

CHAPTER VI

RANGE OF JOINT MOTION

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The range of motion of body joints is obviously an important factor in the assessment of body mobility or in the determination of arm and leg reach capabilities. In Chapter V, Stoudt discussed many of the problems faced by the design engineer who must determine the capability of the operator to reach, grasp, and actuate various controls. The information presented in this chapter, integrated with Stoudt's work, should enable the designer to better lay out work stations.

In this chapter we will discuss (1) selected reviews of the range of joint motion literature; (2) techniques for measuring range of joint motion; (3) range of joint motion terminology; (4) recommended range of joint motion data for the design engineer; (5) differences in the range of joint motion due to the effects of age; (6) differences in range of joint motion between men and women; (7) the assessment of differences in range of joint motion caused by protective clothing; and (8) the range of joint motion of selected two-joint muscles.

Selected Review of the Literature

The best of the several reviews of the literature pertaining to the range of joint motion measurement are those by Holland (1968) and Clarke (1975). These two papers cite 136 and 55 references, respectively, pertaining to different aspects of the range of joint motion. Although they are geared toward the physical educator and the physical therapist, these two excellent reviews point out many of the kinds of problems the design engineer will encounter when dealing with range of motion data. For example, the following generalizations, drawn from Holland's paper are pertinent to the concerns of design engineers:

(1) There appears to be little agreement with regard to the definition and limits of so-called normal flexibility, and with regard to what constitutes hypo- or hyper-flexible joint range of motion.

(2) There appears to be general agreement that range of joint motion is a highly specific factor and that measurement of one or several body joints cannot be used to validly predict range of motion in other body parts.

(3) The use of linear techniques to measure rotational joint motion involves rather gross mathematical error; they should not be used for the collection of objective clinical or experimental data. Although there is

conflicting evidence, it appears also that individual limb and trunk length variability may significantly affect the validity of linear range of motion measurements.

Techniques for Measuring Range of Joint Motion

The problem of accurately evaluating the range of motion of body joints has been, and continues to be, a perplexing one. A number of techniques and devices have been proposed for measuring range of joint motion but none has received widespread acceptance. Adrian (1968), the American Academy of Orthopedic Surgeons (1965), Ayoub (1972), Clarke (1975), Dempster (1955), Garrett, Widule, and Garrett (1968), Holland (1968), Leighton (1955), Miller and Nelson (1973), Plagenhoff (1971) and Roebuck, Kroemer, and Thomson (1975) have discussed in some detail the advantages and disadvantages of past and current techniques and equipment. It is beyond the scope of this chapter to discuss each of these techniques and procedures. The reader who is interested in knowing more about range of joint motion measuring techniques and equipment is referred to the above mentioned sources. However, because the majority of the data we will present later in this chapter have been developed from goniometry, the Leighton flexometer, and photography, we will briefly discuss these techniques.

The goniometer consists of a 180-degree protractor, usually made of plexiglass, with extended arms approximately 40 centimeters long. One of the arms is fixed to the zero line of the protractor while the other is movable. Although the goniometer is a very simple device and is subject to inherent errors in measurement due to the complexity of human body joint movements, it provides an extremely valuable tool for range of joint motion analysis.

The flexometer was developed by Leighton (1955) for measuring joint angles without regard to shifting joint centers. This instrument has a rotating, weighted 360-degree dial and a weighted, movable pointer mounted in a glass-enclosed metal case. The dial and the pointer operate independently and are balanced so they always point upward. The movements of the dial and the pointer are controlled by gravity. The flexometer is strapped to the segment being tested. The dial is locked at one extreme position (e.g., full flexion of the knee) and the pointer is locked at the other after complete movement of the joint has been effected (e.g., full extension of the knee). A direct reading of the pointer on the dial gives the range of joint movement in angular degrees. Leighton has developed 19 range of joint motion tests: neck flexion-extension, lateral flexion, and rotation; shoulder flexion-extension, adduction-abduction, and rotation; elbow flexion-extension; radial-ulnar supination-pronation; wrist flexion-extension and ulnar-radial flexion; hip extension-flexion, adduction-abduction, and rotation; knee flexion-extension; ankle flexion-extension and inversion-eversion; trunk flexion-extension, lateral flexion, and rotation. Roebuck (1968) and Roebuck, Kroemer, and Thomson (1975) have discussed the utilization of the flexometer in measuring mobility of men clothed in pressurized and unpressurized space suits.

A photographic method, often employing double exposures, was developed by Dempster (1955) and was used for recording the range of movement of the limb joints. Photographs were made on 35-mm film with an Argus camera by the flash of a speed lamp. The room was darkened and black backgrounds were provided. For double exposures an initial flash exposure recorded one extreme of a joint range; the lens was then kept open following exposure until the subject assumed an opposing position at which point a second flash exposure was made. Parts of the body which would otherwise present a conflicting background for the test joints were covered with black velveteen cloth.

