QUANTITATIVE MEASUREMENT OF HUMAN FACTORS FOR TASK AND WORKPLACE DESIGN

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INTRODUCTION

Clothing production stretches at least from Neolithic times (1) to the present (2) and has frequently played key roles in the lives of many nations and people along the way (3, 4, 5). Apparel production remains a large, essential, and labor-intensive segment of our industrial base but will probably culminate in almost completely automated processes supervised by a minimum staff, just as refineries and other flow processes are today. However, at this time and for the foreseeable future, human labor and skills will continue to play a major and essential role. While textile and apparel production workplaces are among the oldest and most studied aspects of industry, the fact that workplace systems engineering is on the agenda of this conference is evidence that improvements are still considered possible. Indeed, if the workplaces were optimum, it would be unique in the history of technology.

We are concerned with optimizing performance of a man/machine[1] unit (6). Further, it seems to me that in apparel manufacturing, the human is now being used primarily for tasks which, for any of a number of reasons, cannot yet be delegated to machines, i.e., repetitive, sometimes complex, but primarily mechanical tasks. If this is the case, then for analytical engineering and design, we must know the mechanical properties of the operator as well as the properties of the machines he is to be coordinated with. Further, we should know those properties sufficiently well to insure an analytical approach to the process of designing workplaces. The alternative is to use empiricism and cut-and-try which unfortunately are still the rule today in most workspace engineering, including the space program.

Workplace and work task engineering is progressing rapidly with new design tools available including a number of computer aided programs (7-12). Unfortunately, the elementary mechanical properties of the human operator is information that is usually not available to the engineer today. Conversely, technology has reached the point that we can make such measurements. The design of most complex man/machine interfaces--whether automobiles, spacesuits, or apparel production workspaces--can benefit from improved quantitative knowledge of man's mechanical properties and the use of this information in the design phase. The following describes some methods for more practical and complete characterization of man's mechanical aspects made possible by recent advances in instrumentation and computation. Application of such data is left to those with expertise in the field of apparel manufacturing since it differs greatly from problems we are familiar with, e.g., effects of "space" suits on human motion, equipment and workplaces for weightlessness, etc.

When one more effectively designs man into the man/machine unit, he is faced with a paradox. Man is not a machine--and never will be--and the purely human properties must be as carefully considered as the mechanical properties, if long-term efficiencies are to be realized. This must also be commented on.

MEASUREMENT OF SOME MECHANICAL PROPERTIES OF MAN

To allow quantitative design and analysis of any process, one must know the characteristics of the various units or elements to be used. While the size, start/stop times, speeds, and torques of say a motor may be known to any reasonable degree of accuracy, there are a host of problems with obtaining equivalent data on the human body. First, man comes in an amazing variety of sizes and shapes (see Fig. 1). Not only may they vary from a height of 188 cm in a 95th percentile American male to a 152 cm 5th percentile in a Vietnamese male, but a female of 50th percentile height may have a reach of 66 to 85 cm with similar variation in other body components (13).

The situation gets worse when one considers the dynamic properties or motion. The human arm, for example, is capable of an infinite variety of forces and motions--within circumscribed limits. There is as much individual variation in ranges of

[1]Machine as used here is meant to include not only the active devices but the entire mechanical interface including passive elements such as racks, tables, etc.

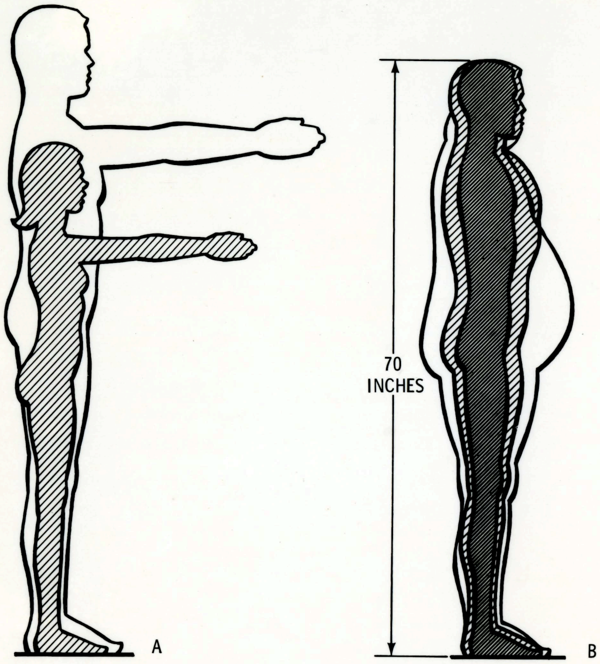

Figure 1. A) Side views of a 97th percentile U.S. male and a 3rd percentile U.S. female are shown for comparison. B) Superimposed side views of a median U.S. male ectomorph, mesomorph, and endomorph. After Human Scale™ Manual, Henry Dreyfuss and Associates, 1974.

motion as in the fixed characteristics and even more variation in strength.

