INTERFACIAL COUPLINGS FOR MAN-MACHINE SYSTEMS

A REVIEW OF THE LITERATURE ON UPPER-EXTREMITY MOTION EFFECTIVENESS TO JULY 1968 [a,b,c]

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ABSTRACT

Today, it is possible to build a complete externally powered prosthetic arm; however, one of the major obstacles to this undertaking is control of the arm. Two of the ways to lessen the problem of control would be to permanently combine or link some of the joint motions, or to eliminate some of the degrees of freedom of some of the joints. The only study to determine whether joint motions can be combined or eliminated, indicates that these avenues of prosthetic/orthotic simplification are not practical except in the case of a design for a single function (for example: feeding). Presently, however, there are several programs to further investigate the coupling of joint motions.

INTRODUCTION

One of the largest problem areas in prosthetic/orthotic research is control. This problem has existed as long as man has used tools and machinery to extend his capabilities. However, in the case of prosthetic and orthotic designs, one of the objectives is to have the mechanism perform a normal function as naturally as possible when conventional control methods are not available.

The key word here is "naturally." Naturalness of operation implies

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[c] The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

that not only does the device have to appear and operate as nearly as possible as its normal counterpart, but that controlling the device should not interfere with other bodily functions. While it is socially acceptable to have a person totally occupied with operating a common machine such as an automobile (with a very obvious man-machine interface), it is not as acceptable to have a person totally or obviously involved with the operation of a prosthetic or orthotic device. The more naturally a device can be operated, the better for the handicapped person.

As more artificial joints are required to replace those lost with increasing levels of amputation or paralysis, more sites are required for operation and/or control of these joints (if they are other than friction pre-position types). There are only a small number of sites on the body that can be utilized to control these devices without interfering heavily with other unimpaired body actions. (Among these are the shrug, shoulder hike, and chest and abdomen expansion.) Of these, only two are practical enough for usage in a purely mechanical system.

PURPOSE

The purpose of the Interfacial Couplings project is to study the methods of control and the sites of control on the body (especially with respect to the person with a high level of amputation or paralysis) to determine whether these can be enlarged, improved upon, or be made multifunctional.

The initial phase of the project consists of a literature search of previous motion studies to determine what motions are required (how many degrees of freedom and the range of motion in each degree) to perform the maximum number of essential daily activities. Perhaps this could be summed up in the phrase "motion effectiveness"—how much benefit can be obtained from each degree of freedom and what is the optimal range within each degree. (Keller et al. (27) used the term "kinematic complexity cost.") The ultimate goal is the simplification of prosthetic and orthotic design and the reduction of control site requirements.

This literature survey has been restricted (due to the lack of translations) to those studies written in English. References to foreign studies are through information contained in the English language studies.

HISTORY

Historically, the published study of human motions can be traced as far back as Leonardo da Vinci (1452–1519), but the scientific study of motion seems to have begun with the work of German and Swiss investi-

gators in the late 19th century (notably Albert, 1876;[d] Strasser and Gassman, 1876;[e] Fick, 1904–1911;[f] and Braune and Fischer, 1887[g]).

Little work had been done on motion study in the United States prior to the 1920's. Since then, there has been an increasing number of investigations conducted most of which are devoted to the lower extremity. This disparity in research efforts is due to the fact that while the joint motions of the lower-extremity motions are complex, they are also repetitive. The upper-extremity motions are so diverse that not until relatively recent times (1947) has anyone tried to measure the coordinated motions of daily living. Most of the studies were concerned with terminology and were, primarily, studies to determine the rotation range of each joint, acting independently of the others. The majority of the investigators used a goniometer to make the measurements, and the rotations were measured as angles (to the nearest 5 deg.) in a given plane. Also, all but a few of the studies used very small and specialized

[d] Albert, E. Zur Mechanik des Hüftgelenkes, Wien: Med. Jahrb, K.K. Gesellsch. D. Arzte, 1876, pp. 107–129 (cited by) Dempster, W.T., SPACE REQUIREMENTS OF THE SEATED OPERATOR, Technical Report No. 55–159, Wright Patterson AFB, Ohio: Air Research and Development Command, Wright Air Development Center, 1955.

