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Digital Human Models Of People With Disabilities

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DIGITAL HUMAN MODELS OF PEOPLE WITH PHYSICAL DISABILITIES

by

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Introduction

Thesis Problem Statement

The current state-of-the-art in Digital Human Modeling (DHM) allows for full simulation and analysis of any task a person is required to perform at home, at work, in the military, in space, in sports, etc. These analyses help identify tasks that may lead to bodily injury, or can help identify efficiency concerns. The problem is that the software is missing a very important population: people with physical disabilities. What modifications and enhancements must be made to existing, commercially available DHM software to include this population?

Target Population

The goal of this research is to bring the capabilities and potential benefits of DHM to people with physical disabilities who want to work.

Thesis Outline

In order to address the central question: "What modifications and enhancements must be made to existing, commercially available DHM software to include people with disabilities?" – it is necessary to review the current state-of-art of the technology. The technologies that support digital human modeling (DHM), virtual environment (VE) creation, virtual ergonomic analysis (VEA), and other data that are used, or could be used, to develop DHMs for people with physical disabilities will be introduced and discussed in detail.

This chapter will provide definitions for basic terms as well as provide an overview of the main concepts related to digital human modeling. This will be followed by a description of the available data for the creation of digital human models, as well as a review of related technologies.

Three specific case studies will be presented illustrating the use of DHM in virtual environments. The first study, conducted by Osaka Gas Co. Ltd., was a physical and physiological study of people working in their kitchens (Osaka Gas Company Ltd., 2010; The American Society of Mechanical Engineers, 2004). The remaining two studies are of DHMs created, using commercially available tools, to simulate two different individuals with disabilities. These studies provide insight into the current capabilities of the existing software, and what modifications and enhancements could be made to properly support digital human modeling of people with physical disabilities.

The final chapters discuss future directions for the research, and hypothesize conditions under which DHM, VE, and VEAs might become viable and readily available tools for serving the needs of people with physical disabilities.

Digital Human Model Definition

A digital human model (DHM) is a virtual human in 3D space that can be moved and manipulated to simulate real and accurate movements of people, see Figure 1 below. A DHM is typically part of DHM software programs that are meant to simulate human functions.

Figure 1: (a) Image showing different possible sizes and genders for DHMs, (b) Image showing a task simulation of a driver climbing into his cab, (c) Image showing a simulation of pilots using controls in a cockpit (Human Solutions, 2010b).

(a) (b) (c)

Definition of Disability

The definition of ‘disability’ is somewhat ambiguous, as evidenced by several definitions that can be found in books and across the internet. US government agencies also use differing definitions. The Americans with Disabilities Act (ADA) of 1990 (updated with amendments in 2008) defines a disability with a very elaborate and complex definition. Summarized briefly, it says that a disability is “a physical or mental impairment that substantially limits one or more major life activities”, and there is “a record of such an impairment” (Appendix A lists the full definition by the ADA and others) (Americans with Disabilities Act, 1990, 2008).

Digital Human Model Software

There are many different DHM software programs that are commercially available for ergonomic analysis, human factors analysis, processing, and timing. Some limited-function versions are included in CAD (Computer Aided Design) systems, while others are full-function stand-alone versions that rely on CAD and CAE (Computer Aided Engineering) systems for all other objects, or the virtual environment (VE), to be used in the analysis. For example, to analyze ingress and egress from a vehicle, the 3D manikin (aka DHM) and the motion are created in the DHM software, but the vehicle geometry is imported from a CAD or CAE system. Another example is given in Figure 2 which illustrates the results of a Posture Analysis. Depending on the user-set parameters for the analysis, the different color bands on the arms, legs, and torso convey information such as muscle exercition, angular displacement, or whatever physical parameter is being analyzed for being a safe posture.

The different DHM software programs all have typically the same functions and capabilities. Here is a list of the most common capabilities and functions they share:

- The ability to create customizable 3D manikins
- The ability to move the manikins in predefined motions
- Reach analysis
- Posture analysis
- Push/Pull analysis
- Carrying analysis
- RULA based motion (Rapid Upper Limb Analysis)

Figure 2: Human Posture Analysis allows users to create their own specific comfort, safety, and strength library for the needs of each individual (Dassault Systèmes, 2010).

What Is It Used For?

For years now there have been several different Digital Human Modeling (DHM) software programs available for commercial purchase. The most common use of this type of software is in conjunction with CAD (Computer Aided Design) software, in industrial settings, to create Virtual Ergonomic Assessments (VEA). VEA's are studies created in the 3D virtual world using the aforementioned to assess the feasibility of a certain motion, or repeated motions, and analyze them to see if a real-life person can safely complete the task without any unnecessary physical stress. An example would be simulating the motions a worker is asked to perform during the installation of a component during the assembly of a vehicle on an automated line. Another example would be the simulation of vehicle maintenance in the repair shop; which is important to make sure that an item is serviceable once it is designed and put into production. The use of the DHM software has saved countless man-hours, money (virtual prototypes, less hours, etc.), and shaved several months off of concept to creation timelines (Siemens, 2010a). DHM software is heavily used in a variety of fields, automotive, aerospace, military, clothing and uniform design, heavy machinery (earth movers/mining equipment/etc.), boats, cruise ships, cargo ships, locomotives, and many others (Dassault Systemes; Human Solutions, 2010d; Siemens, 2010a).

