasp and a very limited range of turn ability. When in the normal hand any functional feature, either mechanical or sensorimotor is impaired, manipulative skills are reduced correspondingly. In the amputee, the most delicate neuro-musculo-skeletal mechanisms essential to prehension, those in the hand itself, have been lost. Lacking of control in present-day artificial hands, as compared to that in natural hands, is necessarily limited by the state of the art of mechanical design. This accounts for the fact that the functioning of hand prostheses falls far short of duplicating the natural mechanisms. Furthermore, the artificial hand is incapable of providing tactile sensory feedback; thus, the amputee must perform maneuvers under visual control, where he normally would be guided by tactile feedback. It is common that visual control of the hand contributes to slowness of movement. Inasmuch as the socket through which the prosthesis is attached to the stump depends in profile and depth upon the forearm stump, the magnitude of torque which the forearm can transmit through the prosthesis depends on length and conditions of the stump. Likewise, dimensions of the stump for the design of the suspension mechanism which holds the sockets in place, as well as the hinges of the prosthesis[2]. However, terminal devices that are used for object manipulations and shoulder harnesses employed for secondary suspension and control do not vary greatly between prostheses of the same type. The grasp force available from the terminal device of the prosthesis, must be adequate to cope with the forces required to perform tasks of everyday living, incidental to the use of the wide variety of devices commonly found in our civilization. The design of which evolved from the existing and increasing knowledge of the forces available from the natural hand. It is self-evident that safe and skillful use of tools and implements demands the ability to vary grip strength in accordance with the requirements for performing safe release of the tool (graded prehension). Also, during actual tool usage, the aptitude of maintaining a firm grasp (isometric prehension) is equally important. Hence, any mechanical replacement of the hand should be capable of adequately simulating these two skills. The "hook" which is a forceps-like terminal device of a mechanical upper-extremity prosthesis, was designed to be similar to the natural hand with respect to basic prehension operations, but is still different with relation to prehensile adaptiveness for multiform objects and to cosmetic appearances. Nevertheless manual workers of all classifications find the hook adaptable, durable, and generally satisfactory.

The handicap of the disabled is deemed by this researcher to be due to the absence of the natural hand, resulting in total loss of the aptitude to perform the complete act of prehension, which permits the performance of the motion element "grasp" in a variety of ways, and without the need for accurate positioning of the scapula, upperarm, forearm, and corpus. The hook which replaces the natural hand on a prosthesis, admits a simple forceps grasp, but requires exact positioning of the residual upper extremity, as well as of the prosthesis. Furthermore, to operate the hook, shoulder and scapular abduction/adduction, by means of insertion of the large muscles into shoulder blade, must be performed which is time-consuming. The limb configuration while opening the hook is such that the radius of gyration about the shoulder of the arm-prosthesis aggregate is large[3]. It was established that the speed of upper extremity motion is inversely proportionate to the radius of gyration of the limb and that in turn, this later dimension is a function of the angle of abduction of the upper arm, which must be large at the moment of opening the hook. Thus, based on this biomechanical consideration, the act of grasping by the hand is seen to be slow and fatiguing.

3. THE EXPERIMENT

Aiming to find out if PMTS can be used to correlate the performance values of impaired with those expected from the unimpaired worker, an experiment was conducted to analyze the ability of amputees and evaluate it on the basis of MTM-1 (Methods Time Measurement - Version 1)[4]. Performance time is calculated as the arithmetic sum of the times necessary to perform all of these elemental motions making up the task. The basic ME (Motion Elements) involved in the manipulative process are: Reach, Move, Grasp, Position, and Release; these constitute 97.5% of all motions used in manual manufacturing processes. The experiment was designed to investigate the performance of amputees performing manipulative tasks. The objectives were: (1) to analyze a manipulative task performed by amputees and compared quantitatively as well as qualitatively with non-amputees' performance of same task, (2) to identify taxonomically and by time values the motion elements, which cause amputees to require more time for the performance of a work cycle. For the purposes of the study BE (Below Elbow) amputees who were rehabilitated and live normal active lives were employed.

Twenty six subjects, amputees and nonamputees, participated in the experiment. In order to compare performance and manipulative times, both groups were tested on the same task. Thirteen amputees who ranged in age from 26 to 64 years ($\bar{X}$ = 36 years), performed the given task with their BE prostheses, which were equipped with a standard hook device. Thirteen nonamputees formed the ablebodied control group, ranging in age from 24 to 62 years ($\bar{X}$ = 39 years), and performed the same given task with their nondominant arm. This procedure was based on the observation that, with practice, the prosthesis is used as a "second" hand, in much the same way that the nondominant hand is used by nondisabled employees in the work situation. Two identical task boards were employed in the experiment, twelve objects differing from each other in shape and dimension were removed in a fixed sequence from one board and placed in the appropriate recess on the other board. Performance time of the subjects during demonstration of objects' manipulation was obtained by filming procedures and analysing the movie films. Performance of all subjects was recorded on the basis of motion elements. Kinesiological events and their duration were identified, as well as the temporal relationship to each other in the course of frame-by-frame analysis. The frame was the sole time base used in this study. Figure 1 shows the task boards with 12 different objects; the experimental set up is seen in Figure 2.

4. RESULTS

Analysis of motion patterns of the nonamputees indicates that these individuals used their nondominant arm in flexion/extension motions simultaneously with hand motions. No back or shoulders movements were required. The hand manipulated the object while employing various finger combinations, of which the most frequent is the three finger pinch grasp (including the thumb, index finger, and middle finger). In the case of the amputees, the basic function provided by the BE prosthesis fitted with a hook is prehension. The movements used to control these functions are shoulder flexion and scapular abduction. For the amputee, mobility of the shoulder girdle is an important factor in controlling and positioning the terminal device. More specifically, prehension movements of the hook are executed by a combination of shoulder shrug (scapular abduction) and thrusting movements of the stump. The major muscles involved are: the serratus anterior, the pectorialis minor and the subscapularis for scapular movement; the coracobrachialis and the anterior deltoid for forward thrust of the stump; the triceps and the anconeus for elbow flexion. In order to analyze the movements involved in the twelve tasks employed in the experiment, the movements of each subject were recorded and investigated, trying to detect and isolate the extra movements required by the amputees to complete these tasks. A summary of the analysis of amputees' body motions on the basis of MTM-1 ME is presented in a tabular form in table 1. It was observed that while nonamputees perform five motions the amputee has to perform more than twice this amount

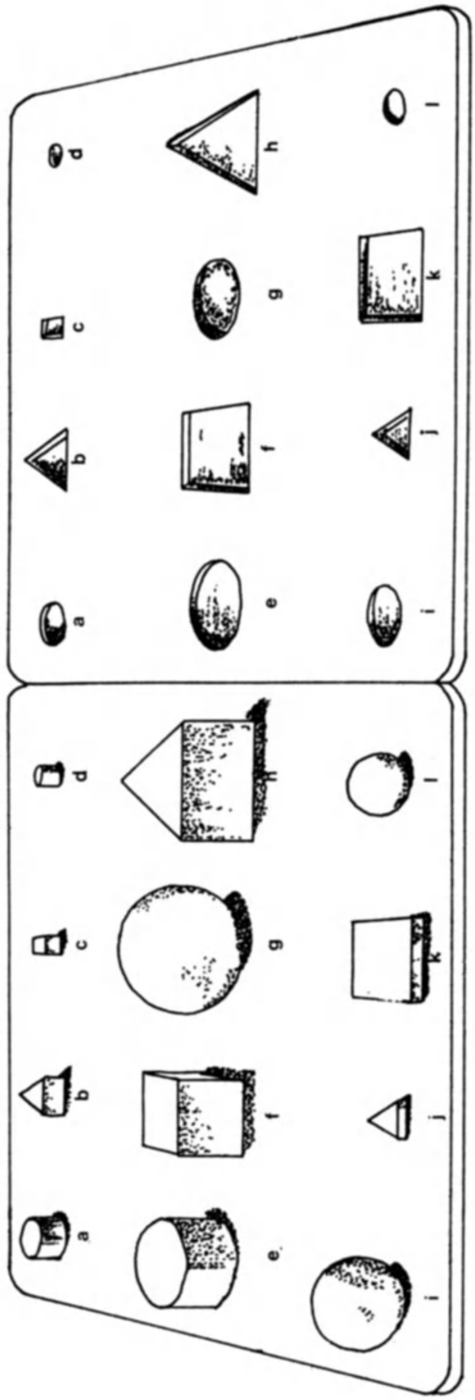

Fig. 1. Task boards and objects.

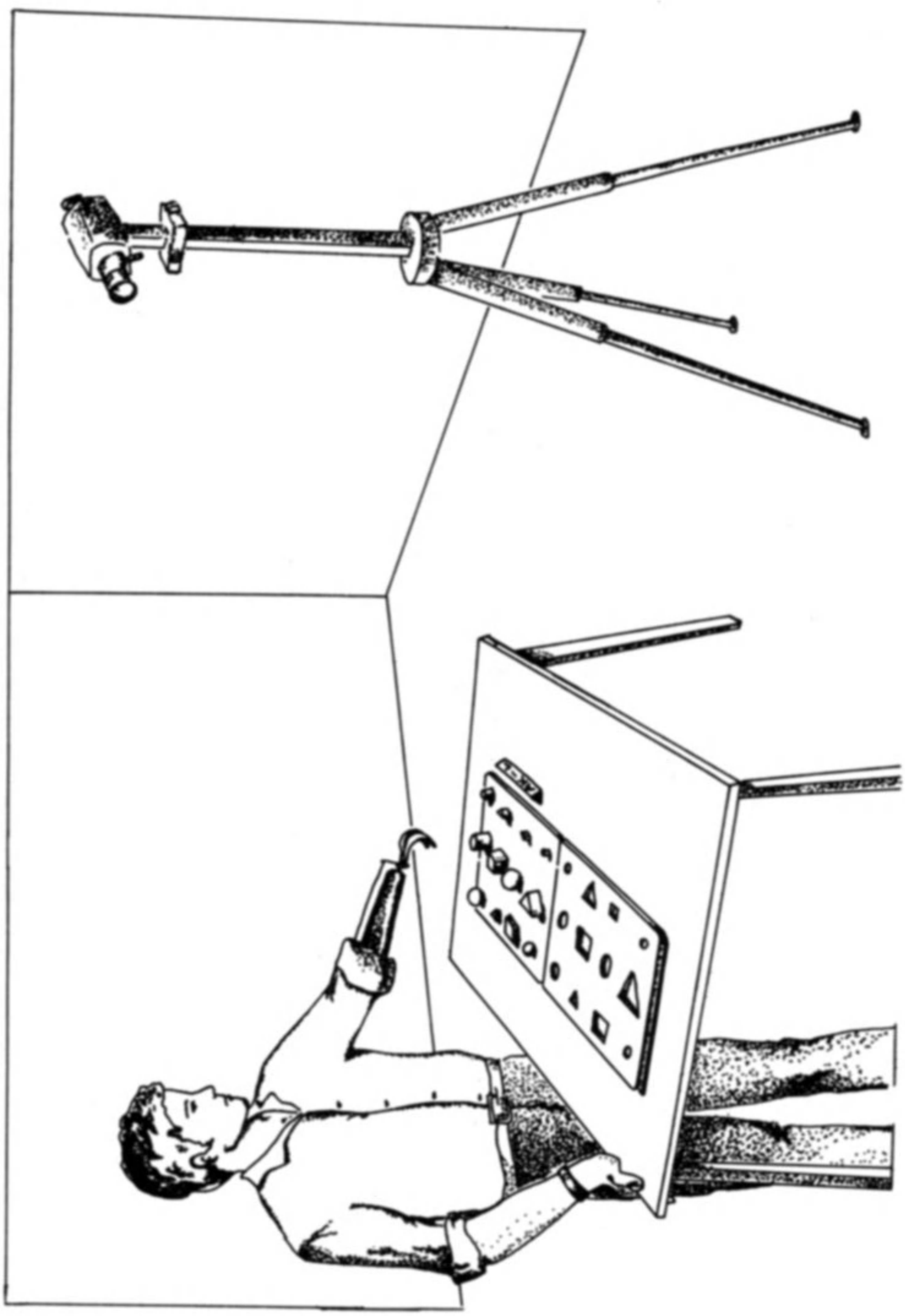

Fig. 2. Experimental set up.

Table 1: Number of extra motions per object as obtained from kinesiological analysis.

Body Movements	a	b	c	d	e	f	g	h	i	j	k	l
Trunk Flexion	1		1					1		1		
Trunk Rotation	1	2	2	1	1	2	1	3	1	2	2	1
Shoulder Abduction	3	3	3	3	2	3	2	5	3	3	2	3
Shoulder Adduction	1	1	1	1	1	1	1	1	1	1	1	1
Shoulder Flexion	2	1	1	1	1	1	1	1	1	2	1	1
Shoulder Rotation			1			1		1				
Scapular Abduction	2	1	1	1	1	1	1	1	1	1	1	1
Elbow Flexion	1	1	1	1	1	1	1	1	1		1	1
Elbow Rotation					4	3	3	2			3	

(Column headers a–l are printed under the heading "Objects".)

to complete the same task. This explains the time delays between amputee and nonamputee individuals for executing the same job but using different body segments due to differences in kinesiology.

In order to find out how and which of the MEs affect the performance of amputees, a three-way ANOVA was performed on the deviations of amputees' performance time from that of nonamputees by shape, size, and MTM-1 ME. Figure 3 demonstrates the results in four graphs for the four shapes used. This clearly indicates that ME Grasp has the highest contribution to the longer overall performance time of all tasks.

5. CONCLUSION

Engineering anthropometry and biomechanical approaches to human posture and locomotion of upper extremities performance in work situations indicate that the amputee experiences additional work stress and time delays. This is due to the need to use shoulder and trunk movements and to the need to perform maneuvers under visual control, where normally a worker would be guided by tactile feedback. It has been established that there are motions essential to the operation of prostheses which are not described in Methods Time Measurement or similar PMTS. This advocates the development of special editions to such methods which will address themselves to the taxonomy of upper extremity amputee motions and their pertinent time requirements. Performance analysis, in accordance with the principles developed, can become guidelines to the design of new and competent terminal devices and harnesses, for better and effective "handle" manipulative motion elements. This will assist impaired workers to cope with the demands of competitive, nonsheltered, industrial environment.

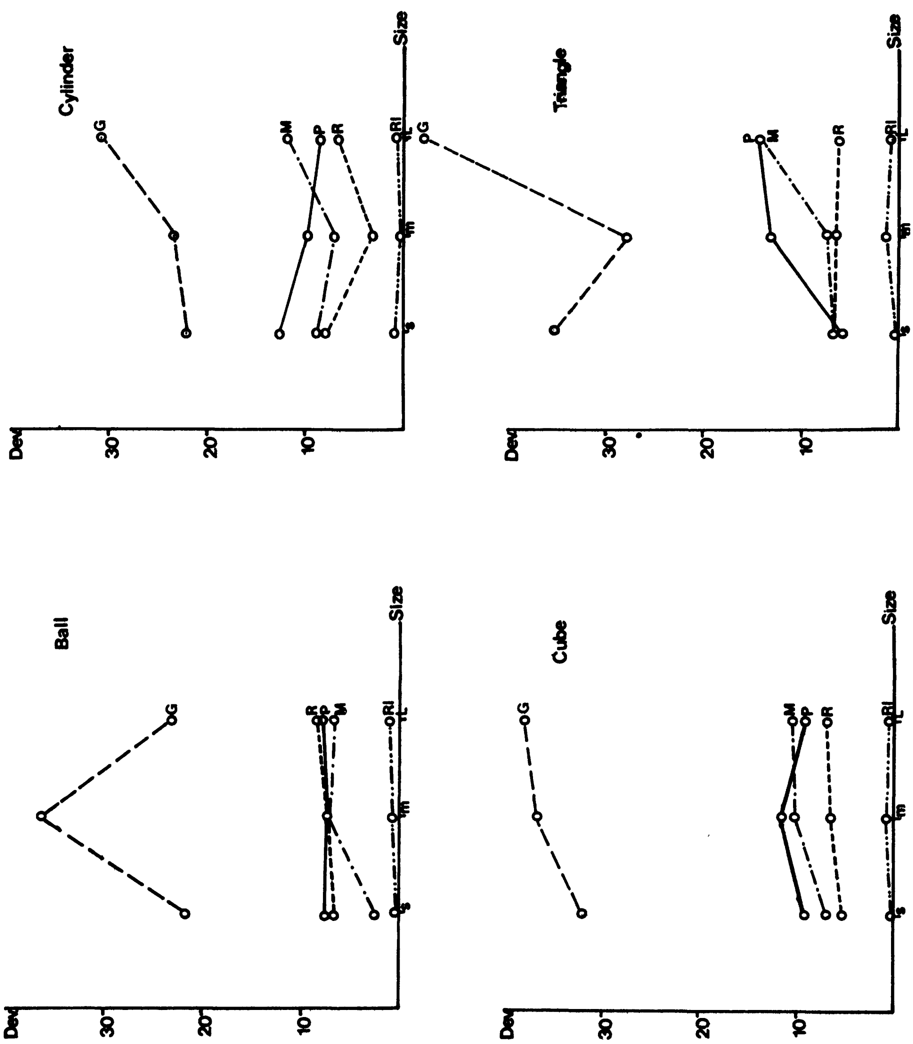

Figure 3. 3 way ANOVA for deviations of amputees' performance time from that of nonamputees by size, shape and MTM-1 elements

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Session VII
Applications II

ANTHROPOMETRIC AND STRENGTH DATA IN TOOL DESIGN

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INTRODUCTION

With the increasing number of women entering jobs that have been traditionally classified as male jobs, there has developed an awareness that tools and equipment used on these jobs are not adequate for the characteristics of the female population. Using adjusted male data is difficult, because the strength of women compared to men is a function of the particular strength measurement being compared (Lauback, 1976). Snook (1974) has illustrated that the women working on industrial jobs involving lifting are significantly stronger than women who do not work outside of their homes.