[e] Strasser, H. and Gassman, A. Hilfsmittel und Norman zur Bestimmung und Veranschaulichung von Stellungen, Bewegungen und Kraftwirkungen am Kniegelenke, Meckle: Bonnet: Anat. Hefte, 2:6/7, 1893 (cited by) Steindler, A., KINESIOLOGY OF THE HUMAN BODY, Springfield, Ill.: Charles C Thomas, 1955, p. 121.

[f] Fick, R. Handbuch der Anatomie und Mechanik der Gelenke. Part 1, Anatomie der Gelenke, 1904, Part 2, Allgemeine Gelenk-und Muskelmechanik, 1910. Part 3, Spezielle Gelenk-und Muskelmechanik, 1911. Jena: G. Fischer. (cited by) Dempster, Op. cit.

[g] 1. Braune W. and Fischer, O. Uber den Schwerpunkt des Menschlichen Korpers, Vol. XV, abh. Math. Phys. Klasse kgl. Sachs. Ges. d. Wiss. 20 VII. Leipzig, S. Hirzel, 1889 (cited by) Steindler, Op. cit. p. 121.

2. Braune, W. and Fischer, O. Untersuchungen uber die Gelenke das menschlichen Armes; 1. Das Ellenbogengelenk (O. Fischer); 2. Das Handgelenk (W. Braune and O. Fischer). Abh. d. Math. Phys. Cl. d. K. Sachs. Gesellsch. d. Wiss. 14 (2):29–150, 1887 (cited by) Dempster, Op. cit.

3. Braune, W. and Fischer, O. Uber der Antheil, den die Einzeinen Gelenke des Schultergurtels am der Beweglichkeit des Menschlichen Humerus Haben, abh. d. Math. Phys. Cl. d. K. Sachs. Gesellsch. d. Wiss. 14 (8):393–410, 1888 (cited by) Dempster, Op. cit.

4. Braune, W. and Fischer, O. Die bei der Untersuchung von Gelenkbewegungen Anzuwendende Methode, erlautert au Gelenkmechanismus des Vorderarms beim Menschen, abh. d. Math. Phys. Cl. d. K. Sachs. Gesellsch. D. Wiss. 13 (3):315–336, 1886 (cited by) Dempster, Op. cit.

5. Fischer, O. Kinematik Organischer Gelenke, Braunschweig: F. Vieweg and Sohn, 1907 (cited by) Dempster, Op. cit.

6. Fischer, O. Zur Kinematik der Gelenke vom Typus des humero-radial Gelenkes, abh. d. Math. Phys. Cl. d. K. Sachs. Gesellsch. d. Wiss. 32:3–77, 1909 (cited by) Dempster, Op. cit.

populations, and seldom did the investigators subject their studies to statistical analysis beyond determining the mean for each joint motion measured.

Some of the better joint range studies are:

Gilliland (1921) (18), who measured the voluntary movements of a group of 100 male college students. He listed the range and the standard deviation in addition to the mean. He used several varieties of measuring instruments.

Sinelnikoff and Grigorowitsch (1931),[h] who measured 100 males and 100 females between the ages of 20 and 50 to determine whether there was correlation between constitutional body type or sex and motion range. They also calculated the standard deviation in addition to the mean. However, their measurements were made using a goniometer and are subject to limitations of goniometers. (See measuring methods.)

Glanville and Keezer (1939) (19), who studied 10 males between the ages of 20 and 30. Their joint range data are listed separately, not only for left and right sides, but also for voluntary and forced motions. They also list the range, the standard deviation, and the probable error for each movement. Their measurements were made by goniometer and the description of the motions studied was not precise.

Dempster (1955) (11), who studied 39 male college students. These were grouped and analyzed according to somatotype. He used photography to make the study and listed the mean and the range in his tabulation. Barter (1957) (4) later gave Dempster's data a very thorough statistical analysis.

Table 1 lists the results of the above motion range studies with respect to the upper extremity. Several references have been included in the bibliography that are not listed above. These are summarized in Table 2 and are included because of their wide usage as standards.