A special work table, painted black, was employed as a support for the subject or his limb segments. Horizontal lines were marked on the table edge with light-reflecting tape to serve as references. Frames of the strip of negatives were projected as enlarged images and the best estimates of link lines connecting joint centers were ruled on paper; horizontal or vertical reference lines were also traced. Angles were then measured with a protractor to the nearest degree.

These techniques have been extensively used and further developed by various researchers working in the area of range of joint motion assessment.

Range of Joint Motion Terminology

The range of joint motion is measured at the angle formed by the long axes of two adjoining body segments, or, in some cases, at the angle formed by one body segment and a vertical or horizontal plane. The total range of movement is measured between the two extreme positions of the joint.

Joint movements in the classical kinesiological terminology are considered to begin from the so-called anatomical position. This position is defined as that of a man standing upright, head facing forward, arms hanging down with palms facing forward. The ten types of joint movement that primarily concern the design engineer are:

(1) Flexion - bending or decreasing the angle between the parts of the body. Supplementing the more commonly measured arm and leg flexions, Kelly (1971) has identified several kinds of flexion to meet special descriptive needs. These are: trunk lateral flexion in which the trunk segments move so as to decrease the angle between them and the right thigh; radial flexion which refers to the movement of the thumb side of the hand toward the radial side of the forearm segments; and ulnar flexion which refers to the opposite side of the hand's movement toward the ulnar side of the forearm segment.

(2) Extension - straightening or increasing the angle between the parts of the body. It is generally defined as the return from flexion. When a joint is extended beyond the normal range of its movement, the movement becomes known as hyperextension.

(3) Abduction - movement of a body segment away from the midline of the body or body part to which it is attached.

(4) Adduction - movement of a body segment or segment combination toward the midline of the body or body part to which it is attached.

(5) Medial rotation - turning toward the midline of the body.

(6) Lateral rotation - turning away from the midline of the body.

(7) Pronation - rotating the forearm so that the palm faces downward.

(8) Supination - rotating the forearm so that the palm faces upward.

(9) Eversion - rotation of the foot which lifts its lateral border to turn the sole or plantar surface outward.

(10) Inversion - lifting the medial border of the foot to turn the sole inward.

Roebuck (1975) firmly believes that the above described classical movement terminology can be misleading and inappropriate. In an effort to provide a more precise terminology for the engineering anthropometrist, Roebuck has developed a very elaborate and comprehensive new system of notation for mobility evaluation. While it is beyond the scope of this chapter to discuss the details of Roebuck's new system, the interested reader is referred to Chapter III, "Measurement of Dynamic Characteristics and Movement," pages 79-92, and Appendix A, Part 3, "Engineering Anthropometry Terminology," pages 423-425 in Roebuck, Kroemer, and Thomson's book entitled Engineering Anthropometry Methods.

Recommended Range of Joint Motion Data for the Design Engineer

In spite of the many techniques and test procedures that have been developed for the measurement of range of joint motion, there is a paucity of descriptive data that can be used by the design engineer. Much of the research has been undertaken by investigators working in the areas of physical education, physical therapy, sports medicine and rehabilitation medicine. Obviously, the research purposes and objectives of these investigators differ greatly from those of the design engineer. Nevertheless, the data which are available do characterize the range of human joint motion for many NASA design applications although the effects of prolonged weightlessness on joint motion have not yet been systematically investigated.

TABLE 1
RANGE OF JOINT MOTION VALUES*
(Barter, Emanuel and Truett, 1957)
MALES

<u>Movement</u>	<u>$\bar{X}$</u>	<u>SD</u>	<u>5%ile</u>	<u>95%ile</u>
Shoulder flexion	188	12	168	208
Shoulder extension	61	14	38	84
Shoulder abduction	134	17	106	162
Shoulder adduction	48	9	33	63
Shoulder medial rotation	97	22	61	133
Shoulder lateral rotation	34	13	13	55
Elbow flexion	142	10	126	159
Forearm supination	113	22	77	149
Forearm pronation	77	24	37	117
Wrist flexion	90	12	70	110
Wrist extension	99	13	78	120
Wrist abduction	27	9	12	42
Wrist adduction	47	7	35	59
Hip flexion	113	13	92	134
Hip abduction	53	12	33	73
Hip adduction	31	12	11	51
Hip medial rotation (prone)	39	10	23	56
Hip lateral rotation (prone)	34	10	18	51
Hip medial rotation (sitting)	31	9	16	46
Hip lateral rotation (sitting)	30	9	15	45
Knee flexion, voluntary (prone)	125	10	109	142
Knee flexion, forearm (prone)	144	9	129	159
Knee flexion, voluntary (standing)	113	13	92	134
Knee flexion forced (kneeling)	159	9	144	174
Knee medial rotation (sitting)	35	12	15	55
Knee lateral rotation (sitting)	43	12	23	63
Ankle flexion	35	7	23	47
Ankle extension	38	12	18	58
Foot inversion	24	9	9	39
Foot eversion	23	7	11	35

*Measurement technique was photography. Subjects were college-age males. Data are in angular degrees.

