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ANTHROPOMETRY, BIOMECHANICS, AND STRENGTH

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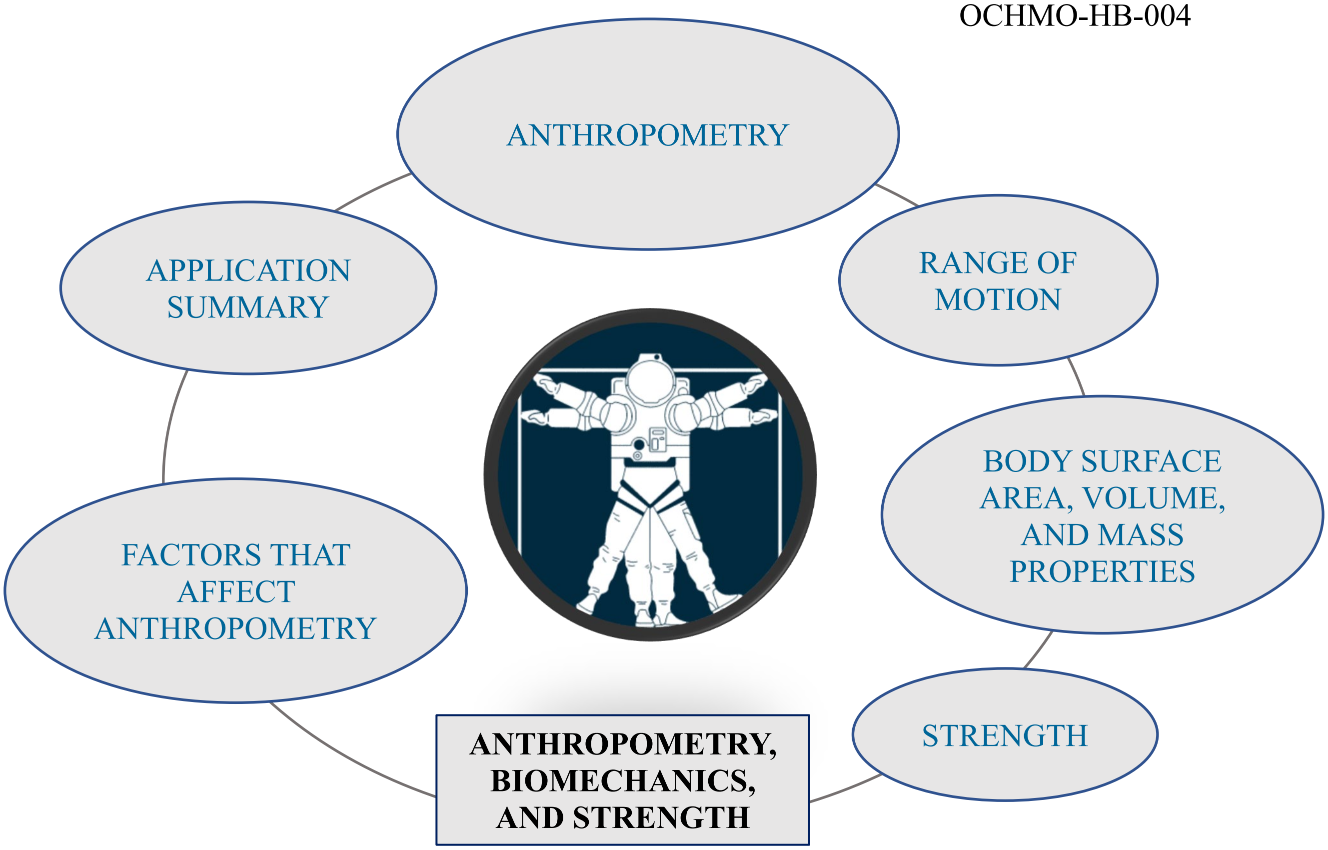

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1.0 INTRODUCTION

It is important to design spacecrafts, spacesuits, and the equipment used therein, to accommodate the physical size, shape, reach, range of motion, and strength of the selected user crewmember population. Adjustments for the effects of external factors (e.g., gravity environments, clothing, pressurization, deconditioning due to mission duration) on crewmember anthropometry, biomechanics, and strength must be included in the design.

This chapter discusses the physical dimensions of humans and how to use this information to support the design of systems to accommodate the full range of selected users and their physical qualities. The following physical dimensions are addressed:

- Physical Dimensions or Anthropometry
- Range of Motion and Reach Envelope
- Body Surface Area, Body Volume, and Body Mass
- Strength

Further, this chapter provides information on how to develop and use human body dimension and strength data. The chapter does not provide specific data, programs must develop their own dimensional dataset based on the selected user population, including any estimates or assumptions made relating to that population.

The datasets provided in Appendix A of this document includes characteristics and capabilities for anthropometric dimensions, range of motion, strength, mass, volume, and surface area. The datasets and their supplemental information take into account human characteristics such as age, sex, and physical condition as well as mission characteristics such as clothing and suit pressurization. Each dataset may be tailored based on program or mission specific criteria. *Confirm you are using the most recent version of NASA-STD-3001 Volume 2 available on the OCHMO website.*

2.0 USER POPULATION AND SELECTION AND VALIDATION OF A DATABASE

One of the most important considerations in human-centered design is the user population. The question of who will be using the hardware must be addressed.

Choosing the user population is a very important consideration because it is a major driver in the overall design and operations of spacecraft as well as the equipment used. It is especially important to determine the range of critical dimensions or values that are significant to overall layout and design of the spacecraft and key equipment used such as couches and spacesuits.

Users should be defined in terms of age, gender, ethnicity, and other special considerations. This information is critical for selecting an appropriate database. Special considerations may include level of physical fitness. A user population of military personnel, for example, usually has a physical fitness level different from a user population of civilians. Other considerations might include the timeframe for hardware use. If hardware is intended to be used far into the future, this may affect the anthropometry needs, because attributes of populations tend to change over time.

Though it may be ideal to collect data for each subject who will use a piece of hardware, it is rarely feasible to do so. Thus, the selection of a database that closely represents the expected user population is crucial to good ergonomic design.

No matter which population range is selected, system developers must consider the implications of not accommodating users who are outside of the design limits. One option would be to change the limits. Further, it is important to pick the dataset that is closest to the user population**.**

A variety of published adult anthropometry data is available for use. Resources commonly used throughout ergonomic and human factors industries include:

- 1988 Anthropometric Survey of US Army Personnel (ANSUR)
- 2012 Anthropometric Survey of US Army Personnel (ANSUR 2012)
- Air Force surveys
- National Health and Nutrition Examination Survey (NHANES; Ogden, et al., 2004)
- Civilian American and European Surface Anthropometry Resource (CAESAR)

Although NASA maintains databases of current (active) astronaut anthropometry, this data is not necessarily the best estimate for future astronauts. While it may be useful for current and ongoing human factors analyses and investigations, it may not fully represent the variation among the population from whom the astronauts are selected. It is necessary to select a suitable database that is (a) current, (b) large enough to overcome statistical issues, and (c) representative of the anticipated user population. Thus, sources such as modified military or civilian databases may be more appropriate representations of a future astronaut population.

The data used by NASA are from the population in the 1988 Anthropometric Survey of US Army Personnel (ANSUR) (ref. Natick/TR-89/044), projected forward by NASA to 2015 to account for the expected small growth in the size of members of the US population.

Various methods exist to adjust existing databases to better represent a user population. For instance, databases may be truncated or combined to include only people of a specific gender, age, or ethnicity to indicate changes over time or between populations.

To validate that the selected anthropometric database (for example, the ANSUR or CAESAR database) is the proper one to represent the user population of interest, the analyst must address the following two questions:

1) Does the database represent who will use the system? Consider:

- Average Crew Age
- Ethnic Origin – Match the population from which crew is selected
- Gender – In most anthropometric dimensions, the female is smaller than the male. Therefore, a size range will span from the smallest female to the largest male.
- Physical Fitness – Crewmembers are generally more fit than the general population. This makes military data a more valuable and appropriate resource than data from the general population.
- Education Level – Crewmembers generally have postgraduate degrees, and, if possible, the database of interest should be screened for this criterion.

2) Is there a sufficient number of subjects in the database?

Collection of anthropometric data for a population is a large undertaking and not typically part of a system's development effort. System developers normally rely on data from surveys funded by large organizations. These surveys are sufficiently large (at least 1,000 subjects) to account for population variances. The size range of the user population must be selected for each program with the following considerations:

- Broad Range – May make it more difficult for designers, and the system could be more expensive: seat adjustments may have to be greater, body supports may have to be more structurally sound for heavier individuals, hatches might have to be larger, and so on.
- Narrow Range – Will limit the population that can use the system. Valuable human resources (skills and abilities) may have to be rejected because the design will not accommodate a broad population range.

2.1 Growth Trends/Equations

Past experience indicates that historical changes have occurred in anthropometric dimensions such as height, weight, and other physical measurements. These changes that occur from generation to generation are referred to as secular change, and the impact of such changes can be significant for hardware design.

To predict secular change, the first step is to select a population that is representative of the future user of the system under development. A database of dimensions should exist for this population. Next, use trend analysis to estimate the stature of a future user population. Finally, use the estimated future stature and the relationships between stature and other dimensions (including mass, body volume, and surface area) to calculate estimated future body segment lengths and other needed dimensions. This procedure is described in Tillman and McConville, 1991.

2.2 Percentiles

A percentile is defined as the value of a variable (or measure) below which a certain percentage of observations fall. Research has shown and corroborated that most anthropometric measures will follow a normal distribution. The term "percentile" is often used in the reporting of values from a norm-referenced database, such as the ANSUR database. Further, when estimating percentiles from an anthropometric database, the data is represented graphically as a normal curve. At the peak of the normal curve, in the center, stands the mean (i.e., 50th percentile) and median of the distribution being graphed. The mean (μ) and standard deviation (σ) define a normal distribution and can be used to calculate percentiles.

The percentile can be estimated by the percentile equation: $X_{(p)} = \mu + \sigma(z)$

Values of *Z* are constant for a given percentile and can be found in a standard normal (*Z*) distribution table.

Values of *Z* for Selected Percentiles

p	z	p	z
1	-2.33	99	2.33
5	-1.64	95	1.64
10	-1.28	90	1.28

An example percentile calculation is demonstrated below. The method used is based on the work of Stephen Pheasant in Bodyspace: Anthropometry, Ergonomics and the Design of Work (Pheasant, 1996).

Percentile limit "stacking" occurs when multiple restrictions are placed on anthropometry and can quickly eliminate large numbers of the population.
Example: Suit critical dimensions – When 1st to 99th percentile limits are imposed, 10% of the population is eliminated. If 5th to 95th percentile limits are imposed for all criteria, 37% of the potential population wouldn't fit in the hardware. A short person may have long arms, or a wide person may be tall. ***The more restrictions, the greater the overall impact.***

2.3 Human-in-the-Loop (HITLs) Testing & Analyses

Accommodating a widely varying user population presents a challenge to engineers and designers. It is often difficult to quantify who is accommodated and who is not accommodated by designs, especially for equipment with multiple critical anthropometric dimensions. One approach to communicating levels of accommodation, referred to as "population analysis," applies existing human factors techniques in novel ways.

The major applications of population analysis are providing accommodation information for multivariate problems and enhancing the value of feedback from human-in-the-loop testing or

Ultimately, the benefit of population analysis is to use an analytical approach and test methodologies to determine whether the intended design would accommodate the entire range of population and in the event it does not, what extremes a design concept can accommodate.

Through analyzing multiple variables simultaneously, it is possible to take understanding beyond one-dimensional percentiles. It is relatively simple to place data into context for one-dimensional cases. For example, the height of a doorway can be based on stature. The door should be designed so that the tallest expected user can walk through it upright. If the height of the doorway is equivalent to 90th-percentile male stature, it can be deduced that approximately 10% of males in that population will have difficulty traversing the doorway.

However, it may also be necessary to determine an appropriate width for the doorway. This should be based on anthropometry as well, with the largest expected bideltoid breadth (shoulder breadth) as an example of a possible appropriate minimum width. If the width of the doorway is 90th-percentile male bideltoid width, approximately 10% of the male population will not be accommodated due to this dimension.

The trouble in defining accommodation arises when the height and width dimensions are taken into account simultaneously. For instance, combining the two previous examples, since stature and bideltoid breadth are not highly correlated it would be inaccurate to conclude that 10% of the total population cannot use the doorway. The group of individuals that is not accommodated due to stature may share some members with the group that is not accommodated due to bideltoid breadth, and thus somewhere between 10% and 20% of the population will not be accommodated.

Differences in measurement posture may lead to different body size envelopes. Through analysis of a sample database of population anthropometry, it is possible to determine a reasonable estimate of the percentage of the population that will not be accommodated.

2.4 Methods for Accommodating Physical Dimensions

Once the user dimensions are determined, the system or hardware must be designed to those dimensions. Three general methods for doing this are described below:

1. Single solution for all – In the case of anthropometry, a single size may accommodate all members of the population. For example, usually if a workstation has a switch located within the reach limit of the smallest person, everyone will be able to reach the switch. In the case of strength, setting the strength requirement at or below the capability of the weakest person will allow everyone to successfully exert effort without exhausting themselves.

2. Adjustment – The design can incorporate an adjustment capability. A common anthropometric example of this is the automobile seat. A common strength example is the setting up of resistance variations on an exercise device, enabling various resistance options for different users.

3. Several solutions – Several sizes of equipment may be required in order to accommodate the full population size range. This is usually necessary for equipment or personal gear that needs to closely conform to the body, such as clothing and spacesuits.

All three methods require the designer to use appropriate anthropometric, biomechanics, and strength data.

3.0 ANTHROPOMETRY

Anthropometry refers to the measurement of human body lengths and circumferences, specifically relating to clearance and reach. To select which measurements are pertinent, it is necessary to understand the task to be performed, equipment that will be used, and who will be performing the work, ensuring selection of the proper database.

Clearance – describes the sufficient room necessary for all crewmembers (suited and unsuited) to fit through passageways and to perform tasks safely and comfortably in a workstation or activity center. It is important to note that people perform differently in 0g than in a 1g environment which may affect clearance, and critical dimensions for body clearance in 0g will often differ from those in 1g.

Reach or Access – affects how controls, displays, and equipment should be positioned so that they can be accessed by all crewmembers.

✓Step-by-step processes used to determine the clearance and reach dimensions that will accommodate a target population are in Appendix A, Section A.1.

3.1 Anthropometry Data

Anthropometry data drives the guidelines for the design of a system, considerations include:

- Selection of the user population and associated database.
- Use of 1st percentile female to 99th percentile male. Deviations from this range quickly reduces the number of people able to be accommodated.
- The nature, frequency, safety, criticality, and difficulty of the tasks to be performed.
- The position of the body during performance of these tasks.
- The mobility and flexibility requirements imposed by these tasks.
- Where design limits based on safety and health considerations are more conservative than performance criteria, they must be given preference.

✓Data regarding common Anthropometric Dimensions can be found in Appendix A, Table 1.

3.2 Anthropometric Data Collection

In many cases, it may be necessary to measure subjects to determine missing anthropometric data. While this is not a discussion of anthropometric measurement techniques, the following points will help ensure that the data collected is useful and accurate.

Subject Clothing –Traditional anthropometric measurements involve minimally clothed subjects, for example wearing spandex shorts (with a sports bra for female subjects). It may be appropriate to collect additional measurements from mission-appropriate clothing to worst-case scenario of a large person in a pressurized suit.

Consistency of Measurements – Consistency of measurements is of great importance. Subjects must be positioned, and landmarks must be precisely used when determining measurements. If measurements taken are standard and intended to correspond to measurements from an existing database such as ANSUR, it is important to position subjects exactly as described and measured at the precise landmarks. If customized measurements are needed, it is important to carefully document the posture of the subject and the landmarks used in the measurement. An example of a customized measurement is the inter-wrist distance required for suit design. This measurement represents the distance between a subject's wrists when the arms are laterally extended, and it is not found in standard anthropometry handbooks.

Measurement Accuracy – For traditional measurements, it is important to properly align measurement devices (e.g., for stature, the anthropometer should be exactly perpendicular to the floor), and measurements should be read carefully to the highest degree of accuracy made possible by the scaling on the measurement device.

Marker Placement for Digital Scanning – For laser scanning measurements, markers should be placed on landmarks to enable measurement of a digital scan that cannot be palpated. For example, if bideltoid breadth is needed during preparation for scanning, an investigator should palpate to find the correct location of the deltoids on each side and place markers appropriately.

Advantages of Digital Scanning – Digital scanning can provide an advantage for anthropometric measurements in that the image will still exist to (re)check measurements in the future. It is not uncommon for clerical errors to lead to unrealistic dimensions in an anthropometric database, and if measurements were taken manually, the subject must return to determine the correct measurement.

More Data - Concerning suited anthropometry for different suit architectures is needed for unpressurized and pressurized conditions. Also, there is a need for more anthropometric data in zero- and partial-gravity (1/6 and 3/8) conditions.

3.3 Additional Anthropometric Considerations

Some basic considerations for the use of anthropometric data and its limitations follow:

Missing Data – Anthropometric databases do not contain percentile information on all possible critical anthropometric dimensions suitable for every design situation. For example, one of the critical design concerns for the hard upper torso of the pressurized extravehicular activity (EVA) suit is determining where the scye (armhole) openings fall on an individual crewmember's shoulders. The military database on which NASA's designs are based does not include a reference for this measurement. Special studies or estimations may have to be performed (depending on the criticality of the interface) when this occurs. Estimations should allow for the worst-case combination of size and interfacing hardware.

Size Combinations – Where two or more individuals are located near each other (such as in a cockpit), be sure to consider all combinations of sizes (e.g., a large person and a small person reaching a common control, two large people positioned shoulder to shoulder, two small people passing equipment through a hatch). This can pose a challenge as the maximum/minimum combination may not always the most cost-effective solution, for example a crew complement consisting of members of all maximum values (99th-percentile seated height and shoulder breadth) would be very cost prohibitive. When considering size combinations, the requirement that a vehicle must accommodate individuals at both extremes of the anthropometric size range, must be considered and trades addressed on a case-by-case basis. A balance must be struck between accommodation of crew within the design constraints and the ability of different crew combinations to fly.

Variation of Sizes Within an Individual – Different human physical attributes from the same individual seldom have the same percentile ranking. For example, a 5th-percentile female in stature may have a 20th- or 40th-percentile arm length. It is inappropriate to refer to a "1st-percentile person" or "99th-percentile person," because the percentile classification will not apply to all dimensions. It should also be noted that the worst-case scenario often depends on a combination of body dimensions and may occur with individuals who would not be considered 'extreme' in a visual inspection – for example, a subject with short torso and long legs, or narrow shoulders but broad hips.

Lack of Correlation Between Stature and Reach or Strength – There is no strong, consistent correlation between anthropometric dimensions and strength or reach.

Cannot Add or Subtract Percentiles – Percentile data does not obey the laws of addition and subtraction. If the anthropometric tables list only the percentiles of forearm and upper arm lengths, for example, it is not possible to calculate the percentile of the entire arm length. One cannot add a 5th-percentile lower-arm length to the 5th-percentile upper-arm length and get the length of a 5th-percentile arm. The correct and best method is to use full arm-length data (measurement across upper and forearm lengths).

