LEVEL III

0

AD-A058716

PRELIMINARY DESIGN OF A FULL-SCALE, WEARABLE, EXOSKELETAL STRUCTURE

Prepared for:
Office of Naval Research
Psychological Sciences Division

FINAL REPORT
By: Neil J. Mizen
Contract No. NONR-3830(00)
CAL Project No. VO-1692-V-2

CORNELL AERONAUTICAL LABORATORY, INC.
OF CORNELL UNIVERSITY, BUFFALO 21, N. Y.

CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo, New York

PRELIMINARY DESIGN OF A FULL-SCALE, WEARABLE, EXOSKELETAL STRUCTURE

FINAL REPORT

Contract No. NONR-3830(00)
CAL Project No. VO-1692-V-2

Approved by Hugo S. Radt Jr.
Hugo S. Radt, Head
Land Vehicles Section
Vehicle Dynamics Dept.

Prepared by Neil J. Mizen
Neil J. Mizen
Project Engineer
Vehicle Dynamics Dept.

Approved by
Leonard Segel, Asst. Head
Vehicle Dynamics Dept.

Prepared for Office of Naval Research
Psychological Sciences Division

Reproduction of this report in whole or in part is permitted for any purpose of the United States Government

FOREWORD

This report describes the work performed by the Cornell Aeronautical Laboratory under Contract No. NONR-3830(00), sponsored by the Office of Naval Research of the Department of the Navy. The time period covered is from 16 April 1962 to 15 February 1963. The program was conducted under the direction of Dr. Gilbert C. Tolhurst, Code 454, Psychological Sciences Division, Office of Naval Research.

ABSTRACT

A preliminary investigation leading to the design of a wearable, full-scale exoskeleton is described. The proposed exoskeleton is intended (1) to follow the major movements of the wearer (except for the fingers, toes, and neck), and (2) to be adjustable so that it can be worn by different subjects. A feature of the proposed exoskeleton is that each exoskeletal joint has adjustable stops that can be used to limit the range of motion. Dimensions of the links between the joints of the exoskeleton have been specified on the basis that the resultant structure should be able to resist any combination of muscular forces caused by the wearer. The weight and inertia are estimated for the arm complex of the exoskeleton.

TABLE OF CONTENTS

Page No.

FOREWORD i

ABSTRACT ii

TABLE OF CONTENTS iii

LIST OF FIGURES iv

LIST OF TABLES v

1. INTRODUCTION 1

2. DESIGN OF BASIC EXOSKELETAL JOINTS 4

3. PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE 10

  3.1 Anatomical Factors Governing Basic Joint Design 10

    3.1.1 Shoulder-Arm-Wrist Complex 10

    3.1.2 Spine Complex 14

    3.1.3 Lower-Extremity Complex 17

  3.2 Sketches of the Assembled Exoskeletal Structure 21

  3.3 General Dimensions of the Human Body 25

4. STRUCTURAL ANALYSIS OF THE EXOSKELETON 29

5. WEIGHTS AND INERTIAS OF THE EXOSKELETON 34

6. CONCLUDING REMARKS 35

7. LIST OF REFERENCES 36

8. APPENDICES 39

  8.1 Data on Human Limb Movement 39

  8.2 Bibliography 42

LIST OF FIGURES

Figure No.	Description	Page No.
1	DEGREES OF FREEDOM	5
2A	BASIC JOINTS	7
2B	BASIC JOINTS (CONTINUED)	8
2C	BASIC JOINTS (CONTINUED)	9
3	EXOSKELETAL JOINT TO PERMIT MOTION OF THE SCAPULA RELATIVE TO THE SPINE	11
4	EXOSKELETAL JOINT TO PERMIT MOTION OF THE HUMERUS RELATIVE TO THE SCAPULA	13
5	EXOSKELETAL JOINT TO PERMIT UPPER ARM (HUMERUS) ROTATION	15
6	EXOSKELETAL JOINT TO PERMIT WRIST MOTION	16
7	EXOSKELETAL JOINT TO PERMIT SPINAL COLUMN MOTION	18
8	EXOSKELETAL JOINT TO PERMIT HIP MOTION	20
9	EXOSKELETAL JOINT TO PERMIT ANKLE AND FOOT MOTION	22
10	PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE SHOULDER-ARM-WRIST COMPLEX	23
11	PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE SPINAL COLUMN	24
12	PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE LOWER EXTREMITY	26
13	BODY DIMENSIONS	27 & 28
14	FORCES REACTED BY THE UPPER-EXTREMITY EXOSKELETON	30
15	FORCES REACTED BY THE LOWER-EXTREMITY EXOSKELETON	31
16	HUMAN BODY MOVEMENTS	40

LIST OF TABLES

Table No.	Description	Page No.
1	FORCES REACTED WITHIN THE EXOSKELETON	32
2	CROSS-SECTIONAL DIMENSION OF EXOSKELETAL LINKS	33
3	PHYSICAL PROPERTIES OF THE SHOULDER-ARM-WRIST COMPLEX	34
4	RANGE OF HUMAN BODY MOVEMENTS	41

1. INTRODUCTION

The Man Amplifier, as conceived by Cornell Aeronautical Laboratory, Inc., (CAL), is an exoskeleton, employing powered joints, that is worn by a man to augment and amplify his muscular strength and to increase his endurance in the performance of tasks requiring large amounts of physical exertion.

In the developed concept, the Man Amplifier would consist of a structural exoskeleton with appropriate articulated joints, compatible with those of man. All external loads, as well as the weight of the Man Amplifier itself, are borne by this structural skeleton. Each joint is powered by one or more servomotors which provide the necessary torques and power boost. These servomotors (1) respond to the outputs of sensors linking man and machine and (2) cause the appropriate mechanism to follow the natural motion of its human counterpart. In the original concept, a portable, self-contained power pack is attached to the back of the exoskeleton to provide the necessary power.

Preliminary investigations* of the Man Amplifier concept (Reference 14) consisted of (1) analytical studies to define some of the major problem areas which must be examined in detail before the technical feasibility of the concept can be established, and (2) experiments, using the CAL elbow-joint amplifier, to obtain a preliminary indication of man-machine compatibility.

---

* Sponsored by the Aerospace Medical Division, Air Force Systems Command under Contract No. AF 18(600)-1922.

It was concluded that: (1) duplication, in the Man Amplifier, of all the human motion capability is impractical, (2) experimentation is necessary to determine the essential joints, motion ranges and dynamic responses, (3) the inability to counter the overturning moments will, in many instances, limit the load-handling capability of the Man Amplifier, (4) conventional valve-controlled hydraulic servos are unsuitable for the Man Amplifier, and (5) particularly difficult problems will be encountered in the general areas of mechanical design, sensors and servomechanisms.

CAL is conducting, during the present program, an investigation of the compatibility existing between a human occupant and an exoskeletal structure possessing limited joint degrees of freedom. The ultimate objective of this program is the determination of the feasibility of surrounding the human with a powered exoskeleton in such manner that he is able to perform tasks applicable to a military mission. This report summarizes the studies that were performed, during the present contract, to (1) select arrangements of and (2) generate a preliminary design for a non-powered exoskeletal structure. The design is intended to represent a reasonable compromise between the need to accommodate the essential joint motions of the human body and the need to produce a device that can be installed on and worn by a human operator.

It is postulated that the exoskeletal structure described in this report can be used to determine qualitatively, the minimal number of joints (and their location) that must be provided in an exoskeletal structure, in order that the wearer can perform certain tasks.

Section 2 of this report presents the preliminary design of three basic exoskeletal joints. Section 3 presents the preliminary design of the overall exoskeleton, wherein basic exoskeletal joints are combined to permit the essential movements of the wearer (finger, toe and neck movements are excluded). Dimensions of the human body, pertinent to the design of the exoskeleton, and the ranges of dimensions required to include 90 percent of the adult, male population are also presented.

Section 4 presents the forces that the non-amplified exoskeleton must resist when the ranges of motion of the mechanical joints are restricted. The cross-sectional dimensions of the exoskeletal links necessary to enable the exoskeleton to resist these forces without yielding are also presented. Section 5 contains a comparison between the physical properties (weight, inertia) of the average human arm and the arm complex of the exoskeleton. Concluding remarks are made in Section 6.

Appendix 8. 1 presents a list of all movements (and the range of each movement) that have been provided in the exoskeleton to accommodate the upper extremity, trunk, and lower extremity. A bibliography is presented in Appendix 8. 2.

2. DESIGN OF BASIC EXOSKELETAL JOINTS

The following factors are considered requirements for proper design of the exoskeletal joints: (a) the joints must permit at least the same range of motion as their human counterpart, (b) the joints must be small to minimize interference with the wearer, (c) the joint must be light in weight, (d) the joint must have mechanisms to limit the motion in each degree of freedom, (e) the joint must have extremely low friction (i. e., with high friction, effort required by the wearer to move a joint will, in itself, cause degradation of performance), and (f) the joints should be similar to one another, mechanically speaking, for ease of design and fabrication.

It has been found (Reference 1) that a point fixed on one body member moves very nearly in a circular path, relative to the adjacent member. Further, Reference 2 states that a circle of one-half to three-quarters inch diameter will enclose the path of the instant center of rotation for most human joints. Consequently, nearly all orthopaedic appliances and prosthetic devices use pinned joints. Some orthopaedic appliances do allow the instantaneous center of rotation to shift; however, the fact that these devices are not widely used leads us to infer that the resulting improvement in simulation of the motion of the joint does not warrant the additional complexity and expense. Because of the above considerations, a decision was made to use pinned joints in the design of the non-powered exoskeleton.

If the motion of a human joint is matched, approximately, by exoskeletal joints with fixed centers of rotation, (i. e., pinned joints) the motion of any exoskeletal joint is limited to three or fewer degrees of freedom. The three degrees of freedom are the three angles of rotation, φ, θ, and ψ, shown in Figure 1.