REVIEW OF THE LITERATURE

Numerous studies of anthropometry have been made, but only a few can be mentioned in this paper. Clauser, et al. (1972) Churchhill, et al. (1977), Nordgren (1972), Snook and Ciriello (1974), Assmussen and Heeboll-Nielsen (1961), Lauback (1976), and Kamon and Goldfuss (1978), have reported on the anthropometry of women and/or the strength of women. Most of these studies were concerned with areas other than tool design.

Specifically related to hand tools, we need to know the effect of body position and of repetitive application of force on the force that people are willing to use. Molbech (1963) showed that as the frequency of contractions increases the maximum force decreases rapidly. Rohmert (1960) showed the maximum duration of an isometric contraction as a function of percentage of maximum voluntary strength. Terrell (1975) studied the effect of forearm position and wrist position on grip strength and demonstrated that significant reductions in grip strength result from changing the forearm position of supination or midposition and the wrist from a neutral position. For example, the use of a pair of long nose pliers on a vertical work surface requires the forearm to be in the midposition and the wrist to be in ulnar flexion. This results in a reduction of maximum grip strength to 72 percent of the strength in the best position.

The Problem

A large United States corporation was receiving a substantial number of complaints from its female employees that the tools were too large, too heavy and/or required too much strength to use. In response to these complaints, the company sponsored a study to collect appropriate anthropometric and strength data upon which to redesign the tools for the women. Some of the anthropometric and strength measurements were selected to permit direct comparisons with other studies. Once the characteristics of the subjects of this study were verified as similar to the subjects of the comparison studies, much larger collections of data would be available for the design phase of the project.

Only one of the tools, a stapler (gun tacker) used to fasten wire, will be discussed in this paper. The two most frequent complaints from women using this tool were: (1) the required grip span was too large and (2) the grip strength required to activate the stapler was too large.

The Data Collected

Four measurements were taken using the procedures of Clauser, et al. (1972). These were: (1) stature, (2) overhead reach, (3) clenched hand (forward) reach and (4) clenched hand (forward) reach, extended. The clenched hand reaches are slightly different than the thumb-tip reach measurements taken by Clauser, because we were interested in the distance the subject could reach when they were holding an object. We had the subjects hold a pen in the clenched hand and mark the scale at the furthest point they could reach.

The three lifting strengths: (1) arm lift, (2) torso lift, and (3) leg lift were measured by techniques described by Chaffin, et al. (1977). Two additional strength measurements were made to evaluate common working position. The first, called push strength, was measured in an overhead position required to install wire in the basements of modern homes. The second, called arm strength, was measured with the arm to the person's side with the hand at waist height.

Grip strength was measured with the forearm in a midposition, the wrist in a neutral position and the forearm either vertical or horizontal. Two configurations were used for the handles of the hand grip dynamometer. In the first position, the two parts of the handles were parallel and required a grip span of 5.1 cm. In the second position, the two parts of the handles had the same relationship as the stapler and a grip span equal to the grip span required by the stapler.

These measurements were taken on 96 female workers. Except for six of the workers, all of them had at least several months of on-the-job experience. Three cities were selected from different geographic regions of the United States, for the purpose of including any ethnic and racial differences found between the regions.

Table 1 is a summary of the data from the study. Comparing the stature and reach data with the study of Clauser, et al. (1972) it was discovered that the women measured in this study were, on the average, 5.2 cm taller than those measured by Clauser. The comparison of the women in this study with the female industrial workers studied by Chaffin, et al. (1977) showed substantially differences. The greatest difference was 16.2 Kg for the leg lift. A comparison of the women tested in each of the three cities showed that the women in one of the cities were substantially stronger than the women in the other two cities. These comparisons demonstrated that substantial errors in describing a population can occur, if data are used from another group which intuitively appear to be similar. Even people performing the same jobs, but in different geographic regions can have significant differences in their characteristics.

<u>Combining Data to Derive a Design Criterion</u>

Once sufficient data are available to the designer, the designer faces the task of combining these data with information available on the effects of repetition, arm position and wrist position. Without research on the interaction of these variables, the only assumption which can be made is that the variables are additive. In addition, the following decisions were made in consultation with the company: (1) although a common working position required the tool to be held overhead, no allowance would be included for fatigue, because periods of work were short and the worker had control of their pace, (2) a reasonable work pace required 15 contractions/min., therefore only 72% of the maximum strength could be used, (3) a frequently accurring work position required the forearm to be in a pronated position with the wrist flexed; therefore, grip strength would be approximately 57% of the strengths measured in the study and (4) the tool should be designed to permit 95% of the women to use the tool without difficulty. Based on the data and the assumptions, the design force should be 10.3 Kg for the stapler. The current stapler requires a force of 22.2 Kg to activate it. The grip span for a 5th percentile women was 6.1 cm. The grip span of the stapler was 7.5 cm. The assumption of additivity probability resulted in a greater reduction in grip strength due to working position and frequency of contraction that would be necessary, if appropriate data was available. One of the greatest needs in the tool design area is for information on the interaction of variables affecting a person's ability to use a tool.

TABLE 1: SUMMARY OF FEMALE DATA

	5th	10th	90th	95th	Mean	SD
Stature*	157.2	159.5	174.2	178.1	167.1	6.4
Overhead reach*	189.0	190.8	211.6	215.9	201.2	8.4
Clenched hand reach*	63.0	65.0	78.7	81.0	71.6	5.1
Clenched hand-extended reach*	73.9	74.9	87.4	90.2	81.3	4.8
Grip size*	6.1	6.4	7.9	7.9	6.9	0.5
Grip strength**						
Par. horizontal	26.7	27.9	44.2	47.2	35.4	6.5
Par. overhead	25.7	28.8	44.9	48.1	36.4	6.5
Stap. horizontal	24.7	26.1	40.4	42.7	32.1	5.6
Stap. overhead	24.8	26.1	40.9	43.1	32.9	5.6
Push strength**	17.7	20.7	49.8	53.4	34.6	11.6
Arm strength**	3.3	3.7	8.4	9.5	6.1	2.2
Lifting strength**						
Arm	14.8	15.8	28.7	29.6	22.7	5.9
Torso	21.8	25.2	56.8	59.8	42.5	11.3
Leg	40.8	45.6	74.7	87.4	58.8	13.2

* in cm
** in Kg

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CONTAINER AND HANDLE DESIGN FOR MANUAL HANDLING

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1. INTRODUCTION

In Manual Materials Handling the ergonomic maxim of designing systems to suit human capabilities and limitations is a truism. The consequences of giving the human the burden of adapting to the system have been well-documented: widespread muscular-skeletal overstrain, particularly in the lower back. However, recognition of the problem is but a first step towards prescriptive solutions. The container or load lifted is a natural place to start because it affects safety directly through the biomechanical stresses imposed by its weight and size and indirectly though the limitations it imposes on methods of holding and carrying it.

2. CONTAINER DESIGN

From biomechanical considerations containers should be as small as possible. In particular every biomechanical model or formula shows that L5/S1 disc pressure is minimized when the center of gravity of the container is as close to the spinal column as possible (eg. Tichauer 1971, 1978; Ayoub 1978). Compactness also allows a load lifted from the floor to move between the worker's legs in a squat lift, again decreasing spinal disc pressure.

Any factors which decrease the predictability of the container's response to applied forces will contribute to human error in manual handling. Examples are loads with an unexpected center of gravity (perhaps offset towards one face of the container) or those with a shifting center of gravity. Baffles, dividers or packing should be used to keep the center of gravity in a constant position.

The shape and size of the container are affected by anthropometric dimensions of the worker as well as biomechanical considerations. The method of lifting and/or carriage determines the body posture adopted and thus the critical dimensions for safe handling.

For narrow containers one posture adopted is carriage by one hand at the side of the body, as with a suitcase. Containers carried in this way should be as narrow as possible, as the maximum acceptable weight is directly related to container width. McConville and Hertzberg, 1966, showed that for male military subjects

Maximum Acceptable Weight (kg) = 35.52-0.0169 x Width (mm)
(formula converted to metric by Ayoub, 1978)

With weights carried in one hand in this way an equal and opposite torque about the center line of the body is required for lateral balance. This contributes to the spinal stress so that it is usually preferable to carry two lighter containers, one in each hand, for improved balance.

For containers carried at the side of the body the main anthropometric requirement is that the arm can be fully extended downwards so that there are no unnecessary static tensions in the arm muscles. Maximum height to handle center, if the container is to be carried at arm's length, would be 725mm for a 5th percentile male and 650mm for a 5th percentile female.

For containers carried in front of the body, it is usual to grip the container on each side, either along the base or along the forward edge, and pull the container against the frontal surface of the trunk, thereby supporting part of the weight with body/container friction and thus relieving the static forces in the arm and shoulder muscles. It is possible to set limits on container size for this mode of carriage from anthropometric considerations. For the general population, if the forward edge is to be reached the length in the fore- and aft direction should not exceed 710mm (males) or 650mm (females). To prevent interference with forward vision, the maximum height of the container above handle position should be 825mm (males) and 800mm (females). If handles are not placed so that the whole container is above hip height with elbows extended, then interference with the legs will result during walking. In general, handles should be placed above the container center of gravity for ease of container control but this may not be possible with bulky containers which would then interfere with leg movement. Kellerman & Van Wely (1961) in evaluating different shaped boxes to carry a constant (17.5 kg) weight of flower bulbs found both subjective preference and physiological evidence of the superiority of a wide, shallow container. Their optimum 1000 x 300 x 120mm deep container allowed the worker to carry it at arm's length without interfering with the legs during walking. A compact container is recommended but if deep ones are used it is suggested that handles be above the center of gravity for lifting from floor to table height to reduce stooping, and at, or below, the center of gravity for carrying or lifting above table height to reduce leg interference. For holding and carrying tasks more detailed recommendations are now possible. Handle placement for two-handed lifting has been studied at SUNY at Buffalo. Ten male subjects each performed one hundred trials of a static holding task - holding a box in front of them as shown in Figure 1. The one hundred trials consisted of all ten pairs of hand positions (1/1, 1/2, 1/3, 1/4, 2/2, ... 3/4, 4/4) performed once each on ten different boxes. The ten boxes were either 10 kg or 15 kg in weight and measured from 400 x 400 x 400mm in five steps to 500 x 500 x 400mm.

The handle was free to pivot in each position so that the 'natural' handle angle could be determined at each position. The handle forces were measured, and the reaction and friction forces at the torso/box interface calculated. Heart rate during the task, Rated Perceived Exertion (Borg, 1962), and body part discomfort (Corlett & Bishop, 1976) were measured in each trial.

The results showed that handle position had a very large affect on all measures ($p < 0.001$) and box weight affected everything except handle angle, heart rate and body part discomfort ($p < 0.001$). More important than the significance of the results was the actual pattern of changes induced by changes in handle position. The variables fell into two groups with a separate, but internally consistent, pattern in each group.

The biomechanical variables, faces and angles, showed a smooth decrease in force (an angle from the vertical) as the handle positions moved from the top of the box to the bottom. When the hands, one or both, were in positions 1 or 2, high forces were needed to pull the box against the body, generating high reaction forces and therefore high friction forces to help support the

Table 1 Hand forces as a function of handle positions

	kg.	Right Hand Position 1	2	3	4
	1	13.4	11.7	10.5	8.9
Left	2	—	10.2	9.2	8.3
Hand	3	—	—	9.0	8.0
Position	4	—	—	—	8.9

box. When the hands were under the box (positions 3 or 4) the forces on hands and body were minimized. Table 1 shows a typical result from this group .

But low forces does not mean low stress. Heart rate and the other 'cost to the operator' measures showed a very different pattern, for example that shown in Table 2. Subjective and physiological costs were higher at both positions 1 and 4, with lower values at 2 and 3. Thus both measure groups agree that position 1 is to be avoided and that positions 2 and 3 are reasonably good. However, position 4, while generating low forces, forces subjects to use elbow flexors under static tension for support, while positions 2 and 3 allow a much more straight arm position and remove much of the static load in the biceps.

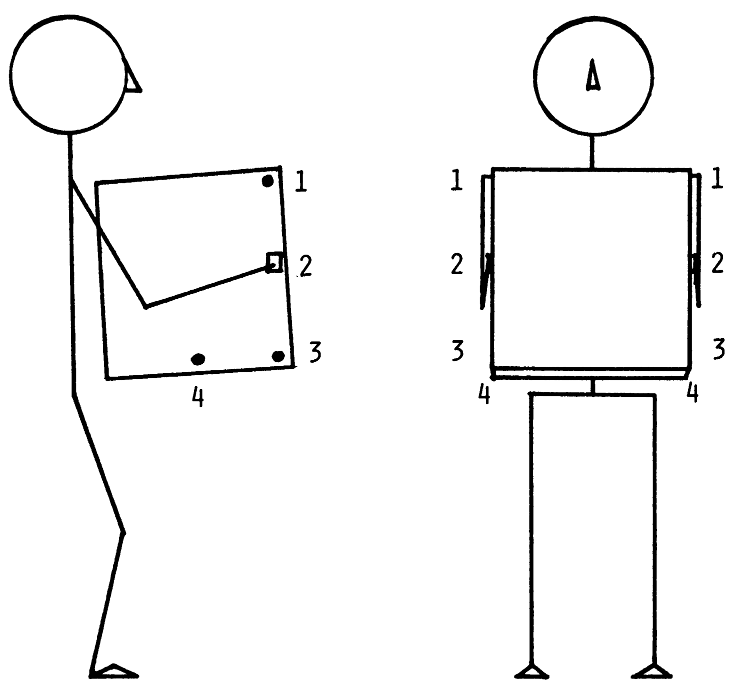

Figure 1. Handle Positions for Two-handed Holding Experiment

Table 2 Heart rates as a function of handle positions

	b/min.	Right Hand Position 1	2	3	4
Left	1	98.8	97.0	96.2	95.4
Hand	2	—	94.6	95.6	94.1
Position	3	—	—	95.8	96.4
	4	—	—	—	100.7

The general recommendations on container design and handle placement for holding and carrying tasks are to encourage gripping the box at its lower front corner. If hands are not symmetrically placed, one hand should be on the lower front corner and the other hand either along the front edge or along the bottom of the box.

3. HUMAN CONTAINER COUPLING DESIGN

The handle or hand-hold is the coupling between the container and the worker and should be designed with the worker's hand in mind. The importance of proper hand/container couplings cannot be overstressed. They have a large affect on both the maximum force a worker can exert on a container and on the energy expenditure in manual materials handling tasks (W.J. Nielsen, private communication, 1978). Aside from manual materials handling injuries, Rigby 1973, shows that lack of handles is a prime reason for people dropping products, with resultant product damage. The coupling which is least stressful to the operator is that which attaches the container to the body without active gripping. Thus yokes (eg. Lind and McNichol, 1968) and backpacks (eg. Soule and Goldman, 1969) are preferable to any carrying handles. However handles have an important safety feature in that they can be released in any emergency, such as slipping, tripping or avoiding vehicles, allowing the operator to take emergency action unencumbered by the container.