AN UPPER-EXTREMITY JOINT REVIEW

Not counting the hand, the upper extremity is commonly thought to consist of three separate joints with a total of 7 deg. of freedom. Actually, the upper extremity begins at the sternum with the sternoclavicular joint, which possesses 3 deg. of freedom. The next joint in the upper-extremity linkage is the scalpuloclavicular, also possessing 3 deg. of freedom. The joint that is commonly thought to be responsible for all the shoulder motion is the humeral joint. This joint also has 3 deg. of freedom. The last two joints are the elbow and the radiocarpal or wrist joint with 2 deg. of freedom each. This gives the arm an actual total of 13 deg. of freedom. The first two joints in this chain of links actually

[h] Sinelnikoff E. and Grigorowitsch, M. Die Beweglichkeit der Gelenke als sekundares geschlechtliches und konstitutionel les merkmal. Zts. F. Konstitutionslehre, 15 (6): 679–693, 1931 (cited by) Dempster, Op. Cit.

TABLE 1 [a]

	Ref. 18 Gilliland (1921) (n=100)		Sinelnikoff & Grigorowitsch (1931) (n=100)		Ref. 19 Glanville & Keezer (1939) (n=10) (right side)				Ref. 4 & 10 Dempster Analyzed by Barter (1955) (n=39)	
					Voluntary		Forced			
	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
SHOULDER										
Forward flexion			180		179.0	7.2	184.6	6.4	188	12
Backward extension			59.8	8.0	55.2	10.1	67.7	11.9	61	14
TOTAL	261.8	13.5	239.8		234.2		252.3		249	19
Horizontal flexion									134	17
Horizontal extension									48	9
TOTAL									182	20
Abduction (coronal plane)	207.5	10.5			129.3	11.7	136.7	12.4		
					without humeral rotation					
Rotation										
Arm horizontal—up					94.1	22.1	101.1	22.5	97	22
down					82.7	10.0	92.0	7.2	34	13
TOTAL					176.8		193.1		131	24

ELBOW										
Flexion	152.3	9.5	142.1		138.3	8.5	143.2	7.6	142	10
FOREARM										
Pronation					91.1	25.8	104.9	22.1	77	24
Supination					99.4	11.0	114.3	15.2	113	22
TOTAL			180.5		190.5		219.2		190	30
WRIST										
Dorsiflexion—(extension)			63.2	8.4	95.0	10.6	105.6	13.0	99	13
Palmar flexion (flexion)			78.2	9.2	54.1	15.2	91.8	13.0	90	12
TOTAL	166.0	9.0	141.4	11.5	149.1		197.4		189	21
Ulnar deviation (adduction)			38.3	7.6	66.1	8.1	74.1	7.4	47	7
Radial deviation (abduction)			23.9	5.3	27.1	7.1	39.7	6.1	27	9
TOTAL	96.5	16.7	62.2		93.2		113.8		74	13

[a] All measurements in degrees of arc.

TABLE 2 [a]

	Ref. 2 Am. Acad. of Ortho. Surg. (1965)	Ref. 8 AMA (1958)	Ref. 24 US Army (1968)	Ref. 34 Nemethi (1953)	Ref. 5 Batch (1955)
SHOULDER					
Forward flexion	158	150	180		180
Backward extension	53	40	60		45
TOTAL	211	190	240		225
Horizontal flexion	135				
Abduction (coronal plane)	170	150	180		130
Adduction	50	30	75		40
TOTAL	220	180	255		220
Rotation					
Arm at side—medial	68				
lateral	68				
TOTAL	136				
Arm horizontal—up	70	40	90		90
down	90	90	70		90
TOTAL	160	130	160		180

ELBOW					
Flexion	146	150	150		145
FOREARM					
Pronation	71	80	80		90
Supination	84	80	80		90
TOTAL	155	160	160		180
WRIST					
Dorsiflexion (extension)	71	60	70	60	70
Palmar flexion (flexion)	73	70	80	60½	80
TOTAL	144	130	150	120½	150
Ulnar deviation (adduction)	33	30	30	46	30
Radial deviation (abduction)	19	20	20	29	15
TOTAL	52	50	50	75	45

[a] All measurements in degrees of arc.

do not have much range, but serve to allow a greater amount of humeral flexion, extension, and rotation than would otherwise be available, by allowing the humeral joint to face in different directions.