The usefulness of DHM software is quickly being realized by other industries, and its implementation and adaptation is ongoing. A field previously mentioned, clothing design, is a relatively new industry for DHM software, but its importance is increasing. Clothing designers are using DHM for material type, fit, and comfort in virtual design, which saves both time and money (Human Solutions, 2010e). The military is also spending great sums of research money on new uniform designs that include bio-sensors for real-time bio-feedback of soldiers' conditions in combat situations, of which DHM plays a key role in the design process (Human Solutions, 2010e; Munro, Campbell, Wallace, & Steele, 2008; Steele, 2005).

DHM software is very powerful and its usefulness is unquestioned in dozens of industries, but it is not without limitations or flaws. There is one growing population that could benefit from DHM software, but in its current state it is not very helpful: people with physical disabilities. The databases that DHM software is built upon are of normal, fully functioning human beings with symmetric anthropometric proportions (information on the databases can be found in a later section). People who are physically disabled may not necessarily have full range-of-motion and their biomechanics of movement and anthropometric proportions may be asymmetric from one side of their body to the other; current DHM software does not account for this.

Chapter Summary

The problem statement was introduced. Definitions of key terms and ideas were introduced and defined, especially the term 'disability' and how it is used in the context of this paper. DHM software was introduced and what it is used for was explained. Also, how this software can help the target population was discussed.

Chapter 1: The Need for Change

The Need for Change

This chapter will explain why a change in technology is needed. It will also discuss the laws in place to aid people with disabilities to find the work they seek, as well as incentives for employers to hire people with disabilities. Most importantly, how this technology and the modifications suggested will help the target population will be explained.

Why Is A Technology Modification Needed?

A modification in the technology is needed so that the target population can benefit from its use. Just as the technology can show how a person without physical impairment can perform certain tasks, it can be, and should be, modified to include people with impairments and physical disabilities. Obtaining and retaining a job is an ongoing problem for an individual with a physical disability (Conti & Erlandson, 2009a, 2009b). "The number of people in the U. S. with significant disability who are eligible for vocational rehabilitation is great and increasing" (Conti & Erlandson, 2009b). In 2005, vocational rehabilitation services were provided for 1,273,064 people with the most significant disabilities (U.S. Department of Education, Office of Special Education and Rehabilitative Services, & Rehabilitation Services Administration, 2009). Michigan Rehabilitation Services reported in 2008 that services were provided to 244 people with significant disabilities as well as 17 people identified as most significantly disabled (Michigan Rehabilitation Services & Business & Disability Management Services, 2008).

VEA and related technology can potentially help a person with a disability obtain a job by showing potential employers that a specific individual can perform the required task(s) for the job. What are needed to complete a VEA of a healthy person are their anthropometric measurements. Those measurements can be easily transferred to the DHM software for analysis. A VEA of a person with a physical disability is a little more involved, though. A qualified person, such as an Occupational Therapist, must take the anthropometric measurements of the prospective employee, record their available active range-of-motion, and assess what other limits must be placed so as to not injure that specific individual. This will allow the DHM user to show if the prospective employee can perform the task that is required to fulfill the job requirements. The VEA and DHM together can also show what, if any, assistive devices may be needed, and cost estimation for the workspace changes can be more accurately estimated; which currently is done by trial and error! By law (Americans with Disabilities Act of 1990 and amendments of 2008), an employer, with 15 employees or more, must make reasonable accommodations for an employee if a disability requires minor changes in the work environment (U.S. Equal Employment Opportunity Commission, 2002). Reasonable accommodation is defined below in the ADA, Title 1, paragraph one item (ii), and paragraph two:

> "Title I of the Americans with Disabilities Act of 1990 (the 'ADA') requires an employer to provide reasonable accommodation to qualified individuals with disabilities who are employees or applicants for employment, unless to do so would cause undue hardship. 'In general, an accommodation is any change in the work environment or in the way things are customarily done that enables an individual with a disability to enjoy equal employment opportunities.' There are three categories of 'reasonable accommodations':
>
> > '(i) modifications or adjustments to a job application process that enable a qualified applicant with a disability to be considered for the position such qualified applicant desires; or
> >
> > (ii) modifications or adjustments to the work environment, or to the manner or circumstances under which the position held or desired is customarily

performed, that enable a qualified individual with a disability to perform the essential functions of that position; or

(iii) modifications or adjustments that enable a covered entity's employee with a disability to enjoy equal benefits and privileges of employment as are enjoyed by its other similarly situated employees without disabilities.’

The duty to provide reasonable accommodation is a fundamental statutory requirement because of the nature of discrimination faced by individuals with disabilities. Although many individuals with disabilities can apply for and perform jobs without any reasonable accommodations, there are workplace barriers that keep others from performing jobs which they could do with some form of accommodation. These barriers may be physical obstacles (such as inaccessible facilities or equipment), or they may be procedures or rules (such as rules concerning when work is performed, when breaks are taken, or how essential or marginal functions are performed). Reasonable accommodation removes workplace barriers for individuals with disabilities.

Reasonable accommodation is available to qualified applicants and employees with disabilities. Reasonable accommodations must be provided to qualified employees regardless of whether they work part- time or full-time, or are considered ‘probationary.’ Generally, the individual with a disability must inform the employer that an accommodation is needed.