Small-Sample Errors – Estimates of anthropometric percentiles are generated from the mean and standard deviation using large samples ($n > 100$) that are normally distributed. When using estimates, failure of either condition (small samples or non-normal data distribution) will lead to imprecise calculation of percentiles.

✓Data regarding Lack of Correlation Between Common Measurements is located in Appendix A, Table 2.

✓Operating-Environment Values of Factors Affecting Anthropometric Dimensions and Spacesuit Effects on Anthropometry (including Unpressurized and Pressurized suits) are located in Appendix A, Tables 3 and 4.

3.4 Application of Data and Standards

NASA-STD-3001 Volume 2 – Relevant Technical Requirement

[V2 4102] Functional Anthropometric Accommodation The system shall ensure the range of potential crewmembers can fit, reach, view, and operate the human systems interfaces by accommodating crewmembers with the anthropometric dimensions and ranges of motion as defined in data sets in Appendix E, Physical Characteristics and Capabilities, Sections E.2 and E.3.

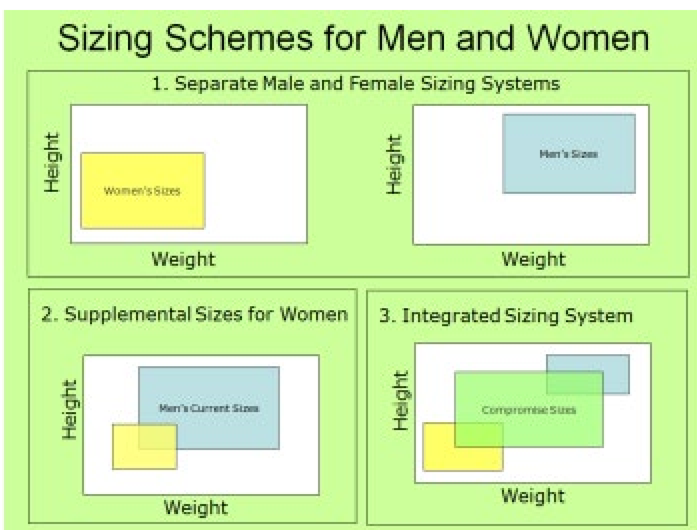
All crewmembers need to be able to perform any planned tasks efficiently and effectively. The intent is to accommodate the entire potential user population, not just meet the criteria in the datasets, which provide the most frequently used values in standard reference postures. When a design requires a posture outside of the standard reference posture, such as rotation from upright to recumbent seating, minimum and maximum values for the new posture must be developed for the unique design posture.

Identification of a posture, dimension, or range of motion not provided needs coordination and concurrence from NASA Stakeholders. When a system must accommodate a suited crewmember, an additional suited dataset can be provided that accurately identifies suited human dimensions. A tailored data set may be provided by NASA based on program or mission specific criteria, especially when a specific spacesuit has been identified.

> It is important to consider asymmetry in design. For example, not all individuals of short stature also have narrow hips or not all tall individuals have a longer reach. Additionally, critical dimensions of spacesuits are imperative to include during design.

3.5 Example of Anthropometric Design Lesson Learned

Shuttle-era Extravehicular Mobility Unit (EMU) spacesuits were designed using individual mix-and-match pieces to fit a population to include everyone from a 5th percentile female to 95th percentile male. Original designers made the assumption that a woman could fit the same size as a small man. This strategy did not take into account other factors, such as a woman in similar height and weight as a man is likely to have much broader hips and narrower shoulders. The overall lack of properly strategized suit design led to issues with suit fit and mobility while suited, as well as extravehicular activity schedule constraints based on the availability of different suit pieces.



From: Benson, E. & Rajulu, S. Complexity of Sizing for Space Suit Applications

Figure 1. Example Sizing Schemes for Men and Women with the Same Gear

Another example of how different body dimensions for an individual can affect design is looking at seated vehicle interactions. Often only the minimum and max dimensions are evaluated, however interferences can occur when there are variations in body size (min torso-max legs, max torso-min legs, etc.). During developmental evaluations, the variation between torso length and leg lengths identified instances when the knees would impact a display panel and when the feet would impact hardware along the vehicle wall. The minimum and maximum was not an issue but the middle of population who had odd variations of body dimensions were impacted.

4.0 RANGE OF MOTION AND REACH ENVELOPE

4.1 Range of Motion

Refers to how far you can move or stretch a part of your body, such as a joint or a muscle. Humans do not maintain standard and static postures while performing a task. Human movement varies from whole-body movement (e.g., locomotion or translation) to partial body movement (e.g., controlling a joystick with the right arm) to a specific joint or segment movement (e.g., pushing a button with a finger while holding the arm steady). Regardless of the type of movement, the entire body and/or various body segments are involved either by working together or by maintaining a posture while isolated or specific movements are involved.

4.2 Additional Range of Motion Considerations

Range of Motion Multi-Joint Versus Single-Joint Effects – Frequently, human motion involves interaction of two or more joints and muscles. The movement range of a single joint is often drastically reduced by the movement of an adjacent joint. In other words, joint movement ranges are not always additive. For example, an engineering layout may show (using a scaled manikin) that a foot control is reachable with a hip flexion of 50° and the knee extended (0° flexion). Both ranges are within the individual joint ranges; however, the hip flexion is reduced by over 30° when the knee is extended. Therefore, the control would not be reachable.

Body Size – Generalities can be made regarding body physique and its relationship to joint mobility. For example, one may assume that slender humans have greater joint movement than obese humans. However, as with other physical properties, variability always exists. Individuals must be considered on an individual basis.

Exercise – Increases mobility; however, weight-training exercises aimed to increase muscle bulk may restrict mobility.

Awkward and Constrained Body Postures – or loads carried by a person will restrict mobility.

Fatigue and Injury – or pain affects a person’s ability to maintain his or her normal range of mobility.

At present, no data is available for 0g or hypergravity environments. Indications are that joint motion capability is not drastically affected in 0g, but hypergravity will have strong effects dependent on the vector of gravity and orientation of the body.

✓Illustrations of Unsuited and Suited Range of Motion Data is available in Appendix A, Tables 5-7.

4.3 Collection of Data

Collection of range of motion and reach envelope data is dictated by the needs of the assessment. Several methods of measurement are available, including:

Goniometer	Device with two straight edges that can rotate relative to a protractor, against which the angle between them is measured. The goniometer must be aligned with physiological landmarks on the subject, and the subjective nature of this alignment can cause variation in measuring technique between experimenters or different tests by the same experimenter.
Photographs	Can supply direct data during an experiment. The subjective nature of data extraction can cause variation in measurements between extractors or tests.
Inclinometer	Device that measures deviation from the vertical and can be used to measure trunk mobility. Accuracy can be affected by initial misalignment or slipping where it is affixed to the subject.
Motion Capture	Is a more objective tool than goniometry or photography. The position of the markers used to track motion can shift or they can become occluded.
Radiographic Examination	Range of motion is measured by taking a series of radiographs of the body and using visual inspection or a computer model to determine the relative rotation of body segments. Requires exposing subjects to large quantities of radiation and may not accurately measure rotations that are not in a single plane.
Lumbar Dynamometer	Measure mobility of the back.
Motion Capture tools (i.e., Vicon Motion Analysis System)	Capture reach movements needed to generate work envelope data. The drawback is that the markers used to track motion can shift or become occluded.
Vertec	Specialized apparatus designed to collect reach data.

4.4 Reach Envelope

Refers to the area that a crewmember can reach from a seated or standing position and can be used for design requirements to define hand or foot controls. Gravity transitions (i.e., hyper gravity) can alter reach envelope conditions and impact design considerations such as crew interfaces in spacecraft cockpits for flight control.

Reach envelope data is available for lightly clothed persons of varying sizes. Reach envelope represents the limits in the horizontal plane that may be reached by seated crewmembers wearing specific restraints. It is important to note that functional reach envelopes must be considered in the context of the activity to be performed. Such information can be found in Kennedy, 1977; Pheasant, 1996; Sanders & McCormick, 1993; and Webb Associates, 1978.

✓Example and datasets of Reach Envelope and Side Reach Horizontal Plane Data are located in Appendix A, Figures 2 and 3.

4.5 Reach Envelope Considerations

Optimal Reach Envelope – Within the overall reach envelope, some locations are visible and simple to reach, and require minimal stretching; these areas are within the optimal reach envelope. Safety-critical or frequently used controls and equipment should be located within the optimal reach envelope. Less frequently used or less critical items can be outside the optimal reach envelope. (Within the reach envelope, other location rules apply, such as sequence of use and location of controls adjacent to their associated displays).

Establishing Boundaries – In determining reach envelopes, designers need to define two boundaries:

- Maximum functional reach from the body
- Area close to the body that cannot be reached because of physical restrictions such as a lack of elbow room

Shortest Functional Reach/Maximum Reach Boundary – The individual in the population who has the shortest functional reach should be used to define the maximum functional reach boundary, ensuring that all persons in the population will be able to achieve that reach. As a rule, the largest individual should be used to define the boundary closest to the body. However, some exceptions to this rule may exist, such as individuals with short reach attempting to access controls on the front of a spacesuit.

Restrictions – Reach data for space applications, like range-of-motion data, is greatly affected by the restricted postures maintained by crewmembers while they are wearing bulky flight suits and being restrained by straps in sometimes awkward postures. These factors are discussed in section 4.5.4. When placing controls and access panels, designers of human spaceflight equipment must ensure that they account for the reduction in crewmembers' reach capabilities.

Body Size – Crew stations must accommodate the reach limits of the smallest crewmember. However, reach limits are not always defined by overall size. For instance, the worst-case condition for a constrained (e.g., seated with shoulder harness tight) person may be a combination of a long shoulder height and a short arm. These statistical variations in proportions should be accounted for in reach limit definitions.

4.6 Application of Data and Standards

NASA-STD-3001 Volume 2 – Relevant Technical Requirement

[V2 4102] Functional Anthropometric Accommodation The system shall ensure the range of potential crewmembers can fit, reach, view, and operate the human systems interfaces by accommodating crewmembers with the anthropometric dimensions and ranges of motion as defined in data sets in Appendix E, Physical Characteristics and Capabilities, Sections E.2 and E.3.

The ranges of motion to be accommodated for crewmembers in Appendix E of NASA-STD-3001 Volume 2 were collected in 1g conditions as part of a 2007/2008 study in the NASA JSC Anthropometry and Biomechanics Facility. The values represented in the tables show the level of mobility that was needed to perform a variety of relevant functional tasks. These numbers do not necessarily indicate maximum level of mobility possible in a given configuration.

It is important to note that pressurization causes significant restrictions to range of motion and reach.

4.7 Example of Reach and Range of Motion Lesson Learned

Due to the location of the Soyuz instrument panel, crewmembers utilize a ‘pointer’ instrument to reach and push buttons during spaceflight due to their restricted posture and reach envelope while seated in their pressurized suits (see images below). This increases risk to the crewmember performance in a variety of ways and is not an ideal solution to the inadequate design and implementation of reach and range of motion data.

5.0 BODY SURFACE AREA, VOLUME, AND MASS PROPERTIES

Measurements that assist with design, in addition to anthropometric measurements, are body skin surface area, volume, and body mass properties

Body Surface Area (BSA) – Measures the total surface area of the human body.
Estimated Body Surface Area of the Crewmember based on the projected 2015 astronaut population:

- Female (5th percentile in height with light weight) 15,300cm^2
- Male (95th percentile in height with heavy weight) 22,800cm^2
  This data applies to 1g conditions, density assumed constant at 1 g·cm^3, References: Gehan & George, 1970; Gordon et al., 1988.

5.1 Body Surface Area Data Collection—New Technology

Recent advances in technology have produced a new method for collecting body surface area, volume, and mass properties data. This method is achieved via a three-dimensional whole-body scanner that accurately and efficiently captures the surface of the body. This data can then be used to compute both volume and mass property data for the whole body and body segments.

Calculation - The body surface area of an individual is calculated as a function of stature and weight. DuBois and DuBois (1916) defined this procedure and Martin, Drinkwater, and Clarys (1984) validated the results. The calculation steps are as follows:

Determine the 5th-, 50th-, and 95th-percentile male stature and weight.

Substitute the stature and weight data into the equation below, where W is weight in kilograms, H is stature in centimeters, and the result is surface area in square centimeters.

$$Surface\ Area = 71.84\, W^{0.423} H^{0.723}$$

5.2 Additional Body Surface Area Considerations

- Gravity Environment – Body surface area estimation equations apply to 1g conditions
- Fluid shifts and spinal elongation – in 0g are not accounted for
- Limited population – The body surface area data provided above is most accurate for the Caucasian or African American male and female body forms

5.3 Body Surface Area Applications

Body surface area data has several applications for space module design including thermal control, which provides and estimation of body heat production for thermal environmental control; and estimation of individual crewmember radiation dosage.

5.4 Body Volume

Body volume refers to the volume displaced by the body as a whole and by body segments. ✓Body volume data for whole body (Table 8) and body segment (Table 9) are located in Appendix A.

5.5 Body Volume Data Collection – New Technology

Recent advances in technology have produced a new method for collecting body surface area, volume, and mass properties data. This method is achieved via a three-dimensional whole-body scanner that accurately and efficiently captures the surface of the body. The data collected from the scans can be used to calculate both volume and mass property data for the whole body and body segments.

The body surface area estimation equations only apply to 1g conditions and do not account for the fluid shifts and spinal elongation experienced in the 0g environment.

5.6 Body Mass Properties

Whole Body and Body Segment Mass Data: The select data for whole-body mass and body-segment mass is based on the projected 2015 astronaut population. All data is based on 1g measurements.

Whole-Body and Body-Segment Mass Data Calculation: Although body mass remains constant, body weight depends on gravity conditions. In 1g, body weight is calculated as indicated below:

Weight in newtons = Mass in grams × 0.0098

Weight in pounds = Mass in slugs × 32.2

Center of Mass - Whole Body and Body Segment: The center of mass refers to the position that is the mean location of a distribution of mass in space. The data for whole-body center of mass is based on the projected 2015 astronaut population. All data is based on 1g measurements. Refer to McConville et al. (1980) and Young et al. (1983) for definitions of anatomical axes.

✓Location of whole body center of mass (Table 12) and body segment center of mass (Table 13) is available in Appendix A.

Data for Body Segments' Center of Mass: The locations of the center of mass for select body segments in 1g is based on the projected 2015 astronaut population. The values represented by X, Y, and Z in the Axis column relate to the coordinates for the location of the center of mass with respect to anatomical origin and are measured along the anatomical axes. The axes represented by X_a, Y_a, and Z_a are shown to represent the anatomical axes. Refer to McConville et al. (1980) and Young et al. (1983) for definitions of anatomical axes. All data is based on 1g measurements.

Factors That Affect Whole-Body and Body-Segment Center of Mass Considerations: The 0g environment causes fluids to shift upward in the body and leave the legs. This results in an upward shift of the center of mass for the whole body and a loss of mass in the leg segments. The data does not account for the fluid shifts and spinal lengthening in 0g.

Application of Whole-Body and Body-Segment Center-of-Mass Data: In 0g, the body mass properties define body reaction to outside forces including:

- Reactive to forces exerted by the crewmember or a hand tool.
- Active forces from devices such as the Manned Maneuvering Unit.
- The reaction of the body to a force depends on both the mass and the relative positions of the body segments. The whole-body center-of-mass and moment-of-inertia data is provided for standing posture only. Whole-body mass properties for other positions would have to be determined by mathematically combining the mass properties of the individual segments and the appropriate postures maintained by these segments.

Whole Body Moment of Inertia: A quantity expressing a body's tendency to resist angular acceleration. It is the sum of the products of the mass of each particle in the body with the square of its distance from the axis of rotation.

Data for Whole-Body Moment of Inertia: The data for whole-body moment of inertia is based on the projected 2015 astronaut population. All data is based on 1g measurements. The moments of inertia for the whole body are given with respect to the principal axes of inertia, and these are denoted by X_p, Y_p, and Z_p. The relationship between the principal axes and the anatomical axes can be found. Refer to McConville et al. (1980) and Young et al. (1983) for definitions of anatomical axes.

✓Data regarding whole body moment of inertia is located in Appendix A, Table 14.
✓Data regarding select body-segment moment of inertia of the crewmember is located in Appendix A, Table 15.

5.7 Data for Body-Segment Moment of Inertia

Body-segment moment-of-inertia data for the American male crewmember in 1g is in based on listing of Constellation program body-segment moment-of-inertia data.

The moments of inertia for body segments are given with respect to the principal axes of inertia, and these are denoted by X_p, Y_p, and Z_p. Refer to McConville et al. (1980) and Young et al. (1983) for definitions of anatomical axes.

5.8 Application of Data and Standards

NASA-STD-3001 Volume 2 – Relevant Technical Requirement
[V2 4103] Body Mass, Volume, and Surface Area Data The system shall accommodate the body characteristic data for mass, volume, and surface area as defined in Appendix E, Physical Characteristics and Capabilities, Sections E.4, E.5, and E.6.

Depending on mission or design requirements, system developers could need body mass, volume, and body surface area data that accurately describe the entire size range of potential crewmembers. This data is used to make calculations for things such as radiation exposure, designing of body contact cooling systems, gravity or buoyancy, force and exertion for body support systems, or understanding how loads are distributed during accelerations.

5.9 Example of Body Surface Area, Mass, and Volume Application

Spinal elongation due to microgravity is an important consideration. Crewmembers tend to increase in stature by up to 3 percent (6% of seated height), which drives current requirements to allow for such growth in dimensions such as body surface area/stature, eye height, and seated height when designing crew interfaces, vehicle seats, and suits.

Example image: Orion cockpit seating arrangement

6.0 STRENGTH

The term “strength” is often used to refer to a person’s ability to generate force. Because of the difficulty in measuring strength, it is hard to formulate a clear definition of the term. One appropriate definition is “the magnitude of variable force that a [muscle group] exerts on the skeletal system at the attachment site of interest” (Kulig, Andrews, & Hay, 1984).

Information related to physical workload can be found in HIDH Chapter 5.2. Information related to exercise countermeasures can be found in HIDH Chapter 7.5.

6.1 Strength Data Presentation

Unlike anthropometric data, strength data from different populations is not readily available, and limited to small sample sizes causing strength percentile data to be limited. Therefore, strength data often shows maximum and minimum values based on the weakest and strongest members of the population.

✓Data regarding Unsuited Strength Data is in Appendix A, Table 16.
✓Data regarding Unpressurized (Table 17) and Pressurized Suited Strength Data (Table 18) are located in Appendix A.

6.2 Collection of Strength Data

Results of strength studies are highly dependent on the type of strength test done, the measurement techniques, and the measurement devices chosen. In addition, the selection of a population representative of the end-user to study is critical.

The most common types of strength tests are isometric, isokinetic, and isotonic testing (Kroemer, Kroemer, & Kroemer-Elbert, 2001). Isometric testing is static, with muscle lengths remaining the same throughout the exertion; isokinetic tests involve constant velocity; and isotonic tests consist of constant force.

One major factor involved in measurement technique is the device with which strength is measured. Measurements are most often taken with a dynamometer system. A dynamometer can be something as simple as a mechanical device to record maximum force during grip, or a much more advanced machine with computing capabilities that allows testing to be conducted in a variety of conditions.