Further, there is the fatigue/motivation[2] factor which can completely modify all motions and efforts.

Anthropometry

Anthropometry is the traditional science of measurement of human size and shape. This usually includes length and girth of the major body parts in various positions, sometimes their mass, and the maximum angles through which body elements move. After one deciphers the occasionally obtuse terminology and methodology, most of the static data required for design is available, e.g., seat heights required, table levels, standing clearances, etc. However, it is usually available for only a few and limited populations. A major error in designing man/machine interfaces is to use a single mean number often from an unknown population. An even more common and more serious error is for the engineer to design the layout around his own size and shape or that of someone easily available to him. Data consistent with the potential operator population must be used, as well as allowing for their variation. Forcing all operators to fit a single "average" design in size almost invariably results in compromised efficiency of the majority of man/machine units, hence reasonable adjustments must be part of a proper design.

Rather than discuss anthropometry and its applications here, I would refer those interested to what I believe is the most comprehensive single source to date--NASA's Anthropometric Source Book for Designers[3]: Volume 1, Anthropometry, covers the measurements, their derivation, and use; Volume 2, A Handbook of Anthropometric Data, is a compilation of worldwide anthropometric data; and Volume 3, Annotated Bibliography of Anthropometry, is a reference listing and abstract of 264 major publications of the world's anthropometric literature.

Kinesiology and Kinesimetry

Kinesiology and kinesimetry are the study and measurement of human motion respectively. Unfortunately, the literature on kinesimetry is as obscure as the name. Measurement of animal/human motion is at best difficult and while there have been many (15-32) studies since the Webers' work in 1836 (14) most of the methods available have not been practical for widespread application primarily because of the time required for manual data reduction and analysis.

If all the extremes a body segment can reach are measured (Fig. 2A), they will form an envelope which encloses a volume, all elements of which can be reached by the segment. This *maximum reach envelope* (Fig. 2B)[4] now characterizes one aspect of an individual's capacity for motion just as an individual's size is characterized by the more common static measurements of anthropometry, such as statue, and barring injury or slow changes with aging it is a fixed characteristic of the individual. This envelope varies significantly from individual to individual depending upon

[2]Motivation is not discussed here but left to experts in the field. Have no doubt that it is a major if not dominating factor in the performance of any man/machine unit.
[3]It is available as NASA-RP-1024, 1978, from NTIS, 5285 Port Royal Road, Springfield, VA 22161.
[4]It is emphasized that this reach concept applies to any point on the body; e.g., to a finger, toe, elbow, or whatever.