There are a number of possible reasonable accommodations that an employer may have to provide in connection with modifications to the work environment or adjustments in how and when a job is performed. These include:

- making existing facilities accessible;
- job restructuring;
- part-time or modified work schedules;
- acquiring or modifying equipment;
- changing tests, training materials, or policies;
- providing qualified readers or interpreters; and
- reassignment to a vacant position.” (U.S. Equal Employment Opportunity Commission, 2002)

From this definition, it is reasonable to posit that since a DHM, VE and VEA can identify barriers to work, both physical and procedural, and can help redesign both the physical environment and essential functions of a job, the cost of a VEA with DHM is a reasonable accommodation that should be covered by the employer! In most instances, the government will reimburse (in the form of tax credits) a portion, if not all, of the costs incurred to accommodate the employee’s accessibility needs (Internal Revenue Service, 1990a, 1990b, 1990c). The ADA, Equal Employment Opportunity laws, and Rehabilitation Act of 1973 make it unlawful for employers to use an individual's disability as an excuse not to employ them (with few exceptions), or a reason for termination.

The past two decades have seen significant advancements in technology and it is in large part due to computers. Unfortunately, persons with impairments and disabilities are not able to take advantage of the latest technology because it is usually not accessibility friendly. Studies conducted at every level from global, to country, and even down to the state level have shown that persons with impairments or disabilities are not given the same level of technological support as the healthy population, and in some cases they are not given any (Baker, 2003). This lag in technology advancement for the impaired and disabled is yet another obstacle for these individuals that are seeking employment, since they are at a technological disadvantage.

The latest global figures from the World Health Organization (WHO) in 2006 put the estimates of people with disabilities at 650 million people, which is approximately 10% of the world's population (World Health Organization, 2006)! The United States population is growing, and so is the percentage of the population that is disabled; between 1999 and 2005 there was an increase of 3.4 million U.S. adults reporting a disability (Disabled World, 2010a). "People with disabilities represent the third largest market segment in the U.S., surpassing Hispanics, African Americans and Asian Americans, as well as Generation X and teens" (U.S. Census Bureau, 2009a). In 2008, a staggering 12.1% of the U.S. adult population aged 21-64 years reported a disability (Disabled World, 2010c). Today, there are more than 54 million people in the US that have a disability, which accounts for approximately 19% of the total population (Disabled World, 2010c). With respect to the total population of the U.S., 5% of children aged 5 to 17 years have disabilities, 10% of people aged 18 to 64 years have disabilities, and 38% of adults aged 65 and older have disabilities (Disabled World, 2010c). Sadly, 2.7% of the U.S. population age 5 and over have reported difficulty performing self-care activities, or Activities of Daily Living (ADL), such as dressing themselves, grooming themselves, or moving around inside their homes (Disabled World, 2010a). The Social Security Administration (SSA) estimates that three out of 10 individuals today aged 20 years old will suffer some sort of disability before retirement age (Disabled World, 2010a). The SSA also reports that nearly 69% of the private sector workforce does not have long-term disability insurance (Disabled World, 2010a). That means that in the event of a long-term disability, seven out of 10 workers would have to rely on government aid and their own savings accounts to pay their bills (Disabled World, 2010a).

Jobs for people with disabilities are hard to come by according to 13.3 million people age 16 years or older who reported their health condition contributed to the difficulty of finding or keeping a job (Disabled World, 2010c). The percentage of those, age 21 years or older, who did find employment: 46% (Disabled World, 2010c). The data showed that a person with a non-severe disability had a much higher chance than a person with a severe disability: 75% vs. 31% (Disabled World, 2010c). For those without a disability, the employment rate is 84 % (Disabled World, 2010c). More statistics on the U.S. population with disabilities can be found in Appendix B.