Other facets of measurement technique are the speed of contraction, number of joints involved in a movement, and orientation of the subject with respect to gravity (Kulig et al., 1984). Concentric testing involves dynamic contractions in which a subject’s strength overcomes the resisting force, and eccentric testing involves dynamic contractions in which a subject is overcome by a resisting force and the muscle lengthens during the contraction (Kroemer, 1976).

6.3 Strength Data Considerations

User Population	As with any human-centered design consideration, the person who will be performing the activity must be considered. The database selected should reflect the likely user population in terms of age, gender, fitness, and other characteristics as closely as possible.

Activity Type	The type of activity and interactions between the human and environment will dictate whether minimum or maximum strength is of concern. The level of criticality will also determine if factors of safety are needed.
Weakest Crewmember	In most cases, the goal of understanding strength data is to ensure that the weakest crewmember can perform a task. For example, the torque required to open a hatch should be within the capability of the weakest member of the population.
Structural Limits	In some cases, structural limits are in place to prevent accidental damage from crewmembers. For example, the torque required to break a piece of equipment might be required to be more than the maximum torque produced by the strongest crewmember.
Duration	The duration of the activity has a major effect on the strength a person can exert. Strength drops off significantly with the extended duration of an activity.
Anthropometry	Because of the low correlation between strength and size, anthropometry should not be used to determine accommodation of strength and endurance. Though strength is related to the size of muscles, research has failed to predict an individual's strength for given activities based on anthropometry, including circumferences around major muscles (Kroemer, 1976).
Counter-Reactive Forces	The lack of gravity leads to the absence of counter-reactive forces that allow people to effectively perform physical work in 1g. Traction (friction force), which depends on body weight, is also absent, as are forces that result from using body weight for counterbalance. Without proper restraints, a crewmember's work capabilities will generally be reduced and the time to complete tasks increased.
Restraints	The common notion is that when workstation design (including fixed and loose equipment) and task procedures are optimized for the 0g environment, crewmembers' work capabilities while they are restrained can approach their capabilities for performing Earth-based tasks. However, quantitative data (Poliner, Wilmington, & Klute, 1994) has shown that even with foot restraints, the strength exhibited by shirtsleeve subjects in 0g is about 17% less than their strength in 1g.
Body Position	Situations do exist in which a crewmember can achieve improved strength performance in 0g. These situations occur when the crewmember uses the greater maneuverability in 0g to achieve a more efficient body position to be able to push off solid surfaces.

Deconditioning Effects	Strength is reduced with longer missions because of the deconditioning of muscles. Experience in space indicates that both the strength and aerobic power of load-bearing muscles in crewmembers decreases during missions exposing them to 0g. Exercise countermeasures have been used to counter these deficits, but to date have been only partially effective.
Exercise	The results of a study by Adams, Caiozzo, and Baldwin (2003) indicate that spaceflight without exercise may cause greater muscle atrophy than bed rest. It should also be noted that greater loss of leg muscle strength than arm muscle strength is expected because locomotion is performed with the upper body during spaceflight (Cowell, Stocks, Evans, Simonson, & Greenleaf, 2002). Results of spaceflight studies are also affected by countermeasure efforts taken during flights of greater than 10 days (Adams et al., 2003).

✓Data regarding Effects of Spaceflight and Bed Rest Strength is located in Appendix A, Table 19.
✓Data regarding most common approaches to strength data collection is located in Appendix A, Section A.2 (Kroemer, Kroemer, and Kroemer, 1997).

6.4 Application of Data and Standards

NASA-STD-3001 Volume 2 – Relevant Technical Requirement
[V2 4104] Crew Operational Loads The system shall be operable by crew during all phases of flight, including prelaunch, ascent, orbit, entry, and postlanding, with the lowest anticipated strength as defined in Appendix E, Physical Characteristics and Capabilities, Section E.7.
[V2 4105] Withstand Crew Loads The system shall withstand forces imparted by the crew during all phases of flight, including but not limited to prelaunch, ascent, orbit, entry, and postlanding, as defined in Appendix E, Physical Characteristics and Capabilities, Section E.7 without sustaining damage.
[V2 4013] Muscle Effects The effects of muscle endurance and fatigue shall be factored into system design.

Task analysis and human-in-the-loop testing are used to define planned crew tasks, hardware, interfaces, expected postures, task criticality, frequency, and duration to define the maximum acceptable value for actuation and continued operation of hardware interfaces and identify which interfaces must tolerate maximum crew operational loads. It is also used to identify factors that lead to muscle effects including overexertion or fatigue such as task frequency, duration, repetitive motions, high forces, current and previous gravity environments and duration, suit configuration, etc.

A crewmember's posture when performing a task has significant impacts on the amount of strength they are able to exert. Additionally, microgravity does not have many of the counterforces and traction that enables individuals to physically perform at their greatest strength level. Workstations with strategic placement of restraints provides crewmembers with some improvement in work capabilities.

7.0 FACTORS THAT AFFECT ANTHROPOMETRY, RANGE OF MOTION, REACH, BODY SURFACE AREA VOLUME AND MASS, AND STRENGTH

Factors that Affect Anthropometry, Range of Motion, Reach, Body Surface Area, Volume and Mass, and Strength include age, sex, clothing, pressurization, postures, and gravity levels. The application of anthropometry data is also affected by the environment in which a user will operate, such as ground operations, intravehicular activity, or extravehicular operations.

✓Data regarding values in different operating environments for factors affecting anthropometry are located in Appendix A, Table 20.

7.1 Age Effects

The age of a person affects anthropometry in individuals through changes in stature, weight, and mass distribution. Age considerations include:

- Increases in stature and weight occur until maturity is reached.
- Decreases in stature can occur as adults age.
- Fluctuations in weight and mass distribution occur with age.
- Joint mobility and movement can decrease as individuals age.
- Strength peaks around age 20 - 25, with gradual decreases over time. However, age is not a reliable strength predictor as large inter-subject variability exists between individuals.

7.2 Sex Effects

The gender of a person affects anthropometry through differences in stature size, limb size, joint movement ability, and overall strength.

- The body size and strength of males and females follow a bivariate normal distribution and cannot be represented by a single population curve.
- Female body size measurements are typically smaller than male measurements, females are usually shorter in stature, have shorter limb lengths, but the average female hip breadth, both sitting and standing, exceeds the average male hip breadth (Gordon et al., 1988).
- Female weight is typically less than male weight.
- The strength of the average female is generally less than the strength of the average male, mostly because of their smaller size. This measurement has a lot of inter-subject variability and when selecting a population for strength studies, gender is not an accurate predictor of strength.

- In general, the female population has a slightly broader range of joint movement and the designer should consider the upper and lower limits for the combined male and female population.
- Distribution of data is separate; it is necessary to derive male and female data separately and not use any generalized relationships to represent a population of both males and females.
- Unless the equipment in the workspace is gender-specific (i.e., used by only one gender), the designer should consider the upper and lower limits for the combined male and female population. In general, the female population has a slightly broader range of joint movement.
- Female limb lengths are typically shorter than male limb lengths therefore the combination of limb size and joint mobility must be taken into consideration.

7.3 Clothing Effects

- Safety concerns may require crewmembers to wear a flight suit that can be pressurized. The previous NASA design of such equipment consists of an undergarment to maintain and control temperature, a single-piece coverall suit, an oxygen mask or a helmet with a visor, and a parachute backpack.
- The effects of clothing can be very important, especially for differences between shirtsleeve and suited operations. Clothing can significantly affect size, and different suits will affect anthropometry differently. For instance, a lighter launch/re-entry suit might be much less bulky than a hard-upper-torso planetary suit thus can affect the postures that subjects select, and impact hardware design.
- Design considerations must include suit's impact on dimensions such as sitting height and thigh clearance, for unpressurized and pressurized conditions. This information is not available in standard anthropometric databases, so it is often necessary to derive values for the effects of clothing on anthropometry. The suit designers have the responsibility to convey the suit's effects on the anthropometry.
- Ideally, any flight suit with or without pressurization should be able to retain much of a crewmember's joint mobility. However, experience with the current launch and entry and EVA suits has shown that some restriction is unavoidable.
- Sitting height increases by approximately 6% of seated height. This is the result of spinal elongation, straightening of the spinal curvature, and postural effects. For all seated measurements that include the length of the spine, 6% of seated height must be added to allow for spinal elongation due to microgravity exposure (Young & Rajulu, 2011). In addition, clothing effects and suited anthropometry must also be accounted for when determining the overall measurement growth for a crewmember wearing a suit in 0g.

✓Data regarding effect of wearing a pressurized suit on torque is located in Appendix A, Table 21.

7.4 Pressurization Effects

The dimensions of a person in a pressurized suit differ from those of someone in an unpressurized suit, and both differ from dimensions of a minimally clothed crewmember. Pressurization increases the volume occupied by a crewmember by injecting breathing air inside the suit resulting in a ballooning effect which affects the dimensions of the crewmember.

Because it may be unrealistic to obtain pressurized anthropometry data for an entire database, it is necessary to develop conversion factors to apply to available anthropometric data for minimally clothed crewmembers, ratios between suited and unsuited sizes can then be obtained for key anthropometric dimensions. Anthropometric data for minimally clothed crewmembers can be multiplied by these ratios to provide an estimate of that subject's suited anthropometry allowing for variances in individual suit adjustments, tie-downs, restraints, and so on.

Spacesuit effects on anthropometry use of multipliers applied to data from unsuited crewmembers to estimate the anthropometry of suited crewmembers were derived from anthropometric data collected from subjects wearing an Advanced Crew Escape Suit (ACES). ✓Data describing calculation of spacesuit effects on anthropometry is located in Appendix A, Table 22.

7.5 Clothing and Pressurization Effects on Strength

Wearing a pressurized suit affects a person's ability to exert maximum effort. Simply wearing the suit affects strength, and pressurizing the suit reduces strength further. A study by Gonzalez, Maida, Miles, Raiulu, and Pandya (2002) indicated that joint torque production capabilities of subjects decreased up to 39% while they were wearing a pressurized suit.

7.6 Clothing and Pressurization Effects on Reach

Clothing and personal equipment worn on the body can influence functional reach measurements. The effect is most commonly a decrease in reach. This must be considered when designing workstations that will be used by crewmembers in flight suits. The reduction varies from 3% to 12%, with the largest decrement occurring in vertical downward reach with an unpressurized ACES suit. When the suits are pressurized, the reduction in reach varies from 2% to 45%, with the largest decrement occurring in vertical downward reach with the pressurized D-suit.

If spacesuits are required during any phase of the space module operations, this will necessitate a substantial reduction in any design reach dimensions established for shirtsleeve operations. The extent of these differences would have to be determined from using the specific spacesuits and gear to be used in that mission.

Wearing a pressurized suit may affect a person's joint mobility, joint torque production capabilities, ability to exert the maximum effort, and strength. Note that pressurizing the suit potentially reduces strength further. Functional strength tests involving tasks such as pushing and pulling rather than isolated joint movements have shown that a pressurized I-suit reduces functional strength up to 50% (current NASA study, unpublished data). A study by Gonzalez,

Maida, Mijles, Raiulu, and Pandya (2002) indicated that joint torque production capabilities of subjects decreased up to 39%.
✓Data regarding changes in body envelope data with pressurized or unpressurized flight suits is available in Appendix A, Table 23.

7.7 Postural Effects

Traditional anthropometric databases provide only standardized body dimensions. However, changes in posture may greatly affect body dimensions. At least two distinct postural effects must be considered during space operations: seated postural effects during launch and entry, and 0g effects during on-orbit stay. During launch and entry, crewmembers are seated in a recumbent position while wearing a flight suit. Wearing a flight suit and being restrained to a seat may affect the anthropometry significantly, recumbent seated anthropometry and upright sitting posture undoubtedly affect range-of-motion capabilities because significant restraint is associated with these postures. More importantly, the reach envelope characteristics will be significantly different.

The normal working posture of the body in a 0g environment differs substantially from that in a 1g environment (see Figure 4 in Appendix A). The neutral body posture is the basic posture that should be used in establishing a 0g workspace layout.

The major example of this during spaceflight is recumbent seating versus upright seating. If a crewmember must overcome gravity to perform a given task, the force production capability will be greatly reduced.

7.8 Gravity

The major effects of 0g on strength are related to counter-reactive forces, restraints, and deconditioning. Though some activities, such as lifting a box, will require less strength in 0g, other activities, such as opening a hatch, will still require full strength.
✓Data regarding Anthropometric Changes in 0g is located in Appendix A, Table 24.

7.9 0g Postural Effects

The effects of 0g on the human body in normal working posture differs substantially from that in a 1g environment. The neutral body posture is the basic posture that should be used in establishing a 0g workspace layout. The primary effects of 0g on human anthropometry are as follows:

<u>Standing Height Increase</u> – Stature increases approximately 3% as a result of spinal elongation and the straightening of the spinal curvature due to microgravity effects. For all standing measurements that include the length of the spine, 3% of stature must be added to allow for these potential changes. In addition, clothing effects and suited anthropometry must be accounted for when determining the overall measurement growth for a crewmember wearing a suit in 0g.

Seated Height Increase – Sitting height increases by approximately 6% of seated height and requires adjustment as outlined above (Young & Rajulu, 2011). In addition, clothing effects and suited anthropometry must also be accounted for when determining the overall measurement growth for a crewmember wearing a suit in 0g.

Neutral Body Posture – The relaxed body immediately assumes a characteristic neutral body posture (Thornton et al., 1977; Webb Associates, 1978).

Body Circumference Changes – Body circumference changes occur in 0g because fluid shifts toward the head (Thornton et al., 1977; Webb Associates, 1978).

Body Mass Loss – The total mass of the body may decrease up to 8% and can largely be prevented in current programs through better understanding of nutritional/caloric needs (Webb Associates, 1978).

Range-of-Motion – Posture changes noticeably during exposure to 0g, and these changes may affect the overall range of motion. For example, raised shoulders, a 0g effect, could both increase and decrease the capabilities of shoulder motion. However, for the most part, the range of motion may be very similar to that found on Earth. Thus, while working in shirtsleeve environments, crewmembers can safely use ranges of motion for 1g conditions under 0g conditions as well.

Comfort – In 0g, the fully erect standing posture of 1g is not comfortable. Instead, the human body naturally rests in a neutral configuration.

Body Accommodation in 0g – Designing to physically accommodate the human body in 0g differs from comparable accommodation for 1g as a 1g posture in 0g will produce stress on the body when muscles are called on to supply stabilizing forces that gravity normally supplies. Stooping and bending are examples of other positions that cause fatigue in 0g. In 0g, the natural heights and angles of the neutral body posture must be accommodated. Some of the areas to be considered are the following:

- Foot Angle – Since the feet are tilted at approximately 111 degrees to a line through the torso, sloping rather than flat shoes or restraint surfaces should be provided (Webb Associates, 1978).
- Foot and Leg Placement – Foot restraints should be placed under work surfaces. The neutral body posture is not vertical because hip or knee flexion displaces the torso backward, away from the footprint. The feet and legs are positioned somewhere between a location directly under the torso (as in standing) and a point well out in front of the torso (as in sitting).
- Height – The height of the crewmember in 0g is between sitting and standing height. A 0g work surface should be higher than one designed for 1g or partial-g sitting tasks.
- Arm and Shoulder Elevation – Elevation of the shoulder girdle and arm flexion in the neutral body posture also make elevation of the work surface desirable.
- Head Tilt – In 0g the head is angled forward and down, a position that depresses the line of sight and requires that displays be lowered.

7.10 Neutral Body Posture and Clearance Envelope

Anthropometric dimensions can be combined with neutral body segment angles to estimate a total body envelope. Calculating maximum clearance envelopes for 1st-percentile American female dimensions and 99th-percentile American male dimensions provide an example of the use of neutral body posture combined with anthropometric data.
✓Data regarding reach envelopes for neutral body posture is located in Appendix A, Table 25.

7.11 Hyper Gravity Effects

The inability to reach and access controls is the most significant effect of a hyper-g environment on a crewmember's performance. This is valid for crewmembers in a recumbent or an upright position. With a limited reach capability, even if the crewmembers can exert body movements, they may not be able to access the controls they need to reach and operate, particularly during an emergency operation.
✓Data regarding reach movements possible in multi-g environment is available in Appendix A, Table 26.

In hypergravity environments, the weight of the body segments involved in a task increases in unison with gravity, and thus exerting the necessary force becomes an excessive burden. The bulk of the effort exerted by the crewmember goes toward either bringing in or maintaining body segments in a required posture, causing simple tasks to be more difficult in hypergravity environments.

7.12 Restraint Effects

While the absence of gravitational forces will usually facilitate rather than restrict body movement, this lack of gravity will leave crewmembers without any stabilization when they exert a thrust or push. Restraint systems can hinder mobility during spaceflight, but are necessary for crew safety and stabilization. Three basic types of body restraint or stabilizing device have been tested under neutral buoyancy conditions on Earth or 0g conditions in space. These are handhold, waist, and foot restraints. The following is a description of each type of restraint and its effect on reach:

- Handhold Restraint – With the handhold restraint, the individual is stabilized by holding onto a handgrip with one hand and performing the reach or task with the other. This restraint affords a wide range of functional reaches, but body control is difficult and body stability is poor.

- Waist Restraint – A waist restraint affords good body control and stabilization, but seriously limits the range of motion and reach distances attainable.

- Foot Restraint – In Skylab observations and neutral buoyancy tests, the foot restraints were judged to be excellent in reach performance, stability, and control. The foot restraint provides a large reach envelope to the front, back, and sides of the crewmember. Appreciable forces often cannot be exerted because muscles of the ankle rotators are weak. Foot restraints should be augmented with waist or other types of restraint where appropriate.

Restraint Effect on Workstation
The common notion is that when workstation design (including fixed and loose equipment) and task procedures are optimized for the 0g environment, crewmembers' work capabilities while they are restrained can approach their capabilities for performing Earth-based tasks. However, quantitative data (Poliner, Wilmington, & Klute, 1994) has shown that even with foot restraints, the strength exhibited by shirtsleeve subjects in 0g is about 17% less than their strength in 1g. Situations do exist in which a crewmember can achieve improved strength performance in 0g. These situations occur when the crewmember uses the greater maneuverability in 0g to achieve a more efficient body position to be able to push off solid surfaces.

8.0 APPLICATION SUMMARY

The human performance envelope is bounded by physical as well as cognitive limitations. Accommodating these limitations during space flight is critical to all aspects of mission success, including the maintenance of crew health and safety. It is important that the design of equipment, including vehicles, spacesuits, and other interfaces, accommodates the physical characteristics of the entire user population. Adjustments for the effects of external factors such as gravity environments, clothing, pressurization, and deconditioning related to mission duration are to be included in the design. Datasets are provided that include characteristics and capabilities for anthropometric dimensions, range of motion, strength, mass, volume, and surface area. Datasets take into account human characteristics such as age, sex, and physical condition as well as mission characteristics such as clothing and suit pressurization. NASA-STD-3001 Volume 2 provides a set of technical requirements that give guidance on how to implement the relevant datasets to accommodate crewmembers' physical characteristics and capabilities; as well as an appendix of physical characteristics and capabilities datasets. The intent of these technical requirements is to accommodate the entire potential user population, not just meet the criteria in the datasets, which provide the most frequently used values. Identification of a design criteria not provided in the appendix needs coordination and concurrence from NASA Stakeholders. Each dataset may be tailored by NASA based on program or mission specific criteria.