MEASURING METHODS

The most common method of determining the ranges of motion of a joint has been by use of the goniometer. This, basically, is a protractor with two arms, one fixed and the other movable. The fixed arm is aligned with a reference line such as a table edge or a stationary point on the body, and the pivot of the goniometer is centered over the joint axis. Then the member on the other side of the joint to be measured is moved through the range of its motion, the movable arm of the goniometer being aligned with the center line of the member. The difference between the angles measured at each extreme of the joint motion gives the joint motion range in that particular plane.

This method of measurement has some disadvantages, however. One is that there are no joints in the body that act precisely as a pinned joint. Because of the synovial membranes, not only do the lengths of the members on either side of the joint change, but also a gliding motion occurs in the joint. Both of these actions change the actual center of rotation continuously as the joint moves. These effects differ depending on the position of the joint and the load carried by it. Another disadvantage is the difficulty of establishing the approximate location of the joint center and the centers of the extremities on either side of the joint with accuracy due to the flesh surrounding some joints. Differing positioning techniques and different types of goniometers may also produce differing results for the same joint motion. The goniometer, however, is the simplest method of measuring and gives a good approximation if used carefully with consideration for its limitations.

Another method of measuring joint motion was developed by the Swiss and German investigators of the 19th century. These investigators realized that the actual motion pattern of a joint such as the hip described a solid angle and was called a cone of excursion. Langer's (1865)[1] method consisted of rigidly anchoring one part of a cadaver joint and moving the other member to the limits of its excursion in every direction. The limiting positions were measured by protractor and were plotted on the surface of a sphere. Albert (1876)[1] improved this method by placing a wire mesh hemisphere over the joint to be measured. The radius of the hemisphere was approximately the same as the length of the movable member and the wires were placed so that they indicated

[1] Langer, C. Lehrbuch der Anatomie des Menschen, Wien: Wilhelm Braumuller, 1865 (cited by) Dempster, Op. cit.

[1] Op. cit., Albert.

latitude and longitude. The measurements in this form could be easily mapped. The method was further refined by Strasser and Gassman (1876)[k] who referred to it as a globographic presentation.

This method suffers from one of the problems that goniometry suffers, the requirements of a single center of rotation from a system that does not possess one. These early investigators used cadaver or skeleton parts to make their studies, thus introducing additional inaccuracies into their measurements since living flesh has different characteristics. This method also requires a considerable amount of time and trouble to set up.

The use of photography was introduced by Isaacs and Muybridge in 1877 to study the motion of a race horse. Muybridge (33) improved the method and made studies of humans performing various activities. His method consisted of using a battery of still cameras that were triggered in groups of three (one for each plane) at regular time intervals (0.075 sec.). Since Muybridge, various other photographic methods have been used with varying amounts of success. Although motion pictures are the most common, other photographic techniques have been used such as: Interrupted light photography—for situations where the motion progresses linearly (e.g., walking); and the gliding cyclogram, developed by Drillis[l]—for repetitive motions in a limited space (e.g., chopping wood). However, photography requires an elaborate setup and laborious, time-consuming data reduction.

With the advent of photogrammetry and cineradiography, X-rays have provided accurate data in a few limited studies (29). Earlier studies have been done using X-rays (42, 45). Analysis of the X-ray photographs is somewhat more difficult since the X-rays are obtained from a point source, rather than from reflected light used to make common photographs.

Potentiometers have also been used to study motion ranges (13, 25, 43). Karpovich et al. (25) described this method very thoroughly. The potentiometer body was attached to a splint or a metal strip on one side of a joint and the potentiometer slidewire was connected with a splint or a metal strip on the other side of the joint. The position of the joint is indicated by the absolute electrical resistance of the potentiometer. By the use of proper instrumentation, velocity and acceleration can also be determined. This method of analysis lends itself to computer analysis very well. However, inasmuch as this method is similar to goniometric measurement, it also suffers from similar inaccuracies. It suffers the

[k] Op. cit., Strasser and Gassman.

[l] 1. Drillis, R. Chronocyclographische Arbeitsstudien Psychophysiologische Arbeiten, 1A, Riga, 1930 (cited by) Contini, R. Prosthetics Research and the Engineering Profession, Artificial Limbs, 1 (3) :47–76, Sept. 1954.