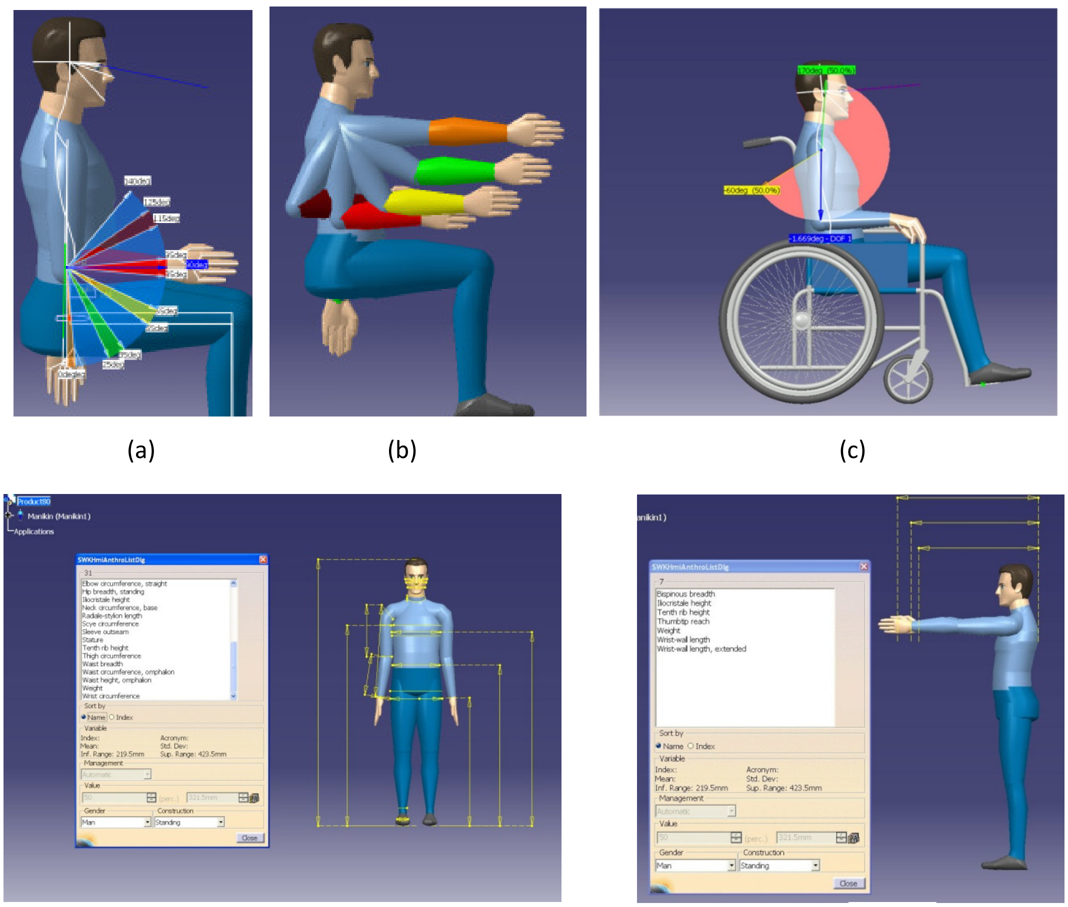
One main contributor to the increase in the population of people with disabilities discussed earlier can be attributed to the baby-boomer generation getting older, but not all of it. Another significant contributor to the increase for the past decade has been the wars in Iraq and Afghanistan. There were approximately 23.2 million military veterans in the United States in 2008 (Disabled World, 2009). Of those, there are approximately 160,000 who served during the Iraq war, and 128,000 who are serving in Afghanistan (approx. 90,000 of which served in Iraq also) (Carden, 2010) . There are 5.5 million veterans reported to have some type of disability, which is 23.7% of the total number of veterans (Disabled World, 2009).

"Total amount of federal government spending for veterans benefits programs in fiscal year 2008 - $84.4 billion. Of this total, $40.2 billion went to compensation and pensions, $37.9 billion for medical programs and the remainder to other programs, such as vocational rehabilitation and education" (Disabled World, 2009).

A Closer Look at DHM Technology

Let us take a closer look at the DHM software and the databases it is built upon. In general, DHM software allows the user to create a 3D digital human that represents a specific population. There are general parameters that are available to create a generic DHM: gender, geographical region, and body size percentile (5% - 50% - 95%). There are also built-in catalogs of standard DHM positions (standing, sitting, kneeling, driving, etc.) that aid in the fast creation and positioning of the 3D manikins, which are what DHM's are called inside the software; see Figure 4 for sample positions.

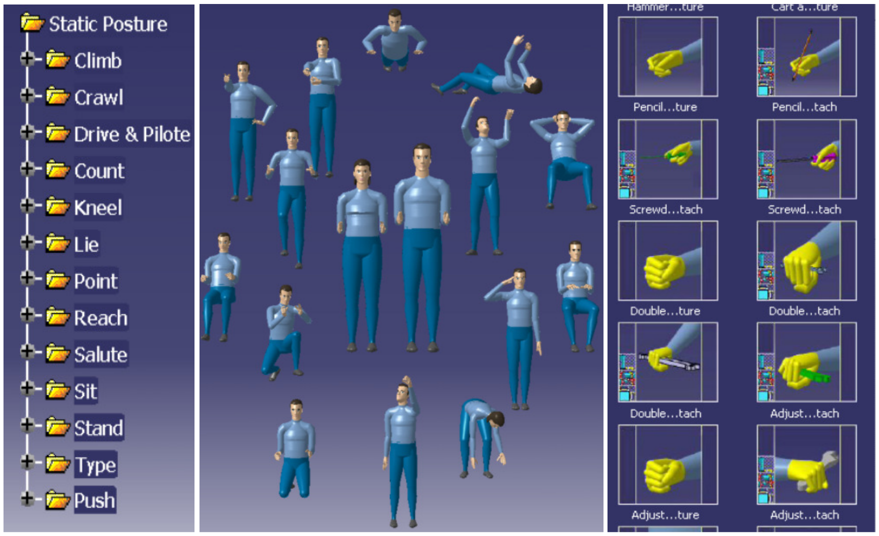
If a DHM is required to closely represent a specific individual, then there are a variety of specific constraints that the user can change; for example, exact weight, exact height, chest and waist girth, arm and leg lengths, etc. See in Figure 3, taken from Catia, which show some of the customizable constraints and measurements that DHM software allow.



(a) (b) (c)

(d) (e)

Figure 3: Figures 3a-3c are computer images of Dassault Systems Delmia V5 DHM customizable constraints (Kemmer, 2008). Figures 3d-3e are print-screens from Dassault Systems Catia V5 showing more customizable constraints. (Hamameh, 2010)



(a) (b) (c)

Figure 4: Define and create specified Human Catalogs or "libraries" for common workplace activities and related manikin characteristics or utilize the many predefined catalogs to reduce model setup. (a) and (b) show the postures catalog, and (c) shows the grips catalog (Kemmer, 2008).