Handle design is usually rather poor in practice. Woodson (1971) notes that off-the-shelf handles appear to be "designed as decorative appointments" rather than "designed to fit the hand". The major problems Woodson reports are insufficient hand clearance, sharp edges which can cut into a worker's hand and too small a handle diameter.

Postures of the hand with respect to grasped objects have been classified by Napier (1956) into

1. A hook grip in which the fingers are flexed around the object and the thumb is not used for gripping.
2. A power grip in which the object is clamped between the partly flexed fingers and palm with the thumb opposing the grip and lying along the plane of the palm, and
3. A precision grip in which the object is pinched between the flexor aspects of the fingers and opposing thumb.

Most handles, hand-holds or gripping aids on containers force the worker to use a hook grip (the least effective) or a power grip. This latter gives a good gripping force and allows a large surface area of hand to be used but it is inefficient if accurate control of the container is needed. Frequently, however, the weight of a container will not allow a precision grip to be used.

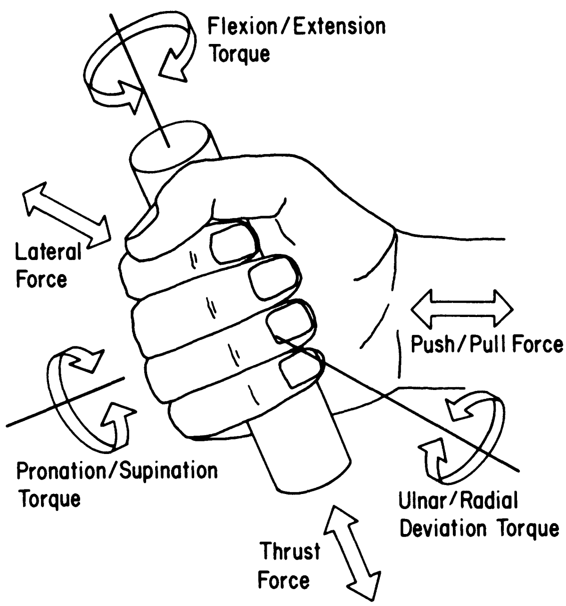

Figure 2. Forces and Torques Exerted on Handles

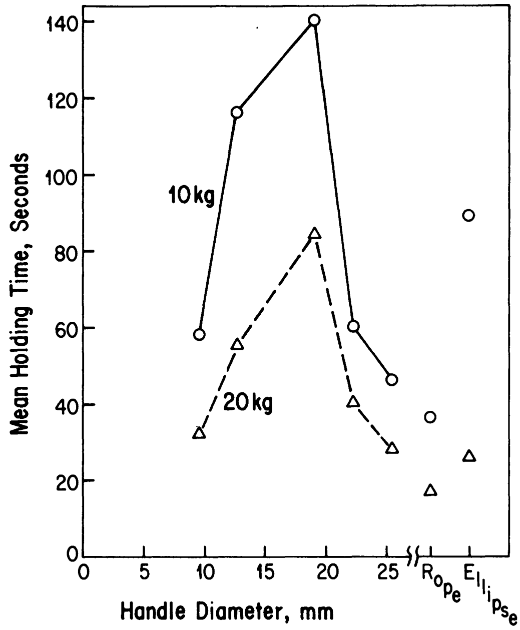

Figure 3. Effect of handle diameter on holding time (Sanderson 1976)

The other main consideration in handle design is the nature of the forces that are to be transmitted through the handle to the container. Figure 2 shows the forces and torques associated with handle use. Most studies of handle design have assumed that the best size, shape and texture of the handle can generalize from one use to another: their results do not show close enough agreement to support this contention.

One major variable has been handle diameter, whose effect has been measured for different forces and torques and using different criteria.

Pheasant & O'Neill (1975) measured flexion/extension torques and found the larger the handle the better, at least up to 70mm diameter, although the maximum shear force at the handle surface was greatest for a diameter of 30-50mm. Thrust forces peaked at about 40mm diameter. Flexion/extension torque was maximized using rough knurled surfaces in place of smooth cylindrical handles. There was no effect of a wide variety of handle shapes on maximum torques when the effect of diameter was eliminated.

The pronation/supination torque was measured as a function of handle diameter by Saran (1973), who found that a 25mm diamater handle was preferred over either a 19 or a 32mm handle. There were no differences between handle diameters in terms of Electro-myogram (EMG) measures of the muscle groups involved in the task.

Tasks requiring the production of a push/pull force (always pull in practice) have been used to evaluate handle diameter in a number of studies. This is perhaps the most relevant type of task for designing container handles. Ayoub & LoPresti (1971) found a relatively flat optimum between about 25mm and 64mm diameter when EMG was measured. However grip forces were optimum for a diameter of 38mm. Khalil (1973) measured EMG activity for three diameters of cylindrical handle, (32, 50 and 70mm) plus an elliptical handle 50mm long x 32mm wide and 50mm diameter sphere. Of all these handles the 32mm diameter handle was best.

Two unpublished studies both requiring a pull force (Sanderson 1976; Salvaterra & Chiusano 1977) have tested cylindrical handles in different tasks. The former used a holding task and handles from 10mm to 25mm and found an optimum at 19mm, Figure 3. The latter used both a subjective scale and a change in grip strength following a one minute holding of a 15kg container to evaluate handles from 10mm to 50mm, finding an optimum at about 38mm, Figure 4. Optima were found in each case at the center of the range, as is typical of all the handle diameter studies quoted. Perhaps there is a problem with the experimental designs used.

Other recommendations can be made based on different criteria. If the hand is to fit the handle with no overlap of fingers and

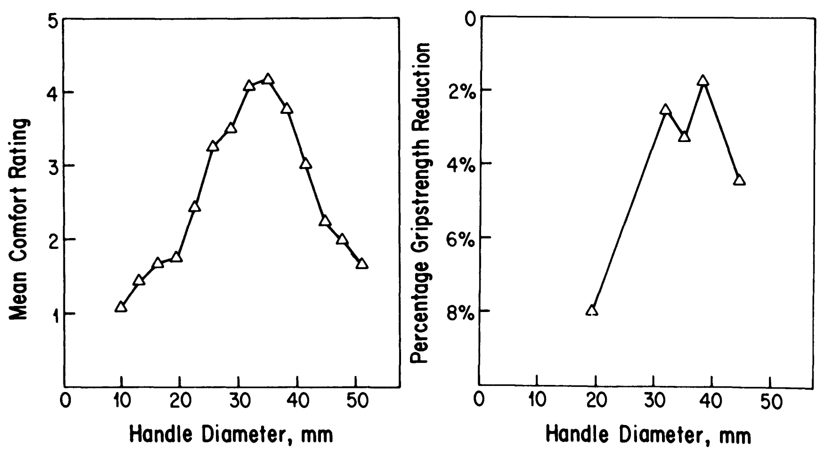

Figure 4. Effects of handle diameter on measures used by Salvaterra and Chuisano 1977.

thumb then Garret's (1971) anthropometric data would suggest 41mm as a maximum diameter for a 5th percentile male without gloves. Similarly, guidebook recommendations in human engineering recommend diameters as follows (quoted from Rigby, 1973)

Weight of Item	Minimum Diameter
15 lb.	6mm
15-20 lb.	13mm
20-40 lb.	19mm
40 lb.	25mm

These values are quoted without evidence as to their efficacy.

Finally, subjective preferences for handrail diameter were measured by Brooks et al 1974 who found an optimum diameter of 32mm for both males and females again showing an optimum near the center of the range tested.

4. DESIGN RECOMMENDATIONS ON HANDLES

For final recommendations on handle diameter, there is little agreement in the literature, although diameters from 25 to 38mm receive more support than most and thus must, reluctantly, be recommended. The elimination of sharp edges, seams, ribbing, and corners appears to be of more importance than actual handle diameter (Nielsen, Private Communication, 1978). The handle should be textured to provide maximum gripping force, particularly if other than a pull force is to be exerted. The shape of the handle is better cylindrical than molded to the contours of the hand. Tichauer (1971, 1978) demonstrates the limitations of form-fitting handles where it is almost impossible to design finger grooves into a handle in such a way that they fit a large percentage of the population. Thus any set of finger grooves will impair performance for those workers not perfectly fitted.

Handle or hand-hold width should be at least 115mm, with 50mm clearance all around the handle to accommodate a 95th percentile hand. If use with gloves is anticipated, at least 25mm should be added to these dimensions.

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APPLICATION OF DYNAMIC TESTING AND ANTHROPOMETRIC COMPUTER MODELING IN DESIGN OF AN AIRCRAFT/EJECTION ESCAPE SYSTEM

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INTRODUCTION

The crew station of the F/A-18 (Figure 1) has somewhat less toe clearance than other fighters in service. Design requirements for the F/A-18 dictated a fourteen (14) inch toe clearance together with a raised heel rest line rather than the more common sixteen (16) inch dimension. This geometry, along with a rudder pedal travel of only 1 inch compared to 3-4 inches in other aircraft, results in the pilot's legs being in a slightly straighter position than usual. This sitting position has increased the probability of foot contact with the instrument panel during escape even though the required thirty (30) inch ejection clearance line has been maintained. Because of the differences in geometry listed above, early effort was concentrated on all aspects of the design and the dynamics of body motion throughout the ejection sequence. This effort involved: (1) anthropometric studies using a range of live subjects in a crew station mock-up to assure static clearance; (2) biodynamic modeling to examine the body motion characteristics relative to fixed structure; (3) sled and tower testing with dummies as well as live subjects in the latter tests[1].

Foot contact with the instrument panel was noted on the eight excape system sled tests using 3rd and 98th percentile dummies at the Naval Weapons Center; China Lake, California. Lipstick was placed on the underside of the instrument panel before each test and lipstick smears were seen on the boots after the tests.

A series of Physiological Acceptance Tests was conducted on the ejection tower at the Naval Air Development Center (NADC); Warminster Pennsylvania using dummies followed by six (6) human subjects of varying anthropometric sizes[2]. For the tests with actual ejection accelerations it was noted that foot contact with a styrofoam simulated instrument panel occurred in almost all cases. Shin contact with the corner of the styrofoam panel was noted on one test of the 98th percentile subject. The subject was sitting higher than can actually be achieved in the aircraft, however, and thus there is some question of the validity of this test. The higher sitting position was necessary because of NADC safety precautions that required full thigh contact with the seat before firing.

INVESTIGATION

Having recognized that the foot contact during escape is probable, two separate studies were initiated to further examine the problem. The first study was to determine if this contact would be injurious. A time-distance-velocity study with data extracted from high-speed film was performed to determine foot velocities at contact. This analysis determined that the maximum foot velocity perpendicular to the kick panel was 22.5 fps and maximum total velocity was 34.5 fps. Experts from various disciplines were contacted to determine if this velocity at impact would be injurious to a pilot upon ejection. They indicated that lack of research in this area made it impossible to make such a determination, especially in

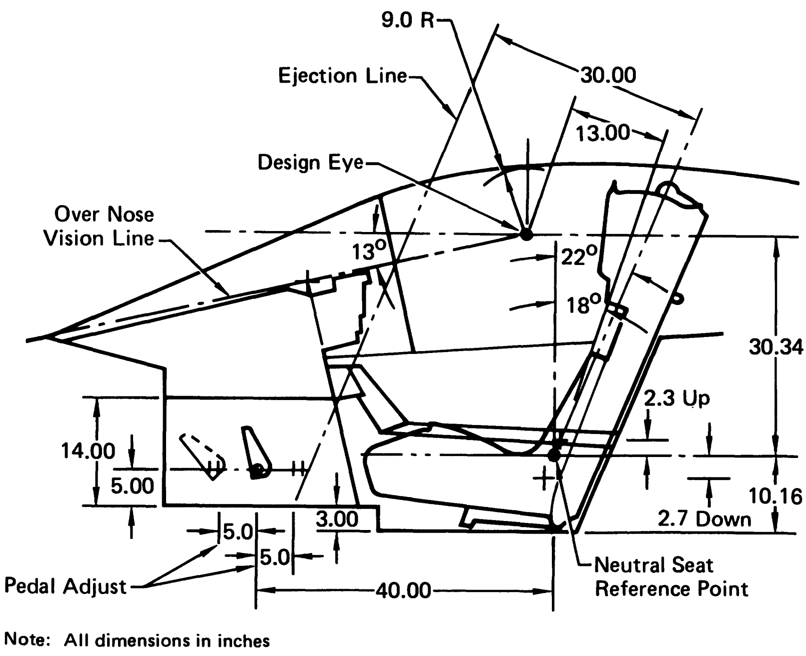

Figure 1. F/A-18 Crew Station Geometry

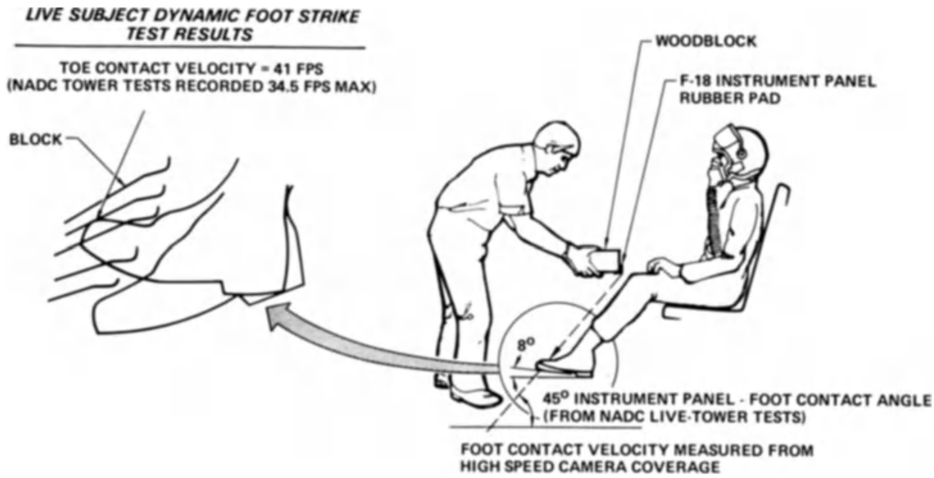

Figure 2. Live Subject Dynamic Foot Strike Test

a dynamic situation. In light of this, in-house studies were conducted to try to answer this question, with the scope during the first phase of this study limited to foot and ankle injury.

Subjects wearing standard Navy steel toe flight boots were positioned on a test fixture to simulate the leg and foot angle at contact (Figure 2). A manually applied load, with a velocity of 41 fps, was imparted to the subjects toe. High-speed movies were taken to determine the velocity and direction of the impact and to observe foot/leg motion. No discomfort was noted by the subjects. To determine the loads that the foot would receive at contact during an ejection, an instrumented panel was designed to simulate the underside of the aircraft main instrument panel. Dummy testing at NADC, using a 95th percentile dummy, instrumented with a rate gyro on the lower leg and a triaxial acceleration package mounted near the ankle, was conducted. Loads measured with the instrumented panel on three tests at representative acceleration loads were approximately two hundred (200) pounds. A test subject wearing flight boots then kicked the panel to determine if this load would be injurious. He far exceeded the expected load by achieving five hundred eighty-nine (589) pounds without injury. The load trace of the subject kicking the panel was similar in signature to that of the dummy tests.

The second phase of this study involved a biodynamic, anthropometric computer model to determine what effect this contact might have on the pelvis or spine. The model used was a modified version of the "Three-Dimensional Computer Simulation of Vehicle Crash Victims" developed by Calspan[3,4]. MCAIR and NADC used this version of the model in their analysis. The model was programmed to simulate a 98th percentile subject restrained in the F/A-18 crew station. The acceleration input used was taken from an actual tower test at NADC (Figures 3, 4). The model was run to simulate the pilot ejection with and without an instrument panel. Results from these simulations showed that only very small mathematical differences were evident in pelvic and spinal parameters. In fact, a 10% increase in the acceleration profile causes a larger change in pelvis motion than is caused by contact.