TABLE 2
RANGE OF JOINT MOTION VALUES*
(Harris and Harris, 1968)

FEMALES				
<u>Movement</u>	<u>Mean</u>	<u>SD</u>	<u>5%ile</u>	<u>95%ile</u>
Neck flexion	58.7	10.3	41.7	75.7
Neck extension	89.3	9.9	73.0	105.6
Neck-lateral flexion, right	50.5	7.6	38.0	63.0
Neck-lateral flexion, left	47.2	8.0	34.0	60.4
Neck rotation, right	83.1	10.2	66.3	99.9
Neck rotation, left	78.5	11.2	60.0	97.0
Spine flexion	61.9	11.3	43.3	80.5
Spine extension	29.3	12.5	8.7	49.9
Spine lateral flexion, right	57.8	8.9	43.1	72.5
Spine lateral flexion, left	58.0	8.7	43.6	72.4
Spine rotation, right	65.4	10.6	47.9	82.9
Spine rotation, left	62.8	10.5	45.5	80.1
Shoulder flexion	167.9	10.0	151.4	184.4
Shoulder extension	41.5	10.0	25.0	58.0
Shoulder abduction-adduction	169.5	11.2	151.0	188.0
Shoulder medial rotation	160.0	12.5	139.4	180.6
Shoulder lateral rotation	33.6	11.1	15.3	51.9
Shoulder horizontal abduction	126.6	15.4	101.2	152.0
Shoulder horizontal adduction	38.9	6.6	28.0	49.8
Elbow flexion-extension	151.4	7.1	139.7	163.1
Elbow hyperextension	7.6	6.4	3.0	18.2
Radioulnar supination	88.9	17.1	60.7	117.1
Radioulnar pronation	101.9	15.2	76.8	127.0
Wrist flexion	79.7	15.1	54.8	104.6
Wrist extension	60.6	10.5	43.3	77.9
Wrist abduction	29.7	9.1	14.7	44.7
Wrist adduction	50.4	10.8	32.6	68.2
Hip flexion, center	79.6	14.5	55.7	103.5
Hip flexion, right	94.6	11.3	76.0	113.2
Hip extension, center	15.4	6.6	4.5	26.3
Hip extension, right	18.1	6.2	7.9	28.3
Hip abduction-adduction	71.8	11.6	52.7	90.9
Hip horizontal abduction	49.5	7.9	36.5	62.5
Hip horizontal adduction	25.3	5.6	16.1	34.5
Hip lateral rotation	55.8	9.5	40.1	71.5
Hip medial rotation	43.8	11.6	24.7	62.9
Knee flexion-extension	133.8	7.8	120.9	146.7
Knee hyperextension	11.3	4.9	3.2	19.4
Ankle flexion	18.8	6.2	8.6	29.0
Ankle extension	49.7	8.6	35.5	63.9
Ankle inversion	37.6	10.8	19.8	55.4
Ankle eversion	30.0	9.5	14.3	45.7

*Measurement technique was flexometer. Subjects were college-age females.
Data are in angular degrees.

The descriptive range of joint motion data presented in the following tables were selected for their usefulness to design engineers.* Table 1 gives values for males; Table 2 tabulates women's values. The differences which are readily apparent in comparing like measurements can be attributed to two major causes. The first, of course, is the difference in sexes; it can be noted that in many cases where measurements are comparable, one sex or the other appears to be considerably more flexible. (Table 3, in the next section, details percentile differences between selected male and female joint motion measurements). A second source of possible discrepancy between the male and female data is the difference in measurement techniques employed in the two studies.

Variations in Range of Joint Motion Measurements

Differences Between Men and Women

The most carefully controlled study that we know of pertaining to the measured differences in range of joint motion between adult men and women was conducted by Sinelkinoff and Grigorowitsch (1931). Their study of 100 men and 100 women ranging in age from 20 to 50 years, indicated that, in general, women exceed men in range of joint motion measurements at all joints except the knee. Table 3 summarizes the data reported by Sinelkinoff and Grigorowitsch and reveals percentage differences between men and women in range of joint mobility ranging from zero percent for knee flexion-extension, to 17% for wrist adduction-abduction.