Digital Human Model Fidelity

There are different DHM fidelity levels that can be used. Conti and Erlandson created the following definitions (Conti & Erlandson, 2009a, 2009b):

- Low Fidelity Model – uses a generic manikin created in DHM Software without any anthropometric modifications.
- Medium Fidelity Model – represents a specific person. The manikin is created from DHM software with anthropometric measurement modifications.
- High Fidelity Model – representing a specific person and their specific motions. The manikin is created from laser body scanning and motion from motion tracking equipment.
- Super-High Fidelity Model – this would be model that would be used in the movie industry representing a specific person and their very specific motions and facial

features. It would include body scanning, motion capture and facial features capture equipment.

The fidelity of the model would be dictated by the clinical service conducting the VEA, and the requirements of the position for which the VEA and DHM are analyzed.

Chapter Summary

This chapter explained the need for a technology modification and how that modification can help people with physical disabilities find the work they seek. The DHM technology was also explained further and DHM model fidelity was introduced. The chapter also discussed some laws that are in place to aid people with disabilities in the workplace, and tax credits exist to entice employers to hire these people. As evidenced by the data presented, there still appears to be a prejudice against hiring people with disabilities.

Chapter 2: DHM & Anthropometric Databases

DHM & Anthropometric Databases

This chapter will discuss the DHM database in-depth. Also discussed will be other databases that contain information relevant for the creation of a new database that would include the target population.

Digital Human Model Databases

All the current commercially available DHM software programs utilize the standard databases of "physically normal" humans from the 5th percentile male/female, up to the 95th percentile, and everything in between; see Figure 5 below. Some software allows the DHM to also be classified by geographical regions, such as American/Asian/French/German/etc., which have their own database of standard sizes for the 5th - 95th percentile human.

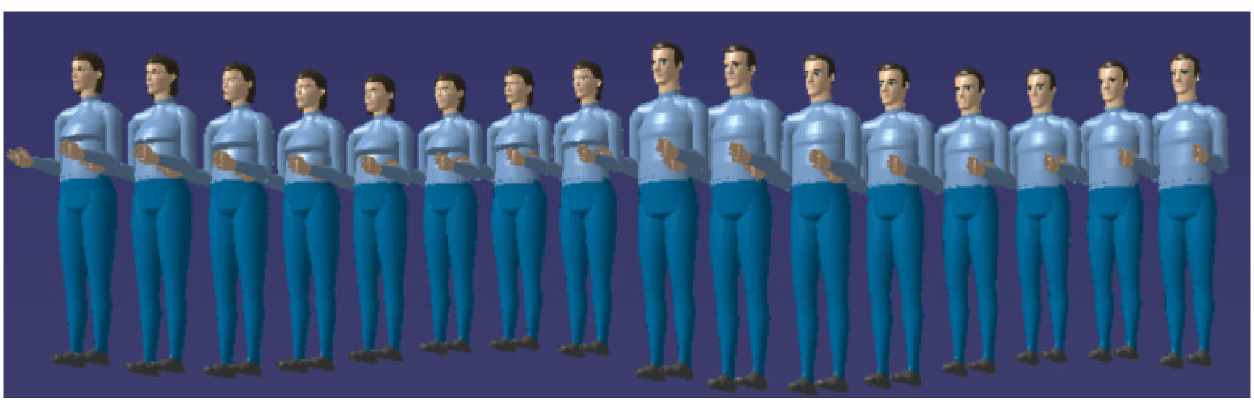


Figure 5: Image of different size male and female DHMs within Delmia (Dassault Systèmes, 2010).

Anthropometric Databases

Definition of Anthropometry

Anthropometry is now one of the principal techniques in physical anthropology, and is defined as the "systematic collection and correlation of measurements of the human body" (Encyclopedia Britannica, 2010).

Anthropometric Percentiles

Given any population, there is variability among body types and dimensions due to factors such as age, gender and ethnicity. So, in anthropometry, the population is divided, for study purposes, in 100 categories (percentiles); from the smallest (in size) to the largest, with respect to one type of measurement (height, weight, arm length, etc.) (Ing.Alexandra Carranza B., 2005). A Gaussian distribution, or frequency curve, is then used to illustrate standard percentiles (Ing.Alexandra Carranza B., 2005).

Anthropometric Data Sets

Anthropometric Data Sets are a collection of civilian and military measurement acquisition surveys spanning over the past fifty years (Defense Technical Information Center, 2010c). The data was formerly archived by the Air Force Armstrong Laboratory Human Engineering Division: Center for Anthropometric Research Data, now the U.S. Air Force Research Laboratory Crew System Interface Division (Defense Techinical Information Center, 2010). "The Human Systems Information Analysis Center (HSIAC) turned the raw data into the Anthropometric Data Sets." (Defense Techinical Information Center, 2010)

The first recorded anthropometric data used for building the modern databases was the 1946 Survey of U.S. Army Female Separatees; where a total of 64 body measurements were collected at the end of World War II (Defense Technical Information Center, 2010c). Since 1946, there have been many anthropometric surveys conducted on military and civilian personnel (Appendix C lists a full timeline and history of the data sets) (Defense Technical Information Center, 2010a, 2010b, 2010c).

Anthropometric Data of Children - AnthroKids

In the 1970s, Dr. Jerry Snyder and fellow coworkers at University of Michigan Transportation Research Institute (UMTRI) conducted two large-scale studies, commissioned by the Consumer Product Safety Commission, of child anthropometry: body dimensions and strength (Matthew P. Reed, 2010; Ressler). "The data from these studies remain the most widely used child anthropometry data in the U.S." (Matthew P. Reed, 2010). The National Institute of Standards and Technology (NIST), through a joint effort with the Information Technology Laboratory (ITL), have made the data available in a variety of ways on their AnthroKids website (Ressler).