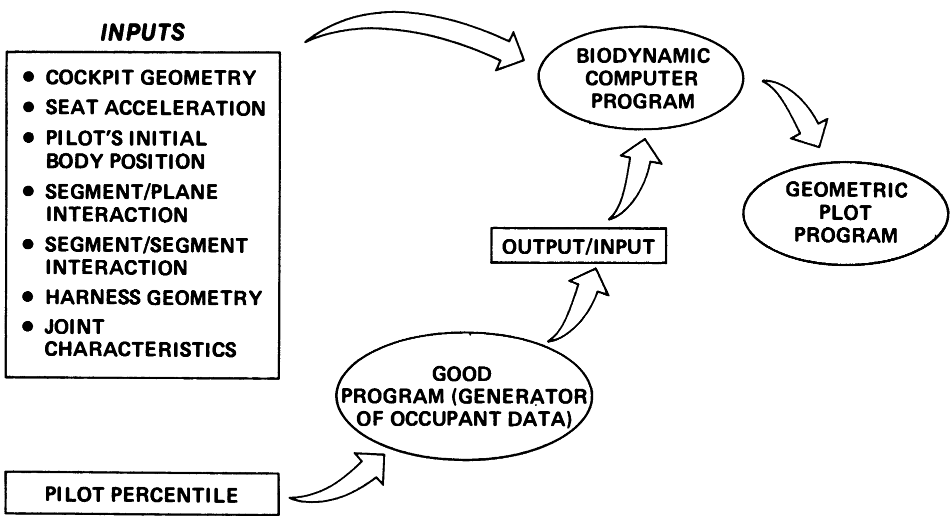

Figure 3. Flow Chart for Model Usage

A Navy medical panel was convened at this point to review the NADC and MCAIR studies. It was their opinion that it could not be determined conclusively whether or not contact would be injurious. They, therefore, recommended that impact be eliminated.

A second study was then undertaken to eliminate foot impact. Obvious changes to crew station geometry, such as raising the instrument panel or lowering the heel rest line, were considered. These changes would have required extensive redesign resulting in weight

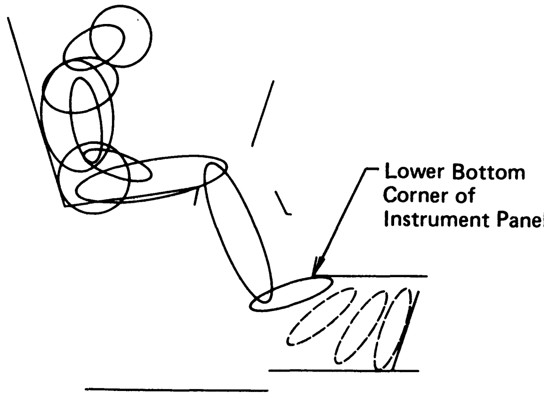

Figure 4. Model Output Showing Contact

and performance penalities; therefore, a simpler more innovative solution was sought.

Three candidate designs (Figure 5) were analyzed using the model as an evaluation tool. To ensure that the model was programmed properly for examination of these alternatives, a consultant from Calspan was brought in to supervise the model operation.

The first design considered was the addition of a crushable energy absorber to the underside of the instrument panel. It was determined that approximately one (1) inch of absorber was necessary to limit the impact load. This scheme was simple, passive and while it did not entirely eliminate impact, it would attenuate the impact load to an acceptable level. The disadvantages of this design were that it reduced foot clearance, would not prevent potential shin contact and would add approximately four (4) pounds of weight to the aircraft.

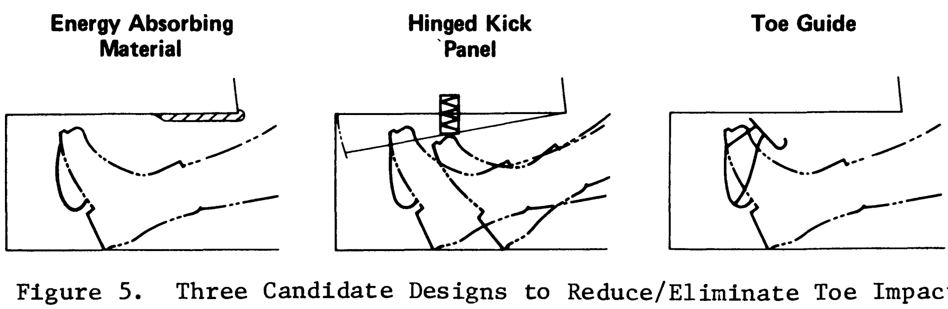

Figure 5. Three Candidate Designs to Reduce/Eliminate Toe Impact

The second design evaluated was the hinged kick panel. In this design, a spring loaded panel would be released by a pyrotechnic device at the time of canopy jettison in the escape sequence and would drop down to the pilot's foot. The foot would then be lightly forced downward and guided aft during the ejection stroke thereby eliminating impact. NADC independently tested a similar concept[5], which they called a "dynamic kick panel", with encouraging results. The model output indicated that this design could work very well. The main disadvantage of this design was its complexity. It included springs, pyrotechnic releases and added ballistic lines for signal transmission. There was also concern about a possible inadvertent release of the panels during flight. The design was estimated to weigh approximately five (5) pounds.

The third design which was examined was a toe guide. This device, made of light sheet aluminum, would be attached directly to the rudder pedal and would guide the boot down as the lower leg comes aft upon ejection. The computer model was used to examine various pivot locations, toe guide lengths, angles and spring rates. The objective was to achieve a change in foot trajectory enough to miss the instrument panel with minimum force applied by the toe guide. The resulting design applies a peak load of only thirty-five (35) pounds to the foot while deflecting it to miss the instrument panel. (Figure 6).

At this point a prototype toe guide was evaluated in the crew station mock-up by MCAIR Project personnel and pilots, along with the Navy Crew Station Advisory Team. Careful attention was given to possible hang-ups in either ingress or egress and to rudder/brake pedal operation. No problems were incurred. The device is passive, simple and the model analysis indicated toe impact and potential shin contact was eliminated. The weight was estimated to be less than one (1) pound per aircraft.

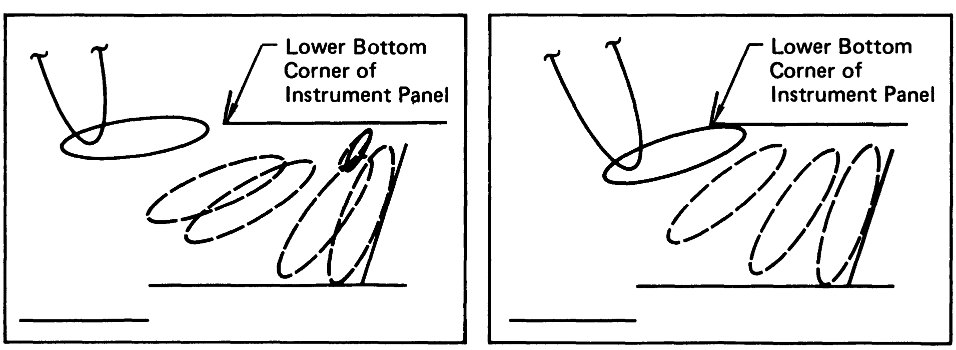

Figure 6. Model Output with and without Toe Guides

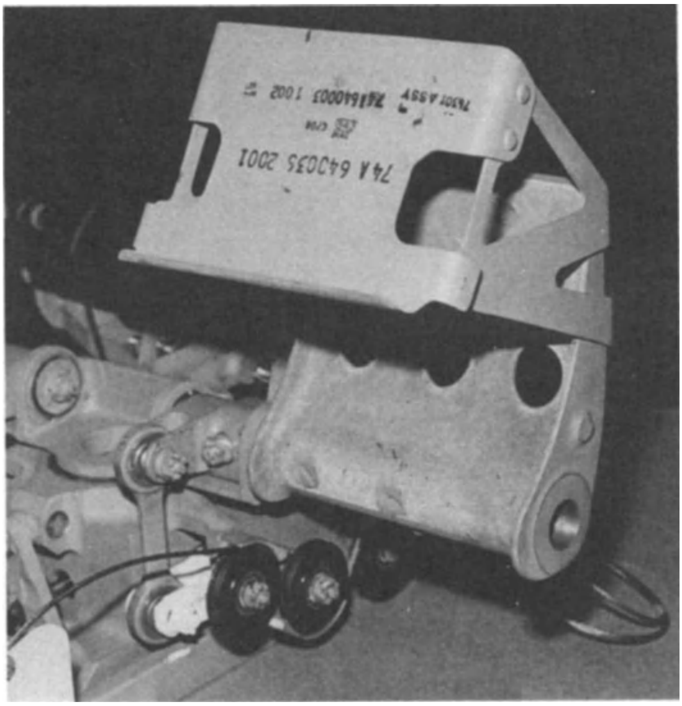

Figure 7. F/A-18 Toe Guide

VALIDATION

NAVAIR reviewed the study and agreed with MCAIR's recommendation that the toe guide was the best solution and that a series of tower tests at NADC to verify the design was in order. Detailed design of a production version of the toe guide (Figure 7) was accomplished and the hardware was fabricated for the tests. Four of the original six subjects and three new subjects were used in this test series. This gave a good before and after comparison of the effect of the guide. (Table 1.)

The model had predicted an improvement of over five (5) inhces in the contact point with the use of toe guides. This prediction agreed very well with the average improvement of over four (4) inches seen during the tower tests. The fact that the model predicted that toe impact with the instrument panel would not occur when the tower tests actually had contact indicates that the model may be slightly optimistic in comparison with live subject testing. A modification of the restraint system modeling and/or a small increase in joint friction/damping characteristics of the model may be warranted to more closely simulate the average test subject. A good deal of variation in leg motion was noticed between repeated runs of identical test conditions for the same test subject. Even the left and right leg of the same subject did not respond in exactly the same manner. However, with the toe guides, contact is limited to the steel tipped portion of the flight boot and is similar to that which is generally felt to be experienced in current fleet aircraft.

To demonstrate flight acceptability, one of the development aircraft has been retrofitted with the guides at the Naval Air Test Center; Patuxent River, Maryland.

CONCLUSION

Considerable study on the foot impact problem has brought us to the following conclusions. First, there is a need to examine this

Table 1. Tower Test Results

Test Subject	Contact Point from Edge (in.)		
	Without Toe Guide*	With Toe Guide	
	L	L	R
1	7.7		
2	1.3	None	None
3	Note 1	None	None
4	0.5	None	0.5
5	2	None	None
6	Note 2		
1	Note 3		
2	0.3		
3	2.1		
5	1.3		
7		0.5	0.5
8		None	None
9		1	1

Notes:

1. No contact was made with left foot
2. Seat was raised 2.6 in. above correct position. Contact above boot top, toe contact 7 in.
3. Foot slipped off pedal when firing handle pulled, toe contact 8.9 in.

* Photo analysis not complete for right foot, contact occurred in almost all cases

question more thoroughly from a research point of view. Specifically, determination as to whether foot contact has any injurious consequences should be investigated. Second, we feel that computer modeling of body movement with regard to escape systems has reached the point where we have relatively high confidence in its results. This is especially true of the Calspan model. With this tool, industry can make early and more accurate design decisions by predicting clearance paths of escape systems. Third, we feel that the toe guides have been shown to be an effective means of reducing both the probability of foot impact during escape and the severity of impacts should they occur. Fourth, the use of toe guides and biodynamic computer model analysis offers an important advantage for future crew station design.

We feel that the toe guides are a useful innovation to achieve additional cockpit instrument panel area in addition to providing foot trajectory control during ejection.

ACKNOWLEDGEMENT

We wish to thank Mr. Gene Butler of Calspan Corporation for this effort in programming and model set-up in the design cases which were analyzed.

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THE COLLECTION AND APPLICATION OF ANTHROPOMETRIC DATA FOR DOMESTIC AND INDUSTRIAL STANDARDS

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INTRODUCTION

In this paper three standards are examined to find out how far anthropometric-biomechanic procedures and data have been applied, and to comment on the suitability of anthropometric data in its traditional static form to the workplace, where the activity is dynamic and the worker can come from any section of the community male-female, 1st - 99th percentile.

STANDING WORKTOP HEIGHTS

It has been shown by many authors (e.g. Drillis 1963, Hertsberg 1960) that, for working efficiency and convenience, bench heights for standing work should be related to the type of manual work being carried out and the elbow height of the worker. For the mainly light tasks that are performed on a kitchen worktop bench, Ward and Kirk (1970) experimentally determined preferred heights below elbow height of 8.8 cm for light work to 12.2 cm for work requiring force on the surface. With the proposed standardisation by the International Standards Organisation and the British Standards Institution (ISO 3055/BS 1195) of kitchen fitments (Figure 1) it is relevant to examine the proposals for worktop heights in the light of the most recent survey (Thompson et al, 1973) of the elbow height of adult British females. (A similar study of male workers is planned.) These heights (olecranon to floor) are shown in Figure 2, and Figure 3 shows the heights recommended by Ward and Kirk together with the ISO 3055 alternative options of 850 and 900 mm.

If current ergonomic research on standing worktop heights is accepted the adequacy of the proposed ISO standard for the British adult female population is in doubt. Clearly no one height will suffice and therefore alternative heights designed to suit the user population are desirable.

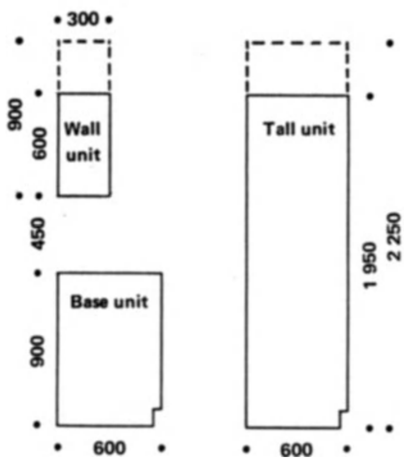


Figure 1. Standard range of fitments (mm)

n = 7187 $\bar{x}$ = 100.60 SD = 4.94

Percentile values

1st	5th	95th	99th
88.5	93.5	109.5	112.5

Figure 2. Elbow height survey results (cm)

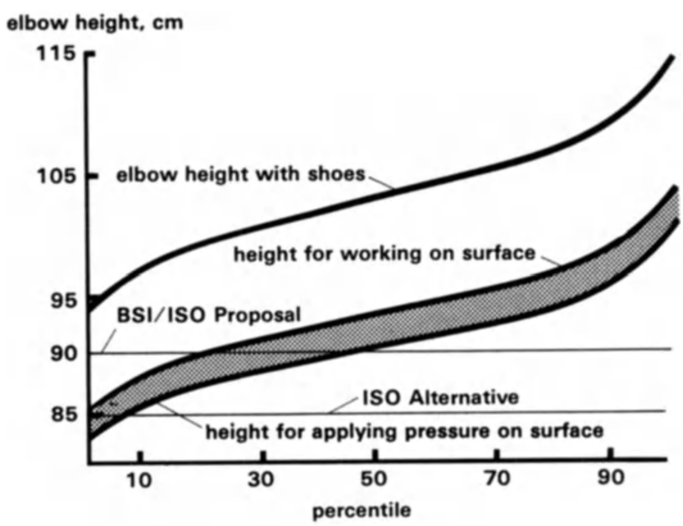


Figure 3. Elbow height distribution and proposed worktop height standards

FUNCTIONAL REACH AND SHELF LOCATION

Certain minimum standards for domestic kitchen storage for public sector housing in Britain were given in the Parker Morris Report (1961). The recommendations are given in terms of volume, but to convert this into usable storage, shelves which are required for the majority of items and their accessibility must be considered.

An experiment was therefore carried out applying the recommendations on reach dimensions given in Ministry of Housing and Local Government. Design Bulletin 6 *Space in the Home*, 1968 (Figure 4). Firstly a survey of British adult female static vertical reach (Figure 5) was carried out and, on the basis of this, 60 subjects were selected from various percentile groups to carry out a series of functional reach tests. These consisted of subjects placing two objects on a 30cm-deep shelf and then removing them. The objects were a weighted tray moved using two hands, and a can of beans moved with one hand. Starting at a height at which the object could be placed at the back of the shelf (maximum utilisation), the shelf was then raised until only the front of the shelf was accessible (Figure 6). The results are shown in Table 1.