2. Drillis, R. Investigation on Axe and Woodcutting, Riga: Latvijas Lauksaimnieks, 1935 (In Latvian) (cited by) Contini, R. Prosthetics Research and the Engineering Profession, Artificial Limbs, 1 (3) :47–76, Sept. 1954.

additional fault of being influenced by relative movements between flesh and bone. This method requires slightly more sophisticated equipment and techniques.

The rise of computer technology has brought about what promises to be one of the most rapid methods for the study of joint motion. Thus far, there have been no papers published about this method, but some recent articles indicate that some research is presently being done using this approach (17, 32). The method utilizes a television camera that is linked directly to a computer. The body parts under study are instrumented with miniature light sources or special markers. The desired motions are then televised. The television signal is fed directly into the computer where it is immediately analyzed and the results plotted, indicated, or printed out. This method promises to be one of the best methods of collecting joint motion data, but it too requires a considerable amount of sophisticated equipment and technology.

DISCUSSION OF MOTION STUDIES

The first study to make an attempt to determine what movements were essential to daily living was made in 1947 by Keller, Taylor, and Zahm (27). Their study is brief and used only one subject who had been coached prior to the study. The study does, however, provide a general approximation of what the required motion ranges will be. They chose the photographic method for this study. Rather than attempt to photograph and study every conceivable upper-extremity movement, the investigators chose 51 activities which they considered to be representative of most usual daily activities, or that used movements similar to daily activities.

The subject, after some prior coaching and training, was fitted with landmarks and placed behind a three-sided Cartesian coordinate grid framework where he was photographed performing each representative activity. Two diagonally placed mirrors allowed the activity to be viewed from the top and side simultaneously with the front viewing. Each representative activity was photographed by a 35-mm. motion picture camera (at a speed of 24 frames per second) placed 35 ft. away from the subject. A positive print of the film was made and studied on a cinematic editing machine. The projected coordinates were estimated to ¼ in. and then mathematically corrected for parallax and angular deviations.

A kinematic analyzer was then used to more carefully study the photographed movements. This analyzer consisted of a mechanism of joints and linkages which was half the size of the subject and could be moved through similar ranges of motion. The analyzer was fitted with protractors that would allow measurement of each of the joint rotations. Landmarks on the analyzer were adjusted so that they would have the

same relationship to one another as those on the subject. The analyzer was used on a table with a positioning grid network drawn on it, scaled to represent the grid used during the photographing. The landmarks on the analyzer were aligned with mathematically corrected coordinates of the subject's landmarks taken from the photographic data. When the analyzer was adjusted, the angular relationship between its members was comparable to similar relationships on the subject and the angles were read directly from the protractors. These data were then statistically treated.

Keller et al. studied the frequency distributions obtained and determined that for some motions ranges could be diminished. They established cutoff points after careful consideration of the ease and feasibility of compensating for the reduced motion range. Their data showed that only one joint motion—radial and ulnar deviation of the wrist—can be eliminated entirely. They suggest the ranges of motion for the joints shown in Table 3 as the minimum required for normal daily activities.

They hoped that the data obtained by these experiments would reveal an indication for permanently coupled rotation. A coupling of this nature can be justified only if the motions that it combines are used frequently, have sufficient importance, and do not hinder other necessary motions. They found, based on one subject, ". . . . no functional basis for a permanent coupling."[m] The only group of motions that might be adapted to a joint coupling concerned eating, where a combination of rotations is used to keep utensils level during the path to the mouth.

Presently, however, there is additional research being done to further

TABLE 3

Humeral rotation (arm torsion)	Inward Outward	45° 10°
Forearm	Flexion Extension	60° 60°
Forearm	Supination Pronation	30° 60°
Wrist	Dorsiflexion Volar flexion	20° 30°

(The above values can be compared with the Table of Normal Ranges of Motion—Table 1.)

[m] Keller, A.D., Taylor, C.L., and Zahm, V. Studies to Determine the Functional requirements for Hand and Arm Prosthesis. Los Angeles, Calif., Dept. of Engineering, Univ. of Calif., 1947, p. 18.

investigate the possibility of eliminating or linking some of the upper-extremity motions. One of the agencies doing some investigation in this area is the Swedish Central Committee for Rehabilitation (SVCR). Enger (16) of the SVCR reports on a shoulder joint utilizing 1 deg. of freedom. Although the clinical evaluation had not been completed at the writing of the article, the shoulder was found to have ample mobility for feeding movements. Enger does not, however, present much evidence that contradicts the conclusions reached by Keller et al. The SVCR also is designing a shoulder mechanism that will link a supinatory movement with that of the shoulder.