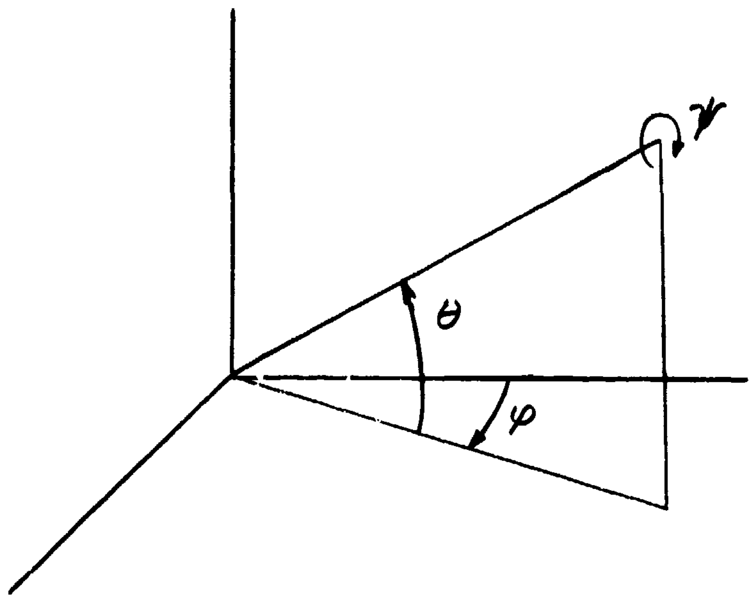


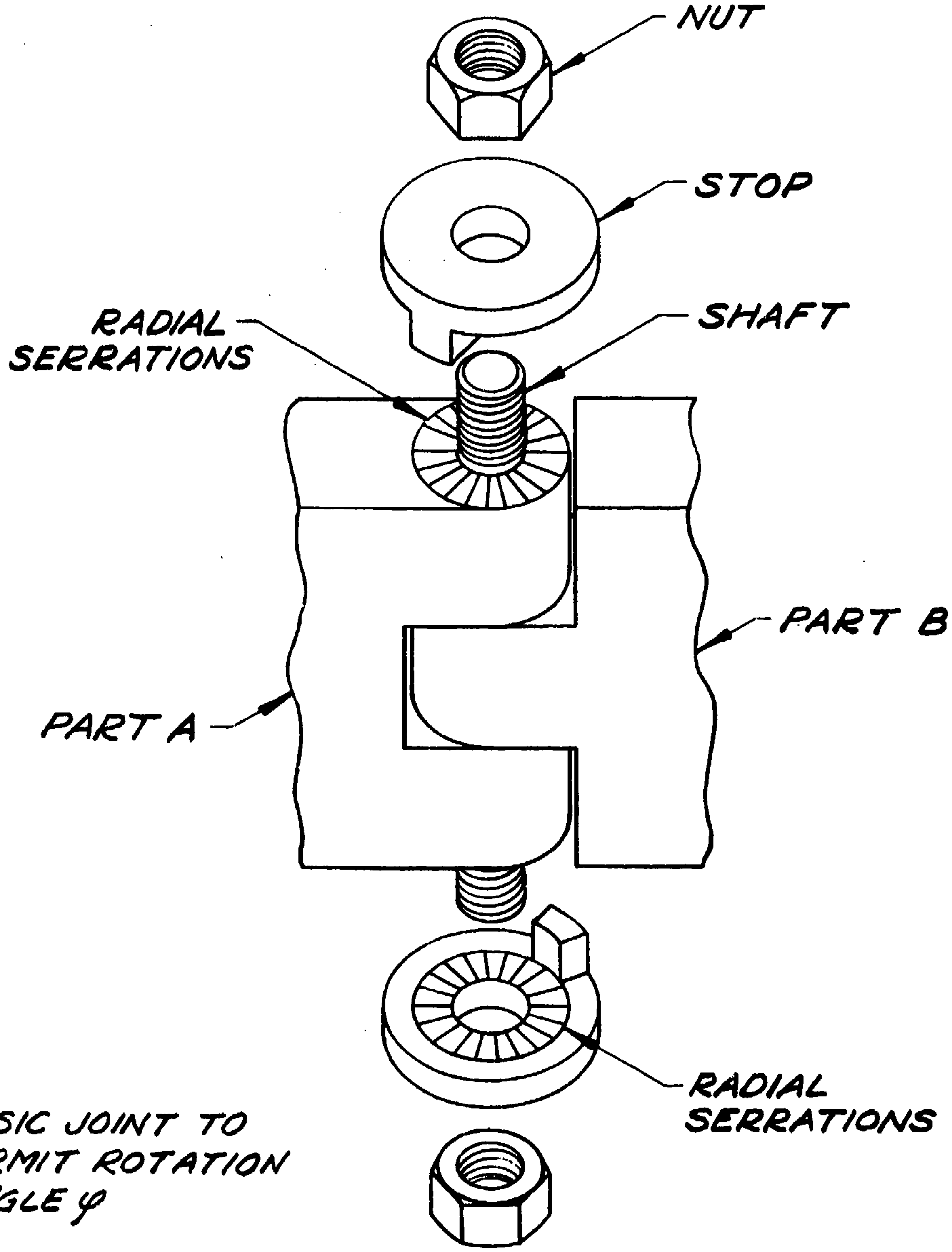
FIGURE 1 - DEGREES OF FREEDOM

Rotation through these angles may be produced in the exoskeleton by combining the mechanisms shown in Figure 2. "Stops", shown on each joint in Figure 2, can be used to limit the range of rotation.

The operation and adjustment of the stops of the joint shown in Figure 2A, can be described as follows. Parts A and B are free to rotate about the shaft. The two outer surfaces of Part A, adjacent to the shaft, are serrated. The stops have mating serrations so that tightening the nuts locks the stops firmly to Part A. Protrusions on the stops limit the motion of Part B relative to Part A. Adjustment of the range of rotation between stops is made by placing the stops in different positions and tightening the nuts. The operation of the joint shown in Figure 2B can be described in a similar manner. Part A is free to rotate on the hinge shaft, and the shaft is fixed to Part B. The clamping screw fastens the stops to the shaft, and mating serrations hold the stops in place. Protrusions on the stops contact a protrusion on Part A, thus limiting the range of rotation. Adjustment of the limits of rotation is made by rotating the two stops relative to Part A and reclamping.

In Figure 2C, Parts A and B are sections of cylinders, able to slide relative to each other but held in contact by Part C. Part D, (two parts are required, but only one is shown) clamped to Part A, limits the relative motion. The limits of rotation are adjusted by changing the position of Part D. This joint is shown assembled in Figure 5.

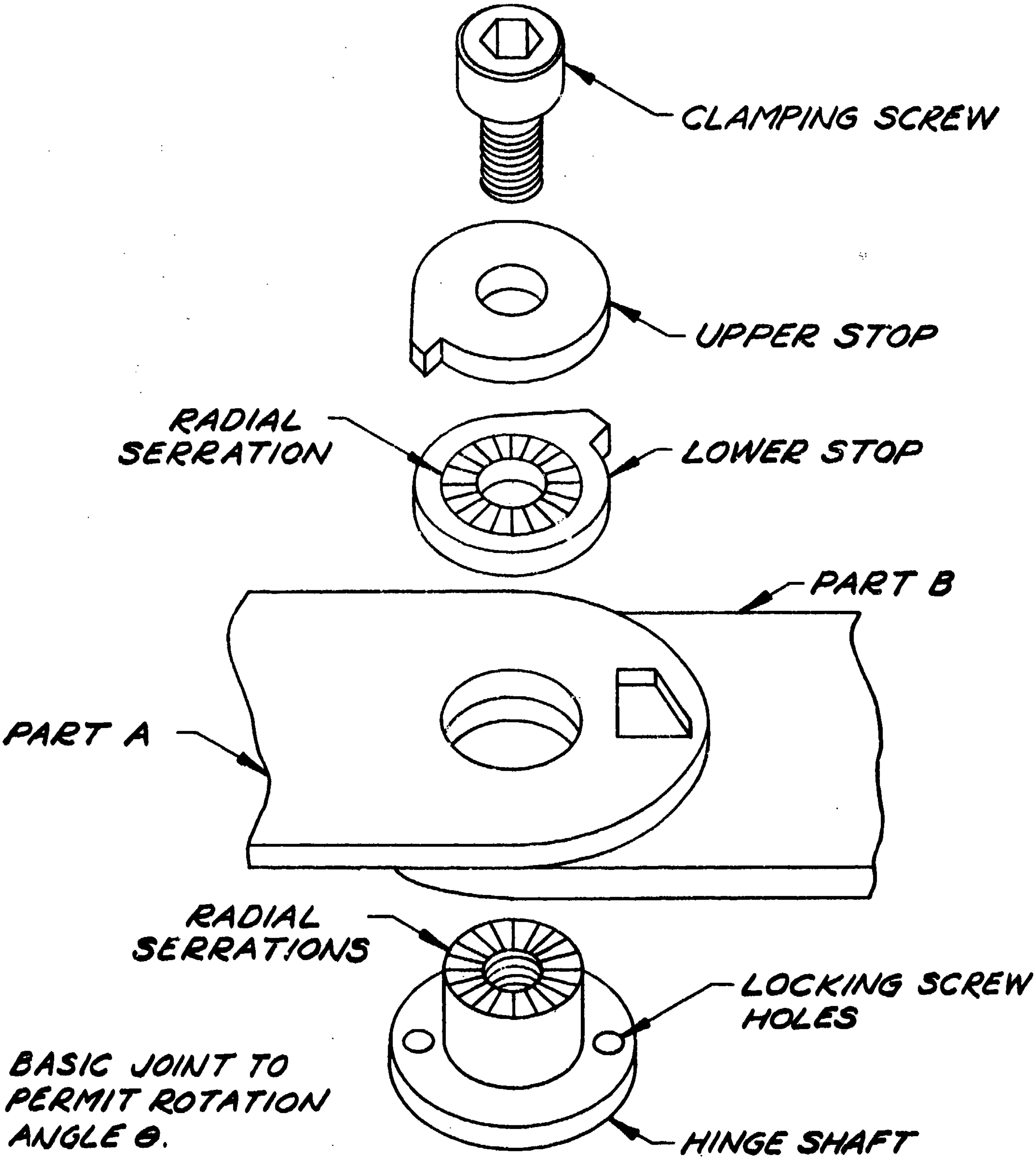
The basic joints shown in Figure 2 can be used to construct the entire joint system of the exoskeleton (except the spine where a different configuration is desirable) because they can be appropriately combined to permit all degrees of freedom of a joint. Section 3 describes how movement of each human joint is matched approximately by the appropriate selection of the basic joints.



BASIC JOINT TO PERMIT ROTATION ANGLE φ

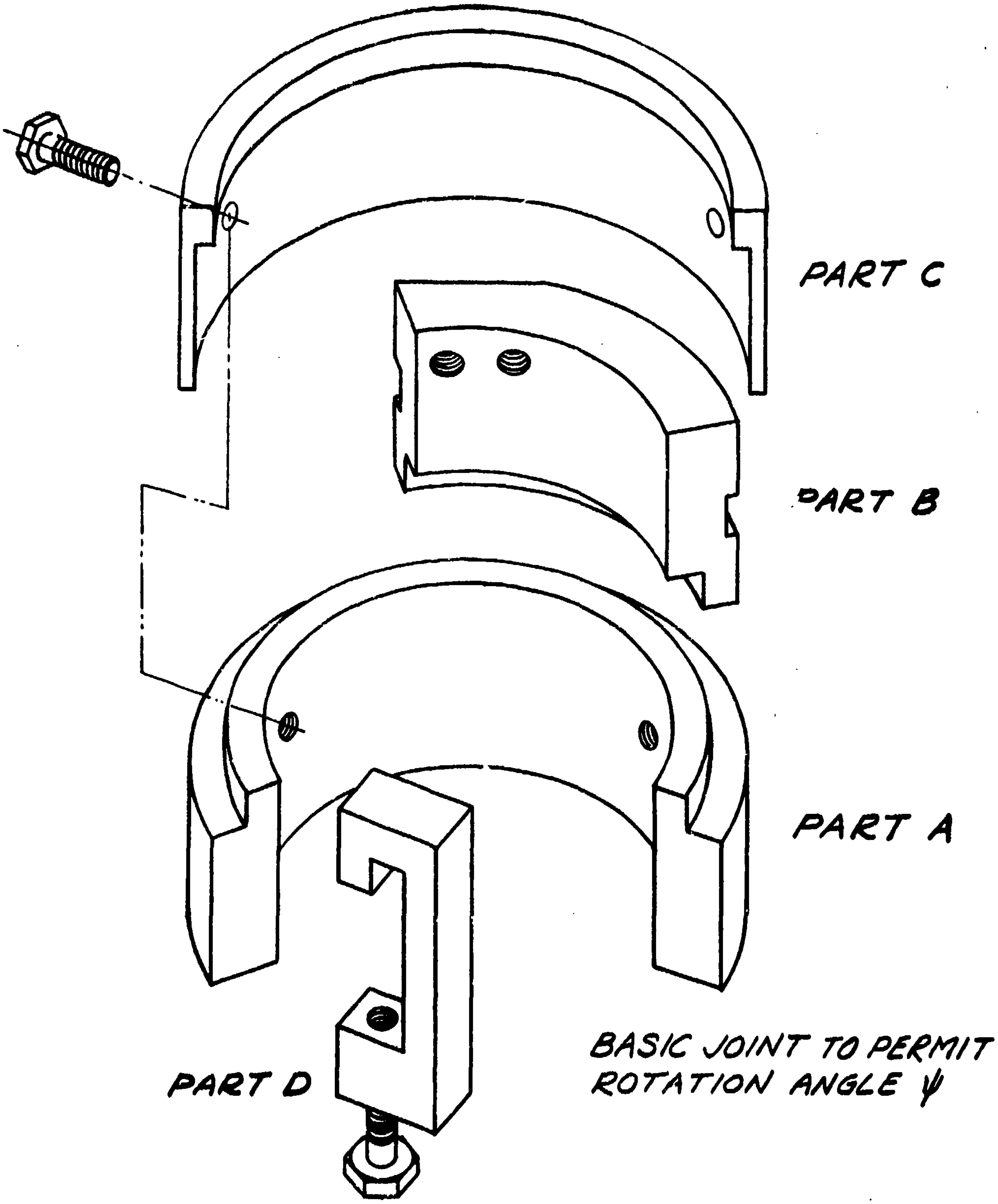
BASIC JOINTS

FIGURE 2A



BASIC JOINT TO PERMIT ROTATION ANGLE θ.

BASIC JOINTS (CONTINUED)
FIGURE 2 B



BASIC JOINT TO PERMIT ROTATION ANGLE ψ

BASIC JOINTS (CONTINUED)

FIGURE 2C

3. PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE

3.1 Anatomical Factors Governing Selection of Basic Joints

The motion of each joint in the human skeleton is discussed below, in relationship to the manner in which the exoskeleton permits the wearer to perform normal body motions. Sketches of assembled portions of the exoskeleton are included where appropriate, and sketches of complete assemblies of the exoskeleton, showing all exoskeletal joints, are presented in Section 3.2.