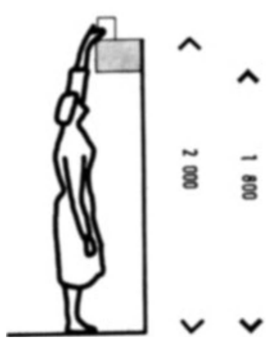


Figure 4. Reach dimension. Maximum vertical reach and maximum shelf height for general use, assuming height of woman to be 1 630 mm. Design bulletin recommendations.

n = 7187 $\bar{x}$ = 202.6 SD = 9.25

Percentile values

1st	5th	95th	99th
180.5	187.5	217.5	222.5

Figure 5. Static vertical reach survey results (cm)

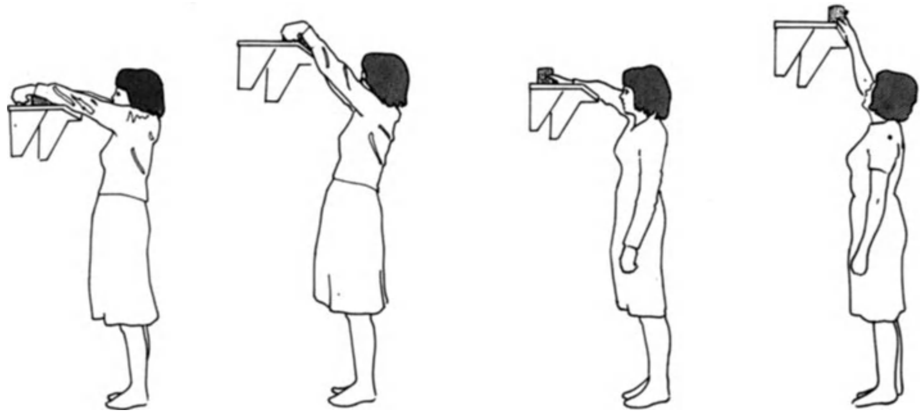


Figure 6. Functional reach experiment

Table 1. Maximum functional reach to whole shelf or edge shelf related to stature

Stature percentile group	Two handed reach		One handed reach	
	Whole shelf	Edge of shelf (10cm)	Whole shelf	Edge of shelf (8cm)
1 - 5	125.6	156.3	135.1	168.3
6 - 30	146.2	173.2	150.9	182.5
70 - 95	156.0	188.9	162.6	198.3
96 - 99	164.7	193.8	168.5	206.2
Design bulletin Maximum shelf height for general use 180cm				

Two points of concern are apparent: the underlying assumption indicated by a foot note in the Design Bulletin "Assuming height of women to be 1630 mm", and the discrepancy between the recommendations and the functional data found. Minimum volume storage standards for housing must take into account functional use of the storage facilities by the whole of the user population.

REACH AND SAFETY

The examples we have looked at so far have been related to storing objects *within* reach for the ease and convenience of the worker, the typical ergonomics approach to interface design. At the other end of the reach continuum is the requirement to place hazards *beyond* reach. Such reach distances are within the province of machinery guarding standards.

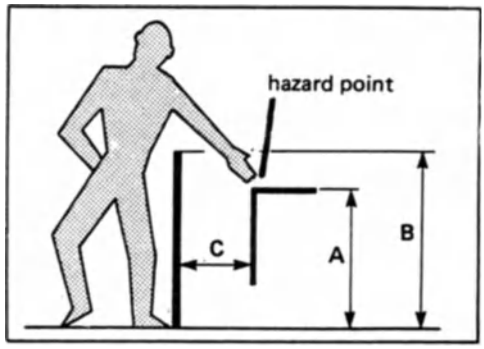
REACH OVER BARRIERS

In a recent review of guarding standards suitable for adoption in Britain it was decided to examine and verify experimentally parts of the standard issued by Deutsches Institut fur Normung (DIN) 31 001: 1976. *Safety Devices: definitions, safety distances for adults and children.* This gives the most complete list known to be published to date of anthropometric dimensions applicable to machinery guarding. The aim therefore was to find out what level of protection the standard would give the working population in Britain. The extent to which a national standard will protect nationals of another country will assume increasing importance with the creation of community and international standards.

DIN 31 001 proposes protection of 95% of the workforce: "In the case of the dimensions specified here the attempt was made on the basis of ergonomic measurements, which apply to 95% of the group of persons comprising adults and children over 14 years . . ."

The safety distances recommended are shown in Figure 7 and it should be noted that these safe distances also include a safety margin i.e. the actual reach distance plus an allowance to place the hazard beyond reach.

For the "reach over a barrier" experiment, because there is a good correlation between reach and stature, i.e. the tallest have the longest reach (Churchill et al 1970, Thompson et al 1973) male subjects were selected on the basis of their stature, choosing the 95th percentile group (184.0 to 185.9 cm) in order to establish a direct comparison with the DIN 95% of the population criterion. This stature value was based on Haselgrave's (1979) survey and included an allowance for the standard error of Haselgrave's sample size of 1584. Subjects were civilian and Royal Air Force apprentices of average age 22 years.



Reaching downwards and reaching over

The reach distance over the edge of machine frames or protective devices is calculated from

A = distance of hazard from standing point

B = Height of top of protective guard from standing point

C = horizontal distance from guard to hazard

Distance of hazard point from floor A	Height of protective guard B							
	2400	2200	2000	1800	1600	1400	1200	1000
	Horizontal distance C from hazard							
2400	–	100	100	100	100	100	100	100
2200	–	250	350	400	500	500	600	600
2000	–	–	350	500	600	700	900	1100
1800	–	–	–	600	900	900	1000	1100
1600	–	–	–	500	900	900	1000	1300
1400	–	–	–	100	800	900	1000	1300
1200	–	–	–	–	500	900	1000	1400
1000	–	–	–	–	300	900	1000	1400
800	–	–	–	–	–	600	900	1300
600	–	–	–	–	–	–	500	1200
400	–	–	–	–	–	–	300	1200
200	–	–	–	–	–	–	200	1100

Figure 7. DIN 31 001 safety distances for reach over a barrier

The apparatus (Figure 8) was rigidly constructed so deformation or inaccuracy of the measuring point from the datum line (the barrier) was ± 1 mm. Subjects wearing light indoor clothing and shoes had 3 trials at all combinations of barrier and hazard heights and the furthest horizontal reach was used in subsequent analysis. The results from the experiment at a barrier height of 1200 mm are shown in Figure 9 and a summary of the complete results are shown in Table 2. In Figure 9 the discrete points of the DIN standard have been joined to give a comparison with the experimental curves. The mean reach value and the mean reach value plus three standard deviations of the latter are also shown. The plus three standard deviation curve is shown because the data of this selected percentile group was normally distributed and therefore the line constructed on the third standard deviation gives an indication of the distance some of the population having this stature will be able to reach.

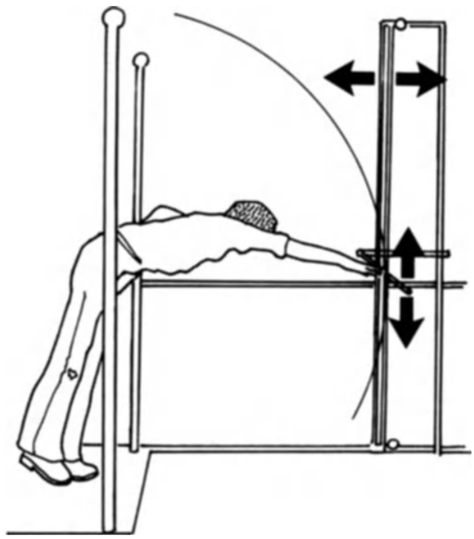


Figure 8. Forced reach over barrier

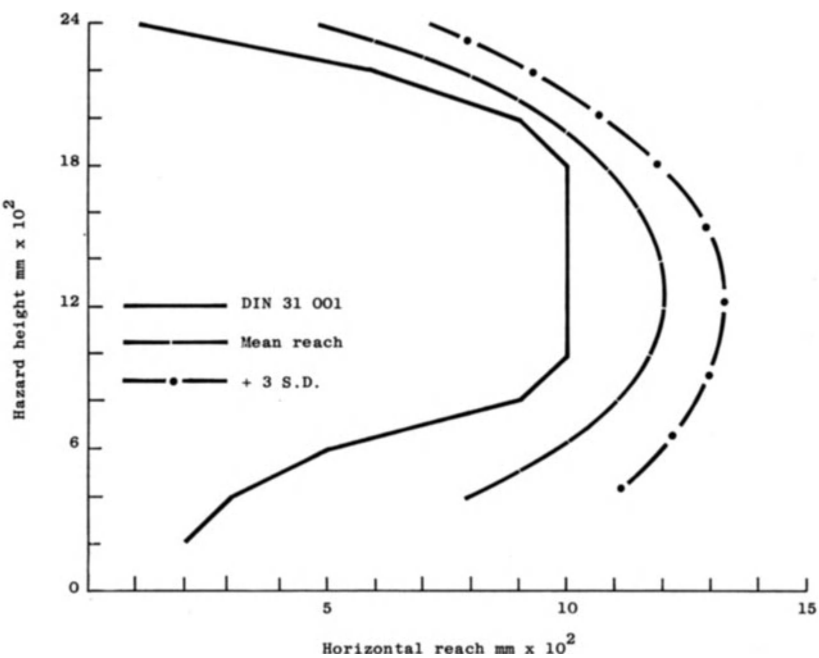


Figure 9. Reach profile over 1200 mm barrier

Table 2. Summary of results of reach profile of 95th percentile male

Distance of Hazard Point from floor mm	Height of edge of safety feature (barrier) mm 2200	2000	1800	1600	1400	1200	1000
	*100**	*100*	*100*	*100*	*100*	*100*	*100*
2400	308	425	534	486	591	701	761
	+208	+325	+434	+386	+491	+601	+661
	250	*350*	*400*	*500*	*500*	*600*	*600*
2200	321	528	699	718	794	920	994
	+ 71	+178	+299	+218	+294	+320	+394
		350	*500*	*600*	*700*	*900*	*1100*
2000		537	785	824	920	1071	1171
		+187	+285	+224	+220	+171	+70
		–	*600*	*900*	*900*	*1000*	*1100*
1800		477	826	890	993	1189	1295
		+477	+226	-10	+93	+189	+195
		–	*500*	*900*	*900*	*1000*	*1300*
1600		271	835	898	1026	1267	1397
		+271	+335	-2	+125	+267	+97
			100	*800*	*900*	*1000*	*1300*
1400			764	869	1026	1218	1456
			+664	+69	+125	+318	+156
				500	*900*	*1000*	*1400*
1200				788	976	1322	1484
				+288	+76	+322	+ 84
				300	*900*	*1000*	*1400*
1000				637	889	1310	1482
				+337	-11	+310	+ 82
					600	*900*	*1300*
800					740	1273	1449
					+140	+373	+149
					–	*500*	*1200*
600					422	1160	1373
					+422	+660	+173
						300	*1200*
400						1116	1313
						+816	+113

Horizontal reach mm

100* = Safety Distance (reach distance + safety allowance) recommended by DIN 31 001
308 = Reach distance found by experiment ($\bar{x}$ + 3 SD)
+208 = Distance by which experimental reach exceeded (+) or failed (–) to reach DIN standard

STRUCTURE OF STANDARD

The structure of the DIN standard profile in the form of discrete values 200 mm apart can lead to difficulty in interpretation if the height of barrier or hazard is at a distance between these points. It can be seen from Figure 9 that the reach profile takes the form of a natural convex curve; the DIN standard does not always recognise this, recommending a vertical line at some barrier heights, see Figures 7 and 9. Profiles can of course be constructed from discrete points, but then each of these points and any line joining then must be beyond the natural reach curve and the point intervals would have to be close together to avoid inconsistencies in the safety distance. It would therefore be useful if standard profiles of this type could be shown graphically with the additional supportive data given in tabular form.

Safety Allowance

The experimental results show the distance reached i.e. *touched.* The safety distance recommended by the DIN standard is based on a reach distance value plus a safety distance, i.e. the standard distance should be beyond reach by 95% of the workforce. Our results do not confirm this for the British population.

Height of Barrier Rail

Although the standard shows a safety distance for a hazard at 200 mm and a barrier at 1000 and 1200 mm, this was not examined in the main experiment in order to avoid injury to subjects. During the pilot study prior to the main experiment, approximately 15% of subjects fell over the 1000 mm barrier when reaching for a hazard set at 200 mm. It is probable that other subjects constrained their reach from fear of falling. When the arms are raised above the head in a natural reaching action, the centre of gravity of the body is raised, thus increasing the tendency to overbalance when reaching forward and down over a barrier.

Supplement to Natural Reach

The DIN standard reasonably makes the point that the reach distances they give refer to reach without aids or devices such as chairs, ladders, etc. However, during the pilot studies it was noted that if subjects were told to 'reach as far as they could' (forced reach) and given no instructions to limit the method they adopted, (N.B. experimental instructions to subjects restricted them to at least one foot on the floor), when the hazard was above the barrier they would place one hand on the barrier rail and use this as a support to help them jump up and so increase the distance reached with the free hand. It can be argued that this is a natural response and, if something is out of reach in the workplace, is the type of behaviour that might well take place. It should therefore be recognised by a standard either in its basic recommendations, or at least under the general heading 'safety allowance'. This will of course entail the use of dynamic anthropometric measures.

Percentage of Population Protected

As has already been stated, the "95 percent of the population" criterion was chosen for comparative purposes. However, to leave out the top 5th percentiles is to ignore those workers *most at risk* i.e. those with the longest reach. Therefore it is suggested that where safety standards are concerned the conventional percentile ranges 5th to 95th are replaced by 1st or 99th percentile whichever is of relevance.

REACH THROUGH SMALL OPENINGS

Another investigation that is currently under way is to study the actual opening size and shape that will prevent whole limb access. The first experiments concern index finger access and the distance hands can reach through 10, 20 and 30 mm slot openings. This work is initially being carried out with particular reference to the multi-racial female work force in Britain, in order to find out if racially determined anthropometric differences (Stoudt et al 1965) would influence reach through apertures. Some preliminary findings are reported here.

The apparatus was constructed from non-deformable metal plate and subjects were instructed to use their maximum voluntary force (a split place design allowed for limbs to be released!). The results are shown in Figure 10 and Table 3, and two points are of interest. It was found that the West Indian subjects had larger diameter fingers ($p < 0.001$) than either the European or Asian and therefore they will be automatically protected by any standard dimension which prevents the other two races from putting the whole length of the finger through an aperture. However, the results of a slot experiment (Figure 11 and Table 3) may be of relevance, implying that if the aperture is sufficiently large as to allow access of the whole limb, the West Indian Group would be able to reach significantly further ($p. < 0.01$) than the other two groups. The shape of the aperture is also of importance. Significantly more subjects of all races ($p. < 0.001$) could insert their finger through a square aperture than a round aperture, side length and diameter being equal, as a comparison between the results in Figure 10 shows.