Example 1. International Space Station (ISS) Glovebox and Workstations

Reference: Mount, F.E., and Foley, T. Extended Duration Orbiter Medical Project. Section 6: Assessment of Human Factors.

Operators of confined work stations, such as gloveboxes and the General Purpose Work Station (GPWS) used on ISS, often experience significant impacts on posture and remain in unnatural positions for extended periods of time. This in turn leads to increased fatigue and muscle loading, and a decrease in overall performance. Constrained arm movements, postural limitations, and visual constraints are some examples of human factors that should be established in the design of these work stations. A study of four crewmembers on a new glovebox design flown on STS-50 examined anthropometric characteristics using a Posture Video Analysis Tool (PVAT) and subjective crew feedback to assess the new design (see Figure 2 below). The study concluded that future designs should provide more flexible arm holes for increased range of motion, improved foot restraints to provide better control of postural positioning, and be height adjustable.

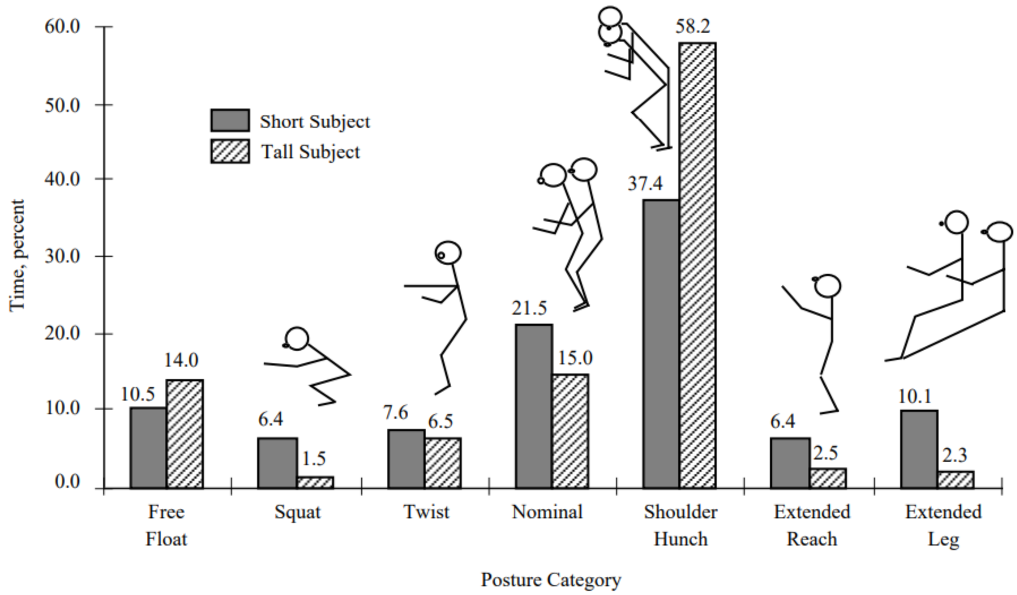


Figure 2. Percentage of time primary crewmembers spent in each posture category

<u>Example 2. Anthropometric Considerations for Spacesuit Fit</u>

Reference: Abercromby, A.F.J., et al. (2020). Crew Health and Performance Extravehicular Activity Roadmap: 2020. NASA/TP-20205007604.

Critical anthropometric dimensions of suited crewmembers can have significant impacts on comfort and performance. Suit fit, degree of suit customization, and changes in anthropometric characteristics during spaceflight have been examined for microgravity and planetary environments. Strategies such as human-spacesuit interaction modeling, virtual suit fit assessments, and sizing validation using postural and anthropometric databases have been employed to make recommendations of factors to consider during spacesuit design. An inflight study conducted on the ISS titled “Body Measures” assessed in-flight changes to crewmember anthropometric measurements that are critical to suit sizing. Changes to the body because of the neutral body posture and associated spinal elongation effect experienced during microgravity were collected. Results determined that most changes to crewmember anthropometric measurements occurred during the first 15 to 20 days of a mission, thus the predicted changes in crewmember measurements during this timeframe are critical for determining suit fit and potential changes in suit sizing needs. Human-spacesuit interaction models and human-in-the-loop (HITL) testing can estimate the extent of in-flight anthropometric changes that are expected to have an impact on suit fit, comfort, and overall performance.

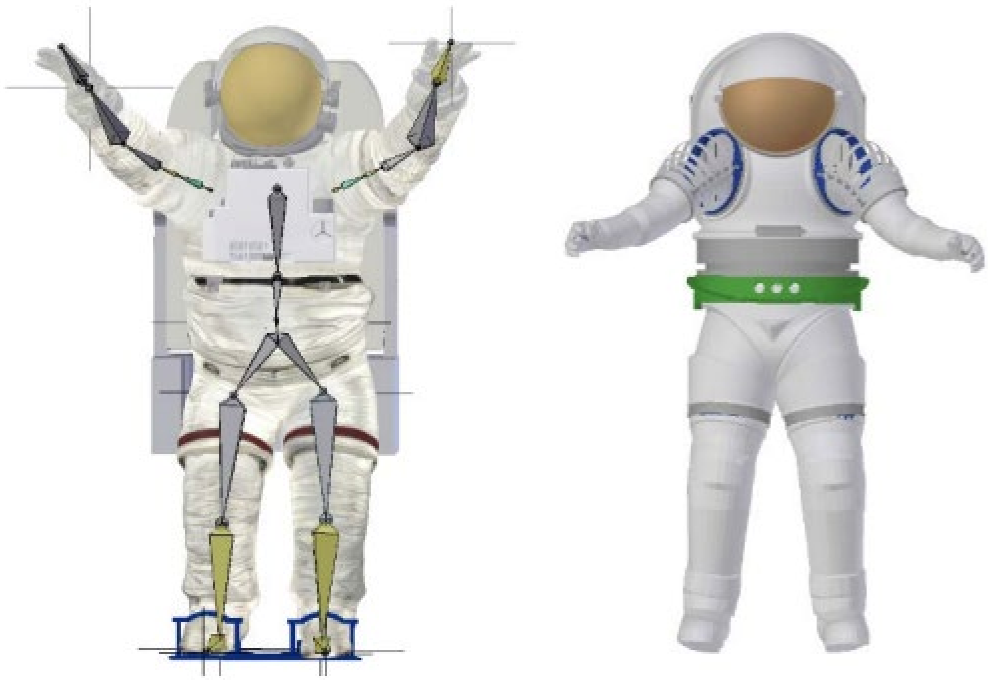


Figure 3. Prototype versions of the EMU (left) and MK III (right) computer models showing the armature that is used to control the posture of the suit.

Computer modeling tools used to assess human-spacesuit interaction are used to predict suit design issues and functional limitations. These modeling techniques utilize individual anthropometric dimensions and a spacesuit’s design features to provide quantitative estimates of performance aspects of a suited crewmember such as range of motion.

In addition to the changes crew experience in microgravity, future exploration missions will involve lunar surface missions lasting up to 180 days, giving the crew time to adapt to the lunar gravity environment. Previous Apollo surface missions lasted no more than three days and the lunar module cabin was too confined to observe and record anthropometric changes, thus data on the potential anthropometric changes crewmembers will experience while working and living on the lunar surface are not well understood (Griffin, Howard, Rajulu, & Smitherman, 2009). The possible effects of lunar surface gravity on crewmembers will need to be considered in the design of the next generation of EVA suits and surface terrain vehicles (i.e., rovers).

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10.0 APPENDIX A.

The majority of data, figures, and tables presented in Appendix A are from NASA-STD-3001 Volume 2, Human Factors, Habitability, and Environmental Health: Appendix E. Physical Characteristics and Capabilities Data Sets. Confirm you are using the most recent version of NASA-STD-3001 Volume 2 available on the OCHMO Standards website. The ranges of motion to be accommodated for crewmembers were collected in 1 g conditions as part of a 2007/2008 study in the NASA JSC Anthropometry and Biomechanics Facility.

Table 5 —Unsuited Range of Motion, provides several joint measures that were present in old versions of this table but were not reinvestigated as a part of the 2007/2008 mobility study. These values are specifically called out when listed in the table.

Tables 6 and 7 provide Range of Motion (ROM) for several joint measures under unpressurized and pressurized suit conditions. It should be noted that since pressurization causes severe restrictions to range of motion, no pressurized ROM for a LEA type suit is provided. Hence, pressurized ROM data are applicable only for an EVA type suit. The values represented in these tables show the level of mobility that was needed to perform a variety of relevant functional tasks. These numbers do not necessarily indicate maximum level of mobility possible in a given configuration.

A.1 – Steps to determine the dimensions that will accommodate a target population:

Clearance

1.Identify the critical physical clearance dimension (using mock-ups, if necessary).

2. Define possible human body movements and positions relative to the critical dimension (consider the task being performed, including rescue operations or possible errors in an emergency, such as improper orientation for passage through a hatch).

3. Select the worst-case body position(s) that would cause clearance to be an issue.
4. Determine the body dimensions that are associated with the worst cases. Make sure to give due consideration to the involvement of other body dimensions in the worst-case body position(s).

5. Use the appropriate database to determine the value of the worst-case dimension(s) for the largest expected person. Also determine the full range (smallest person to largest person) that will define the position of the human.

6. Define the worst (bulkiest and largest) possible clothing and equipment worn or carried by the human and add this dimension to the worst-case body dimension. The results will define the design dimensions required to meet the clearance requirements.

Reach or Access

1.Identify the critical physical access dimension (using mock-ups, if necessary).

2. Determine possible human body movements and positions relative to the critical dimension (consider the task being performed).

3. Determine the worst-case body posture(s) or dimension(s) that will cause a reach or access problem. Consider the effects of other body dimensions or body positions. For example, a person with a long torso may have to lower their seat to properly position their eyes. This must be considered when designing for an operator to reach an overhead control.

4. Determine relevant factors such as clothing, pressurization, gravity (such as spinal elongation in 0g), and any other environmental factors before using the data charts for the relevant data.

5. Use the appropriate database to determine the value of the body dimensions for the smallest expected person. Also determine the full range (smallest person to largest person), as well as other critical body dimensions that will define the worst-case scenario (i.e., body position of the human). The results will define the design dimensions required to meet reach or access requirements.

Table 1. Anthropometric Dimensions

Critical Dimension	Application Example	Minimal Clothing	
		Min (cm, (in))	Max (cm, (in))
Stature, Standing[3]	Maximum vertical clearance	148.6 (58.5)	194.6 (76.6)
Sitting Height[2]	Vertical seating clearance	77.7 (30.6)	101.3 (39.9)
Eye Height, Sitting[2]	Placement of panels to be within line-of-sight	66.5 (26.2)	88.9 (35.0)
Acromial Height, Sitting[2]	Top of seatback	49.5 (19.5)	68.1 (26.8)
Thigh Clearance, Sitting	Placement of objects that may be overlap (panels, control wheel, etc.)	13.0 (5.1)	20.1 (7.9)
Knee Height, Sitting	Height of panels in front of subject	45.5 (17.9)	63.5 (25.0)
Popliteal Height, Sitting	Height of seat pan	33.0 (13.0)	50.0 (19.7)
Wrist Height, Sitting (with arm to the side)	Downward reach of subject	39.6 (15.6)	54.6 (21.5)
Biacromial Breadth	Placement of restraint straps	32.3 (12.7)	44.5 (17.5)
Bideltoid Breadth	Width of seatback	37.8 (14.9)	56.1 (22.1)
Forearm-Forearm breadth	Side clearance envelope, possible seatback width	38.9 (15.3)	66.0 (26.0)
Hip Breadth, Sitting[1]	Width of seat pan	31.5 (12.4)	46.5 (18.3)
Buttock-Popliteal Length, Sitting	Length of seat pan	42.2 (16.6)	57.2 (22.5)
Buttock-Knee Length, Sitting	Placement of panels in front of subject	52.1 (20.5)	69.9 (27.5)
Foot Length, Sitting	Rudder pedal design, foot clearance	21.6 (8.5)	30.5 (12.0)
Thumb Tip Reach, Sitting	Placement of control panels, maximum reach	65.0 (25.6)	90.9 (35.8)
Shoulder to Elbow Length	Placement and adjustability of hand controls; Vehicle reach access	29.6 (11.6)	41.9 (16.5)
Elbow to Center of Grip Length	Placement and adjustability of hand controls; Vehicle reach access	28.7 (11.3)	40.8 (16.1)
Hip Breadth, Standing[1]	Clearance while traversing and egressing the vehicle	29.8 (11.7)	40.6 (16.0)
Bust Depth, Standing	Clearance while traversing and egressing the vehicle	19.1 (7.5)	30.2 (11.9)

Waist depth	Placement and length of restraint straps	15.0 (5.9)	30.0 (11.8)
Hand Length	Placement and adjustability of hand controls; Vehicle reach access	15.8 (6.2)	22.1 (8.7)
Elbow to Wrist length	Placement and adjustability of hand controls; Vehicle reach access	22.5 (8.9)	33.1 (13.0)
Cervical Height, Standing[3]	Posture based clearance while traversing and egressing the vehicle	127.7 (50.3)	169.8 (66.9)
Trochanteric Height	Posture based clearance while traversing and egressing the vehicle	75.2 (29.6)	105.4 (41.5)
Ankle Height	Posture based clearance while traversing and egressing the vehicle	4.8 (1.9)	8.1 (3.2)
Acromion (Shoulder) Height, Standing[3]	Posture based clearance while traversing and egressing the vehicle	120.4 (47.4)	161.8 (63.7)

[1] The largest female hip breadth is larger than the largest male hip breadth, and the smallest male hip breadth is smaller than the smallest female hip breadth; therefore, male data are used for the Min dimension, and female data are used for the Max dimension.

[2] For measurements that include the length of the spine in sitting postures, 6% of the sitting measurement must be added to allow for spinal elongation due to micro-gravity exposure.

[3] For measurements that include the length of the spine in standing postures, 3% the standing measurement must be added to allow for spinal elongation due to micro-gravity exposure.

Table 2. Lack of Correlation Between Common Measurements

	Stature	Elbow Height	Knuckle Height	Fingertip Height	Waist Height	Hip Height	Knee Height	Ankle Height	Buttock to Knee	Foot Length	Arm Length
Stature	1.00	0.94	0.84	0.80	0.89	0.82	0.85	0.42	0.79	0.77	0.05
Elbow Height	0.94	1.00	0.90	0.87	0.86	0.79	0.82	0.42	0.74	0.70	0.01
Knuckle Height	0.84	0.90	1.00	0.94	0.74	0.68	0.69	0.39	0.64	0.55	0.02
Fingertip Height	0.80	0.87	0.94	1.00	0.71	0.66	0.65	0.38	0.59	0.47	0.01
Waist Height	0.89	0.86	0.74	0.71	1.00	0.85	0.86	0.41	0.78	0.69	0.08
Hip Height	0.82	0.79	0.68	0.66	0.85	1.00	0.81	0.38	0.73	0.61	0.09
Knee Height	0.85	0.82	0.69	0.65	0.86	0.81	1.00	0.44	0.75	0.67	0.07
Ankle Height	0.42	0.42	0.39	0.38	0.41	0.38	0.44	1.00	0.33	0.30	0.07
Buttock to Knee	0.79	0.74	0.64	0.59	0.78	0.73	0.75	0.33	1.00	0.65	0.03
Foot Length	0.77	0.70	0.55	0.47	0.69	0.61	0.67	0.30	0.65	1.00	0.04
Arm Length	0.05	0.01	-0.02	0.01	0.08	0.09	0.07	0.07	0.03	0.04	1.00
Source: Astronaut Candidate database, internal analysis, 2004.											

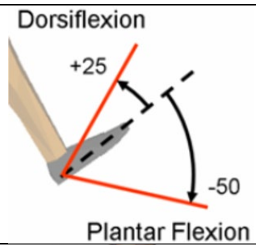
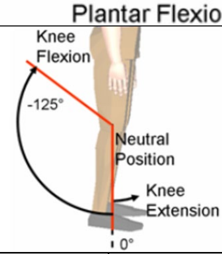
Table 3. Operating-Environment Values of Factors Affecting Anthropometric Dimensions

Operating Environment	Factors Affecting Anthropometric Dimensions		
	Clothing	Posture	Pressurization
Ground operations	Flight suit	Standing, sitting	None and Yes
EVA suit design	Minimal clothing	Standing, sitting	NA
Hypergravity (launch, entry)	Flight suit	Recumbent	None
Emergency during launch or entry	Flight suit	Recumbent, upright	Yes
Hypergravity (launch, entry)	Flight suit	Upright	None
Emergency during flight	Flight suit	Recumbent, ght, neutral body	Yes
IVA 0g	Minimal clothing	Neutral body	None
EVA 0g or partial-gravity	Spacesuit	Neutral body	Yes

Table 4. Spacesuit (Unpressurized and Pressurized) Effects on Anthropometry

	Male		Female	
Dimension	**Unpressurized**	**Pressurized**	**Unpressurized**	**Pressurized**
Sitting Height	1.11	1.09	1.08	1.11
Eye Height - Sitting	0.99	0.95	0.92	0.85
Knee Height - Sitting	1.04	1.10	1.04	1.13
Popliteal Height	1.02	0.98	0.96	0.97
Bideltoid Breadth	1.18	1.26	1.40	1.54
Buttock-Knee Length	1.06	1.18	1.15	1.27