3.1.1 Shoulder-Arm-Wrist Complex

The scapula, or shoulder girdle, can be abducted, adducted and rotated. These motions, shown in Figure 16, page 40, as movements A and B, are permitted in the exoskeleton by four axes of rotation, two for each shoulder (axes A and B in Figure 10, page 23). Reference 1 states that the center of the circular path that approximates the motion of the scapula is at the intersection of the humeral axis and sagittal plane. The exoskeletal joint cannot be located at this point within the body; therefore, it has been placed near the sagittal plane at the back of the wearer. Some relative motion will occur between the exoskeleton and the shoulder because the exoskeletal joint is not located at the equivalent center of rotation of the scapula; however, the relative rotation of the scapula on the thoracic wall is small, thus the motion between the exoskeleton and shoulder will also be small. A sketch of the exoskeletal joint to permit motion of the scapula is shown in Figure 3.

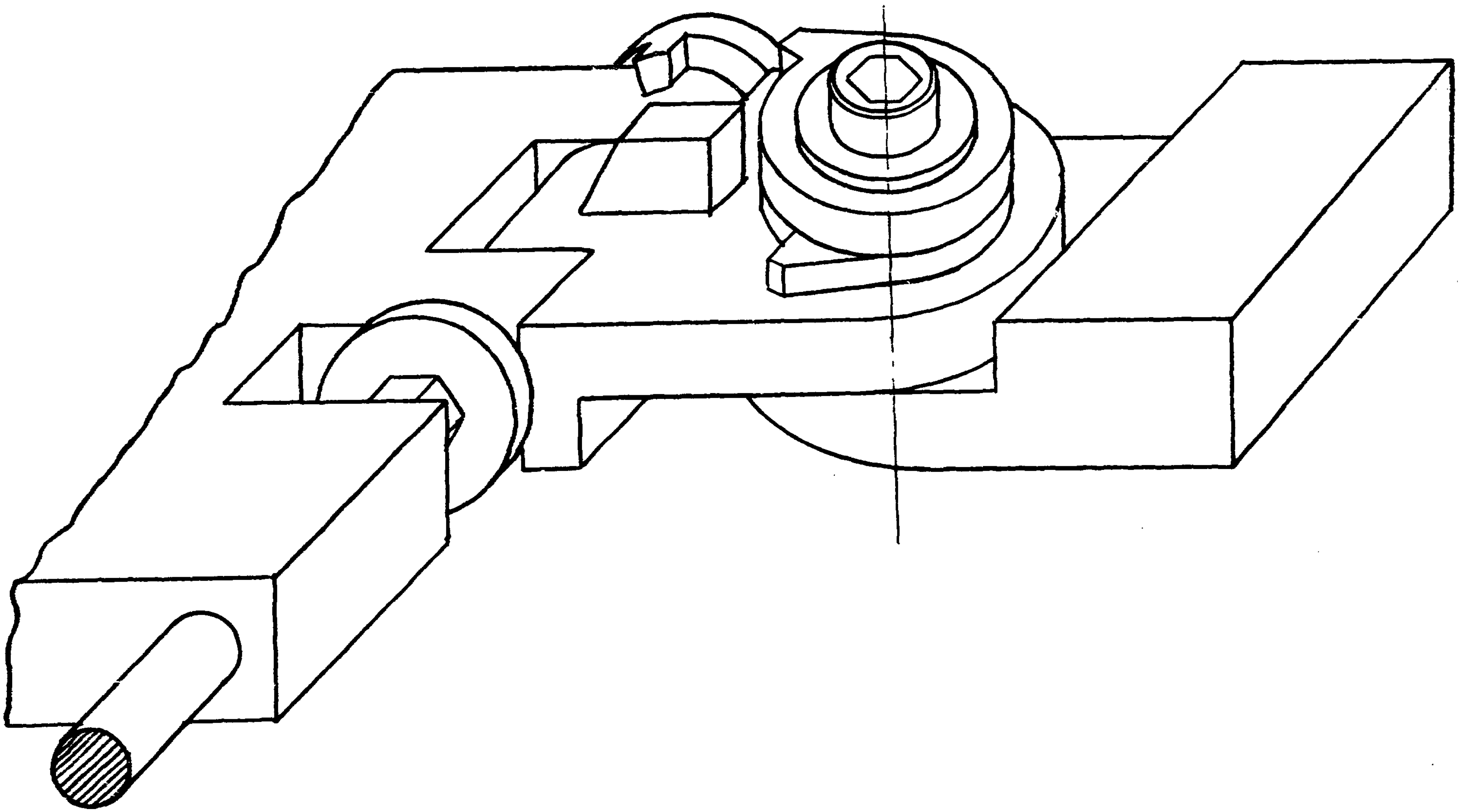


FIGURE 3 EXOSKELETAL JOINT TO PERMIT MOTION OF THE SHOULDER GIRDLE

The humerus, or upper arm, can be moved relative to the scapula in the following ways:

1) flexion, extension and forward elevation, (Figure 16, movement C)

2) abduction, adduction and sideward elevation, (Figure 16, movement D)

3) internal and external rotation, (Figure 16, movement E).

Flexion, extension and forward elevation are permitted in the exoskeleton by rotation about an axis passing through the joint between the humerus and scapula (Figure 10, axis C). Flexion and extension of the upper arm, after sideward elevation, is permitted in the exoskeleton by a joint located above the shoulder, with the axis passing through the shoulder joint (Figure 10, axis C'). Abduction, adduction and sideward elevation are permitted in the exoskeleton by two parallel axes located above the shoulder (Figure 10, axes D and D'). Both of these axes, rather than one axis in front of or behind the shoulder, are used for the following reason. Any mechanical device in front of the shoulder would prevent the wearer from first elevating his arm sideward and then adducting it. Similarly, any mechanical device behind the shoulder would prevent the wearer from first elevating his arm forward and then abducting it. The two parallel axes are not coincident with the axis of the joint between the scapula and the humerus; however, rotation about each axis is independent so that the center of rotation of the exoskeletal joint is not held fixed but is free to match the motion of the instant center of rotation of the human skeleton. A sketch of this joint is shown in Figure 4.

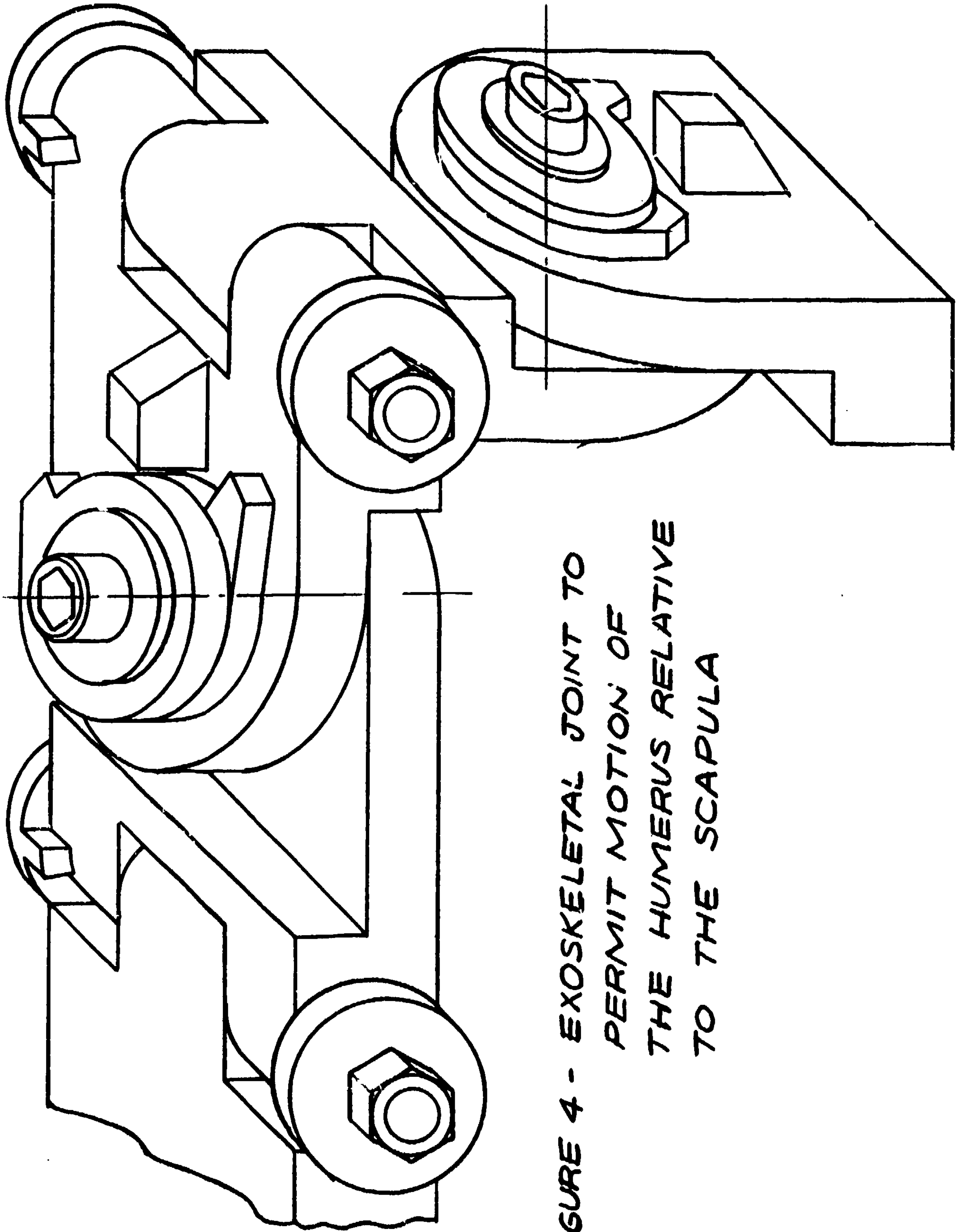


FIGURE 4 - EXOSKELETAL JOINT TO PERMIT MOTION OF THE HUMERUS RELATIVE TO THE SCAPULA

Internal and external rotation of the upper arm are permitted in the exoskeleton by a sleeve located between the elbow and shoulder of the wearer (Figure 10, axis E). A sketch of this exoskeletal joint is shown in Figure 5.

The elbow joint is capable of flexion - extension (Figure 16, axis F) and supination - pronation (Figure 16, axis G). Elbow flexion - extension is permitted in the exoskeleton by a pinned joint, with the axis of rotation passing through the elbow joint of the wearer (Figure 10, axis F). Supination - pronation is permitted in the exoskeleton by a sleeve located between the wrist and elbow of the wearer (Figure 10, axis G), similar to the sleeve for the upper arm.

Wrist extension - flexion (Figure 16, movement H) and ulnar - radial deviation (Figure 16, movement I) are permitted in the exoskeleton by two perpendicular axes (Figure 10, axes H and I), crossing at the approximate center of the wrist joint. A sketch of this exoskeletal joint is shown in Figure 6. A handgrip is provided for attaching "hand" devices and to cause the wrist of the exoskeleton to follow the movement of the wearer.

3.1.2 Spine Complex

The spinal column is capable of the following motions:

1) lateral, sideward, flexion (Figure 16, movement J),
2) forward flexion and hyperextension (Figure 16, movement K),
3) rotation (Figure 16, movement L).