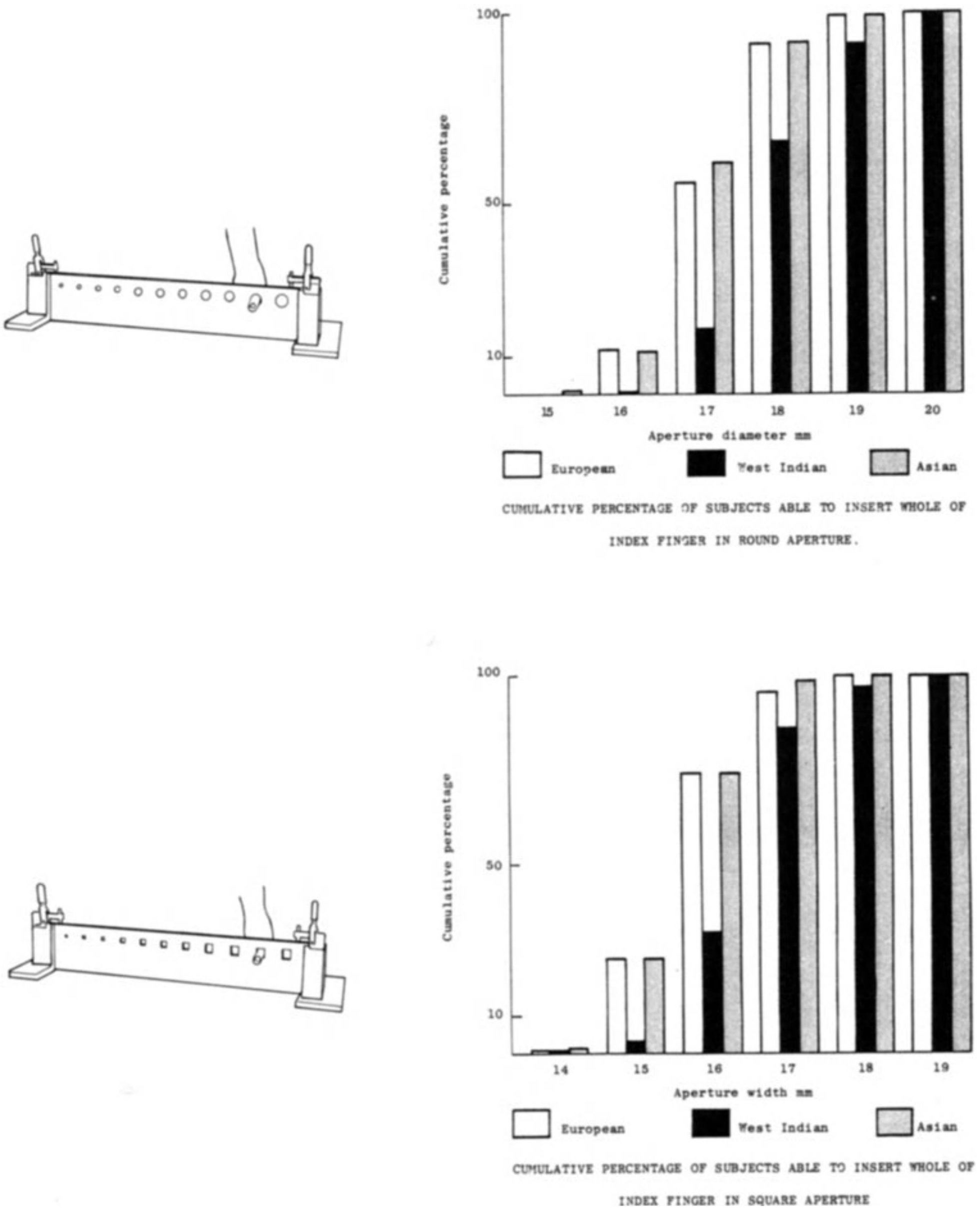


Figure 10. Forced reach through round and square apertures

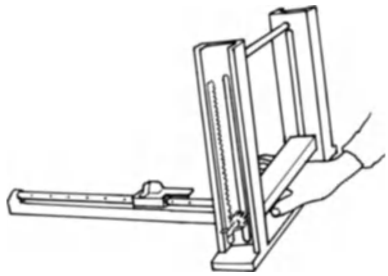


Figure 11. Slot apparatus

CONCLUSION

I hope this paper has served to illustrate the lack of application of anthropometric data to the civilian workplace. There are currently two shortages, static data and dynamic applications. We require a collection of static anthropometric data in the same depth and detail that is available on military populations, and in addition we need to extend this range to include the 1st to 99th percentile, the complete age ranges and the different racial and

Table 3. Reach through 10, 20 and 30 mm slots (mm)

Slot height 10 mm	n	$\bar{x}$	S.D.	Max
Asian	197	18.3	4.9	37
European	159	19.3	5.0	42
West Indian	144	16.7	4.0	39
Slot height 20 mm				
Asian	197	89.3	4.9	102
European	159	87.8	4.5	97
West Indian*	144	94.6	5.0	108
Slot height 30 mm				
Asian	197	139.1	8.1	156
European	159	138.4	8.0	156
West Indian*	144	142.7	8.7	163

* P. <0.01

ethnic groups present in the population. A collection of such data will serve as a useful reference point for the selection of subjects to provide the dynamic data essential to workplace application.

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COMPUTER AIDED CREW STATION DESIGN FOR THE NASA SPACE SHUTTLE

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INTRODUCTION

The development of human habitats, whether they be work stations, leisure, or personal maintenance areas, typically calls for a preliminary design which, at some point in the design process, is converted to a mockup for evaluation by personnel of various and usually somewhat random anthropometric sizes. The problems inherent in this process are numerous. Source books on anthropometry are rarely available, up-to-date or appropriate to the intended user population. Mockup evaluation is often done by available personnel (as opposed to the user group), and the thoroughness of such an evaluation is limited by cost and schedule. Finally, physical mockups are rarely placed in a representative environment where tasks and time-lines can be evaluated under operational conditions.

A system representing a solution to these problems is described herein. It combines interactive modeling of the human habitat with highly accurate digitally obtained anthropometric data, integrates these items with geometrically modeled individuals, and to a limited degree, places the combined whole in a simulated operating environment for evaluation. The result is greater efficiency and flexibility in the design process, overall programmatic cost savings, and a projected improvement in operational output.

SYSTEM CONFIGURATION

The OSDS is configured around a Systems Engineering Laboratories (SEL) 32/35 data processor. A more complete hardware description is discussed by Lewis (1979a). Software installations currently include Panel Layout Automated Interactive Design (PLAID) and Crewstation Assessment of Reach (CAR) systems. CAR was originally developed by Boeing Aerospace Corporation for the U. S. Navy, and is based on the Computerized Accommodated Percentage Evaluation (CAPE) model, designed by Alvah Bittner, then of the Naval Missile Test Center.

PLAID was originally designed to provide capability in the preliminary and detail design stages for layout and installation of displays and controls in spacecraft flight stations. It has, however, proved to be a highly versatile tool, and its usage extends far beyond those applications for which it was originally intended (Lewis, 1979b).

Design Features

PLAID provides the user with the capability to accomplish 3-D modeling in a real-time interactive environment with accurate internal and external representation of objects under construction. It also permits assembly of objects with user-specified tolerance limits, and designation of desired subassembly or component levels. Objects can be viewed in wire-frame or hidden-line form with the option of seeing hidden-lines in dotted or dashed format. Clearances and objects in collision are explicitly identified and located at the user's option. Any viewing angle is possible by specifying the six 3-space coordinates which identify the position being viewed and the point at which the eye is located. Perspective or isometric projection, along with cut-away views and variable scaling, are also options available to the user.

Anthropometric Evaluation Potential

With these features, PLAID becomes a tool of near-maximum versatility when dealing with anthropometry and biomechanics. Work-station access can be approached with three different methods, depending on the needs of the designer.

CAR permits reach evaluations of a PLAID generated crew station of a single individual or of a population with designer-specified percentile ranges.

BACKGROUND

With the advent of the Space Transportation System, the civilian space program became committed to the accommodation of a wide range of personnel sizes. This generated a need in the design areas for accurate static and dynamic anthropometric data and for the capability to rapidly and efficiently utilize such data. The NASA Johnson Space Center's (JSC) Spacecraft Design Division (SDD) initiated a program in 1976 to fill such needs.

Initially, the Anthropometric Source Book, NASA publication RP1024, was developed by Webb and Associates of Yellow Springs, Ohio, with the technical guidance of Mr. John Jackson of NASA JSC. It provided the most complete colation of anthropometric data across ethnic and sex groups in existence at that time (Jackson, 1979). RP1024 is now being used in industry, academia, and government on a world wide basis.

While the source book was in work, a research and technology development effort was initiated to configure a system which could semi-automatically and accurately acquire dynamic (angular excursion, reach, and strength) data for use in an interactive digital data base. Initially, a feasibility model was developed to demonstrate, in two-dimensions, experimental use of a microprocessor controlled, video-based, single angle, one-plane body segment measurement system to provide accurate angular excursion data for the digital data base. Following this, the concept was extended to a three-camera system capable of recording on digital magnetic tape a time-sequenced data stream of points located in three-space. These points are utilized to define the reach volume of individuals with ± 1 cm accuracies. This system can be coupled with an isometric force measuring device to provide radial and tangential force measurements in three-space. Both systems, now called the Anthropometric Measurement System (AMS), were developed for JSC by Southwest Research, Inc., of San Antonio, Texas, with the guidance of Dr. W. E. Thornton of the JSC Astronaut Office (Thornton, 1979).

Finally, also beginning in 1976, efforts were undertaken to develop a stand-alone, mini-computer based, interactive graphics design system which could utilize the anthropometric data previously discussed in the context of relevant human habitats such as work, leisure and rest stations in a zero-gravity environment. This capability was developed for JSC by Rothe Development, Inc., of San Antonio, Texas, and is called the Operator Station Design System (OSDS). The AMS and OSDS are resident in the SDD Design Performance Laboratory (DPL) at JSC, Houston, Texas.

The time-sequenced data stream output by the AMS to PLAID represents an individual reach volume that can be assembled in a PLAID generated crew station with respect to the design eye or seat reference point. The PLAID clearance/collision logic can then be utilized to exactly identify usable areas with respect to a given individual. The force measurement system data is also available in time-sequenced format, and both radial and tangential force values can be overlayed on the contour assembly at any needed location. Because the reach volume contours are uniquely generated by an individual, equations of motion describing limb and joint movement are not required. However, the use of the system in this manner provides the vehicle by which both equations of motion and biomechanical model approaches can be validated. In this manner, a biomechanical model can be configured to represent a series of specific individuals, programmed to perform like maneuvers, and the resultant data compared until a known degree of accuracy can be generalized to a given population.

Often, studies require a visual image of a modeled individual. Toward this end, PLAID has been used to generate a dimensionally accurate 3-D model of the Space Transportation System Shuttle Orbiter's extravehicular pressure suit. Work is currently in progress to build graphics models based on the CAR thirty-three link form and the COMputerized BIomechanical MAN (COMBIMAN) thirty-five link form. Incorporation of the application equations of motion in these PLAID generated models will not only enable NASA/U. S. Navy/U. S. Air Force cross utilization of them but will provide additional validation potential.

USAGE

PLAID became operational in July 1979. The AMS was added to the OSDS/PLAID complex in November 1979. By January 1980, the system had been utilized to model various Orbiter/payload designs for the purposes of establishing visual access, determining redesign requirements, and developing crew procedures. The AMS has been used extensively in the design process for the Orbiter inflight thermal repair system. Control programs have been written to pass data from the construction and assembly modules to the display module and subsequent output to copier or plotters such that a dynamically changing scenario can be graphically generated and recorded as a continuous run (e.g., overnight). This capability has resulted in savings of several thousands of dollars in the initial usage alone and has provided a more detailed result in a shorter timeframe than a comparable full-scale mockup study would have accomplished.

FUTURE DEVELOPMENT

PLAID will be installed by the U. S. Naval Air Development Center during 1980, and cooperative data base development on standard displays and controls initiated with NASA such that detailed component fabrication need not be duplicated by different users.

Real-time dynamic picture display and shaded image capability are potential long-term future additions to PLAID. Software modularization to facilitate transfer to different equipment and additional development of user-automation software to extend the concept of configuring dynamic scenes for processing during non-peakload hours are near-term tasks scheduled for 1980.

SUMMARY

The OSDS/PLAID/AMS complex provides explicit biomechanical modeling with a high degree of accuracy without the use of conditional probabilities and analogies. In the case of the Orbiter pressure suited individual, the model and empirical data represent an exact fit because the model is an exact replica. Validation studies are planned for U. S. Navy and Air Force derived link models. Finally, significant cost savings over the use of a full-scale mockup were demonstrated in an initial test.

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Session VIII
Future Needs and Perspectives

POSTURAL CONSIDERATIONS IN WORKSPACE DESIGN

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1. INTRODUCTION

The first point in this paper is that its subject matter is most definitely not a matter only for the future, but also for the immediate present. This symposium is, in part, concerned with the applications of anthropometry and biomechanics. Here we are looking at the need to see posture as an outcome of the workplace design process and to design for postural requirements against a specification, as is usual for other areas of design.

A specification presupposes that we have criteria, against which we select our requirements. Furthermore, design assumes that we have basic knowledge about the materials incorporated into it and that we have methods for manipulating this basic knowledge to conform to the design requirements.

In general, the engineer is better off than the ergonomist. He does not say a strut must not break, he calculates it not to exceed a chosen stress; he has substituted calculations for principles. Ergonomists, however, must still rely on principles to a great extent, for their scientific underpinning is still being built up. Principles for workspace postures have been set out (Corlett 1978) and are given in Table 1. They provide a simple framework against which design decisions can be tested. Further developments from such principles will result in their replacement by predictive laws, capable of specifying numerically the consequences of changes in the design variables.

The provision of such laws needs measurements of the behaviour of the material under study and an analysis of these measures to provide generalised theories.

Table 1. A sequence of workplace design principles. They are arranged in order, so that those higher in the table take precedence over those lower if a conflict arises during design.

1. The worker should be able to maintain an upright and forward facing posture during work.
2. Where vision is a requirement of the task, the necessary work points must be adequately visible with the head and trunk upright or with just the head inclined slightly forward.
3. All work activities should permit the worker to adopt several different, but equally healthy and safe, postures without reducing capability to do the work.
4. Work should be arranged so that it may be done, at the worker's choice, in either a seated or standing position. When seated the worker should be able to use the back rest of the chair, at will, without necessitating a change of movements.
5. The weight of the body, when standing, should be carried equally on both feet, and foot pedals designed accordingly.
6. Work should not be performed consistently at or above the level of the heart; even the occasional performance where force is exerted above heart level should be avoided. Where light hand work must be performed above heart level, rests for the upper arms are a requirement.
7. Rest pauses should allow for all loads experienced at work, including environmental and information loads, and the time interval between successive rest periods.
8. Work activities should be performed with the joints at about the mid-point of their range of movement. This applies particularly to the head, trunk and upper limbs.
9. Where muscular force has to be exerted it should be by the largest appropriate muscle groups available and in a direction co-linear with the limbs concerned.
10. Where a force has to be exerted repeatedly, it should be possible to exert it with either of the arms, or either of the legs, without adjustment to the equipment.

2. THE LIMITS TO MAINTAINING A POSTURE

Before dealing with such considerations it is necessary to return briefly to the criteria. Work must be viewed as a lifetime's activity. adaptation to which should not distort the physical characteristics of the worker. (We refer in this paper only to the postural influences on the worker). Postural criteria must include, therefore, the times for maintaining given postures, required recovery periods and the effects of subsequent activities on recovery. By comparison with dynamic work we are clearly ill supplied in the field of posture. Static work investigations, dealing either with a single muscle, or a group of muscles associated with a single joint, give some guidance. Where a person has only limited opportunity for change, the time for which a posture can be maintained will probably be equivalent to that for the most heavily loaded muscle group; it will thus approximate to the times suggested by, e.g. Rohmert (1965). Where exchange between various muscle groups is possible, by modifying the posture, the holding time may be extended.

Where the work activity is not physically hard, then pain arising from the muscles used to maintain the working posture will be the factor deciding whether the work will continue or not. The pain level is correlated with lactic acid levels in the muscle. We propose that energy expenditure and postural pain represent independent criterion limits to performance. There may be situations where they will operate together; how they combine in such circumstances we do not know but for the industrial jobs studied by us we consider that the observed changes in performance arose either from one criterion or the other.

3. THE RECORDING AND ANALYSIS OF POSTURE CONFIGURATION

The use of body diagrams to investigate the development of pain during the working day, as well as for assessing the improvements for the worker concerned arising from the analysis of the pain records in conjunction with other ergonomic aspects of the work situation, have been described elsewhere (Corlett and Bishop 1976). The initial evaluation of measures of discomfort can be assisted by the use of a simple table, (van Wely 1970); developed from clinical information gathered from industrial health records.

If the perceptions of the worker concerned are not part of the investigative procedure, or where some predictive procedure is required, it is even more necessary to know the relationships between postures, exerted forces and holding times. These are needed for whole body postures. It is also necessary to have some readily analysable system for recording postures and forces.

Perhaps the two extreme attempts to solve this problem, both of which have useful practical applications, are the OWAS system developed by Ovako Oy in conjunction with the Finnish Institute of Occupational Health (Karhu, Kansi and Kuorinka 1977) and the analyses done by Computerised Biomechanic Analysis Inc. of Amherst, Mass.

The former uses a simple procedure for classifying postures by means of a three digit code. The analyst assesses the position of the back (four possible choices) the upper limbs (three choices) and the lower limbs (seven choices). The postures so classified are referred to a chart, where all possible classifications are grouped into four categories ranging from "Normal postures not requiring special attention" to "postures needing immediate consideration". The procedure is simple to learn and consistent between users; it is now used as a regular part of all work studies in Ovako. It is effective in drawing attention to bad postures, but does not allow for the time to hold postures and recovery from them.

The work of Computerised Biomechanic Analysis uses a TV recording of an activity. A light pen feeds coordinates from the display into a computer, successive frames providing the data to assess the acceleration of the various body parts. Forces exerted at various joints and at points of contact with the ground may then be calculated.