Table 5. Unsuited Range of Motion

<table>
<tr><th colspan="2">Diagram</th><th>Anatomy</th><th colspan="2">Unsuited ROM (in degrees)</th></tr>
<tr><td colspan="2" rowspan="2">
</td><td rowspan="2">Ankle</td><td>Dorsiflexion</td><td>Plantar Flex</td></tr>
<tr><td>25</td><td>-50</td></tr>
<tr><td colspan="2" rowspan="2">
</td><td rowspan="2">Knee</td><td>Flexion</td><td>Extension</td></tr>
<tr><td>-125</td><td>0</td></tr>
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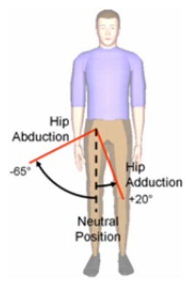
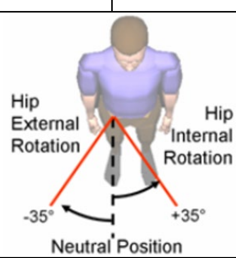
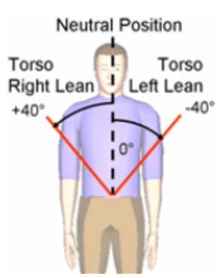
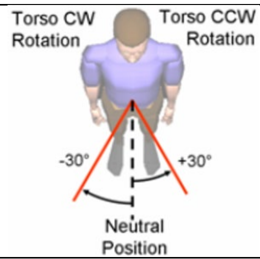
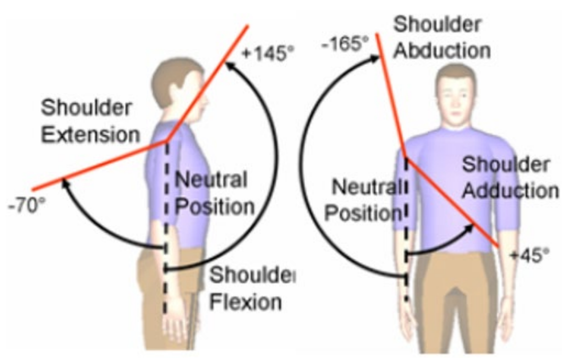
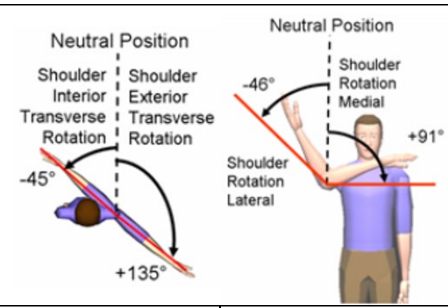
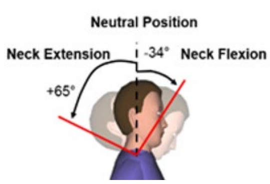
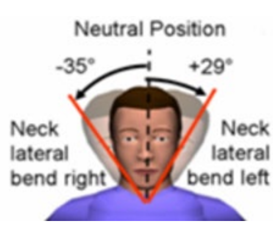
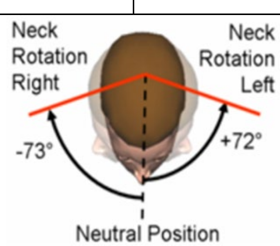
</td><td rowspan="4">
</td><td rowspan="6">Hip</td><td>Flexion</td><td>Extension</td></tr>
<tr><td>165</td><td>-15</td></tr>
<tr><td>Abduction</td><td>Adduction</td></tr>
<tr><td>-65</td><td>20</td></tr>
<tr><td colspan="2" rowspan="2">
</td><td>Internal Rotation</td><td>External Rotation</td></tr>
<tr><td>35</td><td>-35</td></tr>
<tr><td rowspan="4">
</td><td rowspan="4">
</td><td rowspan="5">Torso</td><td>Flexion</td><td>Extension</td></tr>
<tr><td>-45</td><td>15</td></tr>
<tr><td>Right Lean</td><td>Left Lean</td></tr>
<tr><td>40</td><td>-40</td></tr>
<tr><td colspan="2"></td><td>CCW</td><td>CW</td></tr>
</table>

Diagram	Anatomy	Unsuited ROM (in degrees)	
		30	-30
	Shoulder	Flexion	Extension
		145	-70
		Abduction	Adduction
		-165	45
	Shoulder 1979 Study	Interior Transverse Rotation	Exterior Transverse Rotation
		-45	135
		Lateral	Medial
		-46	91
 	Neck 1979 Study	Flex	Ex
		-34	65
		Bend Right	Bend Left
		-35	29
		Rotation Right	Rotation Left
		-73	72
	Elbow	Flexion	Extension

<table>
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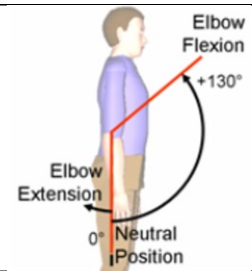
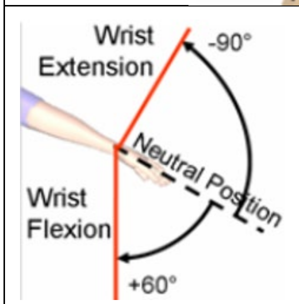
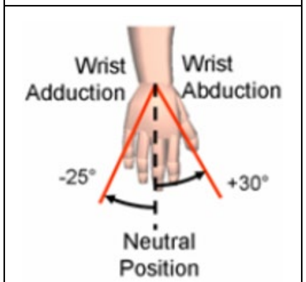
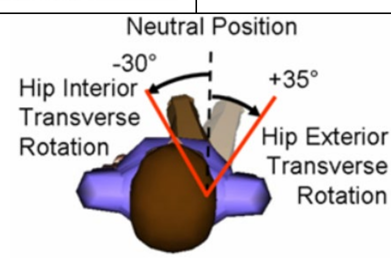
<tr><td colspan="2">
</td><td></td><td>130</td><td>0</td></tr>
<tr><td rowspan="4">
</td><td rowspan="6">
</td><td rowspan="6">Wrist</td><td>Extension</td><td>Flexion</td></tr>
<tr><td>-90</td><td>60</td></tr>
<tr><td>Abduction (Radial Deviation)</td><td>Adduction (Ulnar Deviation)</td></tr>
<tr><td>30</td><td>-25</td></tr>
<tr><td rowspan="2">
</td><td>Supination</td><td>Pronation</td></tr>
<tr><td>-80</td><td>80</td></tr>
<tr><td colspan="2" rowspan="2">
</td><td rowspan="2">Hip
1979 Study</td><td>Interior Transverse Rotation</td><td>Exterior Transverse Rotation</td></tr>
<tr><td>-30</td><td>35</td></tr>
</table>

Table 6. Suited/Unpressurized Range of Motion

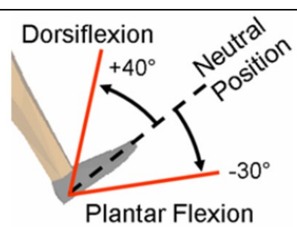
<table>
<tr><th>Diagram</th><th>Anatomy</th><th colspan="2">Suited Unpressurized ROM (in degrees)</th></tr>
<tr><td rowspan="2">
</td><td rowspan="2">Ankle</td><td>Dorsiflexion</td><td>Plantar Flex</td></tr>
<tr><td>40</td><td>-30</td></tr>
<tr><td></td><td>Knee</td><td>Flexion</td><td>Extension</td></tr>
</table>

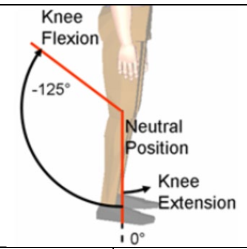
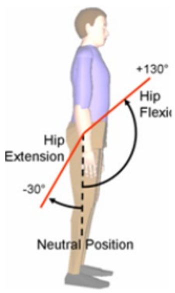
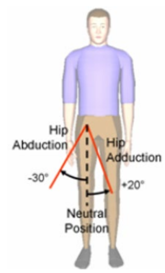
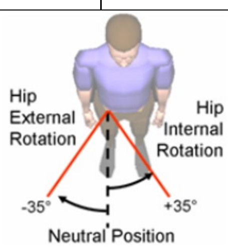
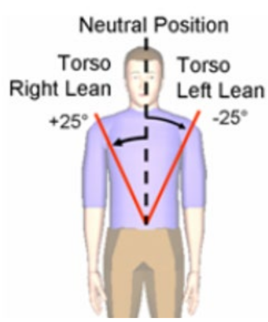
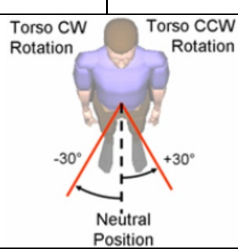
Diagram	Anatomy	Suited Unpressurized ROM (in degrees)	
		-125	0
 	Hip	Flexion	Extension
		130	-30
		Abduction	Adduction
		-30	20
		Internal Rotation	External Rotation
		35	-35
 	Torso	Flexion	Extension
		-45	15
		Right Lean	Left Lean
		25	-25
		CCW	CW
		30	-30
	Shoulder	Flexion	Extension
		140	-60
		Abduction	Adduction

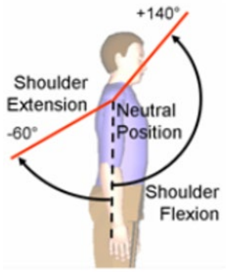
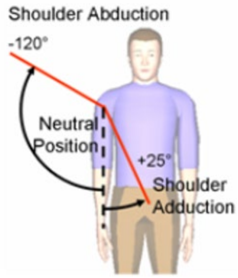
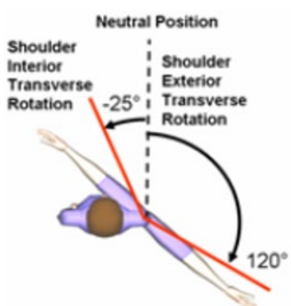
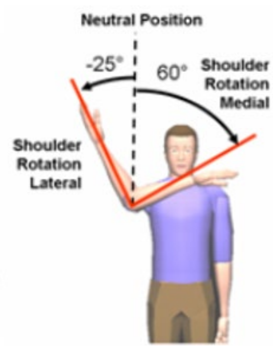
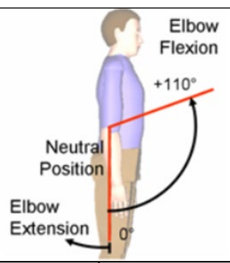
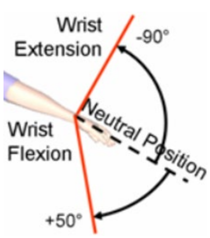
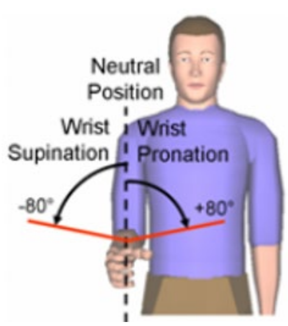
Diagram	Anatomy	Suited Unpressurized ROM (in degrees)	
 		-120	25
 	Addt'l Shoulder	Interior Transverse Rotation	Exterior Transverse Rotation
		-25	120
		Lateral	Medial
		-25	60
	Elbow	Flexion	Extension
		110	0
	Wrist	Extension	Flexion
		-90	50
		Abduction (Radial Deviation)	Adduction (Ulnar Deviation)
		30	-30
		Supination	Pronation
		-80	80

Table 7. Suited/Pressurized Range of Motion

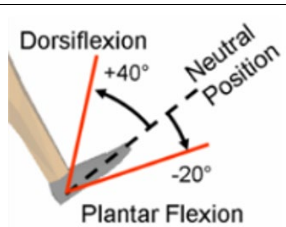
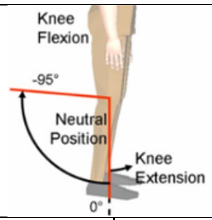
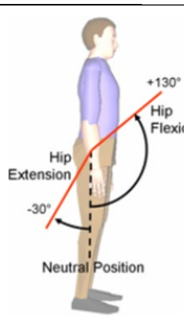
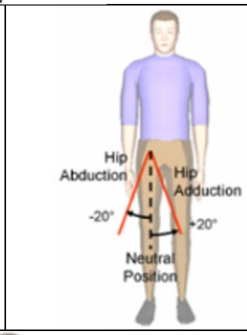
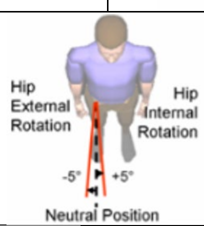
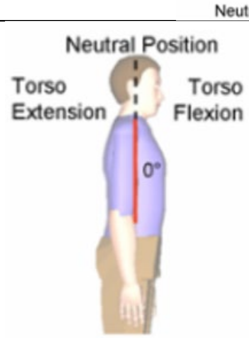
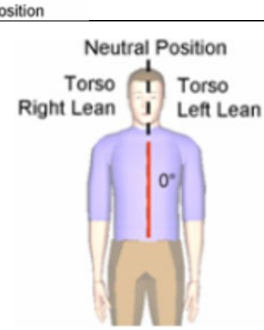
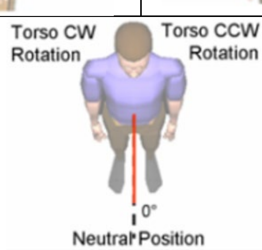
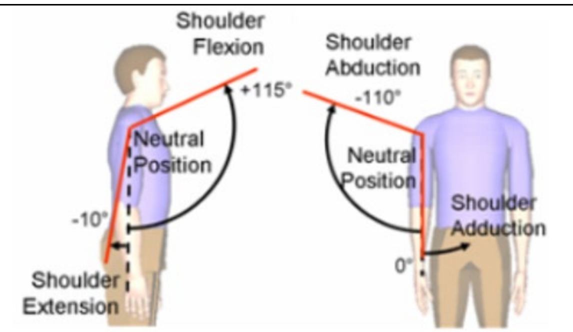
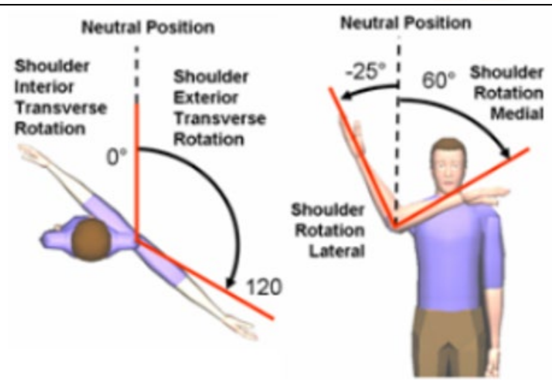
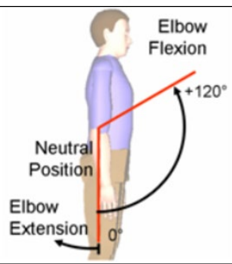
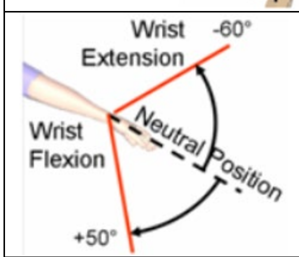
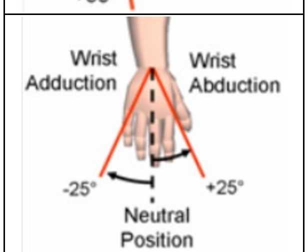
Diagram	Anatomy	Suited Unpressurized ROM (in degrees)	
	Ankle	Dorsiflexion	Plantar Flex
		40	-20
	Knee	Flexion	Extension
		-95	0
 	Hip	Flexion	Extension
		130	-30
		Abduction	Adduction
		-20	20
		Internal Rotation	External Rotation
		5	-5
 	Torso	Flexion	Extension
		0	0
		Right Lean	Left Lean
		0	0
		CCW	CW
		0	0
	Shoulder	Flexion	Extension

Diagram	Anatomy	Suited Unpressurized ROM (in degrees)	
		115	-10
		Abduction	Adduction
		-110	0
	Addt'l Shoulder	Interior Transverse Rotation	Exterior Transverse Rotation
		0	120
		Lateral	Medial
		-25	60
	Elbow	Flexion	Extension
		120	0
 	Wrist	Extension	Flexion
		-60	50
		Abduction (Radial Deviation)	Adduction (Ulnar Deviation)
		25	-25
		Supination	Pronation
		-80	80

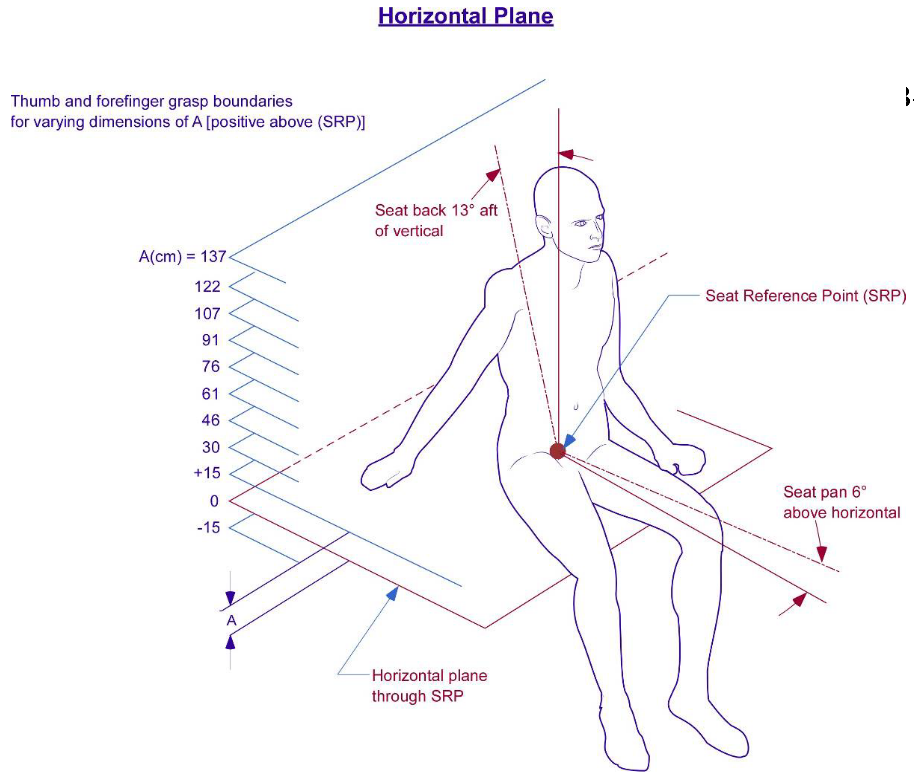


Figure 2. Side Reach Horizontal Planes

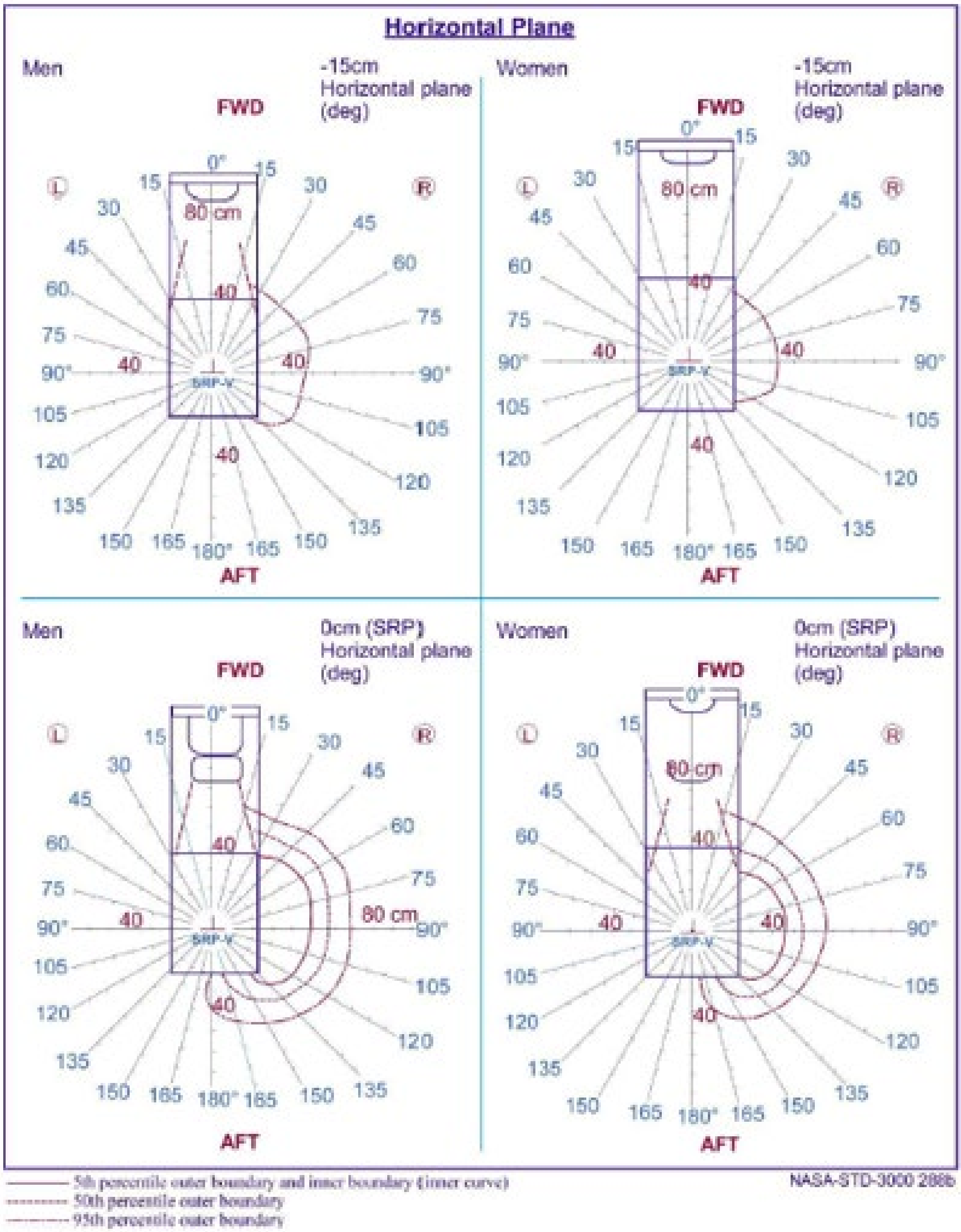
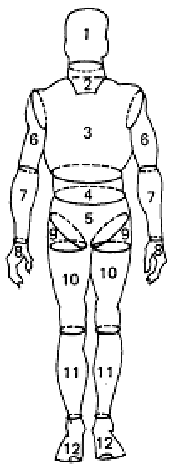