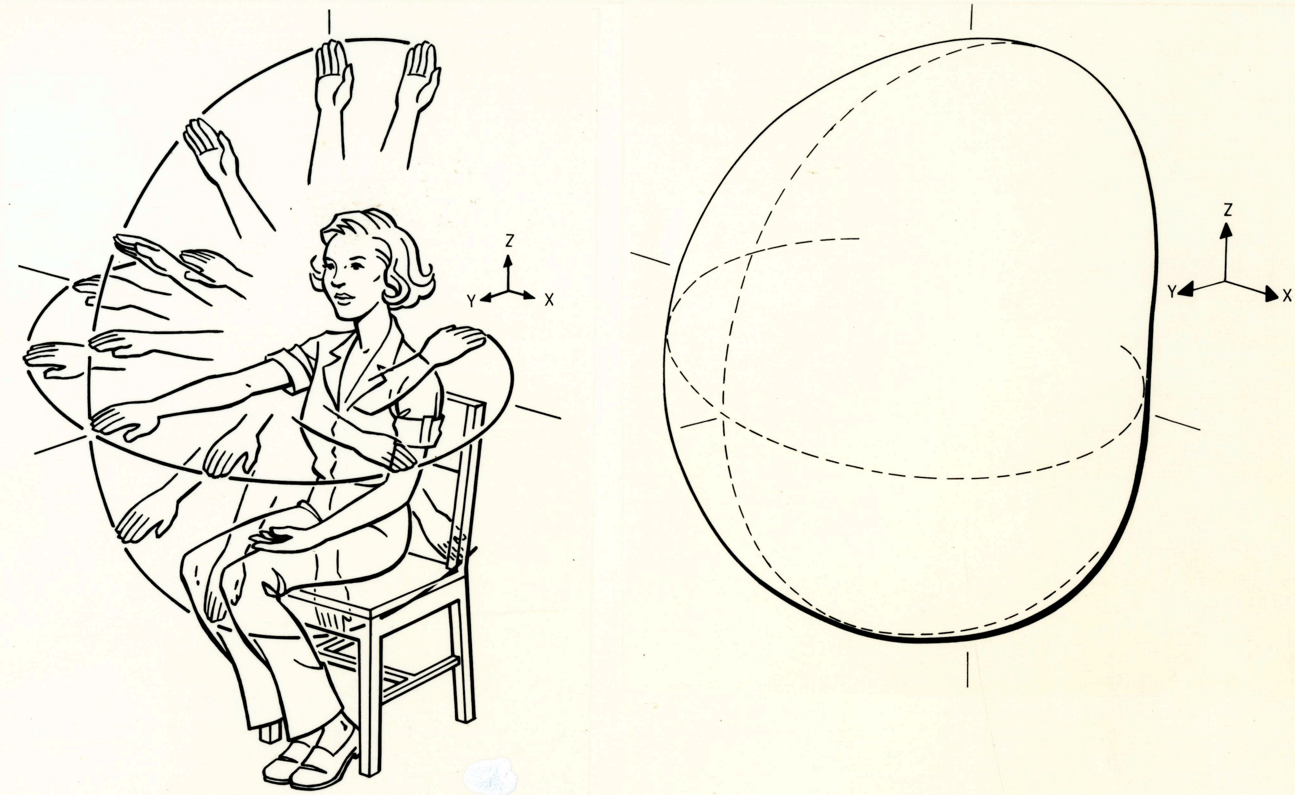

Figure 2A. A subject in a fixed position is anatomically limited to reaching points within a definite space. The extreme limits of this space may be measured and stored in terms of an envelope or closed sheet referenced to a fixed point on the subject as in B.

size, shape, and many other factors. An important point is that it is the product of a myriad of factors, i.e., it summarizes in a mathematical description an aspect of the resultant action of coupled, complex systems. However, it describes only one aspect of motion, displacement of a point, and must be further characterized. Simply being able to touch a point does not insure that useful force, useful in magnitude and direction, can be applied. Further, there are areas which can be reached only with difficulty and rapid fatigue while there are other preferred zones in which a variety of factors including vision tend toward the optimum. We call the limits of this preferred zone *functional reach envelope* while the difficult areas are called *restricted reach envelopes* contained within the *maximum reach envelope*. Other characteristics of motion within the envelopes will be described.

This series of reach envelopes measured in an appropriate population may be used to aid design in a number of ways. The simplest is to obtain the intersections of a plane with the various envelopes, say at a nominal working level (Fig. 3). The resulting boundaries would then represent the areas on a table or other surface corresponding to the maximum, functional, and restricted zones. The layout may be arranged accordingly.

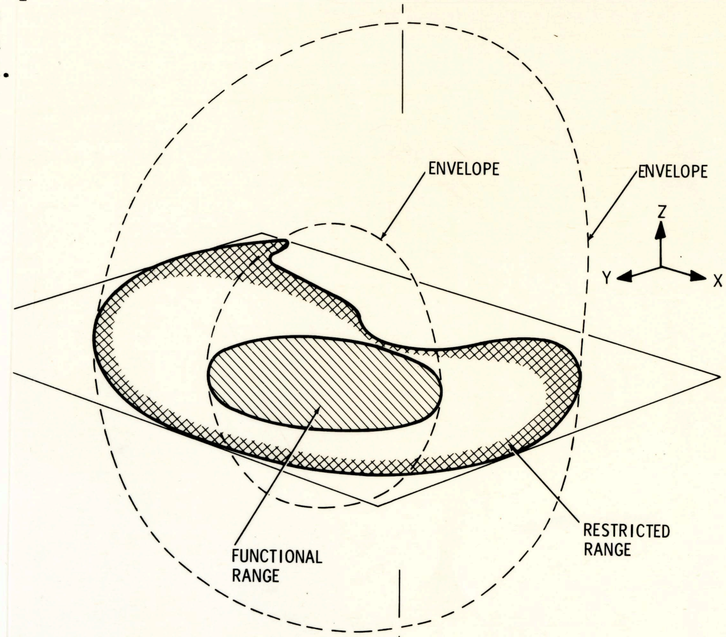

Figure 3. Intersection of a plane with the reach envelopes to produce areas enclosed by the limits of "*maximum*, *functional*, and *restricted reach*" at a given height.

Multiple planes may be taken in any direction to further define optimum work zones. Computer programs are available which would allow two- or three-dimensional interactions of proposed designs with such reach envelopes (Fig. 4) (7-12). Some of the more advanced programs allow interaction of the design and operator such that one can have a simulated "mockup" and "subject" on the drawing board (Fig. 4). However, envelopes are only a first-order representation of the human capacity for motion.