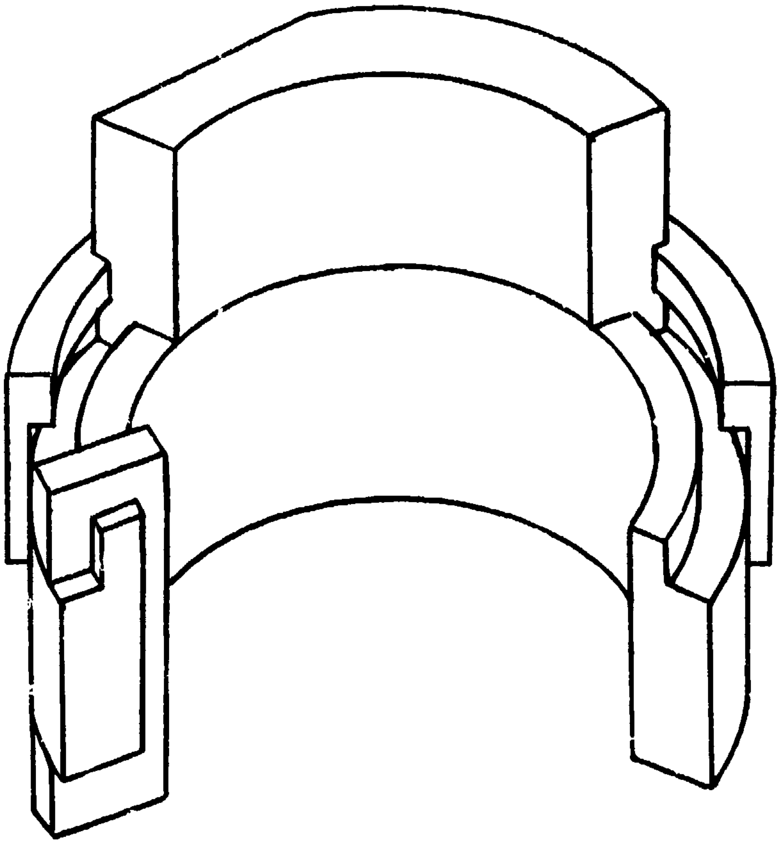
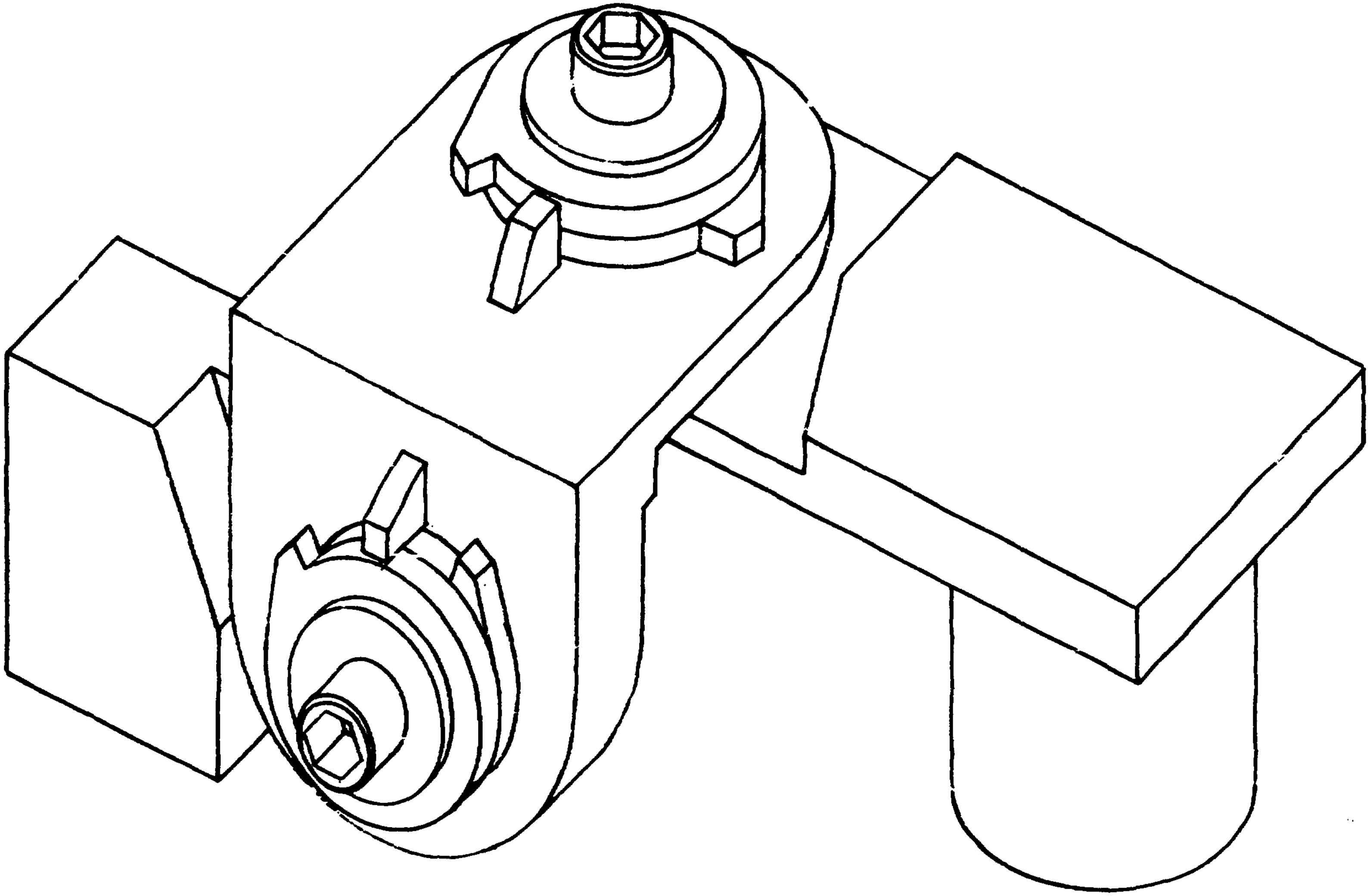


FIGURE 5 - EXOSKELETAL JOINT TO PERMIT UPPER ARM (HUMERUS) ROTATION



EXOSKELETAL JOINT TO PERMIT WRIST MOTION

FIGURE 6

Lateral flexion is permitted in the exoskeleton by an axis lying in the sagittal plane and located near the waist of the wearer (Figure 11, axis J, page 24). Flexion and hyperextension is permitted in the exoskeleton by an axis of rotation that is perpendicular to the sagittal plane and located near the waist of the wearer (Figure 11, axis K). Rotation is permitted in the exoskeleton by an axis of rotation located along the back of the wearer. (Figure 11, axis L).

The above exoskeletal axes are not located at the approximate center of rotation for spinal column motion because, first, the instant centers of rotation are within the body, and second, the motion of the spine is the result of the motion of many small bones and thus does not have a fixed center of rotation. The effect of distance between the center of the exoskeletal joint and the instant center of rotation of the human body is to lengthen or shorten the exoskeletal spinal column during the movements. Therefore, a sliding joint (Figure 11, along axis L') is included in the exoskeletal spinal column. Figure 7 shows the exoskeletal sliding joint that permits spinal column motion.

3.1.3 Lower-Extremity Complex

The hip joint is capable of the following movements:

1) flexion, extension and hyperextension (Figure 16, movement M),
2) adduction and abduction (Figure 16, movement N),
3) inward and outward rotation (Figure 16, movement P).

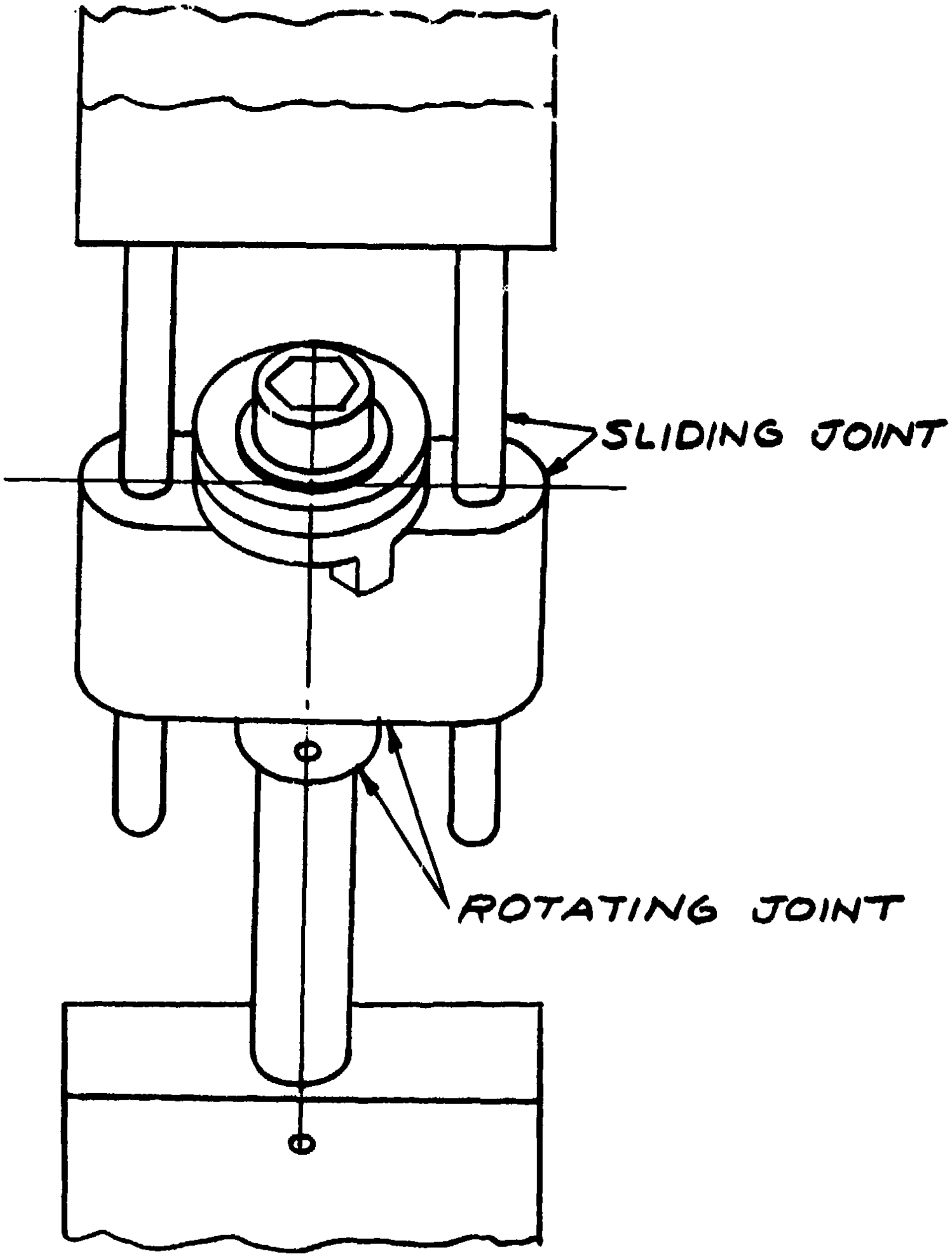


FIGURE 7 - EXOSKELETAL JOINT TO PERMIT SPINAL COLUMN MOTION

Flexion, extension and hyperextension are permitted in the exoskeleton by an axis of rotation perpendicular to the sagittal plane (in the neutral position) and passing through the hip joint (Figure 12, axis M, page 26). Adduction and abduction are permitted in the exoskeleton by a rotational axis parallel to the sagittal plane and passing through the hip joint (Figure 12, axis N). Rotation is permitted in the exoskeleton by a rotating sleeve (similar in design to Figure 5) placed between the hip and the knee (Figure 12, axis P). The rotating sleeve follows motion of the upper leg and therefore is able to permit inward and outward rotation in any leg position. A sketch of the exoskeletal joint that permits flexion, extension, abduction and adduction is shown in Figure 8.

Flexion and extension of the knee (Figure 16, axis Q) are permitted in the exoskeleton by an axis of rotation passing through the knee (Figure 12, axis Q).

Dorsal and plantar flexion of the ankle (Figure 16, axis R) is permitted in the exoskeleton by an axis of rotation passing through the ankle joint (Figure 12, axis R).