Figure 3. Reach Envelope Data in the Horizontal Plane

Table 8. Whole-Body Volume of Crewmember

Crewmember Body Volume (cm^3 [$in.^3$])	
Minimum	46,431 (2,833)
Maximum	113,556 (6,930)

Table 9. Select Body-Segment Volume of Crewmember



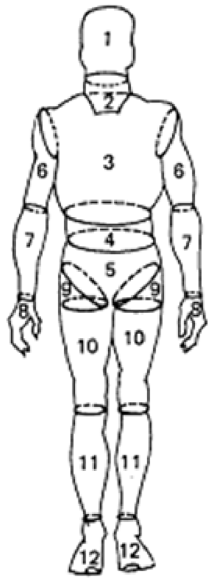
Segment	Volume (cm^3 [$in.^3$])	
	Minimum	Maximum
1 Head	3,692 (225)	4,607 (281)
2 Neck	575 (35)	1,455 (89)
3 Thorax	12,515(764)	36,034 (2,199)
4 Abdomen	1,104 (67)	3,562 (217)
5 Pelvis	4,961 (303)	17,469 (1,066)
6 Upper Arm*	957 (58)	2,901 (177)
7 Forearm*	643(39)	1,920(117)
8 Hand*	285 (17)	637 (39)
9 Hip Flap	2,510 (153)	5,191 (317)
10 Thigh minus Flap*	4,041 (247)	8,399 (513)
11 Calf*	2,195 (134)	5,062 (309)
12 Foot*	518 (32)	1,235 (75)
Torso (3 + 4 + 5)	19,269 (1,176)	57,498 (3,509)
Thigh (9 + 10)	6,571 (401)	13,424 (819)
Forearm plus Hand (7 + 8)*	930 (57)	2,556 (156)

**The minimum and maximum values for these segments were derived from the calculated average between the left and right segment values.*

Table 10. Whole-Body Mass, Unsuited

Unsuited Crewmember Body Mass (kg, (lb))	
Minimum	42.64 (94)
Maximum	110.22 (243)
Data are projected to 2015	

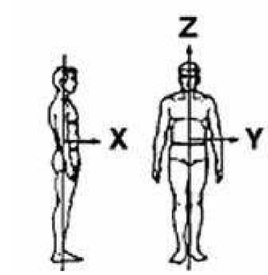
Table 11. Body Segment Mass of a Crewmember, Unsuited



Segment	Mass (kg, (lb))	
	Minimum	Maximum
Head (1)	2.99 (6.59)	5.03 (11.08)
Neck (2)	0.49 (1.08)	1.39 (3.07)
Thorax (3)	11.35 (25.02)	34.33 (75.69)
Abdomen (4)	2.14 (4.72)	3.25 (7.16)
Pelvis (5)	5.62 (12.40)	16.46 (36.29)
Upper Arm (6)	0.91 (2.00)	2.74 (6.04)
Forearm (7)	0.59 (1.29)	1.86 (4.09)
Hand (8)	0.24 (0.52)	0.66 (1.45)
Hip Flap (9)	2.22 (4.90)	4.79 (10.55)
Thigh minus Hip Flap (10)	3.86 (8.12)	8.48 (18.69)
Calf (11)	1.94 (4.28)	5.11 (11.27)
Foot (12)	0.44 (0.98)	1.26 (2.77)
Torso (5 + 4 + 3)	19.11 (42.13)	54.05 (119.15)
Thigh (9 + 10)	5.91 (13.03)	13.26 (29.24)
Forearm Plus Hand (7 + 8)	0.82 (1.81)	2.51 (5.54)

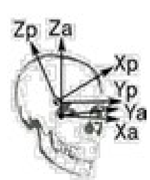
Data are projected forward to 2015.

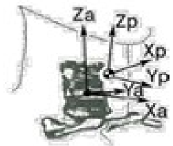
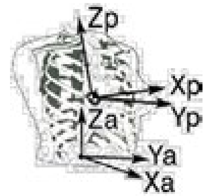
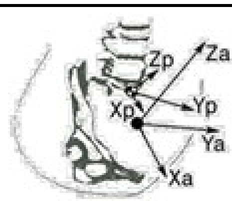
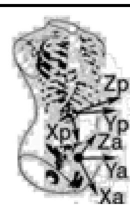
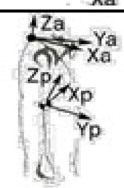
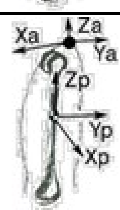
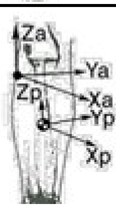
Table 12. Whole Body Center of Mass Location of the Crewmember

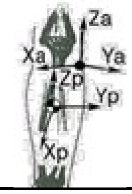
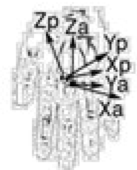
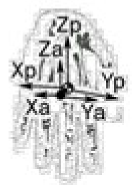
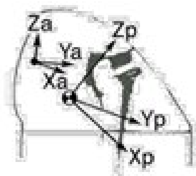
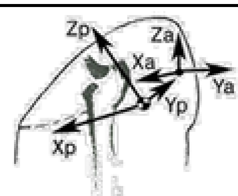
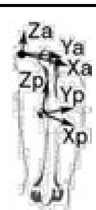
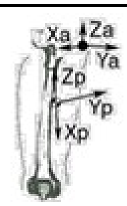
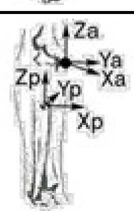


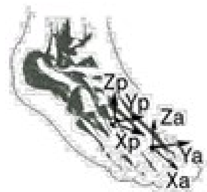
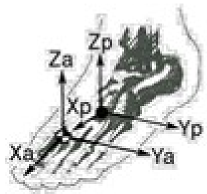
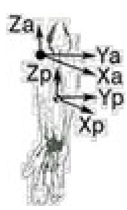
Dimension	Min (cm, (in))	Max (cm, (in))
L (Xa)	-15.27 (-6.01)	-6.40 (-2.52)
L (Ya)	-1.22 (-0.48)	0.97 (0.38)
L (Za)	-3.81 (-1.50)	8.15 (3.21)

Table 13. Body Segment Center of Mass Location of the Crewmember, Unsuited

Segment		Anatomical Axis	Min (cm, (in))	Max (cm, (in))
Head		Xa	-2.44 (-0.96)	0.53 (0.21)
		Ya	-0.61 (-0.24)	0.61 (0.24)
		Za	2.24 (0.88)	4.04 (1.59)
Neck		Xa	3.40 (1.34)	7.32 (2.88)

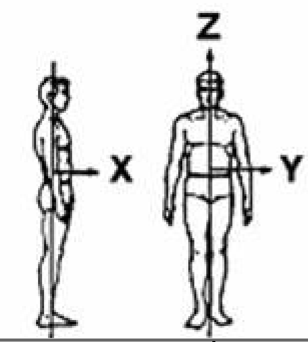
Segment		Anatomical Axis	Min (cm, (in))	Max (cm, (in))
		Ya	-0.56 (-0.22)	0.58 (0.23)
		Za	2.92 (1.15)	6.05 (2.38)
Thorax		Xa	3.76 (1.48)	7.06 (2.78)
		Ya	-0.81 (-0.32)	0.48 (0.19)
		Za	13.44 (5.29)	21.97 (8.65)
Abdomen		Xa	-1.47 (-0.58)	1.55 (0.61)
		Ya	-1.65 (-0.65)	2.26 (0.89)
		Za	-4.85 (-1.91)	-1.14 (-0.45)
Pelvis		Xa	-12.17 (-4.79)	-6.96 (-2.74)
		Ya	-1.32 (-0.52)	0.74 (0.29)
		Za	-0.76 (-0.30)	5.18 (2.04)
Torso		Xa	-10.41 (-4.1)	2.49 (0.98)
		Ya	-1.52 (-0.60)	1.73 (0.68)
		Za	16.33 (6.43)	25.60 (10.08)
Right upper arm		Xa	-0.71 (-0.28)	-0.91 (-0.36)
		Ya	1.85 (0.73)	-2.29 (-0.90)
		Za	-18.59 (-7.32)	-14.27 (-5.62)
Left upper arm		Xa	-0.64 (-0.25)	2.59 (1.02)
		Ya	-3.68 (-1.45)	-1.80 (-0.71)
		Za	-18.72 (-7.37)	-14.33 (-5.64)
Right forearm		Xa	1.02 (0.40)	0.08 (0.03)
		Ya	-2.11 (-0.83)	4.14 (1.63)
		Za	-9.86 (-3.88)	-8.86 (-3.49)
Left forearm		Xa	1.17 (0.46)	0.13 (0.05)

Segment		Anatomical Axis	Min (cm, (in))	Max (cm, (in))
		Ya	-0.23 (-0.09)	-2.44 (-0.96)
		Za	-9.86 (-3.88)	-9.07 (-3.57)
Right hand		Xa	-0.53 (-0.21)	0.03 (0.01)
		Ya	0.43 (0.17)	0.13 (0.05)
		Za	0.71 (0.28)	1.93 (0.76)
Left hand		Xa	-0.71 (-0.28)	-0.23 (-0.09)
		Ya	-1.35 (-0.53)	0.89 (0.35)
		Za	0.84 (0.33)	2.03 (0.80)
Right hip flap		Xa	-7.77 (-3.06)	1.70 (0.67)
		Ya	5.66 (2.23)	7.37 (2.90)
		Za	-6.73 (-2.65)	-6.05 (-2.38)
Left hip flap		Xa	-8.20 (-3.23)	2.41 (0.95)
		Ya	-10.67 (-4.2)	-5.18 (-2.04)
		Za	-6.96 (-2.74)	-6.20 (-2.44)
Right thigh minus flap		Xa	-3.28 (-1.29)	2.36 (0.93)
		Ya	5.18 (2.04)	8.38 (3.30)
		Za	-24.84 (-9.78)	-23.34 (-9.19)
Left thigh minus flap		Xa	3.10 (1.22)	2.21 (0.87)
		Ya	-9.60 (-3.78)	-5.28 (-2.08)
		Za	-24.87 (-9.79)	-23.62 (-9.30)
Right calf		Xa	-4.24 (-1.67)	-0.10 (-0.04)
		Ya	-6.38 (-2.51)	-4.85 (-1.91)
		Za	-16.18 (-6.37)	-12.01 (-4.73)

Segment		Anatomical Axis	Min (cm, (in))	Max (cm, (in))
Left calf		Xa	-4.34 (-1.71)	0.69 (0.27)
		Ya	4.04 (1.59)	6.83 (2.69)
		Za	-16.00 (-6.30)	-12.32 (-4.85)
Right foot		Xa	-8.51 (-3.35)	-6.63 (-2.61)
		Ya	-0.28 (-0.11)	0.43 (0.17)
		Za	0.46 (0.18)	-0.05 (-0.02)
Left foot		Xa	-8.71 (-3.43)	-6.48 (-2.55)
		Ya	-0.86 (-0.34)	0.89 (0.35)
		Za	0.33 (0.13)	-0.10 (-0.04)
Right thigh		Xa	-4.88 (-1.92)	2.11 (0.83)
		Ya	5.64 (2.22)	8.00 (3.15)
		Za	-17.55 (-6.91)	-17.55 (-6.91)
Left thigh		Xa	-4.75 (-1.87)	2.29 (0.90)
		Ya	-9.65 (-3.80)	-5.26 (-2.07)
		Za	-17.91 (-7.05)	-17.83 (-7.02)
Right forearm plus hand		Xa	0.43 (0.17)	-0.36 (-0.14)
		Ya	-2.29 (-0.90)	4.52 (1.78)
		Za	-15.54 (-6.12)	-14.99 (-5.9)
Left forearm plus hand		Xa	0.43 (0.17)	0
		Ya	0.79 (0.31)	-2.82 (-1.11)
		Za	-15.37 (-6.05)	15.01 (-5.91)

NOTE: These values are only applicable if the subject is exactly in the anatomical neutral position.

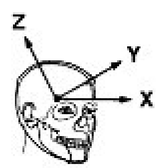
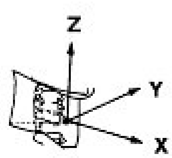
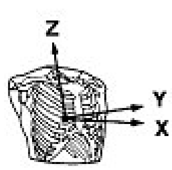
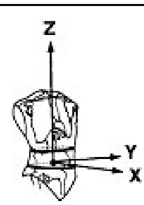
Table 14. Whole Body Moment of Inertia of the Crewmember, Unsuited

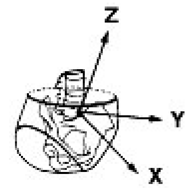
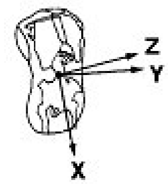
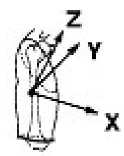
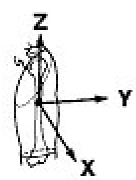
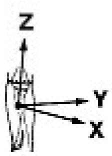
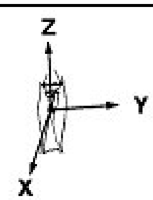
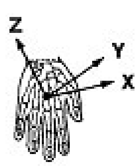
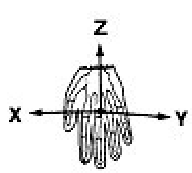


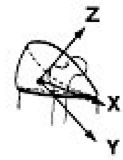
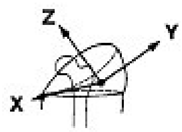
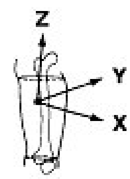
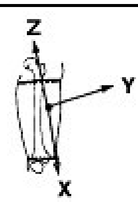
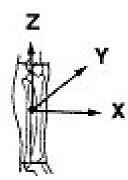
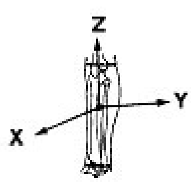
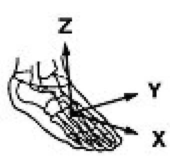
Axis	Min (kg·m2, (lb·ft2))	Max (kg·m2, (lb·ft2))
Xp	6.59 (156.38)	17.69 (419.79)
Yp	6.12 (145.23)	16.43 (389.89)
Zp	0.73 (17.32)	2.05 (48.65)

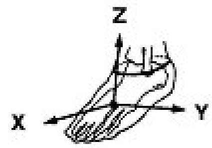
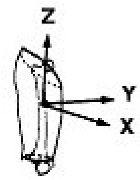
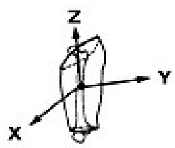
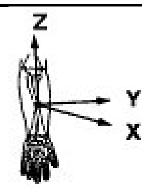
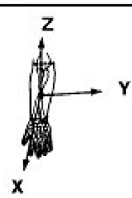
NOTE: The axes in the figure above represent the principal axes. These values are only applicable if the subject is exactly in the anatomical neutral position.

Table 15. Body Segment Moment of Inertia of the Crewmember, Unsuited

Segment		Axis	Min (kg·m^{2}x10^{-3} (lb·ft^{2}x10^{-3}))	Max (kg·m^2 x10^{-3} (lb·ft^{2}x10^{-3}))
Head		Xp	15 (351)	22 (512)
		Yp	18 (424)	25 (587)
		Zp	14 (322)	16 (379)
Neck		Xp	0.7 (17)	2.2 (53)
		Yp	1.0 (23)	2.7 (64)
		Zp	1.1 (25)	3.4 (81)
Thorax		Xp	183 (4,346)	680 (16,134)
		Yp	135 (3,206)	505 (11,984)
		Zp	119 (2,833)	431 (10,236)
Abdomen		Xp	15 (347)	23 (540)
		Yp	10 (241)	13 (309)
		Zp	21 (500)	35 (826)

Segment		Axis	Min (kg·m²x10⁻³ (lb·ft²x10⁻³))	Max (kg·m² x10⁻³ (lb·ft²x10⁻³))
Pelvis		Xp	46 (1,092)	148 (3,514)
		Yp	34 (810)	137 (3,258)
		Zp	61 (1,440)	173 (4,104)
Torso		Xp	638 (15,143)	2,030 (48,178)
		Yp	577 (13,702)	1840 (43,654)
		Zp	205 (4,865)	644 (15,273)
Right upper arm		Xp	5.4 (129)	18 (430)
		Yp	5.6 (133)	19 (462)
		Zp	1.0 (24)	3.9 (92)
Left upper arm		Xp	5.3 (126)	17.7 (420)
		Yp	5.5 (130)	19 (449)
		Zp	0.9 (22)	3.8 (89)
Right forearm		Xp	2.8 (67)	12 (276)
		Yp	2.7 (65)	12 (282)
		Zp	0.5 (11)	1.8 (43)
Left forearm		Xp	2.8 (66)	11 (257)
		Yp	2.7 (63)	11 (265)
		Zp	0.5 (11)	1.6 (39)
Right hand		Xp	0.6 (14)	1.6 (38)
		Yp	0.5 (11)	1.3 (31)
		Zp	0.2 (4)	0.5 (13)
Left hand		Xp	0.6 (15)	1.6 (37)
		Yp	0.5 (13)	1.3 (31)
		Zp	0.2 (4)	0.5 (12)

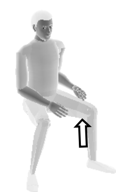
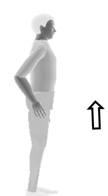
Segment		Axis	Min (kg·m^{2}x10^{-3} (lb·ft^{2}x10^{-3}))	Max (kg·m^2 x10^{-3} (lb·ft^{2}x10^{-3}))
Right hip flap		Xp	8.1 (191)	17 (412)
		Yp	10 (246)	22 (530)
		Zp	13 (318)	29 (696)
Left hip flap		Xp	7.9 (188)	17 (398)
		Yp	11 (255)	22 (519)
		Zp	14 (324)	28 (671)
Right thigh minus flap		Xp	34 (800)	79 (1,885)
		Yp	33 (785)	82 (1,941)
		Zp	14 (327)	32 (753)
Left thigh minus flap		Xp	34 (798)	75 (1,784)
		Yp	33 (789)	79 (1,878)
		Zp	13 (317)	31 (729)
Right calf		Xp	26 (615)	75 (1,790)
		Yp	26 (613)	76 (1,815)
		Zp	3.1 (73)	8.9 (210)
Left calf		Xp	26 (614)	77 (1,826)
		Yp	26 (615)	78 (1,855)
		Zp	3.0 (70)	9.1 (215)
Right foot		Xp	0.4 (9)	1.0 (24)
		Yp	1.6 (37)	5.5 (130)
		Zp	1.6 (39)	5.8 (138)
Left foot		Xp	0.4 (9)	1.0 (24)
		Yp	1.6 (39)	5.4 (127)

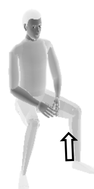
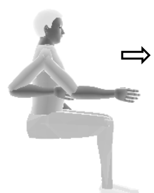
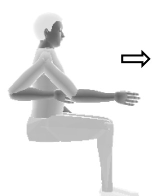
Segment		Axis	Min (kg·m²x10⁻³ (lb·ft²x10⁻³))	Max (kg·m² x10⁻³ (lb·ft²x10⁻³))
		Zp	1.7 (41)	5.7 (134)
Right thigh		Xp	85 (2,009)	208 (4,940)
		Yp	87 (2,063)	220 (5,215)
		Zp	27 (651)	59 (1,401)
Left thigh		Xp	85 (2,022)	200 (4,757)
		Yp	88 (2,088)	212 (5,024)
		Zp	27 (649)	57 (1,350)
Right forearm plus hand		Xp	11 (262)	40 (939)
		Yp	11 (257)	39 (935)
		Zp	0.7 (16)	2.4 (58)
Left forearm plus hand		Xp	11 (260)	37 (887)
		Yp	11 (256)	37 (881)
		Zp	0.6 (15)	2.2 (53)

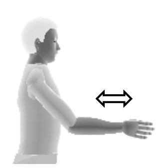
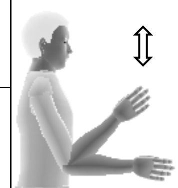
NOTE: The axes in the figure above represent the principal axes. These values are only applicable if the subject is exactly in the anatomical neutral position.