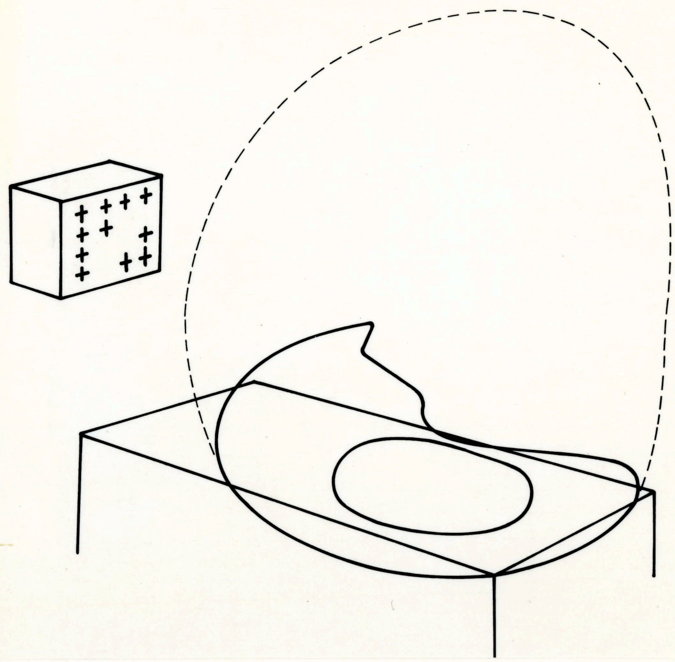

Figure 4. Envelopes of human motion may be computer interfaced with proposed designs and the resulting displays shown for analytical or interactive design.

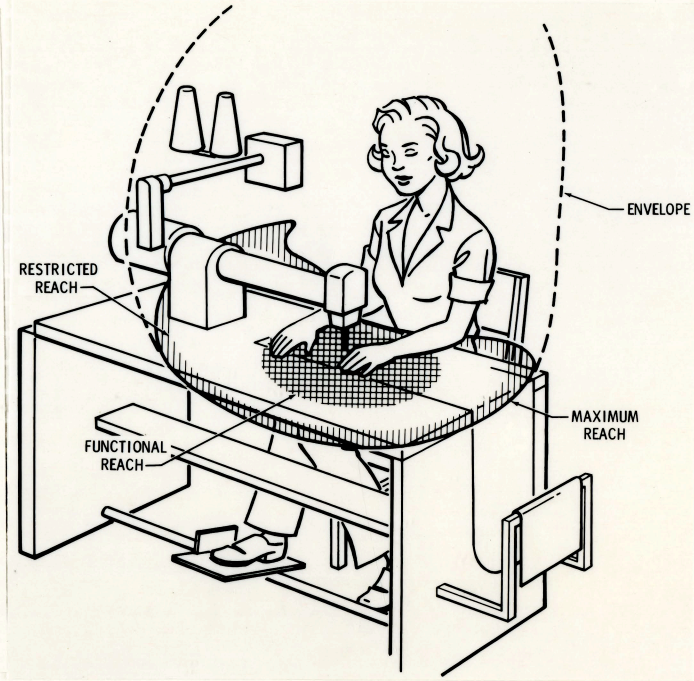

Figure 5. Final product of any design process is the working item. Inherent in such a work station used by an appropriate worker population are the limits described by the envelopes.

For example, these envelopes are obtained in a free and unobstructed field, and the moment that an object is placed within the actual envelope, reach areas will be distorted, particularly those behind the obstruction (Fig. 5).

These are obviously many other considerations as regard this envelope concept and its use, including:

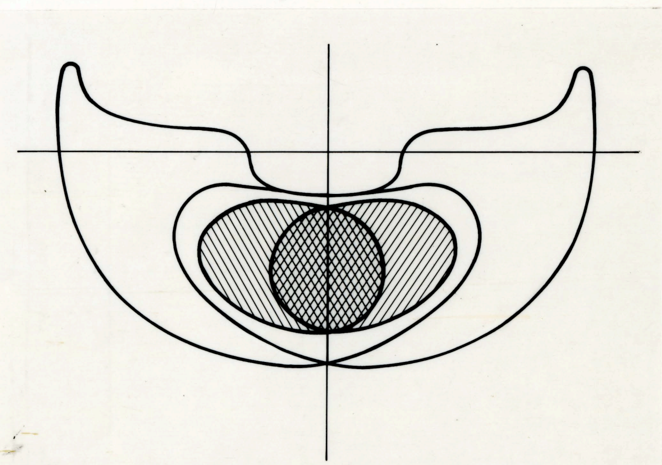

Figure 6. Shown here are the reach areas for one height level of right and left hands. Overlap of the functional areas (single cross hatch) defines the optimum area for bimanual tasks (double cross hatch).