The next study of upper-extremity motions (14, 15) was begun in the early part of 1965 by Engen et al. at the Texas Institute for Rehabilitation and Research. As of July 1968, there was no final report published on this research. The purpose of this study is to compare normal upper-extremity motion with orthosis-assisted upper-extremity motion to develop a mathematical model. This model could then be used to evaluate the effectiveness of orthotic design changes, point to areas needing design improvement and, Engen et al. hope, indicate a pattern of synchronized upper-extremity movements. Engen et al. also used the photographic method of study. Each subject under study was marked with a felt tip marker on significant upper-extremity physiological landmarks and was then photographed with a 16-mm. motion picture camera from a distance of 20 ft. Mirrors were used to provide side and top views simultaneously. Each subject was photographed performing the following five motions that the investigators felt were basic:

1. Table to mouth feeding activities
2. Hair grooming
3. Page turning
4. Writing
5. Diagonal reaching

The film was studied by projection onto a viewing table covered with a sheet of translucent acetate. The landmarks were then transcribed onto the acetate. After all the frames for a particular motion had been plotted, lines connecting the landmark loci were drawn. From these marks and curves, the velocity, acceleration, and angular changes could be measured. The original plans called for an anlysis of 10 subjects performing the five tasks normally, then for an analysis of the 10 subjects using orthotic equipment (without external power), and, finally, an analysis of the 10 subjects using the orthotic equipment with the external power. As of the last obtainable progress report (September 1967), there was still much work to be done on this project.[n] There is no indication that

[n] Engen, T.J. Progress Report on Project RD–1564, Houston, Texas: Texas Institute for Rehabilitation and Research, Sept. 1965, Feb. 1966, Jan. 1967, Sept. 1967.

Engen has taken any steps to compensate for errors in parallax. He is, however, using more than one subject and is using more than one physiological somatotype.

McWilliam of the West Hendon Hospital in London is presently doing a research project that appears to be an extension of some of the work of the University of California group. This study is being made to give data on the kinematic requirements of the activities themselves rather than how the normal arm performs them. This investigator used 180 tasks for his investigation rather than the 51 tasks used by Keller et al. He uses what he terms inspection rather than photography to study the motions. He develops a concept of a task space which expands on Keller's action sphere. This task space consists of a three-dimensional coordinate system centered on the body (rather than the shoulder). McWilliam feels that motion specifications should not be too rigid since the way a patient will make movements with prosthetic devices is not predictable and potential solutions will have to be tested by experiment. No full report of this investigation was available as of July 1968.

Wijnschenk of the Technological University of the Netherlands (43) has done enough study of three-dimensional arm motion to develop some highly nonlinear differential equations that describe the movements. He discovered that arms are moved either on a minimum effort (slow motions) or a minimum time (fast motions) basis. He designed, developed, and built a computer-controlled scale model arm with 5 deg. of freedom that can be used to simulate the motions of a normal arm. Using these equations and the model, he is hoping to build a myoelectrically controlled, electrically driven prosthetic arm. He used the potentiometric method of study. No formal report had been published as of July 1968.

Another investigation in progress, that relates to the subject of this report, is being made by E. F. Furnee of the Technological University of the Netherlands (17). He is using the television camera-computer method of studying human motions. No report had been published as of July 1968. The abstract that mentioned this program was concerned primarily with the method used to obtain the data.

General Electric Company is also using the television-computer method for their Man-Amplified Program (32) but is not studying essential daily activity motion.

The articles mentioning these last two television-computer studies did not make any mention of whether or not these motions were studied in just two or three dimensions, or whether any effort had been made to correct for parallax effects.

CONCLUSIONS

1. The human upper extremity (excluding the hand) is a complex system of five joints with a total of 13 deg. of freedom. The lack of specific fixed centers of rotation and the inaccessibility of these axes, due to the surrounding tissue, hamper accurate measurement of joint motions.

2. Only three of the American investigations of joint motion have been subjected to any statistical analysis beyond determination of the mean.