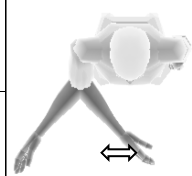
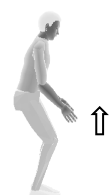
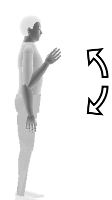
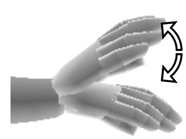
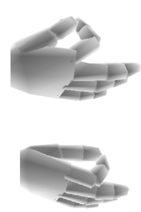
Table 16. Crew Loads, Unsuited

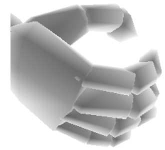
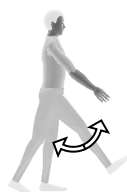
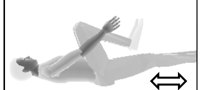
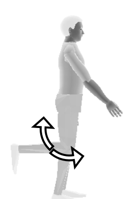
Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
One Handed Pulls						
Seated Horizontal Pull In²	SUBJECT IN A SEATED POSITION PULLS TOWARDS HIS/HER BODY. UNILATERAL/ISOMETRIC MEASUREMENT		111 (25)	147 (33)	276 (62)	449 (101)

Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Seated Vertical Pull Down[2]	SUBJECT IN A SEATED POSITION PULLS DOWNWARDS. UNILATERAL/ISOMETRI C MEASUREMENT		125 (28)	165 (37)	311 (70)	587 (132)
Seated Vertical Pull Up[2]	SITTING ERECT WITH FEET APART, DOMINANT HAND GRASPING D-RING LOCATED DIRECTLY TO THE FRONT ABOVE THE FLOOR, PULLING UPWARD WHILE KEEPING SHOULDER SQUARES & OTHER ARM IN LAP		49 (11)	67 (15)	125 (28)	756 (170)
Standing Vertical Pull Up2	STANDING ERECT WITH FEET APART, DOMINANT HAND GRASPING UNDERSIDE OF D-RING LOCATED DIRECTLY TO THE SIDE ABOVE STANDING SURFACE, PULLING UPWARD WHILE KEEPING SHOULDERS SQUARE AND OTHER ARM RELAXED AT SIDE		53 (12)	71 (16)	133 (30)	725 (163)
Two Handed Pulls						
Standing Vertical Pull Down [2]	STANDING ERECT WITH FEET APART, WITH BOTH HANDS HOLDING HANDLE LOCATED ABOVE SHOULDERS, PULLING DOWNWARD		138 (31)	182 (41)	343 (77)	707 (159)
Standing Pull in[2]	STANDING ERECT WITH FEET APART, WITH BOTH HANDS HOLDING HANDLE LOCATED IN FRONT, PULLING INWARD TOWARDS BODY		58 (13)	80 (18)	147 (33)	391 (88)

Type of Strength			Crew Operational Loads (N, (lbf)) Crit 1 Ops	Crit 2 Ops	Other Ops	Withstand Crew Loads (N, (lbf))
Standing Vertical Pull Up[2]	STANDING WITH FEET APART WITH A SLIGHT BEND AT THE KNEES AND WAIST, GRASPING A HANDLE WITH BOTH HANDS LOCATED DIRECTLY IN FRONT AND PULLING UPWARD		89 (20)	116 (26)	218 (49)	1437 (323)
Seated Vertical Pull Up[2]	SITTING ERECT WITH FEET APART, GRASPING BOTH SIDES OF HANDLE LOCATED DIRECTLY TO THE FRONT ABOVE THE FLOOR, PULLING UPWARD USING ARMS AND SHOULDERS		93 (21)	125 (28)	236 (53)	1188 (267)
One Handed Push						
Seated Horizontal Push Out[2]	SUBJECT IN A SEATED POSITION PUSHING AWAY FROM HIS/HER BODY. UNILATERAL/ISOMETRIC MEASUREMENT		89 (20)	116 (26)	218 (49)	436 (98)
Seated Vertical Push Up[2]	SUBJECT IN A SEATED POSITION PUSHING UPWARD IN A VERTICAL DIRECTION. UNILATERAL/ISOMETRIC MEASUREMENT		67 (15)	85 (19)	160 (36)	280 (63)
One Handed Push						
Seated Horizontal Push Out[2]	SUBJECT IN A SEATED POSITION PUSHING AWAY FROM HIS/HER BODY. UNILATERAL/ISOMETRIC MEASUREMENT		89 (20)	116 (26)	218 (49)	436 (98)
Seated Vertical Push Up[2]	SUBJECT IN A SEATED POSITION PUSHING UPWARD IN A VERTICAL DIRECTION. UNILATERAL/ISOMETRIC MEASUREMENT		67 (15)	85 (19)	160 (36)	280 (63)
Two Handed Push						

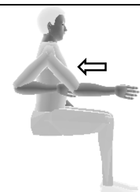
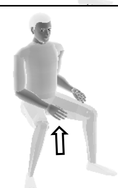
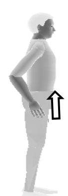
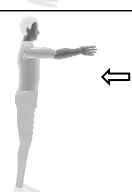
Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Standing Vertical Push Down[2]	STANDING WITH FEET APART WITH A SLIGHT BEND AT THE KNEES AND WAIST, GRASPING A HANDLE WITH BOTH HANDS LOCATED DIRECTLY IN FRONT AND PUSHING DOWNWARDS		102 (23)	133 (30)	254 (57)	525 (118)
Standing Horizontal Push Out1	STANDING ERECT WITH FEET APART, WITH BOTH HANDS HOLDING HANDLE LOCATED IN FRONT, PUSHING OUT AWAY FROM BODY		62 (14)	85 (19)	165 (37)	596 (134)
Standing Vertical Push Up2	STANDING ERECT WITH FEET APART, GRASPING FROM BELOW, BOTH SIDES OF HANDLE LOCATED DIRECTLY IN FRONT ABOVE STANDING SURFACE. PUSHING UPWARDS USING ARMS AND SHOULDERS		76 (17)	98 (22)	187 (42)	1094 (246)
Arms						
Arm Pull[2]	SUBJECT PULLS HANDLE FORWARD AND BACKWARD		44 (10)	58 (13)	107 24)	249 (56)
Arm Push[2]	SUBJECT PUSHES HANDLE FORWARD AND BACKWARD		40 (9)	53 (12)	98 (22)	222 (50)
Arm Up[2]	SUBJECT PUSHES AND PULLS HANDLE IN VARIOUS DIRECTIONS AS SHOWN BY THE FIGURES		18 (4)	22 (5)	40 (9)	107 (24)
Arm Down[2]	SUBJECT PUSHES AND PULLS HANDLE IN VARIOUS DIRECTIONS AS SHOWN BY THE FIGURES		22 (5)	31 (7)	58 (13)	116 (26)

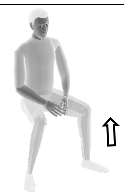
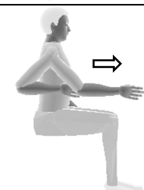
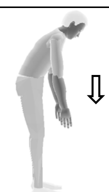
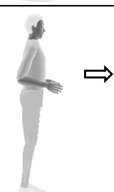
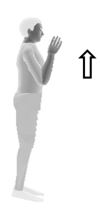
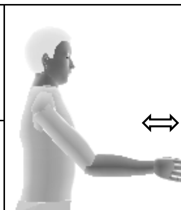
Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Arm In[2]	SUBJECT MOVES HANDLE MEDIALLY		22 (5)	31 (7)	58 (13)	98 (22)
Arm Out2	SUBJECT MOVES HANDLE LATERALLY		13 (3)	18 (4)	36 (8)	76 (17)
Lifting						
Lifting Strength[2]	STANDING WITH FEET APART WITH A SLIGHT BEND AT THE KNEES AND WAIST, GRASPING A HANDLE WITH BOTH HANDS LOCATED DIRECTLY IN FRONT AND PULLING UPWARD USING PRIMARILY ARMS, SHOULDERS, AND LEGS		36 (8)	49 (11)	93 (21)	1228 (276)
Elbow						
Flexion[2]	SUBJECT MOVES FOREARM IN A SAGITTAL PLANE AROUND THE ELBOW JOINT		13 (3)	18 (4)	36 (8)	347 (78)
Extension[2]	SUBJECT MOVES FOREARM IN A SAGITTAL PLANE AROUND THE ELBOW JOINT		27 (6)	36 (8)	67 (15)	249 (56)
Wrist & Hand						
Wrist Flexion[2]	SUBJECT BENDS WRIST IN A PALMAR DIRECTION		31 (7)	40 (9)	76 (17)	209 (47)
Wrist Extension[2]	SUBJECT BENDS THE WRIST IN A DORSAL DIRECTION		13 (3)	18 (4)	36 (8)	85 (19)
Pinch[1]	SUBJECT SQUEEZES TOGETHER THE THUMB AND FINGER		9 (2)	13 (3)	18 (4)	200 (45)

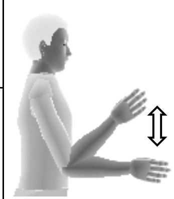
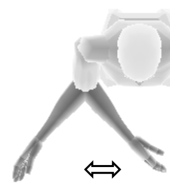
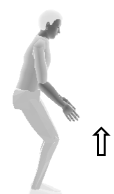
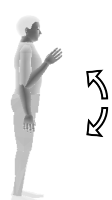
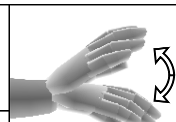
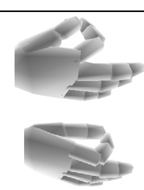
Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	**Crit 2 Ops**	**Other Ops**	
Grasp[1]	SUBJECT MAINTAINS AN ECCENTRIC TIGHT HOLD OF AN OBJECT		347 (78)	463 (104)	694 (156)	1219 (274)
Grip[1]	SUBJECT MAINTAINS A CONCENTRIC TIGHT HOLD OF AN OBJECT		49 (11)	67 (15)	102 (23)	783 (176)
Leg						
Hip Flexion[2]	SUBJECT MOVES LEG IN THE SAGITTAL PLANE AROUND THE HIP JOINT TOWARD THE FRONT OF THE BODY		116 (26)	156 (35)	289 (65)	645 (145)
Hip Extension[2]	SUBJECT MOVES UPPER AND LOWER LEG IN A SAGITTAL PLANE AROUND THE HIP JOINT		191 (43)	254 (57)	476 (107)	658 (148)
Leg Press[1]	SUBJECT MOVES LEG IN A SAGITTAL PLANE AROUND THE HIP JOINT TOWARD THE BACK OF THE BODY		618 (139)	827 (186)	1552 (349)	2584 (581)
Knee Flexion[1]	SUBJECT MOVES LOWER LEG IN A SAGITTAL PLANE AROUND THE KNEE JOINT		53 (12)	71 (16)	138 (31)	325 (73)
Knee Extension[1]	SUBJECT MOVES LOWER LEG IN A SAGITTAL PLANE AROUND THE KNEE JOINT		142 (32)	191 (43)	383 (86)	783 (176)

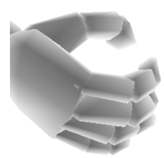
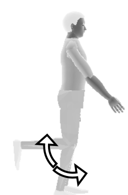
[1] *Post space flight maximal measured strength decrement.*
[2] *Post space flight estimated strength decrement. Range is 0%-26%. Average estimated is 20%. Based on max EDOMP Data. Not all motions were measured on EDOMP.*

Table 17. Crew Loads, Unpressurized Suited

Type of Strength			Crew Operational Loads (N, (lbf)) Crit 1 Ops	Crew Operational Loads (N, (lbf)) Crit 2 Ops	Crew Operational Loads (N, (lbf)) Other Ops	Withstand Crew Loads (N, (lbf))
One Handed Pulls						
Seated Horizontal Pull In[2]	Subject in a seated position pulls towards his/her body. Unilateral/Isometric measurement		78 (18)	103 (23)	193 (43)	314 (71)
Seated Vertical Pull Down[2]	Subject in a seated position pulls downwards. Unilateral/Isometric measurement		88 (20)	116 (26)	218 (49)	411 (92)
Seated Vertical Pull Up[2]	Sitting erect with feet apart, dominant hand grasping D-ring located directly to the front above the floor, pulling upward while keeping shoulder squares & other arm in lap		34 (8)	47 (11)	88 (20)	529 (119)
Standing Vertical Pull Up[2]	Standing erect with feet apart, dominant hand grasping underside of D-ring located directly to the side above standing surface, pulling upward while keeping shoulders square and other arm relaxed at side		37 (8)	50 (11)	93 (21)	508 (114)
Standing Vertical Pull Down[2]	Standing erect with feet apart, with both hands holding handle located above shoulders, pulling downward		97 (22)	127 (29)	240 (54)	495 (111)
Standing Pull in[2]	Standing erect with feet apart, with both hands holding handle located in front, pulling inward towards body		41 (9)	56 (13)	103 (23)	274 (62)
Standing Vertical Pull Up[2]	Standing with feet apart with a slight bend at the knees and waist, grasping a handle with both hands located directly in front and pulling upward		62 (14)	81 (18)	153 (34)	1006 (226)

Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Seated Vertical Pull Up[2]	Sitting erect with feet apart, grasping both sides of handle located directly to the front above the floor, pulling upward using arms and shoulders		65 (15)	88 (20)	165 (37)	832 (187)
Seated Horizontal Push Out[2]	Subject in a seated position pushing away from his/her body. Unilateral/Isometric measurement		62 (14)	81 (18)	153 (34)	305 (69)
Seated Vertical Push Up[2]	Subject in a seated position pushing upward in a vertical direction. Unilateral/Isometric measurement		47 (11)	60 (13)	112 (25)	196 (44)
Two Handed Push						
Standing Vertical Push Down[2]	Standing with feet apart with a slight bend at the knees and waist, grasping a handle with both hands located directly in front and pushing downwards		71 (16)	93 (21)	178 (40)	368 (83)
Standing Horizontal Push Out[1]	Standing erect with feet apart, with both hands holding handle located in front, pushing out away from body		43 (10)	60 (13)	116 (26)	417 (94)
Standing Vertical Push Up[2]	Standing erect with feet apart, grasping from below, both sides of handle located directly in front above standing surface. Pushing upwards using arms and shoulders		53 (12)	69 (15)	131 (29)	766 (172)
Arms						
Arm Pull[2]	Subject pulls handle forward and backward		31 (7)	41 (9)	75 (17)	174 (39)
Arm Push[2]	Subject pushes handle forward and backward		28 (6)	37 (8)	69 (15)	155 (35)

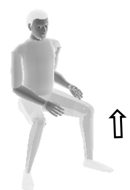
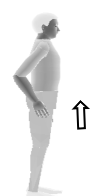
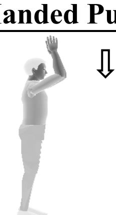
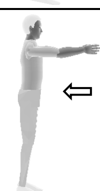
Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Arm Up[2]	Subject moves handle up		13 (3)	15 (4)	28 (6)	75 (17)
Arm Down[2]	Subject moves handle down		15 (4)	22 (5)	41 (9)	81 (18)
Arm In[2]	Subject moves handle medially		15 (4)	22 (5)	41 (9)	69 (15)
Arm Out[2]	Subject moves handle laterally		9 (2)	13 (3)	25 (6)	53 (12)
Lifting						
Lifting Strength[2]	Standing with feet apart with a slight bend at the knees and waist, grasping a handle with both hands located directly in front and pulling upward using primarily arms and shoulders, and legs		25 (6)	34 (8)	65 (15)	860 (193)
Elbow						
Flexion[2,3]	Subject moves forearm in a sagittal plane around the elbow joint		9 (2)	13 (3)	25 (6)	243 (55)
Extension[2,3]	Subject moves forearm in a sagittal plane around the elbow joint		19 (4)	25 (6)	47 (11)	174 (39)
Wrist & Hand						
Wrist Flexion[2,3]	Subject bends wrist in a palmar direction		22 (5)	28 (6)	53 (12)	146 (33)
Wrist Extension[2,3]	Subject bends the wrist in a dorsal direction		9 (2)	13 (3)	25 (6)	60 (13)
Pinch [1]	Subject squeezes together the thumb and finger		14 (3)	20 (5)	27 (6)	300 (68)