The fact of being able to touch a a mechanism does not insure that it can be operated or actuated since ability of the fingers to move in a given direction will vary throughout the envelope, e.g., it is much easier for the right hand to manipulate items located in front, below, and to the left of it than to the right of it and vice versa for the left hand.

For tasks that are bimanual, the functional reach area is reduced even further, consisting of the volumes where the envelopes of right and left handed functional reach overlap (Fig. 6).

Ability to exert force (strength) especially in various directions, varies throughout the reach envelope. This is of more concern in space flight operations, where considerable forces are often needed, than in actuation of mechanized devices as used here. Our approach to the problem of trying to measure an essentially infinite number of forces and directions is to make a

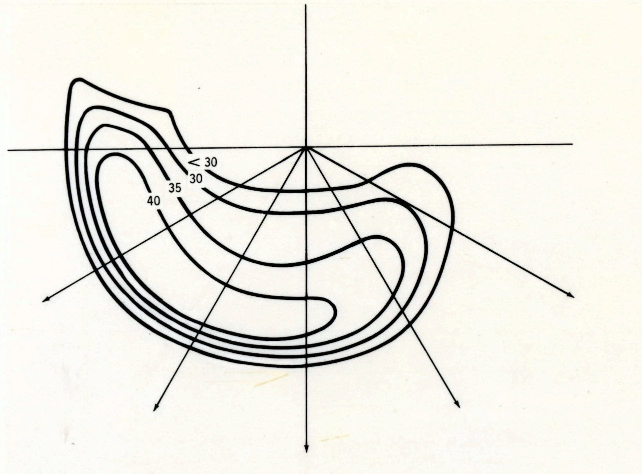

Figure 7. A plane through strength envelopes measured by isokinetic ergometry along several principal excentric axes. Iso-contours for maximum force levels available have been extrapolated from these discrete measurements.

sufficient number of continuous force determinations along axes of interest to allow iso-contours of force to be established. This is shown in Fig. 7 for a single plane for forces away from the body. In three dimensions this becomes a series of shells or envelopes which represent volumes within which forces of between certain limits can be exerted. This series of envelopes can be mathematically expressed, stored on tape or other media, and displayed or interfaced as the reach envelope was.

Of more concern to the design of workspaces and tasks in apparel production (I have assumed the workspace and tasks are inseparable components of the production process) are areas of maximum dexterity. While the subject of dexterity has not been directly investigated, one would assume that preferred regions of dexterity exist. If so, the same display/interface techniques could be used. An analagous display mode for measured velocity and acceleration has been considered and will be described. Again, the scheme of envelopes or shells was used with the same procedures for application.

Fatigue

Fatigue is a mechanical problem unique with animal motion. Figure 8 shows a series of ten maximum effort isokinetic strength measurements which illustrate the decrease in force with fatigue repetitions. For heavy work, repetitions may be continued at 75 percent to 80 percent of maximum loads without undue fatigue in trained individuals but considerably lower levels are required for continuous work in the usual worker.

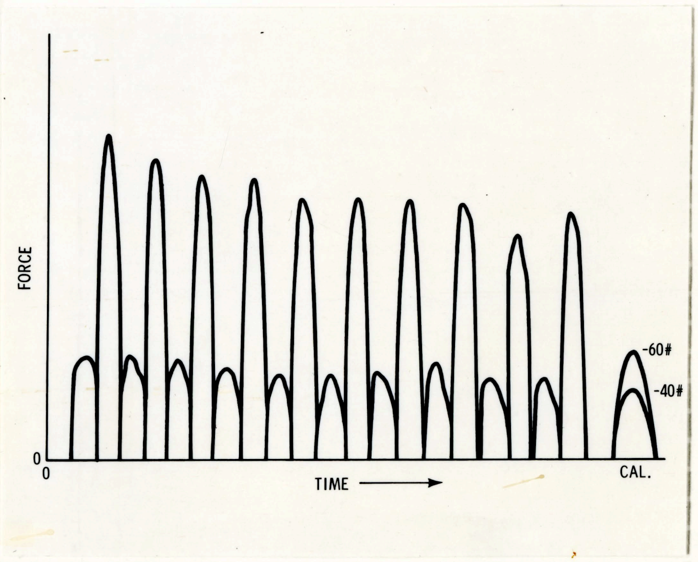

Figure 8. A plot of ten maximum effort isokinetic force (strength) curves from the leg are plotted for hip/knee flexion and extension. A fatigue decrement in force is shown N.B. the apparent increase on the tenth repetition is common when the subject makes a supra-maximal effort on the last repetition.

Fatigue should be redefined and measured in a broader context for the finer tasks such as those in apparel manufacturing. Rather than use a decrement in force, reduction in speed of operation and increased error rate might be used as objective measures. Whatever reliable measure is used, it will be a function of body/limb position and support. Also, it will have individual aspects and, again, I suspect it will be profitable to "map" the various areas in the reach envelope as to fatigue resistance. This is an area which remains to be explored.