The foot is capable of adduction - abduction (Figure 16, movement S), inversion - eversion (Figure 16, movement T) and flexion - hyperextension (Figure 16, movement U). Adduction and abduction are permitted in the exoskeleton by an axis of rotation perpendicular to the ground (in the neutral position) and located behind and outward from the leg (Figure 12, axis S). This axis is not located at the approximate center of rotation. However, the range of movement is small (10 deg. total motion); thus the relative motion between the wearer and the exoskeleton will be small. Inversion and eversion are permitted in the exoskeleton by a pinned joint located behind the foot of the wearer, with the axis of rotation passing through the joint between the ankle and the foot (Figure 12, axis T). Flexion and hyperextension are permitted in the exoskeleton by a separation in the foot plate (Figure 12, axis U). Both

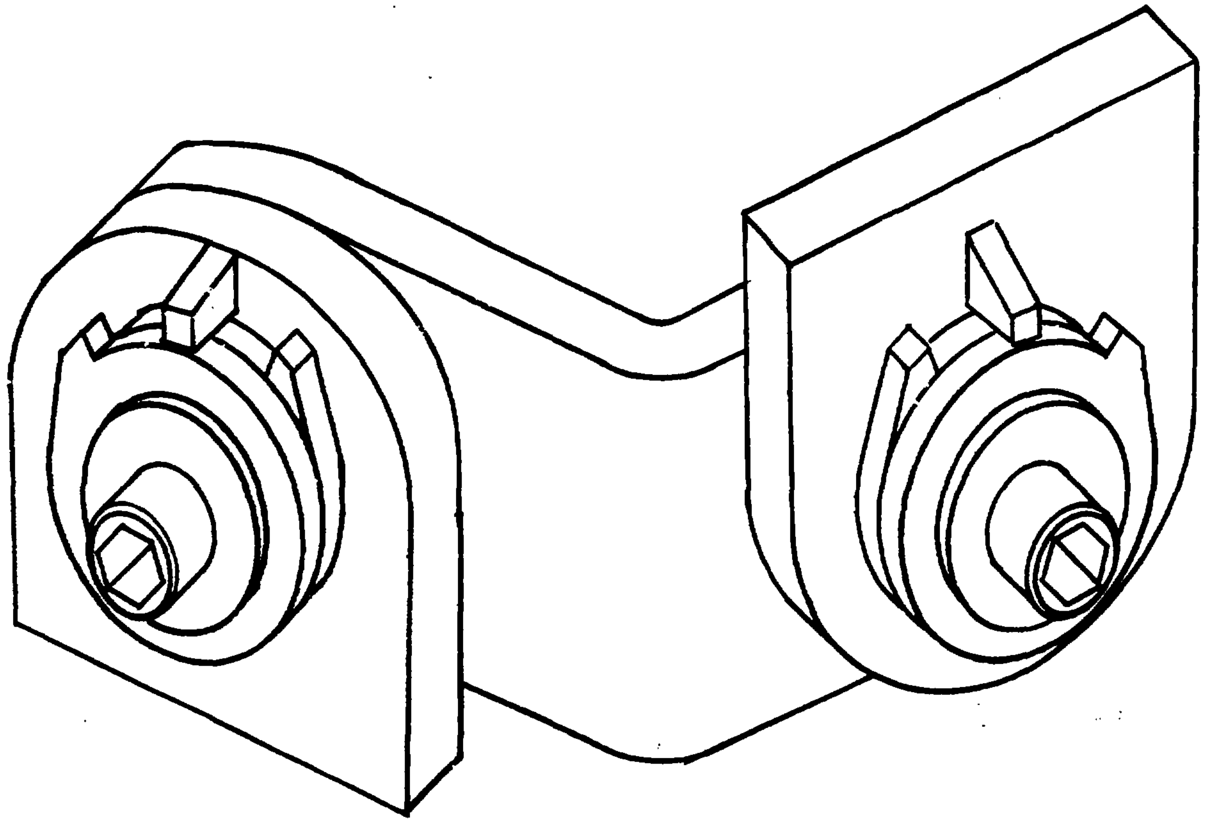


FIGURE 8 - EXOSKELETON JOINT TO PERMIT HIP MOTION

sections of the foot plate are attached to the wearer's shoe. The separation permits the shoe to flex, and thus permits flexion and hyperextension of the foot. A drawing of the exoskeletal joint for the foot and ankle joint is shown in Figure 9.

3.2 Sketches of the Preliminary Design of the Assembled Exoskeletal Structure

Figure 10 is a sketch of the exoskeletal structure proposed for the shoulder-arm-wrist complex. The unit is attached to the wearer in the following manner. A shoulder harness supports the exoskeletal joint at the back of the wearer (axes A and B). A yoke is provided at each shoulder to cause the exoskeletal joint to follow movement of the shoulder during scapula, or shoulder girdle, motion. A handgrip and arm strap are provided to cause the exoskeletal wrist joint to follow the wearer's motion.

When the upper arm is elevated to the horizontal position axes C and C' become parallel and thus become redundant. Likewise, when the upper arm is in the neutral position axes C' and E are redundant. Therefore, an arm strap is provided at the upper arm to cause the exoskeletal link to follow motion of the upper arm for the positions when the axes are redundant.

Figure 11 is a sketch of the exoskeletal structure for the spinal column. The top of the unit is supported by the shoulder harness mentioned above, and the bottom of the unit is supported by a waist harness.

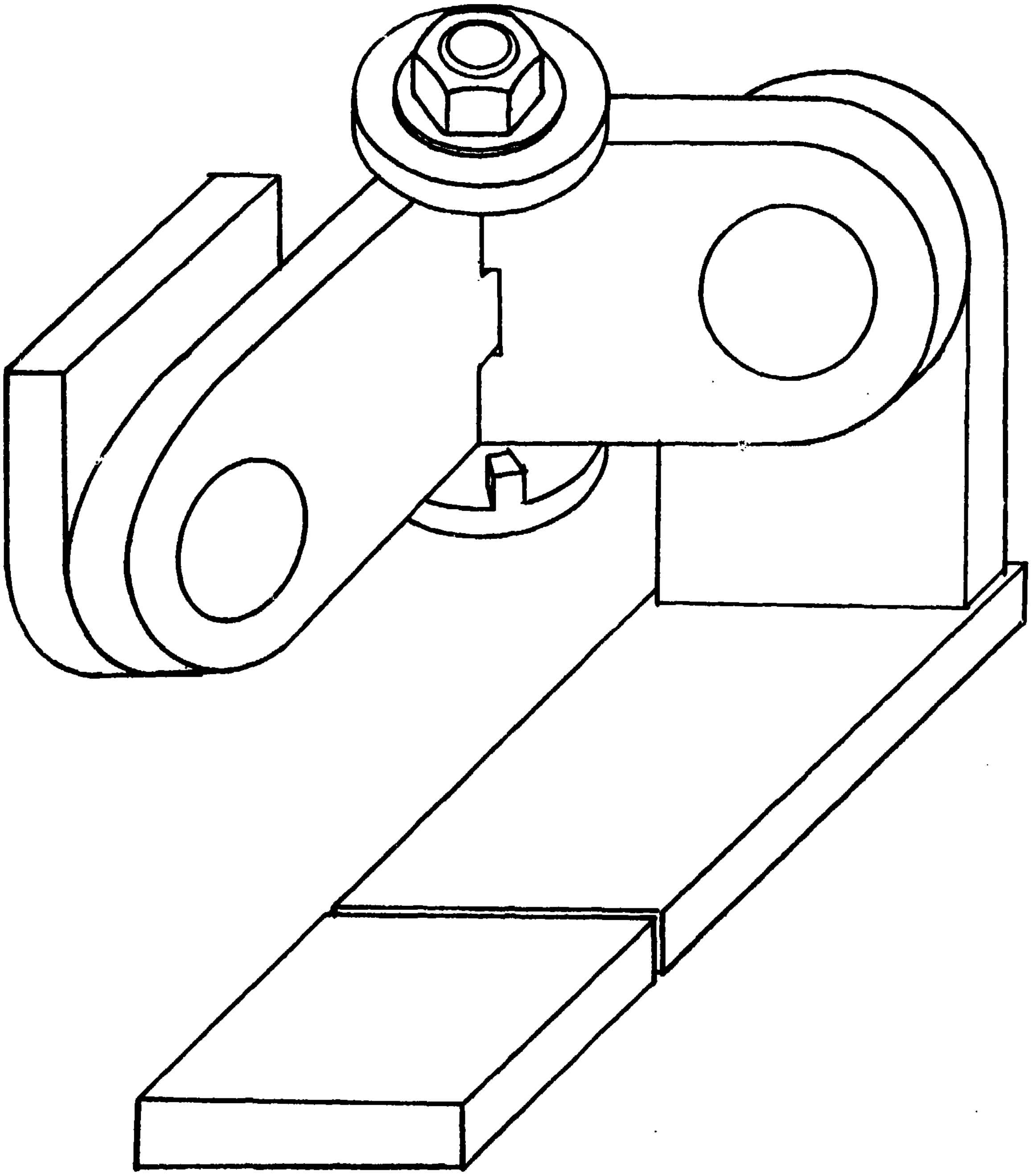


FIGURE 9 - EXOSKELETAL JOINT TO PERMIT FOOT AND ANKLE MOTION

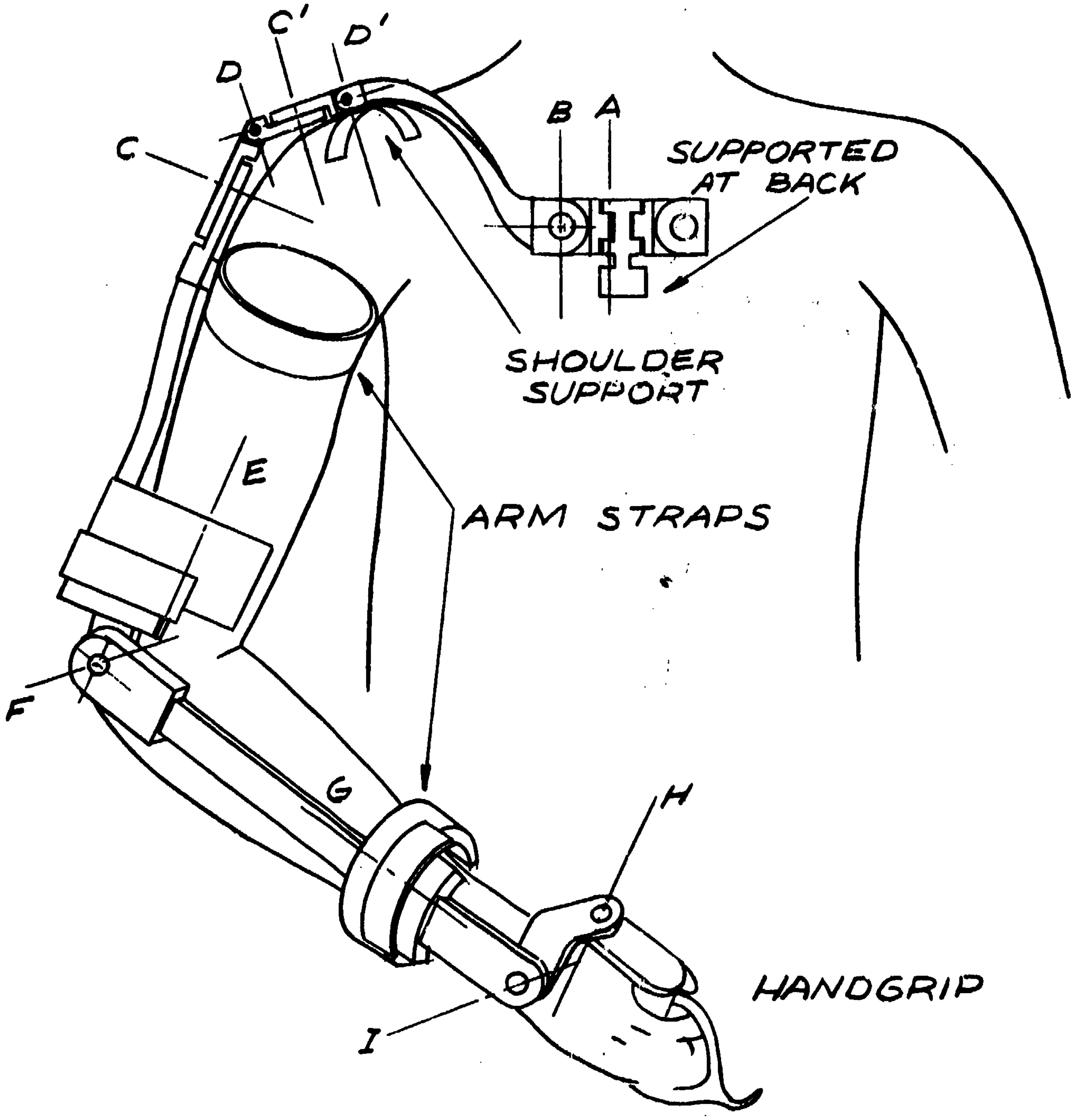


FIGURE 10 - PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE SHOULDER-ARM-WRIST COMPLEX