TABLE 3
DIFFERENCE IN RANGE OF JOINT MOTION BETWEEN MEN AND WOMEN
(Based on Sinelkinoff and Grigorowitsch, 1931)*

	<u>Men's $\bar{X}$</u>	<u>Women's $\bar{X}$</u>	<u>Difference</u>
Shoulder abduction (rearward)	59.8 **	61.4	103%
Elbow flexion-extension	142.1	149.9	105%
Wrist flexion-extension	141.4	154.0	109%
Wrist adduction-abduction	62.2	72.7	117%
Hip flexion (with extended knee)	83.5	86.8	104%
Hip flexion (with bent knee)	117.9	121.0	103%
Knee flexion-extension	140.5	140.1	100%
Ankle flexion-extension	62.6	66.9	107%

*Percentage differences obtained by dividing the women's reported mean value by the men's reported mean value; e.g., 61.4 divided by 59.8 = 103%.

**Mean values reported in angular degrees.

*Additional sources of specific range of joint motion data include: the American Academy of Orthopaedic Surgeons (1965), Dickinson (1963), Gilliland (1921), Glanville and Kreezer (1937), Kendall and Kendall (1948), Laubach (1970), and Sinelkinoff and Grigorowitsch (1931).

Assessing Differences Caused by Protective Clothing

Like all other dynamic measurements, range of joint motion is significantly affected by bulky protective clothing. Little data has been developed on the modifications in joint motion which occur as a result of heavy clothing assemblies and what data have been generated are of limited value since measurements taken in a given protective garment are not likely to match those taken in another. Since each protective garment is dimensionally unique, the most useful information we can offer NASA design engineers is the description of a method by which joint motion changes can best be evaluated in any suit. A technique which has considerable merit was devised by the Navy to analyze two diving suits and was reported on by Bachrach et al. in 1975. Though not directly relevant to NASA design engineering problems, this study has been chosen for presentation here because of the feasibility of the research design for the practicing engineer and its applicability to the evaluation of joint motion in newly developed NASA pressure suits.

Six male U.S. Navy divers served as subjects. Each subject served as his own control with his baseline measurements taken in a swim suit before donning either of the two diving systems under study. Fourteen range of joint motion measurements were obtained from each subject, both on dry land and in the water. Data was summarized in the following fashion:

<u>Movement</u>	<u>Swim Suit</u>	<u>Dry</u>		<u>Wet</u>	
		<u>Suit I</u>	<u>Suit II</u>	<u>Suit I</u>	<u>Suit II</u>
Trunk Flexion					
Mean	116.4°	103.3°	103.4°	83.1°	84.9°
S.D.	7.5°	7.7°	10.3°	9.9°	15.3°

The summary data were further analyzed to arrive at the mean percentage loss of diver flexibility caused by the two diving suits. These data, shown in Table 4, make it clear that Suit II affords the diver considerable more flexibility than does Suit I.

It is recommended that NASA designers use a comparable method--in which subjects serve as their own controls and the garment is tested under the conditions in which it will be worn--to assess the degree to which newly developed pressure suits hamper movement in their wearers. Joint motions to be measured would, of course, be selected for their relevance to operation in a zero g environment.

The Effects of Age

Under normal circumstances the range of joint motion decreases only slightly during the adult years between age 20 and age 60. West (1945) has reported that between the first and seventh decades of life range of joint motion declines about 10 percent, but no significant changes occur after puberty (Salter and Darcus, 1953). So for all practical purposes the designer can ignore the effects of age on the range of joint motion for the adult population.

TABLE 4
MEAN PERCENTAGE LOSS OF DIVER FLEXIBILITY CAUSED BY TWO
DIVING SUITS (Based on Bachrach et al. 1975)

<u>Movement</u>	<u>Dry</u>		<u>Wet</u>	
	<u>Suit I</u>	<u>Suit II</u>	<u>Suit I</u>	<u>Suit II</u>
Trunk flexion	11.1%	11.2%	28.5%	26.9%
Trunk extension	26.9	12.5	38.1	26.8
Trunk lateral flexion	27.2	12.3	29.9	31.0
Trunk transverse rotation	42.2	37.8	29.5	31.3
Shoulder joint abduction	40.4	22.1	35.9	17.6
Shoulder joint flexion	47.5	24.1	39.3	16.1
Shoulder joint extension	29.8	20.2	12.9	13.0
Shoulder joint hor. flexion	37.0	23.7	39.0	22.0
Shoulder joint hor. extension	34.6	29.6	23.2	24.9
Elbow flexion	7.9	8.7	6.4	5.4
Knee flexion	24.8	11.1	17.7	8.0
Hip flexion	35.6	32.9	25.1	24.8
Hip extension	46.7	30.0	43.8	31.0
Hip abduction	56.8	42.4	40.8	21.1
Overall mean loss	33.3	22.7	29.3	21.4