3D Anthropometric Databases

There are two recent databases that were separately commissioned to gather 3D anthropometric data of participating countries. Unfortunately, all other nonparticipating countries must pay a fee to access the information. One is called CAESAR (Civilian American and European Surface Anthropometry Resource Project), and the other is called iSize by Human Solutions GmbH.

CAESAR: Civilian American and European Surface Anthropometry Resource Project

Countries Involved in 3D Scanning: USA, Netherlands, and Italy

The CAESAR project database consists of physical dimensions for men and women of various weights, between the ages of 18 and 65. There were a total of 2,500 people measured in the USA, and 2,500 more in Europe (specifically Italy and the Netherlands), between 1998 and 2000 (S.A.E., 2010). This project digitally scanned the human body in 3D, using the Air Force's whole body scanner, to provide more comprehensive data than was previously available through traditional methods of measurement (S.A.E., 2010). The Society of Automotive Engineers (SAE) Cooperative Research Program was responsible for raising industry funding for CAESAR (S.A.E., 2010).

iSize - Human Solutions N.A.

Countries Involved in 3D Scanning: Germany and France

The iSize database is a unique product from Human Solutions that serves multiple industries: apparel design, fashion, automotive, and manned earth-moving vehicles (Human Solutions, 2010c). Though the iSize database only has 3D scans of the two aforementioned countries, it also has non-3D data of several other countries: USA, Japan, Korea, China, Eastern Europe, and only men's data from Austria (Human Solutions, 2010c). This database allows comparison of size data between countries, which is useful for international companies that need access to anthropometric data for several countries for their product(s) (Human Solutions, 2010c).

HADRIAN Database

HADRIAN stands for HUMAN ANTHROPOMETRIC DATA REQUIREMENTS INVESTIGATION AND ANALYSIS, and the research was carried out at the Loughborough University in the UK in the areas of 'design for all' and accessible transport (R. Marshall et al., 2009). HADRIAN was created through the UK EPSRC (Engineering and Physical Sciences Research Council) 'EQUAL' (Extending Quality of Life) initiative, but is now being further developed through EPSRC Sustainable Urban Environment (SUE) Program (Porter, et al., 2008). SUE's aim is to improve the understanding of the needs, abilities and preferences of people who experience transport-related exclusion in towns and cities in the UK (Porter, et al., 2008).

HADRIAN's database consists of 102 people, 59 of whom have various disabilities, comprised of a broad range of body shape, size, and range-of-motion ability. Anthropological data on the subjects was also collected on a wide range of behavior and lifestyle, both inside and outside the home. The research addresses two major areas: (1) accessible data from the target population, and (2) a means of utilizing the data to asses designs (R. Marshall, et al., 2009). An example of the research would be vehicle ingress and egress, coping with uneven surfaces, steps, and complex pedestrian environments. What makes HADRIAN unique is a tool that can "compare an individual's physical, cognitive and emotional abilities with the demands placed upon that individual by the mode(s) of transport available and the route options selected" (R. Marshall, et al., 2009).

HADRIAN is a small-scale example of a database that includes people with physical disabilities and their anthropometric features. By including this population in the database, engineers and designers can assess and evaluate accessibility issues and thereby directly impact the design process. "A VEA offers more detailed identification of accessibility problems than traditionally possible with human observers" (Conti & Erlandson, 2009b). The thesis is suggesting a much wider scope for a database that analyzes thousands of people with disabilities and supplies engineers and designers with all the information required to create a universal design that works for everyone.

Chapter Summary

The databases that are used by DHM software programs were introduced and explained. There are many other databases that have pertinent information relevant to this research and the target population. A new database with information gathered from all the others would contain all the information necessary to include the target population.

Chapter 3: The National Spinal Cord Injury Database

National Spinal Cord Injury Database

This chapter will discuss another unique database that is relevant, and explain how it can also add to the overall goal of this research; i.e., identifying modifications and enhancements that must be made to existing, commercially available DHM software to include people with disabilities.

The National SCI (Spinal Cord Injury) Database contains a vast amount of information that can be used in the creation of a DHM SCI catalog, but it is not currently being used in the creation of DHMs or VEAs (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010). Building an SCI catalog in DHM software would significantly reduce the time needed for the user to manually restrict motions for each DHM model created of a person with severe range-of-motion constraints.

The SCI Database

Created in 1973, the National SCI Database has been capturing data from an estimated 13% of new SCI cases in the U.S. (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010). Over the years there have been 26 federally funded SCI centers, called Model SCI Care Systems, which contribute data to the National SCI Database (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010) There have been 25,415 people who have been entered into the SCI database, as of October 2007 (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010).

The National SCI Database gathers a great number of statistics from each patient that enters their system. Some of the information they gather includes (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010):

- Age at time of injury
- Gender
- Race/nationality
- Etiology of SCI
- Life expectancy: grouped by age, race, type of injury, range-of-motion, etc.
- Functional Independence Measure (FIM) motor scores

The Functional Independence Measure (FIM) motor scores the SCI database collects are the most significant item to building a new DHM database that includes the target population. The FIM motor scores are a ratings system based on the ability of the subject to complete the following tasks on their own: feeding, grooming, bathing, dressing upper and lower body, toileting, bladder and bowel control, transfer to bed or chair, toilet, tub or shower, locomotion and stair climbing (National Spinal Cord Injury Statistical Center, 2009). Subjects are given a full score for that task if they can complete it, and partial scores on how much they are able to complete.