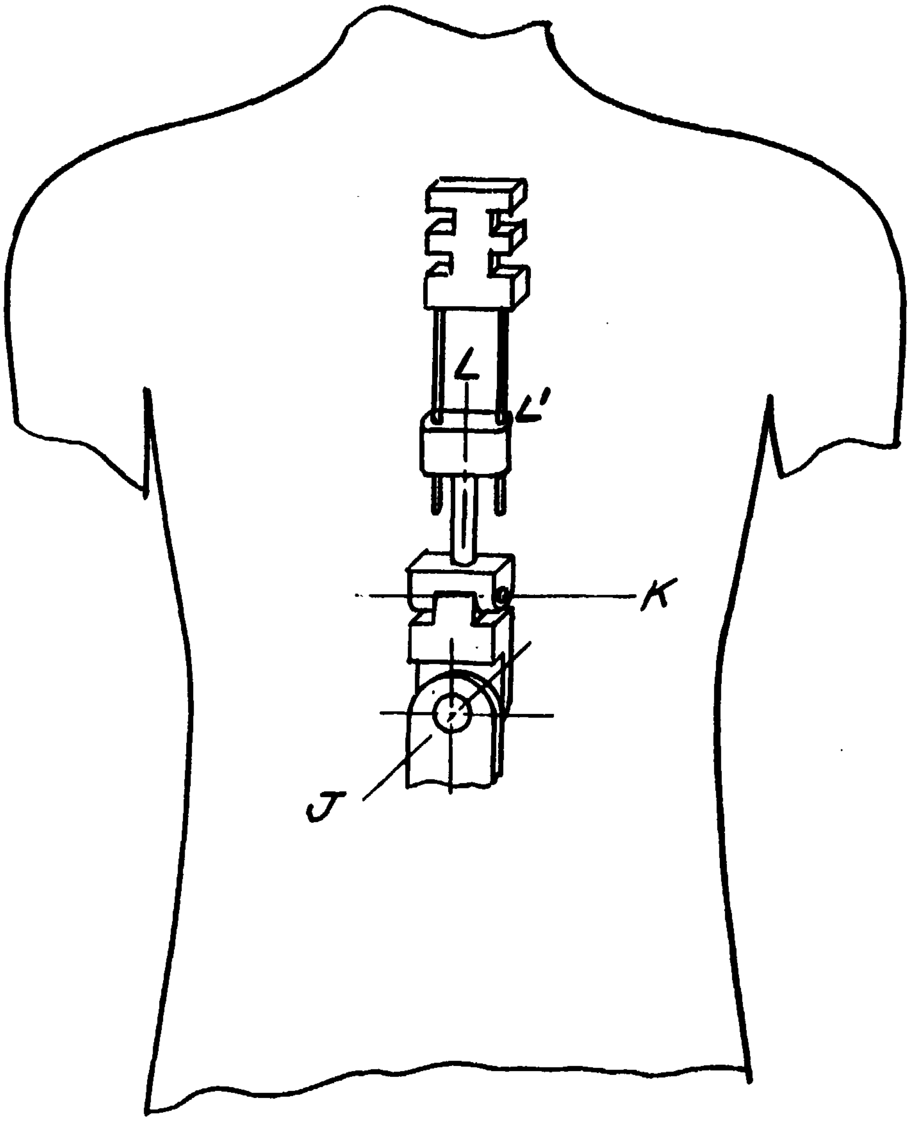


FIGURE 11 - PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE SPINAL COLUMN

Figure 12 presents the preliminary design of the exoskeletal structure for the lower extremity. The unit is attached to the wearer at the waist harness, the thigh and the foot. The waist and thigh attachments are similar to the corresponding devices for the upper extremities. The foot attachment is visualized as a clamp that attaches the shoe of the wearer to the exoskeletal foot plate.

3.3 General Dimensions of the Human Body

The design of the exoskeleton requires that locations of approximate joint centers and pertinent external body points be known. The exoskeleton must be adjustable so that it can be worn by a number of subjects, therefore the probable ranges of the dimensions must be known. Figure 13 presents dimensions that locate the approximate joint centers of the human body, and ranges of these dimensions for 90 percent of the adult, male population. In most cases, the data presented in Figure 13 were taken directly from References 3, 4, 5, and 6. When the desired dimensions were not directly obtainable from the above sources, dimensions were either added or subtracted to yield the desired dimension. The range of this new dimension about its mean was then determined by the method discussed in Reference 7, Section 8. 3.

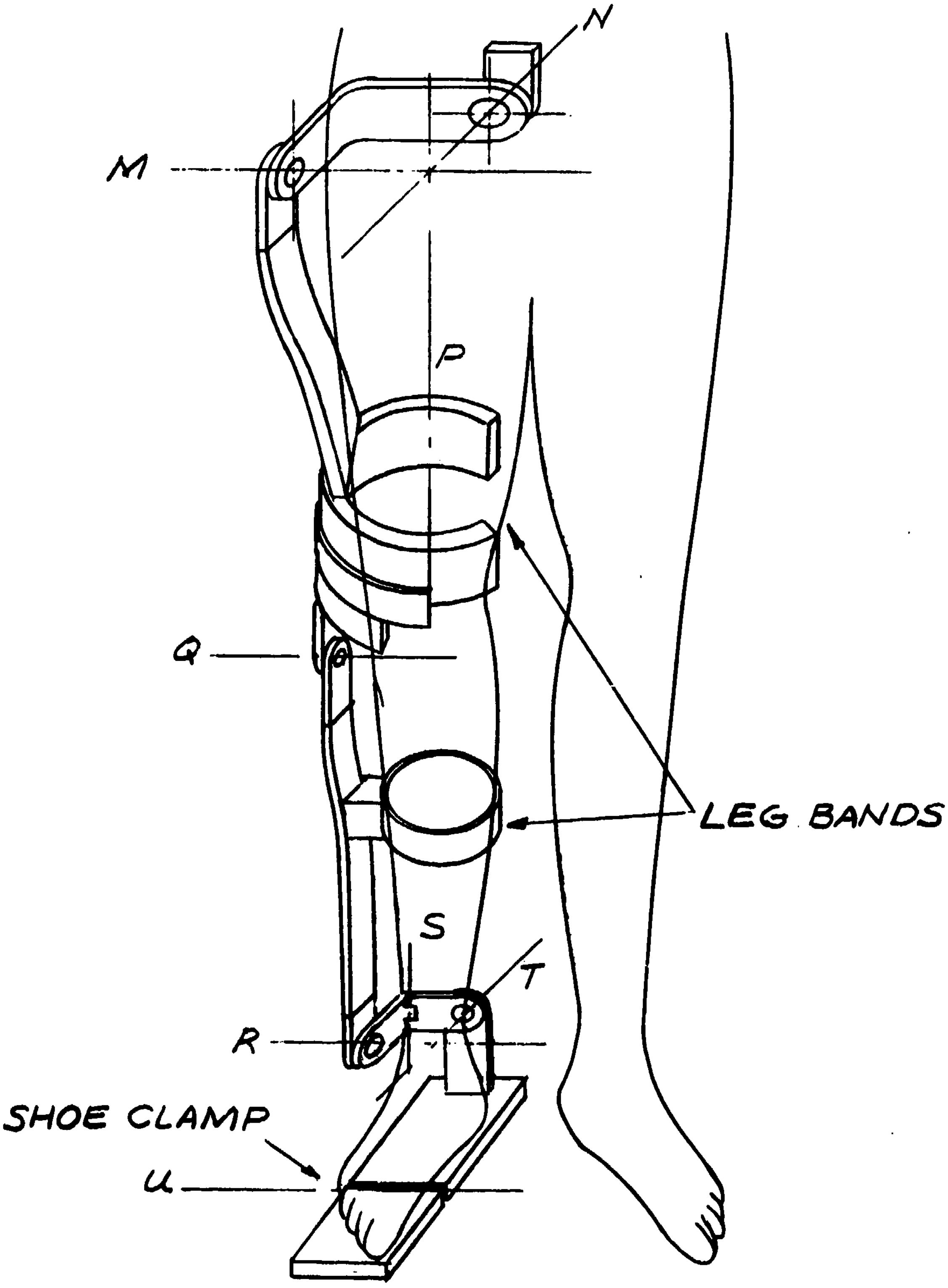


FIGURE 12 - PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE LOWER EXTREMITY

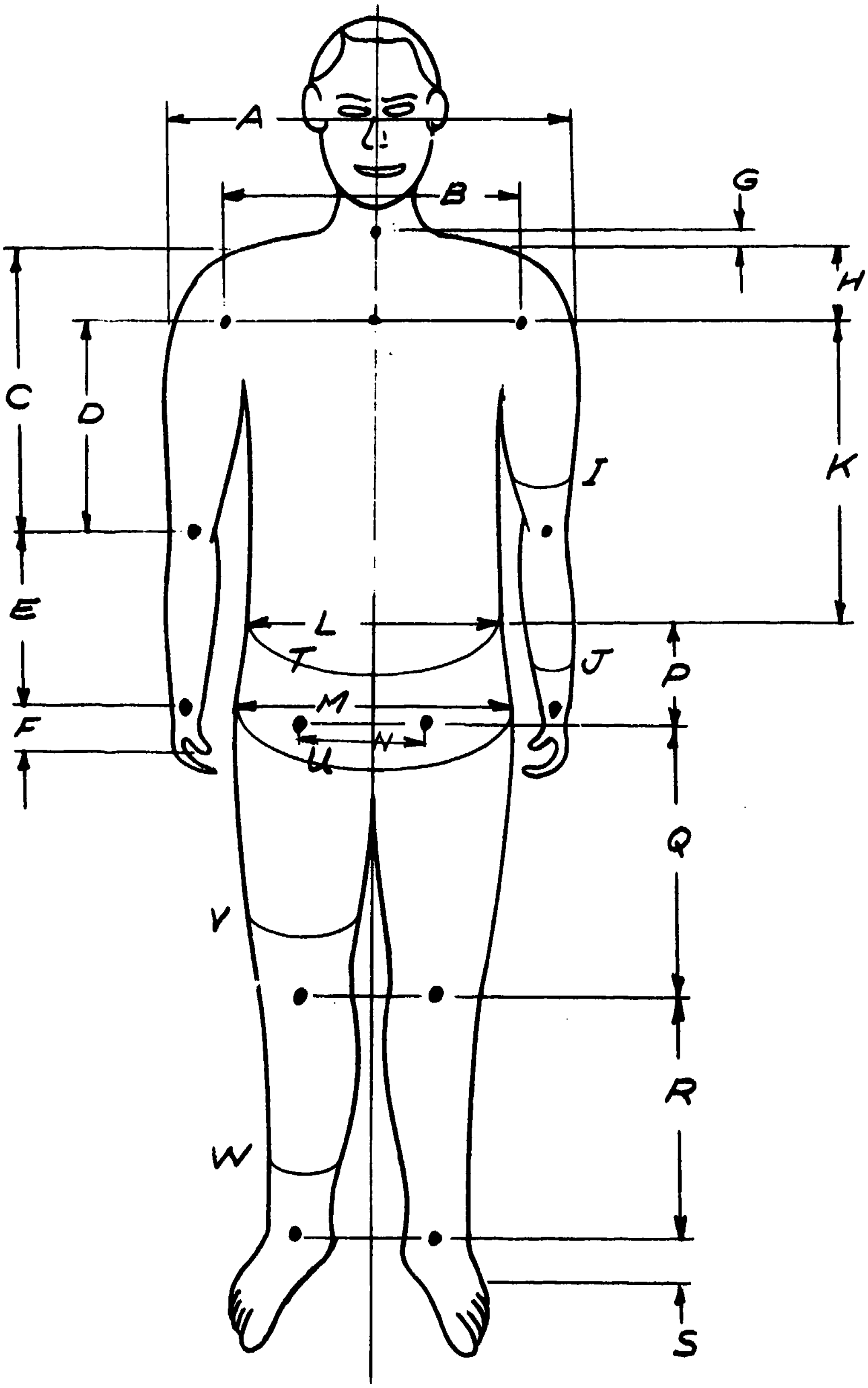


FIGURE 13 - BODY DIMENSIONS

Dimension	Description	Mean Value Inches	Range* Inches
A	Shoulder Breadth - Overall	17.9	16.5 - 19.4
B	Shoulder Breadth - Joint Center to Joint Center	14.3	13.2 - 15.4
C	Top of Shoulder to Center of Elbow Joint	13.0	12.2 - 13.8
D	Center of Shoulder Joint to Center of Elbow Joint	11.3	10.3 - 12.3
E	Center of Elbow Joint to Center of Wrist Joint	9.9	9.6 - 10.2
F	Center of Wrist Joint to Center of Grip	3.5	3.2 - 3.8
G	Cervical to Top of Shoulder	2.6	2.5 - 2.7
H	Cervical to Center of Shoulder Joint	4.2	3.8 - 4.6
I	Upper Arm Girth	10.9	9.7 - 12.1
J	Forearm Girth	10.5	9.5 - 11.5
K	Waist to Shoulder Joint Center	11.9	11.0 - 12.8
L	Waist Breadth	10.7	9.4 - 12.0
M	Hip Breadth	13.2	12.1 - 14.3
N	Hip Joint Center to Hip-Joint Center	6.3	5.7 - 6.9
P	Waist to Hip-Joint Center	6.8	6.1 - 7.5
Q	Hip-Joint Center to Knee-Joint Center	17.1	15.2 - 19.0
R	Knee-Joint Center to Ankle-Joint Center	16.1	14.5 - 17.7
S	Ankle-Joint Center to Base of Foot	3.4	3.1 - 3.7
T	Waist Girth	32.0	29.0 - 35.0
U	Hip Girth	37.8	35.5 - 40.0
V	Thigh Girth	17.3	15.9 - 18.7
W	Calf Girth	14.4	13.4 - 15.4

*Ranges shown include 90 percent of the adult, male population

Figure 13 - BODY DIMENSIONS (CONTINUED)

4. STRUCTURAL ANALYSIS OF THE EXOSKELETON

The non-powered exoskeleton is not intended to resist large forces. However, if the rotation at a particular joint is limited the exoskeleton must be sufficiently rigid so that structural deflections do not permit equivalent rotations. Therefore, the exoskeleton must be able to resist muscular forces without yielding and without deforming significantly.