Range of Motion of Two-Joint Muscles

Up to this point we have discussed joint motion as though each joint existed in isolation from all others. Most investigations of range of joint motion have been confined to the study of simple planar movement of a single joint and these data are of singular importance in our understanding of human motion as well as of practical value to designers dealing with many problems of workspace layout. The placement of a sidearm controller when the forearm is restrained, for example, is dictated by the range of motion of the wrist alone. However, more often than not, human motion involves the interaction of two or more joints and muscles. Little is known about the effect of one upon the other although we know, for example, that hand pronation is considerably increased if shoulder motion also comes into play.

One common type of dynamic interaction involves two-joint muscles in which the action of one joint may either increase or decrease the effective functioning of the other. The problem of evaluating the range of motion of two-joint muscles has received little attention in the research literature. Brunnstrom (1972), Markee et al. (1955), Steindler (1970), and Rasch and Burke (1971) discuss the biomechanical advantages and disadvantages of two-joint muscles which have potential excursions far beyond the range achieved by one-joint muscles. While this may be an advantage under certain conditions, such interaction may also expose the muscle to the hazards of stretching beyond safe limits (Brunnstrom 1972). The efficiency of the two-joint muscles is substantially influenced by the position of the two joints

in accordance with principles governing length-tension relationships of muscles. (The subject has received attention by Basmajian (1957), McLachlin (1969), Olson and Waterland (1967) and Paul (1969) among others.)

There is, however, an almost complete lack of descriptive information in the research literature on specific range of joint motion to show what happens to shoulder flexion, for example, when the elbow is flexed to two-thirds of its total joint range. In a heretofore unpublished piece of research prepared for the Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, Ohio, in 1971, Laubach and McConville reported on an experimental technique for the evaluation of range of motion of selected two-joint muscles. While emphasis in the study was on the development of a usable technique, some of the summary data are presented below.

Using 18 male subjects and a mock-up of a standard USAF aircraft seat (see Figure 1), investigators selected the following two-joint muscle actions for evaluation:

- (1) elbow flexion with shoulder extension
- (2) shoulder extension with elbow flexion
- (3) elbow flexion with shoulder flexion
- (4) shoulder flexion with elbow flexion
- (5) hip flexion with knee flexion
- (6) knee flexion with hip flexion
- (7) knee flexion with ankle plantar flexion
- (8) ankle plantar flexion with knee flexion
- (9) knee flexion with ankle dorsiflexion
- (10) ankle dorsiflexion with knee flexion

The experimental protocol for the determination of range of motion for two-joint muscles involved several steps. The range of motion for single joint muscle actions was established by photogoniometry. In our tests, a rapid-sequence camera was used to record the orientation of the segments at the beginning and end of a joint movement. Oversize prints were then made on which the range of motion could be measured. Range of motion for the two-joint muscles was evaluated using a combination of electrogoniometry and photogoniometry. The electrogoniometer was used to assure a positive fix for the distal joint at a point in its range of motion while the adjacent joint was being exercised.

The restrictions in joint motion caused by blockage with another body segment were ignored. For example, elbow flexion is greatly reduced when the shoulder is extended and rotated inward, a decrement caused by the forearm in flexion striking the posterior torso. Every attempt was made to isolate the joint motion to a pure motion in a single plane from a single joint.

Zero Positions for Measurement

A significant problem in studying two-joint muscles is defining the division of the range of movement between flexion and extension, adduction and abduction, etc. If we define the movement of the shoulder in the sagittal plane as extension and flexion, then we must define the origin of the two motions from a common point. In a general sense we might state that the point of origin of the two motions is with the upper arm hanging loosely at the side, or in the mid-axillary line or assuming some other specified orientation. Unless this origin is firmly established--while the total range of joint motion may remain the same--the values for flexion and extension may change radically and show a negative relationship with one another. It has been suggested that the proper measure of flexibility is the total range of motion without attempting to break it down into two discrete movements. Dickinson (1963), however, believes that the two movements which constitute the range of motion to be so poorly related that "adding these two measures of flexibility would be like adding apples and oranges" and suggests that a stable origin point is possible to achieve. We are of a similar opinion and in each instance have divided the total range of motion at a joint into a series of discrete movements. Figures 2-6 define the terminology which applies to the various movements studied and indicate their points of origin.

Test Procedures

The range of joint motion was obtained by measuring the angular change from sequential photos taken when a joint was rotated from its zero position to its maximum.