An intermediate position is occupied by the procedure known as posture targetting (Corlett, Madeley and Manenica 1979). The targets consist of concentric circles representing the vertical angle of displacement of a body part from the standard anatomical position and radial lines representing displacement in the horizontal plane. They are placed in a standard format to represent limb segments, hands, feet, head and trunk. Each posture, as it is adopted, is rapidly recorded on this diagram and the length of time it is held is also recorded. The procedure is readily learnt, is repeatable by different observers - has precision within about 15^{o}, or less with practice, and lends itself to computer storage and manipulation.

Such techniques, at different levels of sophistication, permit the field recording of postures and their subsequent analysis. The computerised analysis provides some force and torque data, but even this leaves the problem of "what is an adequate posture" as a matter, to a great extent, for subjective judgement. The long term exposure to posture requires long term studies for definition of its effects. Postures held for short periods can be assessed, however, if the extent to which they can be repeated is used as a criterion of their severity.

4. POSTURE HOLDING AND RECOVERY

Where a posture is held until high levels of discomfort are experienced, the ability to exert the posture again may soon be recovered, but the stamina to maintain it for a similar period of time takes longer to return. Muscular anaerobic metabolism utilises muscle glycogen as well as building up lactic acid. Changes in heart activity etc. quickly relieve the muscle of its lactic acid and the worker of his discomfort, but the recovery of muscle glycogen will require some hours (Lind 1959, Lind and McNicol 1967). Studies reported by Corlett and Manenica (1980) showed that a ¾ hour lunch break did not allow full recovery. The afternoon discomfort pattern climbed rapidly to continue the rising morning curves to more severe levels of discomfort.

Studies of postural discomfort and recovery, to be reported more fully later (Barbonis 1979), were to develop a predictive model for the recovery from a given posture. Recovery was defined as the ability to maintain the posture for an equal period after the rest pause, subjects having first maintained the postures for the longest possible time.

In one study forty subjects were used, each of whom experienced ten trials. The trials were for various postures and rest pauses spread over several days. Recovery patterns were analysed statistically and it was demonstrated that recovery followed a common pattern regardless of posture. Subsequently the fitted equations devised for each posture and rest pause were combined to reach a single equation which explained over 95% of the variation about the mean. The equation was

$$T_2 = T_1^{\,0.8541} . e^{\frac{(-0.1523)}{I}}$$

where T_1 = First work time (mins)

T_2 = Second work time (mins)

I = Recovery interval (mins)

The ranges of values from which this formula was calculated were $1.03 < T_1 < 30.6$ mins, and $0.3 < I < 164.56$ mins.

Interesting points arise from the inspection of this formula. Firstly the major contribution to T_2 comes from T_1, I giving a small part only to the second work time value. Secondly the exponential term allows the maximum value for T_2 to be reached well before the end of the maximum rest pause (1200% of T_1), used in this study. A third point, evident if one value for I and various values for T_1 are introduced into the equation, is that postures maintainable only for a short period may be repeated for almost the same length of time. Long held postures, (which might be seen as less severe,) cannot be repeated for as long a time even after an inordinate rest period.

This point is illustrated in the graph of Figure 1, drawn from the above formula. The behaviour of the graph is what would be anticipated considering the anaerobic metabolism in a muscle which is exerting isometric force, as discussed earlier.

Subsequent study with 18 subjects examined the repeatability of sub-maximal postures. The range of work durations studied was 25% or 50% of maximum duration, with rest intervals of 25%, 50% or 75% of the particular sub-maximal work duration being experienced. Thus, if a maximum duration in a posture was 8 mins., 50% sub maximal work and 25% rest would be a 4 min. work period with 1 min. rest.

The data from this study were combined to give the following model:

$T = 1.172\ t \times i$ where T = total duration of work & rest intervals (mins)
t = sub-maximal work duration (mins)
i = rest interval (mins)

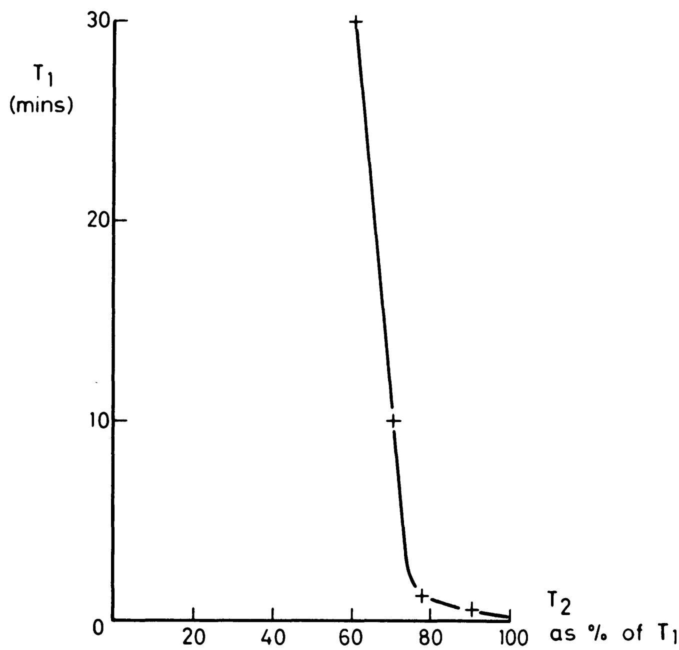
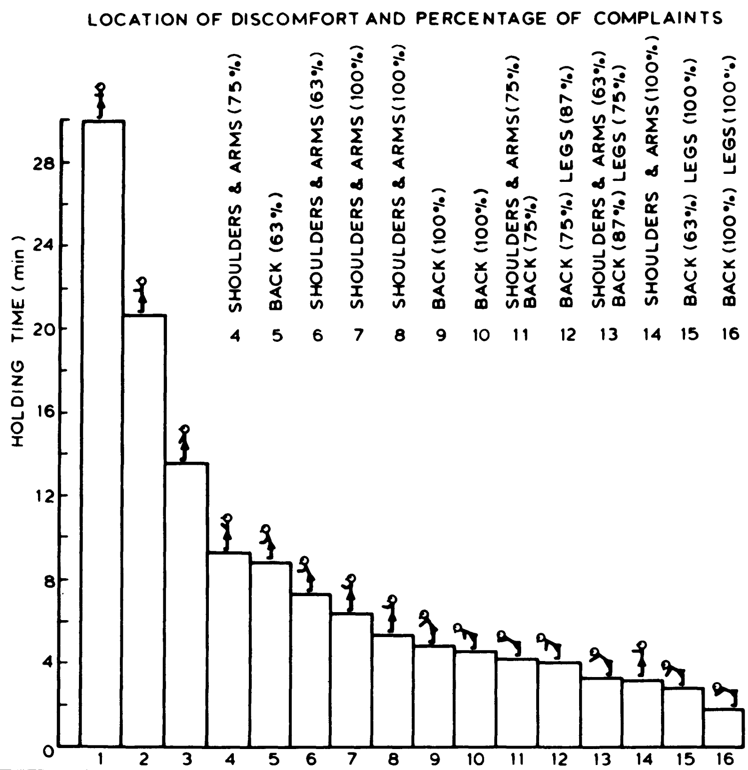


Fig.1. Graph of $T_2 = T_1^{0.854}\ e^{\frac{-0.152}{1}}$ for I = $1200\% T_1$
Developed from experiments with forward bending posture

This equation explained some 50% of the variation about the mean in the study. When the contribution of t on its own was evaluated, it represented 42% of the total variation, showing once again that the length of the first work period is dominant in defining the total time for which the posture can be maintained.

The diagram of holding times for the forward bend posture, Figure 2, (from Corlett and Manenica 1980) demonstrated how a small increase in static muscle loading lead to a rapid decline in holding time. Rohmert proposed that 15% of mean voluntary contraction permitted an indefinite holding time. Our own studies predicate no more than 8%, and a definition of "indefinite" which restricts it to about 30 minutes.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
WORKING HEIGHT (%)	75	75	50	100	50	75	100	100	50	25	75	25	50	100	25	25
WORKING DISTANCE (%)	25	50	25	25	50	75	50	75	75	25	100	50	100	100	75	100

Figure 2.

A final point on the subjective judgement of posture. As remarked earlier, a posture with low maximum holding time may be repeated many times without either significant pain or decrease in its performance time, (there may be other criteria which are overriding but this is not necessarily so). Yet an apparently modest posture, which may initially be held for much longer, could be difficult to repeat more than once or twice during a working day. Such a comparison emphasises the need for data as well as the difficulties of using only judgement to define criteria concerning working posture.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the work of Dr.P.A. Barbonis, who derived the formulae given above whilst a research student at Birmingham University.

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ANTHROPOMETRIC AND BIOMECHANICAL CONSIDERATIONS IN GOVERNMENT REGULATIONS

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INTRODUCTION

The purpose of this paper is to provide an overview of the application of anthropometric and biomechanical data in promulgating government regulations for the protection of worker safety and health. The Occupational Safety and Health Administration (OSHA) is the Agency established by Congress in 1970 to protect worker health and safety through a variety of measures, including:

1. The promulgation and enforcement of mandatory standards to abate workplace hazards;

2. Education of workers to recognize hazards and obtain abatement through training and workplace redesign and;

3. Information and education programs for employers to obtain voluntary compliance with regulations and an enlightened attitude toward safety and health in the workplace.

DEFICIENCIES IN CURRENT STANDARDS

The standards OSHA currently enforces were derived almost wholly from nationally recognized consensus standards which were adopted without substantive review soon after the OSHAct was passed in 1970. Among other deficiencies, there was little or no consideration and/or documentation of the anthropometry and biomechanics upon which the standards were to be based. Therefore, there are often detailed requirements in current standards for the design of workplaces and equipment which have no known documentation of the anthropometric and biomechanical considerations which support the standard.

OSHA is currently conducting a thorough review of the standards originally adopted and revising them as necessary in order to achieve a greater degree of performance orientation, and to simplify them as much as possible. This program has made it necessary to question the adequacy of current standards in light of biomechanical and anthropometric considerations which relate to each standard.

The remainder of this paper presents some of the major areas of the standards review and revision process where anthropometry and biomechanics are important considerations. It also describes some areas targeted for future standards development where similar considerations are important.

REVISION OF FALL PROTECTION STANDARDS: BIOMECHANICAL AND ANTHROPOMETRIC CONSIDERATIONS

One of the major areas of concern in OSHA standards enforcement is the prevention of injuries from falling because of the high percentage of all occupational injuries which involve this area, especially in the construction industry. Every workplace has some element of a falling hazard, whether falling onto a surface on which one is walking or to a lower surface. In order to develop acceptable requirements for these walking and working surfaces, OSHA obtained the assistance of university researchers familiar with anthropometric and biomechanical analysis and asked them to develop the necessary design criteria. The analyses involved a review of the available data bases and their application to the following specific problems:

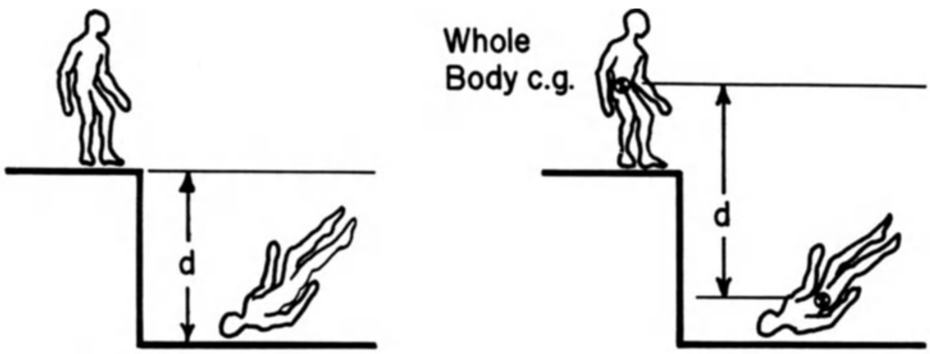
1. Stair design: tread depth and width, riser height and width; step-to-landing ratio; handrail height and shape, etc.

2. Ladder design: width; angle of inclination, rung spacing, rung size, clearance from structure for fixed ladders, spacing of rest platforms, design of safety cages, etc.

3. Scaffold design: clearance from structure, plank widths, guard rail height, spacing and material of construction, etc.

Chaffin, et al., (1978) and Ayoub and Bakken (1978) found that a significant amount of data was available which could be applied to the analyses being performed, and produced recommendations for standards dealing with the areas stated below. Several examples are presented in the following subsections.

Hazardous Fall Height. A major question in protecting workers from fall injuries has to do with the expected injury severity when falling from various heights. In a fall, head impact becomes the major concern, with resulting injury severity largely dependent upon the impact velocity. The velocity, in turn, depends on the height of the fall. If one assumes the worst case, as illustrated in Figure 1, with impact on a hard surface, moderate injury (i.e., temporary unconsciousness but no residual loss) could be expected in about 50% of falls from about three feet.



(a) platform fall height (b) c.g. to c.g. fall height

Figure 1: Fall height affects impact's velocity depending on body orientation with worst case shown (Chaffin, et al., 1978).

The expected severities of varied fall heights is shown in Figure 2. This figure is derived from head impact data collected in various biomechanical research as part of vehicle collision studies.

These types of data certainly justify why guardrails or other fall protection (e.g., floor markers) are necessary when working on platforms elevated more than even a couple feet.

Guardrail Protection. Once it is decided to physically restrain a person from falling from a platform, the design of a guarding system becomes important. Falls are known to occur from scaffolds by overturning the top guardrail or slipping underneath the rail. Protection will depend on the guarding configuration, which

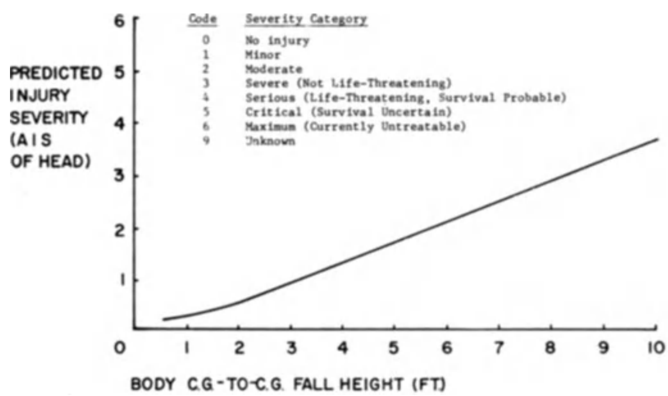


Figure 2: Expected head impact injury from falls of varying heights (Chaffin, et al., 1978).

must reflect normal worker anthropometry. The height of the top rail should be at or above the whole-body mass center-of-gravity for most workers. To restrict a person from slipping under the top rail a combination of a midrail, careful placement of cross-braces and/or a high toe board can be used. Figure 3 depicts one such system.

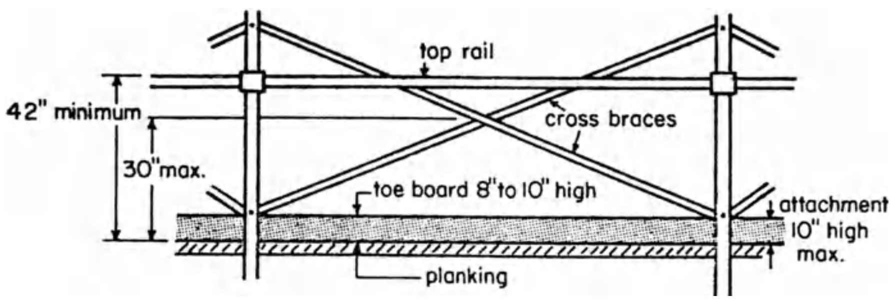


Figure 3: Cross-braces used as part of effective fall prevention system (Chaffin and Stobbe, 1979).

Floor Openings and Scaffold-to-Wall Distances. Clearly the amount and shape of openings through which a person can fall has not been weel researched, but clearly anthropometry must be the basis for such study and specification. Tentative findings indicate that a small adult could slip through a long narrow opening of as little as 9 inches wide. It is hoped that more information of this type will be gathered soon, as the exposure of workers is large.

Stair Handrails. Another type of fall hazard exists on stairs, particularly when descending. Clearly the shape and size of a railing to allow a strong grasp in minimum time is necessary to prevent serious fall injuries on stairs. Figure 4 depicts several railing shapes. The rectangular design in C which does not easily allow a power grasp should not be permitted.