Figures 14 and 15 present forces that the exoskeleton must resist. The following procedure was used to determine the magnitude of these forces as shown in Table 1. The maximum strength of human joints (data presented in References 8, 9, 10, 11 and 12) was specified as a bending moment at the joint center. The force reacted by the exoskeleton was related to the moment at the joint center by assuming that each body attachment is located a distance from the joint center equal to three-quarters of the length of the adjacent human limb. Table 1 also presents the source of each force (i. e., the motion that is resisted in order to cause the force) and the manner in which the exoskeleton reacts the force. It should be noted that the force reaction for the exoskeleton is dependent upon the position of each limb. However, the force reactions presented in Table 1 are for those limb positions for which the exoskeleton is weakest. Further, the reactions shown are with only one force acting at each body attachment at a particular time; thus it was assumed that a given human limb can exert maximum force only in one direction at a time.

Table 2 presents the size of each exoskeletal limb required to limit the maximum stress to a value below 40,000 psi. If the maximum stresses are held to this level, several commercially available alloys of aluminum will be useable for the exoskeleton. The sizes presented in Table 2 are intended to represent the approximate size of the limbs of the exoskeleton. More detailed consideration will be given to the strength and stiffness requirements during the process of detail design of the exoskeleton.

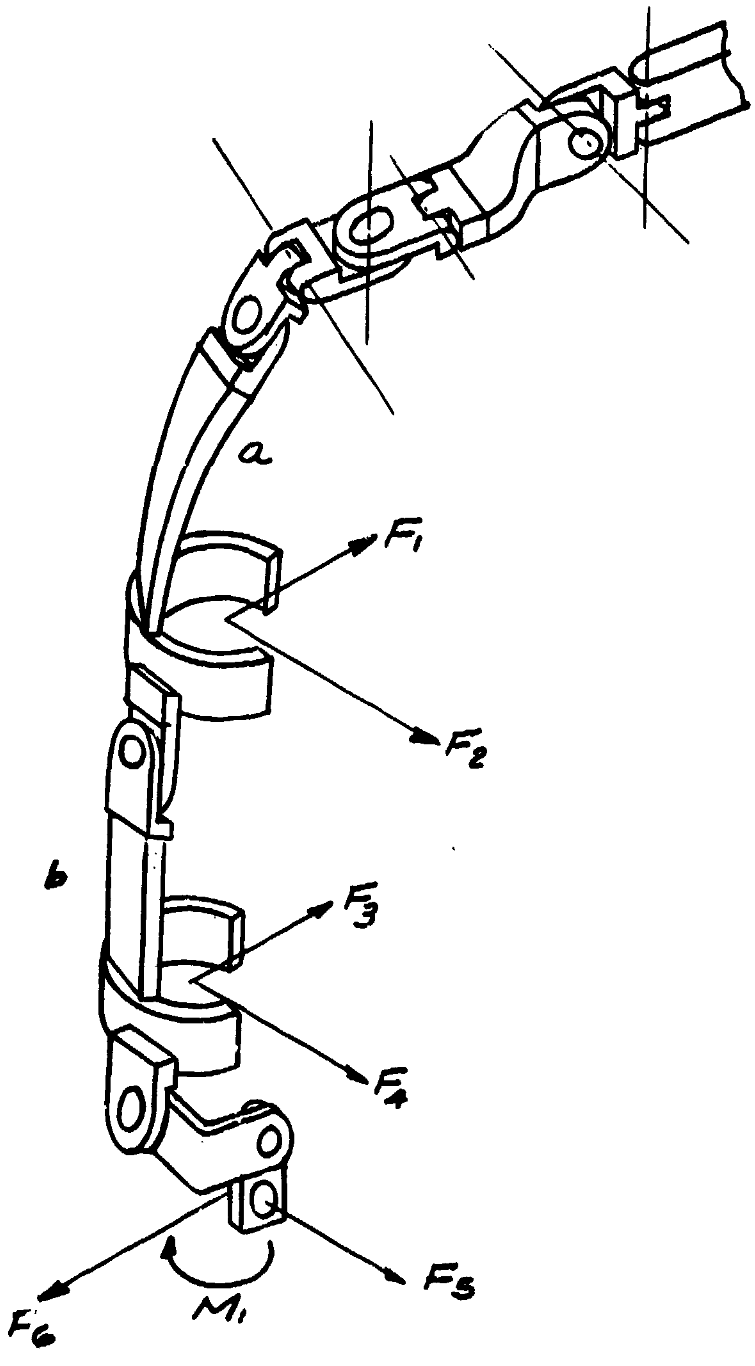


FIGURE 14 - FORCES REACTED BY THE UPPER EXTREMITY EXOSKELETON

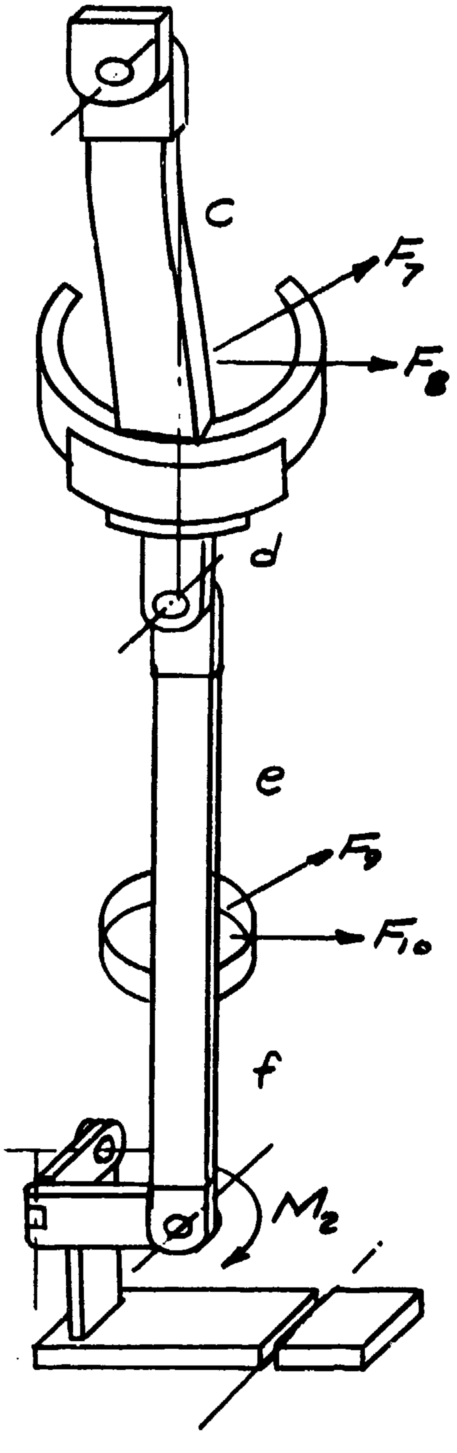


FIGURE 15 - FORCES REACTED BY THE LOWER EXTREMITY EXOSKELETON

Force*	Magnitude of Force-Lbs.	Source	Reaction**
F_1	55	Shoulder Abduction Sideward Elevation	Bend link a about minor axis
F_2	61	Shoulder Flexion Forward Elevation Hyperextension	Bend link a about major axis, twist link a
F_3	78	Rotate shoulder with elbow flexed	Twist link a or bend links a and b about their minor axis
F_4	54	Elbow Flexion	Bend links a and b about their major axes and twist links a and b or bend link b about its minor axis and twist link a
F_5	40	Ulnar, radial rotation of wrist	Bend links a and b about their major or minor axis
F_6	40	Extension, flexion of wrist	Bend links a and b about their major or minor axis
F_7	133	Hip abduction, adduction	Bend link c about its minor axis
F_8	25	Extension, flexion of hip	Bend link d about its major axis and twist link d
F_9	20	Rotate hip, knee flexed	Bend links c, d and e about their minor axes or bend link e about its minor axes and twist links c and b
F_{10}	108	Flexion, extension of knee	Bend links c, d and e about their major axes and twist links c, d and e
M_1	147 (in. -lbs.)	Supination, pronation of elbow	Twist links a and b
M_2	670 (in. -lbs.)	Flexion of ankle and foot	Bend links c, d, e and f about their major axes

* Forces refer to Figures 14 and 15.
** Letters refer to Figures 14 and 15.

Table 1 - FORCES REACTED WITHIN THE EXOSKELETON

Link	Thickness (2) Inches	Width-Inches
a(1)	3/4	3/4
b	1/2	1/2
c	1/2	1-1/4
d	1/4	1-1/4
e	1/4	1
f	1/4	3/4

(1) Letters refer to Figures 14 and 15

(2) Thickness is measured parallel to major bending axis

Table 2 - CROSS-SECTIONAL DIMENSIONS OF EXOSKELETAL LINKS

The maximum lateral deflection of all links, due to any combination of forces, occurs at link 'a' (Figure 14) and is 0.071 inches. The maximum angular deflection occurs at link 'e' (Figure 15) and is 3.61 degrees. These deflections are sufficiently small compared with the 'looseness' inherent in any body attachment (due to stretching of the skin and to comfort considerations) that they may be disregarded.

5. WEIGHTS AND INERTIAS OF THE EXOSKELETON

The exoskeleton should be light in weight and should have minimum inertia. Thus, the weight and inertia of the exoskeletal arm complex, as conceived in the preliminary design, were calculated, and were compared with the corresponding physical properties of the average human arm. It is hypothesized that the relative weights and inertias of the exoskeleton for the lower extremity, when considered as percentages of the corresponding properties of the human limb, would be similar to the values presented in Table 3.

		Exoskeleton	
	Human Limb	Value	Fraction of Human Limb Value
Total Weight	12 lbs	1. 9 lbs	16. 0%
Static Moment About Shoulder Joint	144 in-lbs	25 in-lbs	17. 4%
Moment of Inertia About Shoulder Joint	0. 745 lb-ft/sec^2	0. 107 lb-ft/sec^2	14. 4%

Table 3 - PHYSICAL PROPERTIES OF SHOULDER-ARM-WRIST COMPLEX

6. CONCLUDING REMARKS

It is concluded from this preliminary design study that a full-scale, wearable exoskeletal structure, consisting of pinned joints, one sliding joint, and rigid links will allow the wearer to perform a large number of useful tasks. Complex kinematic mechanisms do not appear necessary in the conceived exoskeletal structure. However, it is necessary to fabricate the exoskeleton to determine if the device will permit the desired freedom of motion of the wearer. Further, it is necessary to fabricate the device in order to determine how many joints can be eliminated, while still enabling the wearer to perform useful work tasks.

Where an exoskeletal joint cannot be located coincident with the corresponding human joint, it is proposed that redundant (i.e., parallel) axes be used to compensate for this lack of alignment. A sliding joint appears to be more practical than pinned joints for the spinal column of the exoskeleton, because the joint must permit the exoskeletal spinal column to lengthen and shorten. Further, it was shown that exoskeletal links of moderate size can resist the maximum forces caused by the wearer's muscles whenever the motion range of the joints is restricted. Accordingly, it is concluded that a practical exoskeleton can be designed and fabricated.