The information gathered in the database, along with the motion assessment motor scores, could be analyzed to show that people with the same type and location SCI would have a similar active range-of-motion (Appendix D lists some information and statistics). In other words, many people with a similar C4-C5 (or any spine location) SCI would have a similar range-of-motion. That information is essential for building a DHM database that has catalogs of predefined SCI locations that automatically restrict the active range-of-motion of the 3D manikin.

Database Objectives

The objectives of the Database, defined within the scope of the SCI Model System program, are as follows:

1. "To study the longitudinal course of traumatic spinal cord injury (SCI) and factors that affect that course." (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010)

2. "To identify and evaluate trends over time in etiology, demographic, and injury severity characteristics of persons who incur a SCI." (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010)

3. "To identify and evaluate trends over time in health services delivery and treatment outcomes for persons with SCI." (National Spinal Cord Injury Statistical Center)

4. "To establish expected rehabilitation treatment outcomes for persons with SCI." (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010)

5. "To facilitate other research such as the identification of potential persons for enrollment in appropriate SCI clinical trials and research projects or as a springboard to population-based studies." (National Spinal Cord Injury Statistical Center, 2009; University of Alabama at Birmingham, 2010)

Chapter Summary

The National SCI database has a wealth of knowledge related to SCIs. This information is crucial to the development of a new database that includes the target population and research of this paper. Also, the proposed DHM and VE technology can play a significant role in satisfying and quantifying the objectives of the National SCI program. Gathering a sequential and periodic collection of DHM for people with SCIs would:

1. Quantify the longitudinal course of traumatic SCI.
2. Help identify trends over time, and injury severity characteristics of SCIs.
3. When comfortable with treatment protocols, help evaluate the efficiency of the treatment.
4. Help establish expected treatment outcome for SCI patients.

Chapter 4: Data Gathering for DHM

Data Gathering for DHM

This chapter will discuss and explain the data gathering portion for DHMs including acquisition of anthropometric measurements and range-of-motion limits and their relationship to one another. Another application for DHM and VE technology will be introduced and the methods and relevance behind that application will be discussed.

Anthropometric Measurement Acquisition

Acquiring anthropometric measurements from individuals for a VEA can be done manually or by means of digital equipment:

- Occupational Therapist (OT) – an OT must manually measure and record both the physical body dimensions of the individual and their available active range-of-motion.
- 3D Body Scanner – the easiest way to record physical body dimensions of an individual is to use a full-body scanner, but the active range-of-motion must be captured by another means.
- Motion Tracking System – the system can capture active range-of-motion automatically.

Motion Tracking Technology

Many of the DHM software programs allow input from motion tracking equipment to directly apply the captured motions to the 3D manikin. There are many different motion tracking technologies that are commercially available, but they all have similar capabilities. For DHM software, motion tracking allows for:

- Real time animation
- Real time angle, force, torque, and work calculation
- Exact movement capturing

To collect the data the subject wears sensors on their body and simply goes through the motion that is to be captured. The number of sensors and where they are placed depends on the system being used. The software captures the motion and stores the information. The animation can be viewed in the software by animating a 3D avatar. An example of this modality in use can be seen in analysis of an athlete's motions, i.e. Tiger Wood's golf swing, Kobe Bryant's jump shot, or Peyton Manning's football throwing motion.

Comparison: DHM & 3D Movie Technology

Having an understanding of the state-of-the-art required for creating super-high fidelity DHMs for film will help define what is practically feasible, and available, for providing clinical and vocational VEA services to people with disabilities.

The technology used in making the 3D movie Avatar is new and cutting-edge for the motion picture industry, but it utilizes customized DHM software, in conjunction with motion capture equipment. This technology has been used for years to capture real-life motion and transfer it to virtual reality. James Cameron's (Avatar's writer, director and producer) vision for the movie uses this technology, but he uses it in a different way, in a different industry, and with cutting edge after-effects (rendering and post-processing).

Cameron uses the same features for DHM creation and motion tracking that could be used for helping persons with disabilities find jobs, but this is where the similarities end. For the movie, Cameron wanted to use super-high fidelity DHMs, so the next step was to translate the real-time DHMs and the motion captured into CGI (computer generated images) and animation software with a virtual reality (VR) "movie set" already created, aka 3D space. For a VEA of a disabled individual, the VR "movie set" would be the workspace that is needed for simulation, which would be brought in from CAD. This VR "movie set", or "volume", for Avatar, in and of itself, is nothing new, but how Cameron combined real scenes, AR (augmented reality), and VR elements superimposed upon each other in real-time goes far beyond any movie that has come before it. Dozens of companies, using dozens of software programs (mentioned later), were needed to build the VR "movie set" from CGI.

Augmented Reality (AR) is simply superimposing a real image into a fabricated image, whether that is CGI or hand-created (cartoon); or vice-versa, superimposing fabricated images into a real image. For example, in futuristic, science-fiction, space movies that have spaceships, the holographic type controls that real people seem to be pressing is all AR.

Virtual Reality (VR) is much different than AR. VR is a view into a completely fabricated world. An example of VR is many of the recent, first-person, 3D shooting games that are out for Sony's Playstation game console, Microsoft's Xbox game console, and PCs.