All of the foregoing has been a rather general system that should allow a designer to set limits on the location of tasks to be performed. It says little about the detailed nature of the tasks, location and modes of action required, pathways between tasks, etc., the items which determine speeds of operation and fatigue. It is now possible to follow individual points, say a worker's finger (Fig. 9), indirectly, continuously, and automatically record, analyze, and display the path of velocities and accelerations involved. Such studies should be of considerable value in fine adjustments to a workplace or task.

DATA COLLECTION AND PROCESSING

Recent availability of computers with increased speed and storage capacity now make it practical to obtain more comprehensive data on human motion in significant samples of the population. The following is an example from our own work in this area (32).

To be useful to the engineer and designer, human motion must be measured in accepted physical quantities, e.g., position, velocity, and acceleration. The quantities, combined with force, characterize any motion. A system for notation including reference system is easily formulated from elementary physical mechanics. Amar and others have discussed application of physics to human motion (22).

A variety of instruments are available today which will track one or more points in space. The Selspot IR system (31) is probably the best known and is capable of tracking up to 50 points at sample rates of hundreds per second. For economic reasons, we chose inexpensive TV cameras which viewed the subject with pulsed lights attached to the points under study (Fig. 10). A video

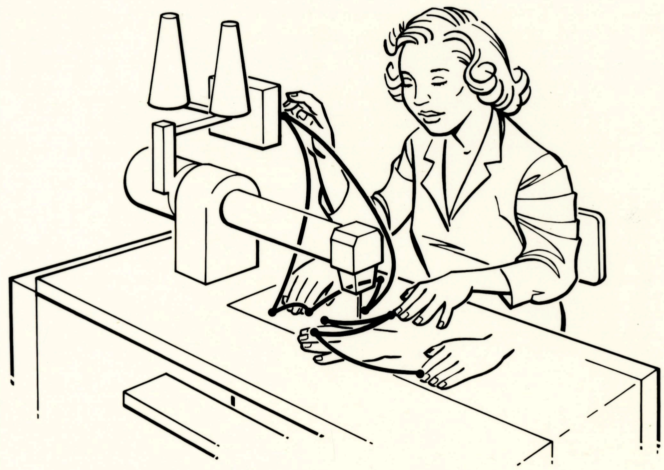

Figure 9. Hand trajectories for repeated or complex tasks may be recorded by the kinesimeter in Figure 10 for detailed studies of individual tasks including velocities and accelerations developed.