The weight of the exoskeleton appears, at this time, to pose the most serious problem. The weight and inertia of the exoskeleton, as currently conceived, was shown to be approximately 15 percent of the corresponding properties of the human body. It is possible that this weight will, in itself, significantly degrade the performance of the wearer. In that event, it will be difficult to determine the minimum number of joints, their approximate locations and their required ranges of motion that must be provided in an amplified exoskeletal structure (e.g., in the Man Amplifier), if degradation of performance is used as the criteria. However, it should prove possible to further reduce the weight and inertia of the exoskeleton, below the values presented above, by more efficient structural design of all members.

7. LIST OF REFERENCES

1. Taylor, C. L., Blaschke, A. C., A Method of Kinematic Analysis of Motions of the Shoulder, Arm and Hand Complex, Annals of the New York Academy of Sciences, 51:7, pp. 1251-1265, January, 1951.

2. Dempster, W. T., The Anthropometry of Body Action, WADC Technical Report 60-18, Aerospace Medical Laboratory, Wright Air Development Command, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio.

3. Dempster, W. T., Space Requirements of the Seated Operator, WADC Technical Report 55-159, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, 1955.

4. Hertzberg, H. T. E., Daniels, G. S. and Churchill, E., Anthropometry of Flying Personnel -- 1950, WADC Technical Report 52-321, United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, September, 1954.

5. Lay, W. E. and Fisher, L. C., Riding Comfort & Cushions, Society of Automotive Engineers Journal (Transactions), Vol. 47, No. 5, pp. 482-496, 1940.

6. Roberts, D. F., Provins, K. A. and Morton, R. J., Arm Strength and Body Dimensions, Human Biology, Vol. 31, No. 4, December, 1959.

7. Mizen, N. J., Investigation Leading to the Design, Fabrication and Tests of a Full-Scale Wearable Mockup of an Exoskeletal Structure, Cornell Aeronautical Laboratory Interim Report No. VO-1692-V-1, Cornell Aeronautical Laboratory, Inc., Buffalo, New York.

8. Harrison, H. H. and Bailey, T. L., Strength Curves for Fourteen Joint Movements, Journal of Physical and Mental Rehabilitation, April-May, 1950.

9. Provins, K. A., Salter, Nancy, Maximum Torque Exerted About the Elbow Joint, Journal of Applied Physiology, Vol. 7, No. 4, January, 1955.

10. Hunsicker, A., Arm Strength at Selected Degrees of Elbow Flexion, WADC Technical Report 54-548, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, August, 1955.

11. Morehouse, L. E., The Strength of a Man, Human Factors Vol. 1, No. 2, April, 1959.

12. Salter, N. and Darcus, H. D., The Effect of the Degree of Elbow Flexion on Maximum Torques Developed in Pronation and Supination of the Right Hand, Journal of Anatomy, Vol. 88, 1952.

13. Cragun, M. K., Stapp Automotive Crash and Field Demonstration Conference, University of Minnesota Center for Continuation Study of the General Extension Division, Minneapolis, Minnesota, September, 1961.

14. Clark, D. C., N. J. DeLeys and C. W. Matheis, Exploratory Investigation of the Man Amplifier Concept, Cornell Aeronautical Laboratory, Inc., Report No. VO-1616-V-1, 15 April, 1962.

15. Batch, J. W., Measurements and Recordings of Joint Function, U. S. Armed Forces Medical Journal, Vol. 6, No. 3, pp. 359-382, March, 1955.

8. APPENDICES

8.1 Data on Human Limb Movement

Figure 16 presents upper extremity, trunk, and lower extremity movements of the human skeleton. The anthropological name and range of each movement taken from References 3 and 15 are presented in Table 4.

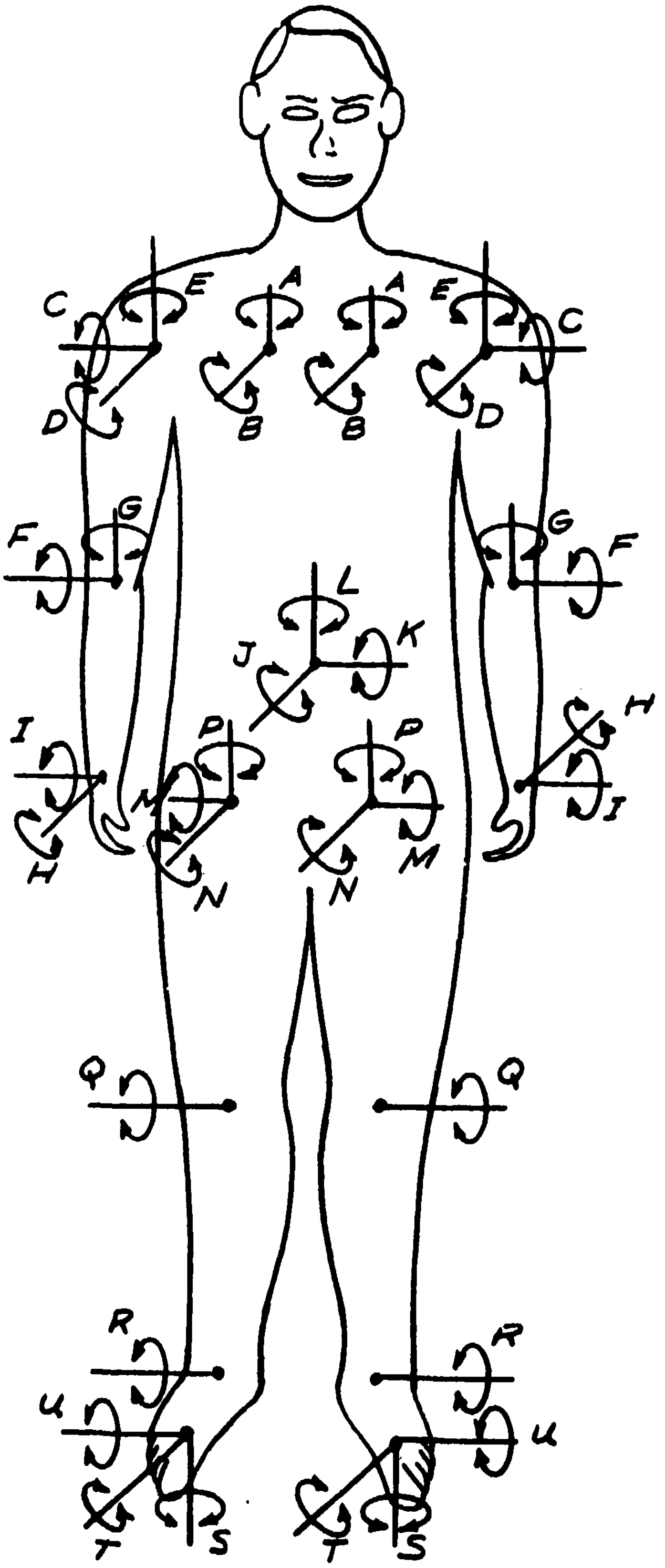


FIGURE 16 - HUMAN BODY MOVEMENTS

JOINT		MOVEMENT	TOTAL RANGE DEGREES
SHOULDER GIRDLE	A*	FLEXION AND EXTENSION	**
	B	ROTATION	**
SHOULDER	C	FLEXION, EXTENSION FORWARD ELEVATION AND HYPEREXTENSION	250
	D	ABDUCTION, ADDUCTION AND SIDEWARD ELEVATION	190
	E	INTERNAL AND EXTERNAL ROTATION	130
ELBOW	F	FLEXION AND EXTENSION	140
	G	SUPINATION AND PRONATION	190
WRIST	H	FLEXION AND EXTENSION	190
	I	ULNAR AND RADIAL ROTATION	75
SPINAL COLUMN	J	LATERAL FLEXION	80
	K	FLEXION AND HYPEREXTENSION	100
	L	ROTATION	70
HIP	M	FLEXION AND HYPEREXTENSION	115
	N	ABDUCTION AND ADDUCTION	85
	P	INTERNAL AND EXTERNAL ROTATION	75
KNEE	Q	FLEXION	120
ANKLE AND FOOT	R	DORSIFLEXION AND PLANTERFLEXION	55
	S	ABDUCTION AND ADDUCTION	10
	T	EVERSION AND INVERSION	60
	U	FLEXION AND HYPEREXTENSION	55

*Letters refer to Figure [illegible]

**Range of shoulder girdle movement is included with shoulder movement.

Table 4 - RANGE OF HUMAN BODY MOVEMENTS

8.2 BIBLIOGRAPHY

1. Alldredge, R. H., and B. M. Snow, Lower Extremity Braces, Orthopaedic Appliances Atlas, Vol. 1, pp. 345-438, J. W. Edwards, Ann Arbor, Michigan, 1952.

2. Ashe, W. F., P. Bodenman, and L. B. Roberts, Anthropometric Measurements, Project 9, File No. 741-3, Armored Force Medical Research Laboratory, Fort Knox, Kentucky, 1 February, 1943.

3. Barter, J. T., I. Emanuel, and B. Truett, A Statistical Evaluation of Joint Range Data, WADC Technical Note 57-311, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, August, 1957.

4. Blaschke, A. C. and C. T. Taylor, The Mechanical Design of Muscle-Operated Arm Prostheses, Journal of the Franklin Institute, Vol. 256, No. 5, pp. 435-458, November, 1953.

5. Catranis, J. G., Some Recent Developments in Lower Extremity Prostheses, Annals of the New York Academy of Sciences, 57:7, pp. 1229-1250, January, 1951.

6. Chaffee, J. W., Andrometry: A Practical Application of Coordinate Anthropometry in Human Engineering, ASTIA-AD No. 256344, General Dynamics Corp., April, 1961.

7. Chaffee, J. W., Anthropometric Considerations for Escape Capsule Design, ASTIA-AD No. 240484, General Dynamics Corporation, January, 1960.

8. Clarke, H. H. and T. L. Bailey, Strength Curves for Fourteen Joint Movements, Journal of Physical and Mental Rehabilitation, April-May, 1950.

9. Daniels, G. S., The "Average Man"?, Technical Note WCRD 53-7, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, December, 1952.

10. Daniels, G. S., Meyers, H. C., Worrall, S. H., Anthropometry of WAF Basic Trainees, WADC Technical Report 53-12, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, July, 1953.

11. Darcus, H. D. and Salter, N., The Amplitude of Pronation and Supination with the Elbow Flexed to a Right Angle, The Journal of Anatomy, Vol. 87, Part 2, April, 1953.

12. Dempster, W. T., Free-Body Diagrams as an Approach to the Mechanics of Human Posture and Motion, Reprinted from Biomechanical Studies of the Musculo-Skeletal System by Evans et al, Copyright 1961 by C. C. Thomas, Springfield, Illinois.

13. Hertzberg, H. T. E., Some Contributions of Applied Physical Anthropology to Human Engineering, WADD Technical Report 60-19, Wright Air Development Command, Wright-Patterson Air Force Base, Ohio, January, 1960.

14. Emanuel, I. and J. T. Barter, Linear Distance Changes Over Body Joints, WADC Technical Report 56-364, ASTIA Document No 118003, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, February, 1957.

15. Glanville, A. D. and G. Kreezer, The Maximum Amplitude and Velocity of Joint Movements in Normal Male Human Adults, Human Biology, 9:197-211, 1937.

16. Hansen, R., H. L. Yoh and H. T. E. Hertzberb, Annotated Bibliography of Applied Physical Anthropology in Human Engineering, WADC Technical Report 56-30, ASTIA Document No. AD-155622, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, May, 1958.

17. Jewell, W. R., A Program for the Improvement of the Below Knee Prosthesis with Emphasis on Problems of the Joint, Denver Research Institute, Denver, Colorado, August, 1953.

18. Lyman, J., Biotechnology Laboratory Progress Report, Engineering Department Report No. 62-31, Department of Engineering, University of California, Los Angeles, June 15, 1962.

19. The Man Amplifier, Cornell Aeronautical Laboratory, Inc., No Number, Buffalo, New York, November, 1960.

20. A Proposal to Design and Build an Arm Amplifier to Demonstrate the Feasibility of the Man Amplifier Concept, No. 146, Cornell Aeronautical Laboratory, Inc., Buffalo, New York, August, 1960.

21. Radcliffe, C. W., Prosthelic Mechanisms for Leg Amputees, Proceedings from the Sixth Conference in Mechanisms, October 10-11, 1960.

22. Tomvic, R. and Boni, G., An Adaptive Artificial Hand, IRE Transactions on Automotive Control, April 1962.