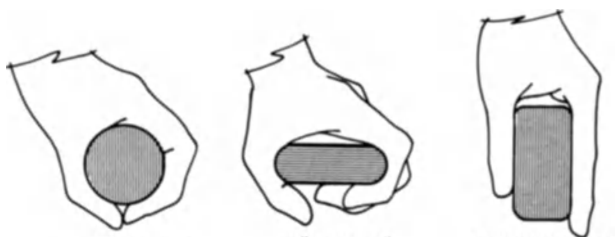


Figure 4: Typical grasping postures with different shaped railings (Chaffin, et al., 1978).

Conversely, the size of the railing must be carefully specified to permit a good power grasp by the majority of the population. One recommendation by Chaffin, et al., (1978) is that handrail circumference should be between 4.4 inches (11.2 cm) and 5.2 inches (13.2 cm), with corner radii greater than 0.25 inches (1.24 cm). Similarly, the height of the handrail above the leading edge of a stair tread should be no lower than 30.5 inches (76.3 cm).

Ladder Related Hazards. The clearance of a fixed vertical ladder from the wall is important to provide adequate foot support, especially in long climbs. Once again both anthropometric and biomechanical data were consulted by Chaffin, et al., (1978 to develop the recommendation in Figure 5.

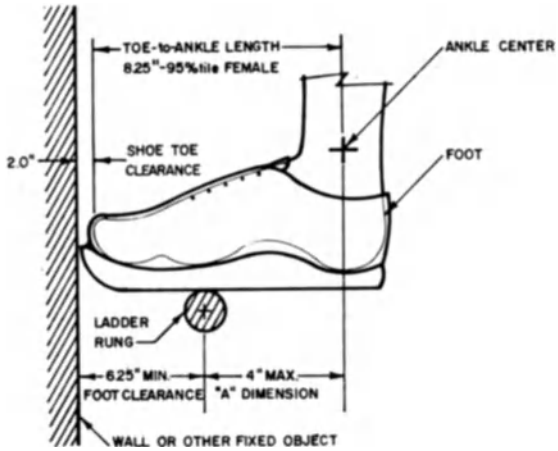


Figure 5: Rung clearance recommendation (Chaffin, et al., 1979).

Such data were also consulted to recommend the minimum width of such ladders, particularly when the climber may be exposed to high lateral wind loads. Foot anthropometry would dictate a ladder width of approximately 13 inches (37.5 cm), but if wind loadings are expected this width should be increased to assist the climber in stabilizing the body.

It was also found by Chaffin and Stobbe (1979) that the strength of ladder rungs needs to be carefully specified to consider a dynamic loading factor which can easily double the climber's weight. Thus, a 200 pound (880 N) climber can create dynamic forces on the ladder rungs in excess of 400 pounds (1760 N).

Another major area related to fall protection is the use of personal fall-safety equipment such as safety belts, lanyards and lifelines. A study performed by Steinberg (1977) for OSHA provided data for the design of such systems. Some of the biomechanical problems relate to the manner and rate of force application to the body where the user falls and reaches the end of the lanyard or lifeline.

FUTURE STANDARDS DEVELOPMENT: ANTHROPOMETRIC AND BIOMECHANICAL CONSIDERATIONS

OSHA is supported in Agency standards development activities by the National Institute for Occupational Safety and Health (NIOSH). NIOSH is charged with providing the research support necessary to developing effective standards for workplace hazards. In recent planning by the two Agencies, a program to deal with the chronic effects of trauma was developed. This area, somtimes called musculo-skeletal problems, has not been the subject of prior regulatory efforts, despite its significant contribution to injury incidence and lost work days. The following paragraphs deal with some of the major concerns and how anthropometry and biomechanics are involved in developing solutions to these problems.

LOW BACK INJURIES

Many of the papers presented during this symposium have addressed topics which must be considered in any regulatory approach to dealing with low-back injuries, i.e., anthropometric data bases, maximum voluntary exertion data and biomechanical models for lifting analysis. Although progress has been made by NIOSH in developing a research base for dealing with lifting hazards, OSHA has not received recommendations from NIOSH which could support general duty citations or serve as the basis for an initial phase of a rule-making dealing with the problem. It is anticipated that NIOSH will transmit to OSHA recommendations for dealing with some types of lifting hazards by mid-1980. One such recommendation which NIOSH is now actively considering is depicted in Figure 6. This pertains to occasional lifts in front of the body.

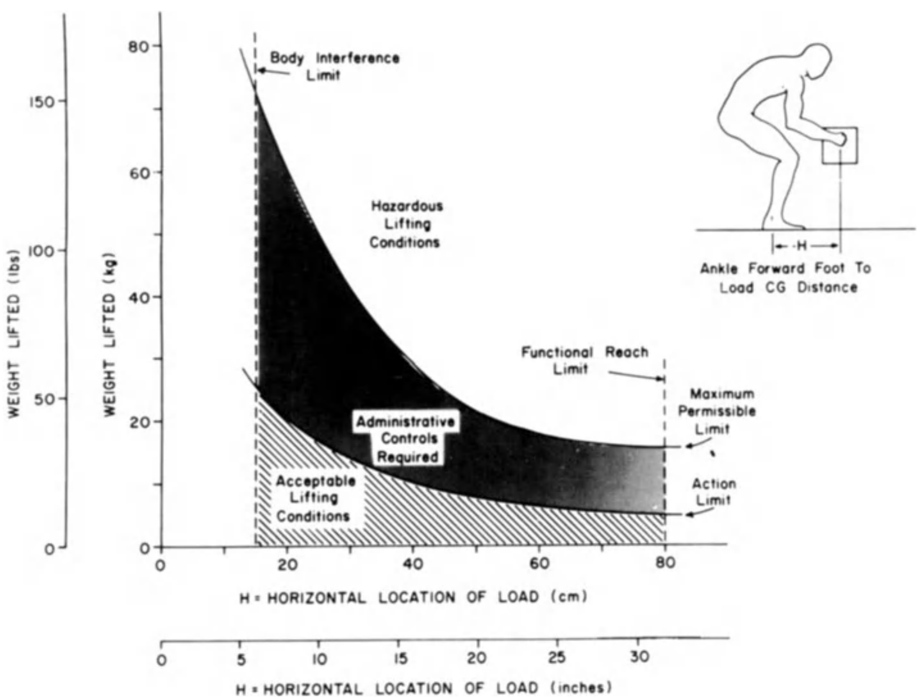


Figure 6: Tentative NIOSH lifting guideline for non-repetitive lifts.

OSHA will move after NIOSH has developed a final recommendation to propose a regulatory program for reducing lifting injuries. This program will undoubtedly focus a great deal of attention on the appropriate methodology for assessment of worker capability (or susceptibility) when lifting and appropriate criteria for designing lifting tasks.

INJURIES TO TENDONS AND NERVES

OSHA has already moved to cite some employers who have work tasks where carpal tunnel injuries frequently occur to workers (see Armstrong paper in this Proceedings). These general duty citations, some of which are being contested in the courts, will bring an awareness to industry of the nature of the problem, and to the courts the questions of epidemiology and biomechanical analysis which must be resolved. OSHA will be seeking further research data from NIOSH in order to consider rule-making to deal with this hazard.

It is anticipated that other injuries to the tendons and nerves produced by chronic trauma will be considered in a similar manner as carpal tunnel syndrome.

OSHA EDUCATIONAL PROGRAMS: ANTHROPOMETRIC AND BIOMECHANICAL CONSIDERATIONS

While not specifically related to OSHA regulatory activities, the New Directions Training Program initiated by OSHA in 1978 to train workers can be expected to significantly impact the areas of anthropometry and biomechanics. This program will result in large numbers of workers being trained to recognize poor workplace designs where anthropometric and biomechanical considerations have been neglected. Already, several labor unions have established educational programs focusing on these concerns, and more can be expected to follow over the next 3-5 years. These concerns will produce pressures for further OSHA regulations in this area and collective bargaining to secure improvements where regulatory action is not forthcoming.

SUMMARY

This paper has discussed major thrusts in the areas of anthropometry and biomechanics occurring in OSHA regulatory activities, as well as educational activities. While both areas now have a sound research base from which to grow, a sizable commitment of research funds will be necessary over the next decade to produce the research results needed for regulatory activities.

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EXTENDING THE STATE OF THE ART IN ANTHROPOMETRY AND BIOMECHANICS

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One of the most challenging assignments that can be given an individual is to put him down in a strange land and ask him to map it. The challenge is increased when one is asked to forecast that territory's future. I have been given both challenges by our program committee. Anthropometry and biomechanics are areas to which I am a recent immigrant, and a newcomer risks misperceiving strange and new terrain. Sometimes, however he is fortunate enough to notice patterns and trends overlooked by regular inhabitants. I hope that I can do the latter without being guilty of the former.

First, some comments on the present scene. In both anthropometry and biomechanics, I see prodigious activity in modeling, measurement and application being carried out by an astonishing group of people. My astonishment stems from the fact that such a large body of important research is being carried out by such a small number of people from a large number of different disciplines. Engineers, physicists, physicians, physiologists, anthropologists, and psychologists are all at work in a common area. What is even more remarkable is that they are collaborating with one another so effectively. Perhaps this unusual cross-fertilization helps explain the vigor and growth of both fields.

All is not entirely well, however. The diversity of disciplines represented in anthropometry and biomechanics means that the literature in these areas is widely scattered across many journals. Since this sprawling body of work is not covered by a single abstracting service, obtaining papers on a related topic is difficult and is a barrier to progress in both fields. Therefore, I would like to propose several remedies for this and some of the other problems that seem to characterize your system of communication and information.

First, I believe you need a single abstracting journal that systematically covers all of the related publications in both fields. Together with an on-line search system, it would make available bibliographic citations and abstracts of all core research available from one comprehensive data base. Although Ergonomics Abstracts is making a valiant attempt to perform this function, its coverage is still far from complete. I expect this is due to a lack of resources which might be increased with the expanded readership that a more comprehensive abstracting and indexing service might stimulate.

Second, I believe you need an annual review of current research and applications that would summarize and distill the most important advances in anthropometry and biomechanics. I am not aware of any such system of reviews in either anthropometry or biomechanics. While the University Press International series on biomechanics performs a valuable service in reporting the papers of international congresses of biomechanics, it does not perform the integrative and review function that is required to assess and evaluate the state of the art in biomechanics and anthropometry.

Third, I believe you need a centralized numerical data base, as well as a bibliographic data base. This data base would store static anthropometric measurements, measures of strength, measurements of the mechanical properties of human tissue, data on human injury and rupture derived from accident analyses, and dynamic human body response data derived from biodynamic tests. It would receive data from all laboratories working in the fields of anthropometry and biomechanics. Such a system of reference data would reduce the number of redundant measurements that otherwise will be made at great expense without it. As Von Gierke (1978) has pointed out, such a data base "would permit model parameters and inputs to be based on the same data and model outputs could be compared to the best and, above all, to all types of response data available."

Finally, I believe you need a one or two solid textbooks in each field that summarize the archival literature, place it in perspective, and describe basic theories, models, and measurement techniques. Improvements in your system of communication of this type represent the hallmarks of a mature discipline. You are at that stage of development at which you need these improvements.

Now let me turn to the matter of theory and measurement in anthropometry and biomechanics. Although the boundary between these overlapping fields is blurred, there are some major differences. In anthropometry there is a great emphasis on the reporting of measurements obtained from various population samples. Much less emphasis is given to measurement method and theory. You have not yet achieved consensus on the definition of the parameters to be measured or upon standard methods for measurement. This makes comparisons of similar measures obtained from different studies most difficult. If you had internationally accepted guidelines, your collective data base would have greater integrity and the separate studies on which it was based would each have greater generality. Such guidelines were proposed for anthropometry near the beginning of this century; to my knowledge no progress has been made in realizing them since then.

If you had standardized terms and procedures for defining and making your measurements on samples of different ages, you would stimulate longitudinal analyses and predictions of future trends in such parameters as body stature, weight, and segment length. This would help enrich theory, contribute to the science of physical anthropometry, and permit future systems to be planned around the geometry of tomorrow's user populations.

Compared with anthropometry, where I see measurement outpacing theory, the reverse seems to prevail in biomechanics. Here the problem is not so much one of needing more sophisticated theory and modeling but one of devising ways to make more and better measurements of the static and dynamic properties of the human body. A good illustration of this need for measurement comes from the extensive modeling now being done on the distribution of loading on the spinal system during automobile crashes and in manual materials handling. Here, optimization models need better validation based on more and better empirical measurement. Until the measurements are extended beyond longitudinal force loadings, the capability to predict injury will continue to be limited. Professor Ignazi has ably reviewed some of the new technologies - photography and lasers - that may be used to strengthen our measurement capability.

As Dr. King has so ably described at this symposium, the biomechanics literature contains many elegant mechanical models of the response of various parts of the body to external forces: of the head and neck, of the hands, wrist and arms, of the spine and of the feet and legs. Is it possible to integrate these models in a unified model of the whole human body? I would hope that such systems as the Articulated Total Body Model developed by CALSPAN and used in aerospace and crash injury research would provide a framework within which such a unified model would be constructed.

Although biomechanics and anthropometry have been somewhat separate fields of endeavor in the past, they are now beginning to merge at that point where a biomechanical model is capable of incorporating anthropometric measurements from a given user population of interest. The U.S. Air Force Articulated Body Model, for example, is now capable of receiving anthropometric measurements for a given operator: a 95th percentile male, a 5th percentile female or whatever. Thus, the body geometry represented in COMBIMAN can now be integrated with body mechanics. I trust that this integration will continue to the point where the data of both fields will be capable of representation in a single unified model for application to problems of internal biomechanics as well as workplace design. SAMMY, the Mottingham model, which Professor Ignazi has described, represents a point of departure for Mottingham further integration of this type.

One of the underdeveloped areas of biomechanics has to do with the theory of the control of biomechanical systems. Modeling and validation research on this topic are represented by the work of J. F. Soechting and his colleagues (1971). These investigators developed a three component model embodying the mechanics of a skeletal joint, a mechanical model of muscle, and a neural feedback model that relates the control variable to the kinematic variables to close the loop. The interesting aspect of this line of research is the attempt that is being made to specify the nature of the control system governing a localized biomechanical subsystem. Further research along the same line is clearly in order if the goal of arriving at a unified model is to be achieved.

To a psychologist research of the type being done by Soechting on the mechanisms underlying biomechanical control is of particular interest because it raises important questions about the effects of the cognitive system on control. At the National Bureau of Standards, we have recently started a research program which I hope will illuminate more fully both the mechanical and the cognitive aspects associated with the active control of a product by an individual.

Our focus is on what we call the "loss of control" event. In such an event an operator, engaged in the control of a product (e.g., a chainsaw, cement drill, or bicycle), represents an active rather than a passive element. He inputs forces to the product in order to control its position or direction. A loss of control occurs when there is an unexpected release of energy that causes the operator to lose control. This may occur when the cutting chain of a chainsaw binds into wood stock, when a drill bit engages an inhomogeneity in concrete, or when a bicycle tire interacts with an obstacle in a pathway.

In some instances loss of control occurs very rapidly, sometimes within an interval less than the brief 100 to 200 msec. reaction time of the operator. In these cases control has been lost before the operator is able to detect and correct for the out-of-tolerance condition. In this case we believe the initial conditions under which the operator engages with the product are those that influence the outcome of the event. In other cases where loss control is preceeded by a warning signal to the operator the initial pattern of forces applied to the product may be altered in the attempt to regain control. By considering a number of such loss of control events one can construct a continuum of situations within which operator intervention may range from a passive response to the exogenous force created by the product to events of longer duration in which various levels or degrees of cognitive intervention may occur in order to regain control. Loss of control events that occur in intervals less than human reaction time may involve neural control activity limited to a segmental or at most a suprasegmental spinal path, while events that extend longer than human reaction time may invoke higher level nervous system control and call on adaptive programs that function to reassert control and avoid injury. The righting reflex of the cat may be an apt example of such an adaptive program.

The laboratory measurement and modeling of interactions of this type, where an operator is actively engaged in product control, present a research challenge that has important implications for cognitive science as well as biomechanics and practical application to problems of product safety. I hope to be able to report on the outcome of our research program at some future time.

Anthropometry and biomechanics have covered a great distance from the days of two-dimensional analysis and link models to the sophisticated, high technology based measurement methods and three-dimensional analytic models of today. I compliment you on your progress and hope to participate with you in further reviews of the state of the art and science of these important fields of study.

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