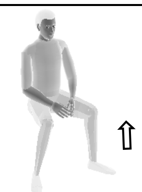
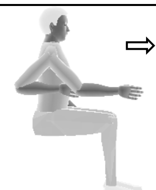
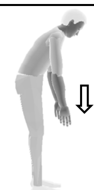
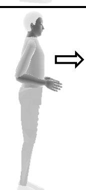
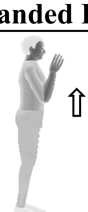
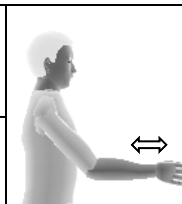
Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Grasp[1,3]	Subject maintains an eccentric tight hold of an object		243 (55)	324 (73)	486 (109)	853 (192)
Grip[1]	Subject maintains a concentric tight hold of an object		25 (6)	34 (8)	51 (12)	392 (88)
Legs						
Hip Flexion[2,3]	Subject moves leg in the sagittal plane around the hip joint toward the front of the body		81 (18)	109 (25)	202 (46)	452 (102)
Knee Flexion[1,3]	Subject moves lower leg in a sagittal plane around the knee joint, decreasing the angle between the upper and lower leg		37 (8)	50 (11)	97 (22)	228 (51)
Knee Extension[1,3]	Subject moves lower leg in a sagittal plane around the knee joint, increasing the angle between the upper and lower leg		99 (22)	134 (30)	268 (60)	548 (123)

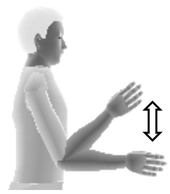
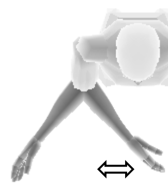
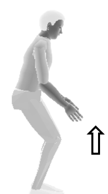
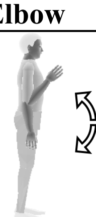
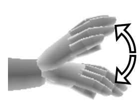
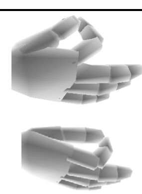
1. Post space flight maximal measured strength decrement.
2. Post space flight estimated strength decrement. Range is 0%-47%. Average estimated is 33%. Based on CRV Requirements Document.
3. Suit decrement not measured directly, but estimated based on functional strength testing of other movements

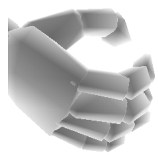
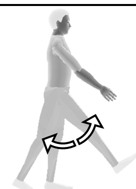
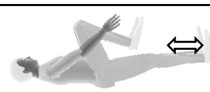
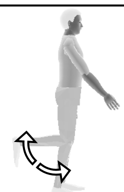
Table 18. Crew Loads, Pressurized Suited

Type of Strength			Crew Operational Loads (N(lbf))			Withstand Crew Loads (N(lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
One Handed Pulls						
Seated Horizontal Pull In[2]	SUBJECT IN A SEATED POSITION PULLS TOWARDS HIS/HER BODY. UNILATERAL/ ISOMETRIC MEASUREMENT		56 (13)	74 (17)	138 (31)	225 (51)

Type of Strength			Crew Operational Loads (N(lbf))			Withstand Crew Loads (N(lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Seated Vertical Pull Down[2]	SUBJECT IN A SEATED POSITION PULLS DOWNWARDS. UNILATERAL/ISOMETRIC MEASUREMENT		63 (14)	83 (19)	156 (35)	294 (66)
Seated Vertical Pull Up[2]	SITTING ERECT WITH FEET APART, DOMINANT HAND GRASPING D-RING LOCATED DIRECTLY TO THE FRONT ABOVE THE FLOOR, PULLING UPWARD WHILE KEEPING SHOULDER SQUARES & OTHER ARM IN LAP		25 (6)	34 (8)	63 (14)	378 (85)
Standing Vertical Pull Up[2]	STANDING ERECT WITH FEET APART, DOMINANT HAND GRASPING UNDERSIDE OF D-RING LOCATED DIRECTLY TO THE SIDE ABOVE STANDING SURFACE, PULLING UPWARD WHILE KEEPING SHOULDERS SQUARE AND OTHER ARM RELAXED AT SIDE		27 (6)	36 (8)	67 (15)	363 (82)
Two Handed Pulls						
Standing Vertical Pull Down [2]	Standing erect with feet apart, with both hands holding handle located above shoulders, pulling downward		69 (16)	91 (21)	172 (39)	354 (80)
Standing Pull In[2]	Standing erect with feet apart, with both hands holding handle located in front, pulling inward towards body		29 (7)	40 (9)	74 (17)	196 (44)
Standing Vertical Pull Up[2]	Standing with feet apart with a slight bend at the knees and waist, grasping a handle with both hands located directly in front and pulling upward		45 (10)	58 (13)	109 (25)	719 (162)

Type of Strength			Crew Operational Loads (N(lbf)) Crit 1 Ops	Crit 2 Ops	Other Ops	Withstand Crew Loads (N(lbf))
Seated Vertical Pull Up[2]	Sitting erect with feet apart, grasping both sides of handle located directly to the front above the floor, pulling upward using arms and shoulders		47 (11)	63 (14)	118 (27)	594 (134)
One Handed Push						
Seated Horizontal Push Out[2]	Subject in a seated position pushing away from his/her body. Unilateral/Isometric measurement		45 (10)	58 (13)	109 (25)	218 (49)
Seated Vertical Push Up[2]	Subject in a seated position pushing upward in a vertical direction. Unilateral/Isometric measurement		34 (8)	43 (10)	80 (18)	140 (32)
Two Handed Push						
Standing Vertical Push Down[2]	Standing with feet apart with a slight bend at the knees and waist, grasping a handle with both hands located directly in front and pushing downwards		51 (12)	67 (15)	127 (29)	263 (59)
Standing Horizontal Push Out[1]	Standing erect with feet apart, with both hands holding handle located in front, pushing out away from body		31 (7)	43 (10)	83 (19)	298 (67)
Two Handed Push						
Standing Vertical Push Up[2]	Standing erect with feet apart, grasping from below, both sides of handle located directly in front above standing surface. Pushing upwards using arms and shoulders		38 (9)	49 (11)	94 (21)	547 (123)
Arm						
Arm Pull[2]	Subject pulls handle forward and backward		22 (5)	29 (7)	54 (12)	125 (28)
Arm Push[2]	Subject pushes handle forward and backward		20 (5)	27 (6)	49 (11)	111 (25)

Type of Strength			Crew Operational Loads (N(lbf))			Withstand Crew Loads (N(lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Arm Up[2]	Subject moves handle up		9 (2)	11 (3)	20 (5)	54 (12)
Arm Down[2]	Subject moves handle down		11 (3)	16 (4)	29 (7)	58 (13)
Arm In[2]	Subject moves handle medially		11 (3)	16 (4)	29 (7)	49 (11)
Arm Out[2]	Subject moves handle laterally		7 (2)	9 (2)	18 (4)	38 (9)
Lifting						
Lifting Strength[2]	Standing with feet apart with a slight bend at the knees and waist, grasping a handle with both hands located directly in front and pulling upward using primarily arms and shoulders, and legs		18 (4)	25 (6)	47 (11)	614 (138)
Elbow						
Flexion[2, 3]	Subject moves forearm in a sagittal plane around the elbow joint		7 (2)	9 (2)	18 (4)	174 (39)
Extension[2, 3]	Subject moves forearm in a sagittal plane around the elbow joint		14 (3)	18 (4)	34 (8)	125 (28)
Wrist & Hand						
Wrist Flexion[2, 3]	Subject bends wrist in a palmar direction		19 (4)	25 (6)	37 (8)	101 (23)
Wrist Extension[2,3]	Subject bends the wrist in a dorsal direction		7 (2)	9 (2)	14 (3)	33 (7)
Pinch [1]	Subject squeezes together the thumb and finger		14 (3)	20 (5)	27 (6)	300 (68)
Grasp[1,3]	Subject maintains an eccentric tight hold of an object		174 (39)	232 (52)	347 (78)	610 (137)

Type of Strength			**Crew Operational Loads (N(lbf))**			**Withstand Crew Loads (N(lbf))**
			Crit 1 Ops	**Crit 2 Ops**	**Other Ops**	
Grip[1]	Subject maintains a concentric tight hold of an object		25 (6)	34 (8)	51 (12)	392 (88)
Leg						
Hip Flexion[2,3]	Subject moves leg in the sagittal plane around the hip joint toward the front of the body		58 (13)	78 (18)	145 (33)	323 (73)
Hip Extension[2,3]	Subject moves leg in a sagittal plane around the hip joint toward the back of the body		96 (22)	127 (29)	238 (54)	329 (74)
Leg Press[1,3]	Subject pushes a weight away from them using their legs		309 (70)	414 (93)	776 (175)	1292 (291)
Knee Flexion[1,3]	Subject moves lower leg in a sagittal plane around the knee joint		27 (6)	36 (8)	69 (16)	163 (37)
Knee Extension[1]	Subject moves lower leg in a sagittal plane around the knee joint		71 (16)	96 (22)	192 (43)	392 (88)

1. Post space flight maximal measured strength decrement.
2. Post space flight estimated strength decrement. Range is 0%-47%. Average estimated is 33%. Based on CRV Requirements Document.
3. Suit decrement not measured directly, but estimated based on functional strength testing of other movements

Table 19. Effects of Spaceflight and Bed Rest on Strength

	Spaceflight w/o Exercise			Spaceflight w/ Exercise			Bed Rest (w/o Exercise)		
Muscle Group	# days	% decrease	Description	# days	% decrease	Description	# days	% decrease	Description
Arm Extensor[1]	28	20	Isokinetic	28	0	Isokinetic	42	10	Isometric
	--	--	--	59	0	Isokinetic	--	--	--
	--	--	--	84	10	Isokinetic	--	--	--
Arm Flexor[1]	28	20	Isokinetic	28	15	Isokinetic	42	12	Isometric
	--	--	--	59	0	Isokinetic	--	--	--
	--	--	--	84	0	Isokinetic	--	--	--
Leg Extensor[1,2,3]	5-13	12	Isokinetic	11	10	Isokinetic	14	15	Isokinetic
	--	--	--	59	20	Isokinetic	30	21	Isokinetic
	--	--	--	84	0	Isokinetic	42	29	Isokinetic
	--	--	--	125-145	31	Unknown	119	30	Isokinetic
	--	--	--	125-145	12	Isokinetic	--	--	--
Leg Flexor[1,2,3]	5-13	6	Isokinetic	28	20	Isokinetic	30	10	Isokinetic
	--	--	--	59	20	Isokinetic	--	--	--
	--	--	--	84	14	Isokinetic	--	--	--
	--	--	--	125-145	27	Unknown	--	--	--
	--	--	--	125-145	27	Isokinetic	--	--	--
Trunk Flexion[3]	--	--	--	11	20	Isokinetic			
Calf Muscle[3]	--	--	--	17	0	Unknown	35	25	Unknown
	--	--	--	~180	42	Isometric	120	45	Unknown

[1] Cowell et al. (2002).

[2] Convertino and Sandler (1995).

[3] Adams et al. (2003).

Section A.2 – Common Approaches to Strength Data Collection

In addition, the interaction of test conductors with subjects can heavily influence results. It is highly recommended that test conductors follow a methodology such as that outlined by Caldwell et al. (1974), which specifies the following regarding isometric (static) testing:

Strength is assessed during a steady exertion sustained for 4 seconds

Effort should be increased to maximum without jerking in about 1 second, then maintained

No instantaneous feedback is provided during testing

No goal-setting, rewards, or competition should occur during testing

A minimum of 1 minute of rest is provided between trials

The aspects of the Caldwell methodology concerning lack of feedback, goal-setting, and rewards should be applied to any type of strength testing to obtain more consistent results. These external factors have been demonstrated to significantly affect force generated during trials (Kroemer, et. al., 1988).

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The aspects of the Caldwell methodology concerning lack of feedback, goal-setting, and rewards should be applied to any type of strength testing to obtain more consistent results. These external factors have been demonstrated to significantly affect force generated during trials (Kroemer, et. al., 1988).

Table 20. Operating-Environment Values of Factors Affecting Anthropometric Dimensions

Operating Environment	Factors Affecting Anthropometric Dimensions		
	Clothing	Posture	Pressurization
Ground operations	Flight suit	Standing, sitting	None and Yes
EVA suit design	Minimal clothing	Standing, sitting	NA
Hypergravity (launch, entry)	Flight suit	Recumbent	None
Emergency during launch or entry	Flight suit	Recumbent, upright	Yes
Hypergravity (launch, entry)	Flight suit	Upright	None
Emergency during flight	Flight suit	Recumbent, upright, neutral body	Yes
IVA 0g	Minimal clothing	Neutral body	None
EVA 0g or partial-gravity	Spacesuit	Neutral body	Yes

Table 21. Torque Values Pronation and Supination, Pressurized Suited

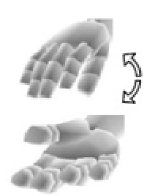
Type of Strength			Crew Operational Loads (N○m, (in○lb))			Withstand Crew Loads (N○m, (in○lb))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
Pronation[2]	SUBJECT ROTATES HANDS AND FOREARMS MEDIALLY		0.9 (8)	1.2 (11)	2.3 (20)	13 (115)
Supination[2]	SUBJECT ROTATES HANDS AND FOREARMS LATERALLY		0.9 (8)	1.2 (11)	2.3 (20)	13 (115)

Table 22. Spacesuit (Unpressurized and Pressurized) Effects on Anthropometry

	Man		Female	
Dimension	**Unpressurized**	**Pressurized**	**Unpressurized**	**Pressurized**
Sitting Height	1.11	1.09	1.08	1.11
Eye Height - Sitting	0.99	0.95	0.92	0.85
Knee Height - Sitting	1.04	1.10	1.04	1.13
Popliteal Height	1.02	0.98	0.96	0.97
Bideltoid Breadth	1.18	1.26	1.40	1.54
Buttock-Knee Length	1.06	1.18	1.15	1.27

Table 23. Change in Body Envelope Data When Wearing Pressurized and Unpressurized Flight Suits

	ACES Unpressurized		ACES Pressurized		D-Suit Unpressurized		D-Suit Pressurized	
	Change (cm)	Change Ratio	Change (cm)	Change Ratio	Change (cm)	Change Ratio	Change (cm)	Change Ratio
Recumbent								
Forward reach	0	1.00	-13	0.85	0	1.00	-4	0.95
Vertical reach - up	--	--	--	--	--	--	--	--
Vertical reach - down	-3	0.88	-6	0.85	-4	0.89	-7	0.83
Side reach	-4	0.95	0	1.00	-3	0.97	-2	0.98
Upright								
Forward reach	-14	0.87	-12	0.85	-4	0.95	-9	0.89
Vertical reach - up	-11	0.93	--	--	-10	0.94	-11	0.93
Vertical reach - down	-6	0.87	--	--	-3	0.91	-18	0.55
Side reach	-1	0.99	-6	0.93	-4	0.96	-6	0.93
"--" indicates data not available								

Table 24. Anthropometric Changes in 0g

Anthropometric Changes in 0g				
Change	**Cause**	**Physical Changes**	**Amount of Change**	**Critical Dimensions Affected**
Spinal elongation	0g	Spinal decompression and straightening start in the first day or two of weightlessness and are retained throughout until re-exposure to 1g.	+ 3% of stature and + 6% of sitting height.	Upper body height measurements and sitting dimensions increase (including height, eye height, and overhead reach). Downward reaches will be difficult since there is no assistance from gravity.
Elimination of body tissue compression	Relief of pressure on body surfaces due to gravity	Seated height increases due to relief of pressure on buttock surfaces. Sitting knee height dimensions increase due to relief of pressure on heels.	Knee height dimensions increase minimally.	Sitting dimensions, such as sitting height, eye height, and knee height, increase.
Postural changes	0g	Body assumes the neutral body posture.	See Figure 4	Ankle, knee, and hip heights increase; elbow, wrist, and shoulder are raised; elbows are abducted; head is tilted down.
Shifting of fluids	0g	Hydrostatic pressure is equalized.	0% to 6%.	Lower limb volume and circumferential measurements decrease. Upper torso

Anthropometric Changes in 0g				
Change	**Cause**	**Physical Changes**	**Amount of Change**	**Critical Dimensions Affected**
				circumference increases, and face gets puffy.
Mass loss	Lack of countermeasures, inadequate diet, nausea	Muscle atrophy, body fluid loss, and bone loss occur.	0% to 8%.	Limb volume and circumferential measurements decrease.

Table 25. Neutral Body Posture and Clearance Envelope

Dimension	1st-percentile American Female (cm)	99th-percentile American Male (cm)	Range (cm) [1]
Height[2]	148.6	194.6	46.0
Height (with 3% spinal elongation)[3]	153.0	200.4	47.4
Width (elbow to elbow)	38.9	66.0	27.2
Depth (back to longest fingertip)	65.0	90.9	25.9

Notes:

1. Range is calculated by subtracting 1st-percentile American female values from 99th-percentile American male values.
2. Standard (1g) height may be used for extremely short-duration missions (up to 48 hours after launch).
3. Body height with spinal elongation must be used for 0g work envelopes in use 48 hours or more after launch.

Table 26. Reach Movements Possible in Multi-g Environment

Acceleration	Possible Reach Motion
Up to 4g	Arm
Up to 5g (9g if arm is counterbalanced)	Forearm
Up to 8g	Hand
Up to 10g	Finger

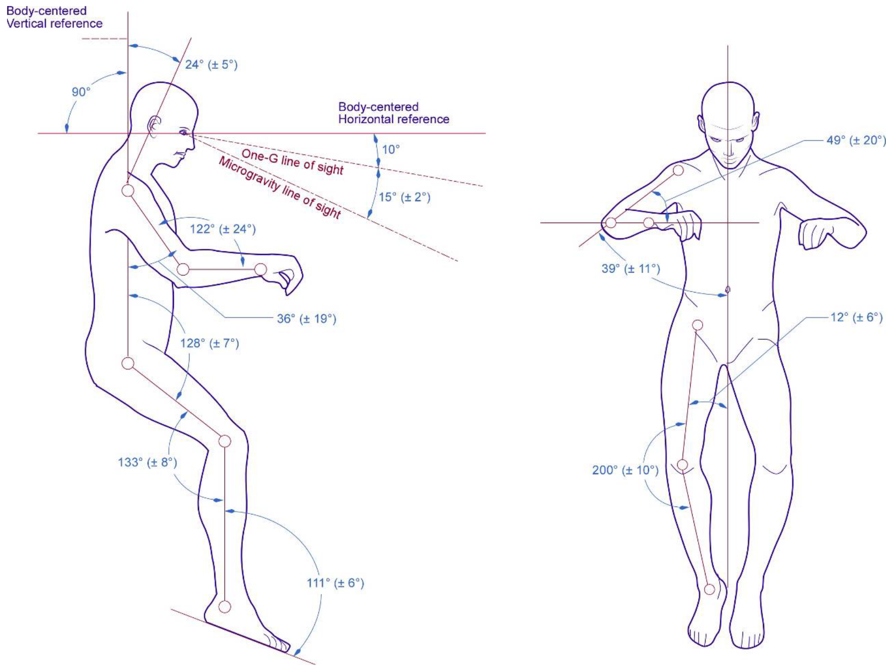


Figure 4. Neutral Body Posture in 0g

Figure 4 illustrates upper- and lower-body movements. Descriptions and ranges of joint movement for the Constellation program males and females are in Appendix B. The range-of motion data is applicable to shirtsleeve or unpressurized flight suit environments, while working in 1g, partial-g, and 0g conditions. At present, no data is available for 0g or hypergravity environments. Indications are that joint motion capability is not drastically affected in 0g, but hypergravity will have strong effects dependent on the vector of gravity and orientation of the body.