The generalized test procedure used in the study was as follows: A joint range base line was established for each of the joints to be tested. The base line was measured with the adjacent joints held in the zero position. Each joint was tested twice for agreement and the greater values were used as the joint range of motion. After the base line value was established the adjacent joint was moved to one of two or three intermediate positions (1/2 and total, or 1/3, 2/3 and total range) and the test joint was again exercised throughout its range. The procedure was then reversed with the joint first tested being held at an intermediate point of its range of motion and the adjacent joint being exercised.

The changes in range of motion of a given joint when supplemented by the movement of an adjacent joint are summarized in Table 5. Shown in this table are the base line values of given joint motions with the adjacent joint in neutral position; the increment or decrement which takes place when an adjacent joint is flexed or extended in varying amounts (1/3, 1/2, 2/3 and/or full); and the resulting value as a percentage of the baseline value. For example, the first entry on Table 5 is read as follows: the shoulder can be extended as far as 59.3° (the mean of the subjects tested) with the elbow in a neutral position (locked in hyper-extension). When shoulder extension was measured with the elbow flexed to 1/3 of its full joint range, the mean

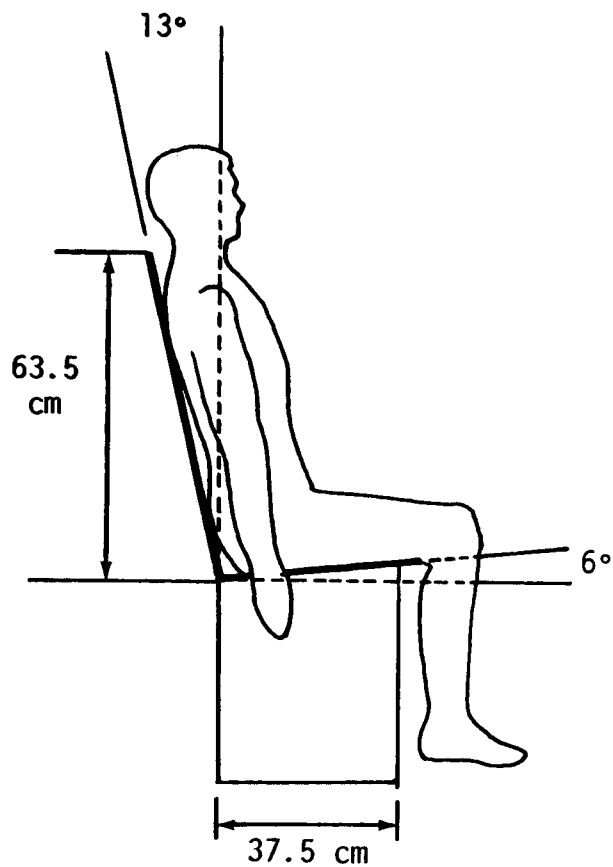


Figure 1. Two-joint muscle test apparatus.

----- Zero point:
located on the torso
from center of the
axilla to the iliac
crest.

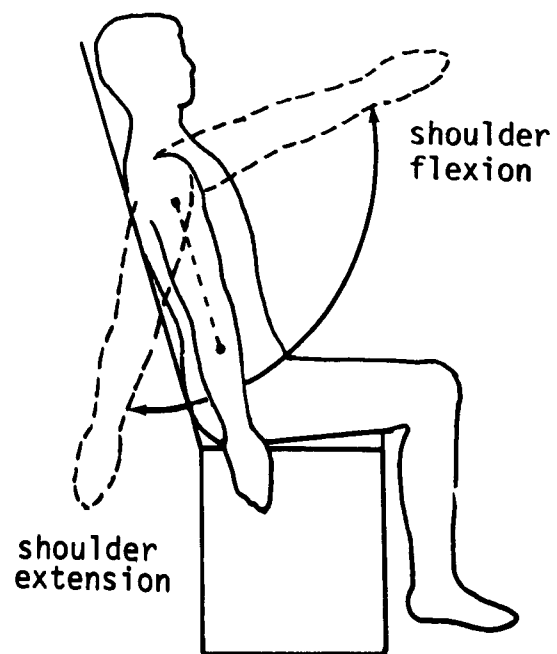


Figure 2. Shoulder extension-flexion.

— Zero point: elbow
locked in straight-arm position.

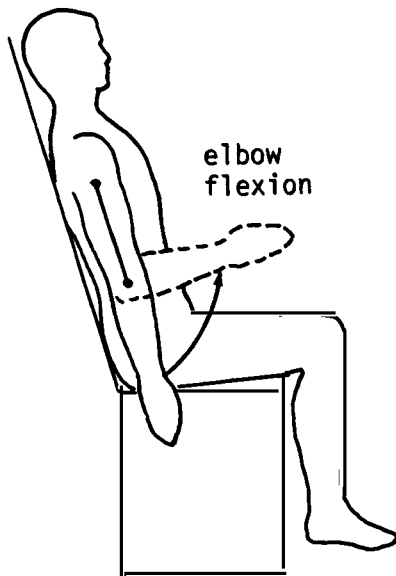


Figure 3. Elbow flexion.