3. Of the several methods of study of joint motions, there are only two that provide a high degree of accuracy and precision. These two are photography and the television-linked computer method. To date, however, there are only two studies published that use one of these methods.

4. There has been only one investigation published that has made an attempt to study the coordinated motions of daily living. From the results of this study of one subject, the investigators concluded that: (a) of the degrees of freedom of the upper extremity, only radial and ulnar deviation could be eliminated entirely without adversely affecting essential daily motions—the other degrees of freedom could be curtailed somewhat, and (b) a permanent coupling of two or more joint motions is not practical. However, further research is being conducted in these areas.

BIBLIOGRAPHY AND ABSTRACTS

1. Albee, F. H. and A. R. Gilliland: Metrotherapy, or the Measurement of Voluntary Movement, JAMA, 75:983, Oct. 9, 1920.

This article, although illustrated with photographs of some of the measuring apparatus (primitive goniometers) used by Gilliland (18), is primarily concerned with the therapeutic aspects of goniometry that gives the patient a record of past achievements to try to surpass.

2. American Academy of Orthopaedic Surgeons: Measuring and Recording Joint Motion, Chicago: American Academy of Orthopaedic Surgeons, 1965.

The Academy of Orthopaedic Surgeons appointed a committe to adopt a "single standard, 'agreed upon' method of measuring and recording joint motion." This is the committee's report. In addition to standardizing the method, a table of standard values is provided for comparative purposes. This table furnishes a list of, and averages the values presented by, four sources: The AMA Committee on Rating of Physical Impairment (8); The Committee of the California Medical Association and the Industrial Accident Commission of the State of California, 1958; William A. Clarke, A System of Joint Measurements, Journal of Ortho-

paedic Surgery, 2:687, Dec. 1920; and the conclusions of the above committee.

3. Bahniuk, E. and M. J. Wijnschenk: Design Parameters for an Orthotic Arm Aid, ASME Paper No. 63–WA–282, New York, N. Y., American Society of Mechanical Engineers, Sept. 26, 1963.

This paper describes design criteria such as forces, velocities, amount of movement precision, and amount of energy required for daily operation which were used in the construction of a research orthotic arm by Case Institute of Technology and Highland View Hospital of Cleveland, Ohio.

4. Barter, J. T., I. Emanuel, and B. Truett: A Statistical Evaluation of Joint Range Data, Technical Note No. 57–311, AD 131028, Wright-Patterson AFB, Ohio, Air Research and Development Command, Wright Air Development Center, 1957.

Barter et al. give Dempster's joint range data (developed in Ref. 11) a thorough statistical analysis, thus rendering it more meaningful. This is one of the few joint range studies to be so thoroughly analyzed. Its only fault is that the population (39 subjects) was not very large. An extensive bibliography on joint range studies is included.

5. Batch, J. W: Measurements and Recordings of Joint Functions: U.S. Armed Forces Medical Journal, 6:359–382, Mar. 1955.

This article was the basis for the 1956 edition of the U.S. Army technical manual TM 8–640, Joint Motion Measurement (Department of the Air Force Pamphlet AFP 160–14). It lists a generalized range of motion table and methods for measuring the various joint functions. The report makes no mention of the size or characteristics of the population studied.

6. Cornell, R. W. and M. J. Wijnschenk: Design and Development of the Case Research Arm Aid, Report No. EDC 4–64–4, Cleveland, Ohio, Case Institute of Technology, Apr. 1964.

This is the full report on the Case Research Arm Aid that incorporates most of the material used in Reference 3 of this report.

7. Clark, W. A.: A System of Joint Measurements, J. Orthop. Surg., 2:687–700, 1920.

Although the information in this Journal is old, it is a good background source. This was an early attempt to standardize the positioning of joints for measurements.

8. Committee on Medical Rating of Physical Impairment: A guide to the Evaluation of Permanent Impairment of the Extremities and Back, JAMA, Special Edition, Feb. 15, 1958.

The AMA's standardization of techniques for joint motion measurement is presented. Also, standard joint motion range data used for physical impairment estimation are listed.

9. Dempster, W. T.: The Anthropometry of Body Action, Ann. N.Y. Acad. Sci., 63:559–585, Nov. 28, 1955.

Precise joint range measurement techniques, both static and dynamic, are discussed with a brief description of joint mechanism. A good bibliography is supplied.