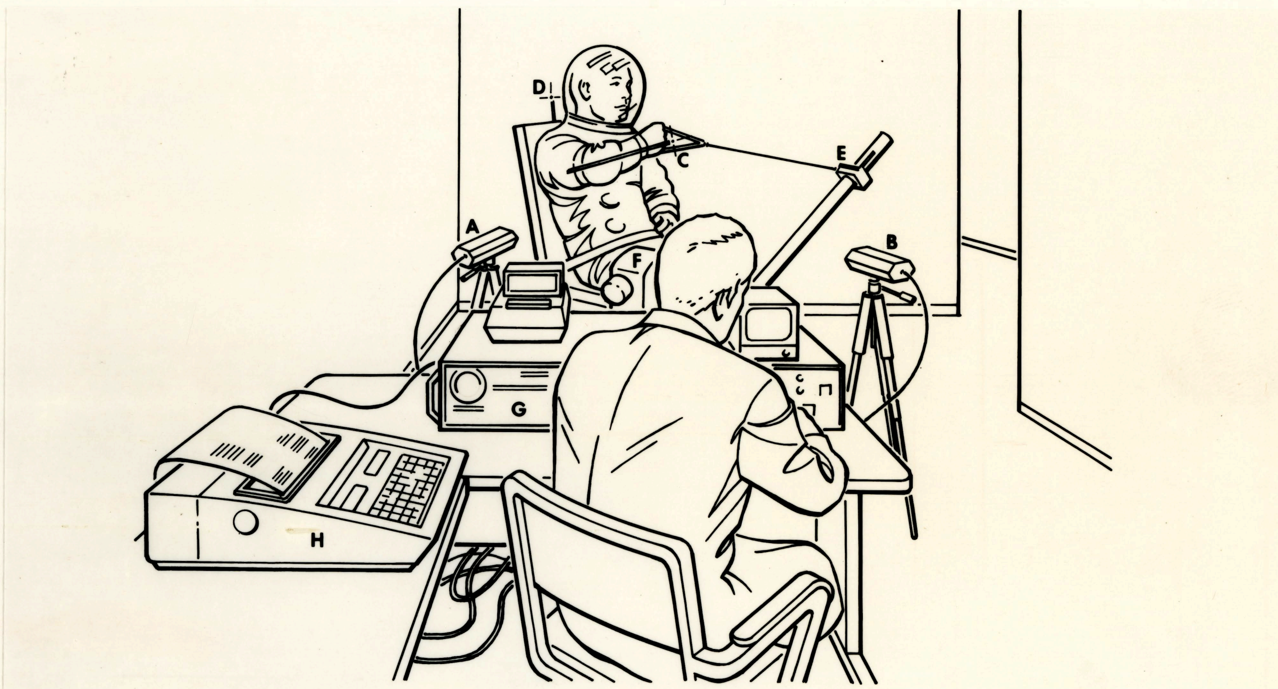

Figure 10. Tracing of photograph of an improved kinesmetric system designed by the author. Orthogonal cameras, AB, continuously record the motion of a point, C, on the right arm with reference to a fixed point, D. Strength envelopes are being generated here by the cable pulley arrangement, E, connected to an isokinetic ergometer, F. A microprocessor controller processing unit, G, converts and stores the data on magnetic tape. A data terminal, H, and video monitor complete the instrumentation. Reach and trajectory data may be gathered anywhere the TV cameras can be set up.

detector determines position of the light in the video raster, encodes it, and sends it to a computer which uses the data from two such cameras at right angles to determine the location in space. This is repeated 20 times per second. This equipment used a memory which allowed direct collection and storage of 6,000 points in 5 minutes. By having the individual make repeated sweeps of the hand along all regions around and over the body (Fig. 1), a maximum reach envelope may be derived by connecting the extreme points with a continuous mathematical sheet or envelope by a computer program. Any segment motion of the body (leg, torso, or finger, etc.), may be examined in the same fashion. An anatomically fixed reference point must be established and maintained. This maximum reach envelope may now be stored on disc or tape and is a measure of all the points that the individual can reach referenced to the given point chosen. The functional reach envelope is derived by simply having the subject make repetitive movements within the region which he feels to be comfortable for prolonged work. An envelope is derived for this region just as in the maximum reach case. Functional reach envelopes have proven to be a consistent measure of optimum location for repetitive manual tasks both single- and two-handed. A third region can be generated which represents areas which can be reached with difficulty by having the subject make a maximum reach envelope and then sweeping through the areas which do not cause undue strain. The difference in these two envelopes define the restricted reach volumes.

Once time and position in space are accurately determined, both velocity and acceleration may be derived from successive determinations of position. While camera limitations restricted our studies to slow motions, appropriate systems can make successive samples in microseconds. An alternative is to use miniature accelerometers on the point under study. By having the subject make a series of random maximum effort start/stop motions in all directions and of all distances throughout the regions of interest, a computer program can give then derive and plot positive and negative accelerations and velocities for various directions throughout the region of study. Again, these may be plotted in the envelope format. Strength is measured in this case by an isokinetic ergometer (33) and cable arrangement which allows continuous measurement of maximum forces along a series of selected axes, at a variety of constant selected speeds.

A much simpler application for this system is the study of a complex work task in which the trajectory of one or more points is recorded continuously as regards location, velocity, and acceleration. Figure 9 shows a potential application.

This is not a unique methodology (31), and various photographic (18) and other schemes have been available for such analysis (26, 27). What is different here is the use of computer and storage systems which allow rapid automatic three-dimensional format which can be put on magnetic disc or tape for a permanent record to be used again and again for studies. A single study now requires minutes versus hours of preparation and days of analysis.

The example shown was concerned with large motions, but by appropriate lens and scaling, it may be used for larger or smaller scales. Obviously, it may also be used for any mechanical motion such as in robotics or human operated manipulators or equipment.

ANALYSIS AND USE OF DATA

A variety of software programs may be used to correlate, analyze, and display the data, including generation of the envelopes and interfacing them with projected designs depending upon the user's requirements.

Simple plots of displacement with velocities and accelerations may be made of single trajectories or any portion of them. Portions of the reach envelope may be studied semi-manually by programming the computer to plot all points through which the hand passed as it swept through the reach envelope, and the extremes of these points approximated. Approximate envelopes may be generated by having a computer connect the extreme points with straight lines (12). For more accuracy, a software program can connect the extreme points by segments of curved sheets. In either case, the coordinates of these envelopes are stored and may be used for the interactions described previously. Several programs (8-12) exist for interaction, recording, and display of the envelopes with machine designs.

We have used this system to collect reach and strength data on space-suited and unsuited astronauts on earth to allow improved designs of suits, working accessories, such as restraints and tools, and extravehicular tasks. The existing system has nominal working errors of 1 cm at working distances of several meters with correspondingly smaller errors for close-up studies.