— Zero point:
located along the
calf with the foot
resting on a platform
parallel to the floor.

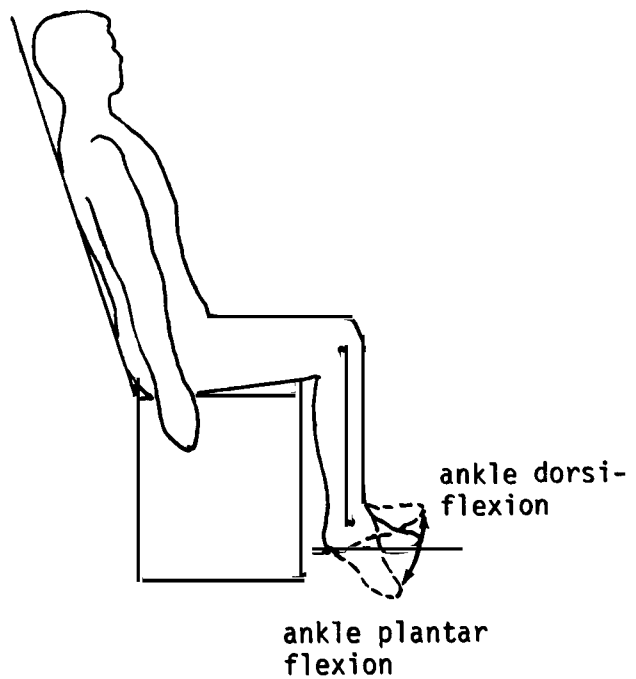


Figure 4. Ankle flexion.

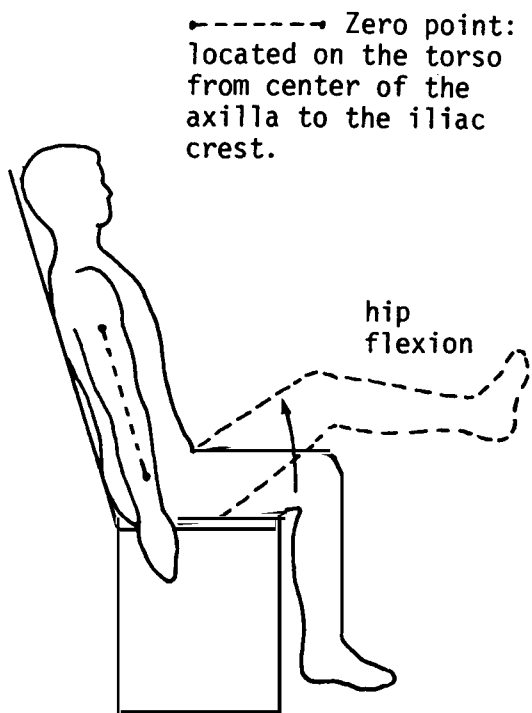


Figure 5. Hip flexion.

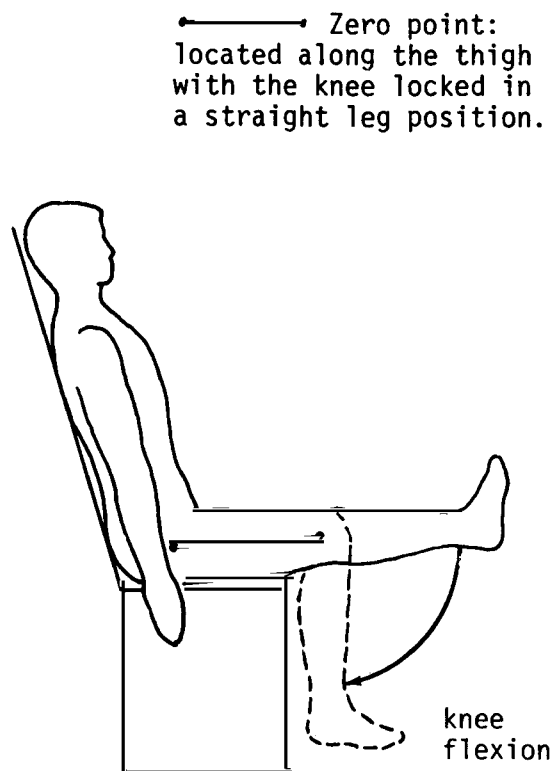


Figure 6. Knee flexion.