10. Dempster, W. T.: Mechanisms of Shoulder Movement, Arch. Phys. Med., 46:49–70, Jan. 1965.

An excellent discussion of the anatomy, mechanism, and kinematics of the three joints that comprise the shoulder is presented.

11. Dempster, W. T.: Space Requirements of the Seated Operator, Technical Report No. 55–159, AD 87892, Wright-Patterson AFB, Ohio, Air Research and Development Command, Wright Air Development Center, 1955.

This excellent and thorough study includes an analysis of the kinetics and kinematics of the upper extremity. The report was done to provide human engineering data for aircraft cockpit design. However, no attempt was made to analyze the "motion effectiveness" of each joint. An extensive bibliography is also presented. The report includes investigations in areas such as:

Range of motion of joints
Effect of somatotype on motion range
Mass and size of body segments
Methods of obtaining body segments
Locations of body segment centers of gravity
Degrees of freedom of body joints
Comparative anthropomorphies

12. Dierssen, G., M. Lorence, and R. M. Spitaleri: A New Method for Graphical Study of Human Movements, Neurology, 11:610–618, July 1961.

A method of studying motion is presented whereby motions are assigned the x-y coordinates and time assigned the z coordinate of a chart. (The photos or drawings can be superimposed.) This method provides no way to indicate the motions in the z direction.

13. Elgons Used to Study Motion, Medical Tribune, 7:24, Sept. 7, 1966.

This is a brief newspaper account of a motion study by Marlene J. Adrian of Springfield College, Springfield, Mass. Elgon is Adrian's name for a potentiometer adapted to measure joint motions. As of July 1968, no other published material has been found concerning the results of this study.

14. Engen, T. J. and L. F. Ottnat: Upper Extremity Orthotics: A Project Report, Orthotics and Prosthetics; Ortho. & Pros. Appl. J. 21:112–127, June 1967.

A portion of this article briefly describes a kinematic study being done at Texas Institute for Rehabilitation and Research (TIRR). The study is being done to broaden the understanding of the biomechanical relationships between the joints to improve the overall function of the more sophisticated orthotic and prosthetic systems. Although only 10 subjects are to be studied, each performing five tasks (table-to-mouth feeding, hair grooming, page turning, writing, and diagonal reaching), an effort has been made to make the study representative by including as many physiological types as possible in the population sample. At the date of this article, three subjects had been evaluated.

The method consists of photographing each subject with a 16-mm. movie camera and a special mirror apparatus (to obtain a picture with three views) as he performs each of the five activities; first without, and then with, orthotic equipment. The photographs are later marked, measured, and studied.

15. Engen, T. J. and W. A. Spencer: Method of Kinematic Study of Normal Upper Extremity Movements, Arch. Phys. Med., 49:9–12, Jan., 1968.

This article primarily restates the information found in the previous reference (14). According to this reference, nine subjects have been studied. The authors indicate that they are making an attempt to program the raw data for computer reduction. They emphasize that the program is still in the preliminary stages.

16. Enger, S.: A Basis for a Prosthetic Shoulder Analogue and a View of Upper Limb Function, Med. Biol. Engin., 5:455–462, Sept. 1967.

Enger, of the Swedish Central Committee for Rehabilitation (SVCR), reports on a research effort at Norrbacka Institute on Stockholm to develop an improved shoulder joint. The Institute, in hopes of combining some joint motions, has developed and fitted a mechanical shoulder joint that pivots about an axis that has been rotated out of the normal x, y, z coordinates and utilizes only 1 deg. of freedom. The Institute has found that the joint allows a large field of action to the hand and does not hamper motions associated with eating. The Institute is planning to build an arm that incorporates a coordinated supinatory function with the shoulder motion. The article indicates that although considerable design analysis went into the shoulder design, there has not been too much objective evaluation of the type used by Keller et al. (27).

17. Furnee, E. H.: Hybrid Instrumentation in Prosthetics Research, Digest of the 7th International Conference on Medical and Biological Engineering, Stockholm, Sweden: Royal Academy of Engineering Sciences, p. 446, 1967.

This abstract describes a method of utilizing a TV camera that is coupled with a computer to study arm movement patterns. Miniature