The equipment is not available as a system but a group with good computer facilities and reasonable hardware support can assemble a system capable of tracking/reach analysis. Complexity and cost will be a function of the requirements and especially of the software programs and displays. The prototype described was assembled by a contractor for approximately $50,000 with a rented computer and government ergometer.

Any discussion of measurement of human motion would be incomplete without mention of an alternative approach--modelling of the mechanical properties of the human (34, 35, 36). It was only when large capacity computers became available that such modelling could be realistically tried (7-12). Two of the best known programs are the USAF COMBIMAN and USN/Boeing CAR. Static body characteristics are entered into these mathematical models which then reproduce various aspects of human motion with varying degrees of fidelity. They are expensive and require extensive programs and machine capacity. My own feeling is that they will reliably reproduce detailed human motion from static measurements at about the same time that robotics replace most workers in the workplaces. Until then I can directly obtain "real" human data at a fraction of the cost.

LONG-TERM MAN/MACHINE INTERFACES

The preceding discussion was aimed at short-term aspects of man/machine interfaces or sub-routines if you will. Both humans and machines have operating limits which must be observed if costly breakdowns are to be avoided. Unfortunately, humans have an array of sensitive areas which can lead to breakdowns corresponding to their greater ability and complexity as compared to the machine. First of these is the emotional/psychological area which I will leave to the appropriate experts after a brief comment. Workspace/task design can have tremendous impact in this area. My earliest medical experiences were with patients in the piedmont mill towns of North Carolina, and the psychiatric toll especially among the experienced workers at tightly scheduled repetitive tasks was high. Such illnesses are expensive--at the very least, it amounts to replacement costs for skilled workers and often results in heavy drains on company or union medical funds. At this point, someone may be asking what business of a design engineer is this? If production efficiencies are realistically accounted, they will include <u>all</u> workplace related labor costs, from hiring or rehiring workers to illnesses and even injury payments--if they are workplace related.

While the highest short-term efficiencies would be obtained by having the operator in a fixed position, properly supported, with hands in the functional reach envelope, the human body cannot work in such a position for continued periods without degeneration. One of the things that we learned in weightless space flights is that unless body functions are used, stressed, they degenerate--not immediately but very surely.

Thus while maximum efficiency demands that repetitive tasks be done within the functional envelopes of performance (reach, strength, etc.) one must also move into the more stressful zones to avoid short-term fatigue and long-term degeneration of joints, connective tissues and muscles. The most efficient way of achieving this is to design the tasks and work spaces such that the worker moves arms, legs, and trunks periodically in some meaningful task, say periodic reaching into other areas with the arms and occasional large movements requiring walking, carrying, etc.

The legs' venous system is especially fragile, particularly in many women of child-bearing age or those with varicosities or other damage. Any prolonged standing tasks should be frequently interspersed with five or six steps of walking with occasional brief sitting. In walking, blood pooled in the legs by hydrostatic pressure is very efficiently returned to the heart by a muscle pumping action, and the pressures are sharply reduced. Sitting also requires occasional but less frequent walking for the same reasons. If such movements cannot be designed into the work tasks, then sham tasks should be used to achieve these goals. Failure to observe such care of legs will result in edema, damaged venous valves, and varicosities in a percentage of workers, and a smaller percentage will be more subject to thrombophlebitis with the potential for still more serious complications. A secondary benefit of exercise of large muscle groups is temporary increases in cardiac output with improved cerebral blood flow and increased alertness. The time constants which are involved here are too short to allow breaks and non-working periods to relieve them.

A region to avoid is any task which requires sharp bending of the back with legs straight, with or without significant lifted load, for back problems are almost as prevalent and expensive as psychiatric ones. There are other areas to be considered in addition to these examples, and details of the tasks should be coordinated with an occupational medicine specialist with experience in the area. These very general comments could be summed up by saying that any continued stress of the body should be periodically relieved and major portions which are unused must be stressed.

SUMMARY

The comments here obviously cannot be used per se as a plan for improved integration of workers into a man/machine unit or improved workspaces. It is a cursory description of system and measurement method for practically obtaining presently unavailable data on individual workers' mechanical aspects. This and a number of other isolated examples portend what will become available to the designer in the future. While the technology is available today, its application will depend upon the perceived needs of the engineers, designers, and others. We, like numerous others past and present, feel that more analytical incorporation of the human operator into industrial man/machine interfaces will not only make production more efficient but benefit both managers and operators as well.

The use of derived human data as advocated here cannot replace other aspects of the design process, only augment them. While the mockup/trial phase should be reduced by the means described, actual testing of the designs will remain an essential feature of any good design process. No doubt that many empirically developed procedures have been earned by experience which will simplify design procedure. The final proof of the design will be its overall performance in actual working conditions.

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