TABLE 5
RANGE OF MOTION OF TWO-JOINT MUSCLES

	Baseline	Zero	1/3	1/2	2/3	Full
Shoulder extension with elbow flexion	59.3°		+1.6° (102.7%)		+0.9° (101.5%)	+5.3° (108.9%)
Shoulder flexion with elbow flexion	190.7°		-24.9° (86.9%)		-36.1° (81.0%)	-47.4° (75.0%)
Elbow flexion with shoulder extension	152.2°			-3.78 (97.5%)		-1.22° (99.2%)
Elbow flexion with shoulder flexion	152.2°		-0.6° (99.6%)		-0.8° (99.5%)	-69.0° (54.7%)
Hip flexion with knee flexion	53.3°	-35.6°* (33.2%)	-24.0° (55.0%)		-6.2° (88.4%)	-12.3° (76.9%)
Ankle plantar flexion with knee flexion	48.0°		-3.4° (92.9%)		+0.2° (100.4%)	+1.6° (103.3%)
Ankle dorsiflexion with knee flexion	26.1°		-7.3° (72.0%)		-2.7° (89.7%)	-3.2° (87.7%)
Knee flexion with ankle plantar flexion	127.0°			-9.9° (92.2%)		-4.7° (96.3%)
Knee flexion with ankle dorsiflexion	127.0°					-8.7° (93.0%)
Knee flexion with hip flexion	127.0°			-19.6° (84.6%)		-33.6° (73.5%)

*The knee joint is locked and the unsupported leg extends out in front of the subject.

value of shoulder extension was found to increase by 1.6° or 102.7% of the base value. The results for the other movements and adjacent joint positions are presented in similar manner.

In a very general way these results suggest that:

(1) Shoulder extension is slightly enhanced with full flexion of the elbow.

(2) There is a marked decrement in shoulder flexion as the degree of elbow flexion increases.

(3) Elbow flexion is little reduced with varying degrees of shoulder flexion-extension except for the marked reduction when the shoulder is fully flexed. This test produced the largest variance in subject response, with some subjects showing little or no elbow flexion possible at full shoulder flexion while others showed only minor decrements.

(4) Hip flexion decrements occur with any variation from baseline position. It is believed that we are dealing with two factors here. In the zero (straight leg) and 1/3 knee flexion position the center of mass of the leg has moved distally and the weight of the unsupported leg out in front of the subject reduced significantly the subject's ability to flex his hip. In the 2/3 and full knee flexion positions we believe the data reflect more directly the effects of the two-joint muscle placement.

(5) Ankle plantar flexion is slightly enhanced by increased knee flexion.

(6) Ankle dorsiflexion is substantially reduced with knee flexion from the base position.

(7) Knee flexion is slightly reduced with ankle plantar and dorsiflexion and is markedly reduced with increased hip flexion.

There is an obvious need for more carefully controlled range of joint motion research. For NASA design engineers we recommend that the following list of standard movements, suggested by Roebuck et al. (1975), be assessed for space suit range of motion measurements.

- Neck Flexion-Extension
- Neck Lateral Flexion, Left and Right
- Forearm Supination-Pronation
- Wrist Palmar Flexion-Dorsiflexion
- Hip Abduction-Adduction
- Hip Flexion-Extension
- Shoulder Flexion-Extension
- Shoulder Abduction-Adduction
- Neck Rotation, Left and Right
- Shoulder Rotation, Inward and Outward
- Elbow Flexion-Extension

Wrist Radial Flexion-Ulnar Flexion
Hip Rotation, Outward and Inward
Ankle Flexion-Extension
Trunk Rotation, Right and Left
Shoulder Horizontal Adduction-Abduction
Knee Flexion-Extension and Hyperextension
Toe Dorsiflexion
Trunk Flexion-Extension
Trunk Lateral Flexion, Left and Right

Summary

A summary of our major findings and recommendations for design engineers are as follows:

- (1) The techniques of photography, goniometry, and the flexometer offer practical and realistic means of evaluating the range of joint motion.
- (2) The data presented in Table 1 compiled from Barter et al. (1957) can be used for "normative" values of range of joint motion data for adult males. Use the data presented in Table 2 compiled from Harris and Harris (1968) for females.
- (3) If it becomes necessary to estimate differences in the range of joint motion between the adult sexes, Table 3 reveals percentage differences for eight different joint range measurements.
- (4) Changes in range of joint motion caused by protective clothing can be significant but are usually suit-specific. Test procedures, such as the one recommended in this chapter, should be undertaken for each new NASA assembly.
- (5) Few descriptive data have been generated on the effects of interacting joints on motion. A test procedure has been described and a list of joint interactions relevant to space operations has been suggested for investigation.

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ADDITIONAL DATA SOURCES

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