Avatar was originally envisioned in 1995, but in order to fully realize his vision for Avatar, Director Cameron had to wait for the new generation of Stereoscopic 3D (S-3D) HD digital cameras, and faster computers capable of running the simultaneous algorithms needed to keep focus on a moving image in real-time; which was the greatest problem with the new 3D cameras. The S-3D cameras that were being developed were not up to Cameron's standards, so he and Vince Pace, a director of photography on the film, created a unique hi-def 3D camera system that fused two Sony HDC-F950 HD cameras 2½ inches apart to mimic the stereoscopic separation of human eyes (Film Contact, 2009; Thompson, 2010). It is this stereoscopic separation that creates the 3D depth of field that we see with our eyes.

Although, there were a few movies for which Cameron and Pace used S-3D HD digital cameras, they were just perfecting the camera setup for eventual use on Avatar. The new S-3D HD camera system Cameron and Pace developed, and perfected, became known as the Fusion 3D camera system. Avatar is the first movie to use the next-generation technology and equipment for creating a true S-3D (Stereoscopic 3D) movie with mixed real images and CGI animation with VR and AR (AssociatedPress, 2009). Until this newer camera system was developed, regular movies were made into 3D movies in post-production, i.e. with computers and CGI.

To have full control of each camera shot in each scene Cameron had to use dozens of workstations to compute the scenes real-time with the VR "movie set" as they were being shot. This allowed him and the cinematographers to use AR during shooting of the CGI scenes of the movie. Real actors, wearing motion tracking suits and head gear (for facial expression capturing), were viewed and shot in real-time; while at the same time, on a special viewing screen, the actors were superimposed into the VR "movie set" (AssociatedPress, 2009). This allowed Cameron to see what the scene would look like instantaneously. He did not have to wait to see the scene after the computer animators were done, which allowed him the creative freedom to know if the shot they just took is what he wanted (AssociatedPress, 2009). This new way of marrying the performance capture by the actors and live-action production was also developed by Cameron, dubbed Simulcam. It allows the user of the Fusion 3D camera system to look into the eyepiece and see the CGI elements in real time (Film Contact, 2009). In this way, Cameron could operate the camera as if he was shooting from within the film's virtual world of Pandora. This was truly ground-breaking technology in the movie industry, and it has now become the standard for movie making after just one film.

Software Used to Make the Avatar

This section lists the software utilized by all the companies involved in creating the movie. The purpose is not to introduce and explain each software program, but rather to show the extent of software that was used to create super-high fidelity DHM's for the epic film. The list of tools is not exhaustive and there's overlap in capabilities, depending on each company's pipeline. Here is a list of the main software used (Niculescu, 2010):

- Autodesk Maya
- Pixar Renderman for Maya
- Autodesk SoftImage XSI
- Luxology Modo (model design, e.g. the *Scorpion*)
- Lightwave (low-res real-time environments)
- Houdini (unknown area)
- ZBrush (creature design)

- Auodesk 3ds max (space shots, control room screens and HUD renderings)
- Autodesk MotionBuilder (for real-time 3d visualizations)
- Eyeon Fusion (image compositing)
- The Foundry Nuke Compositor (previz image compositing)
- Autodesk Smoke (color correction)
- Autodesk Combustion (compositing)
- Massive (vegetation simulation)
- Mudbox (floating mountains)
- Avid (video editing)
- Adobe After Effects (compositing, real-time visualizations)
- PF Track (motion tracking, background replacement)
- Adobe Illustrator (HUD and screens layout)
- Adobe Photoshop (concept art, textures)
- Adobe Premiere (proofing, rough compositing with AE)
- many tools developed in-house
- Also, countless plug-ins for each platform, some of them Ocula for Nuke, Ktakatoa for 3ds max, Sapphire for Combustion/AE.

Chapter Summary

The previous chapters have discussed and defined the essential elements of what is necessary to create a DHM, VE, and VEA. This chapter explained the relationship and complexity of DHMs, VEs, VR, AR, motion capture, etc. The chapters that follow will present and discuss the creation process and the commercially available technology that is required for the process.

Chapter 5: DHM& VE Creation Process

DHM & VE Creation Process

The Avatar technology demonstrates what is required to create super-high fidelity DHM and a virtual environment (VE). Obviously such technology is not practical, cost effective, or necessary for analysis of the ergonomic needs and environmental requirements of people with disabilities. However, this discussion has presented all the elements that must be combined when creating a DHM and VE.

The required model fidelity is directly related to the analysis requirements and functional ability of the person. For example, if the goal of the DHM/VE is to assess wheelchair accessibility in a home or work environment, then a relatively low fidelity model would suffice; the key feature being gross accessibility. However, if the DHM/VE is created for a more complex work environment, where the worker with a disability must perform a variety of tasks with a lot of motor movements, then a higher fidelity DHM/VE model would be required.

All the steps required for DHM, VE, and VEA creation and analysis have already been introduced and briefly discussed, but have yet to be sequentially listed. Here is the complete process, though some steps can be completed simultaneously:

1. Anthropometric data acquisition: manually or by 3D body scanner.
2. Active range-of-motion acquisition: manually or by motion tracking equipment.
3. DHM creation with collected anthropometric measurements and motion tracking data.

4. Creation of virtual work environment: manually measured or with laser-scanner technology.

5. VEA creation with DHM and VE simulation, validation, and analysis in DHM software.

6. Creation of analysis report of VEA in DHM software.

7. Creation and output of video for client.

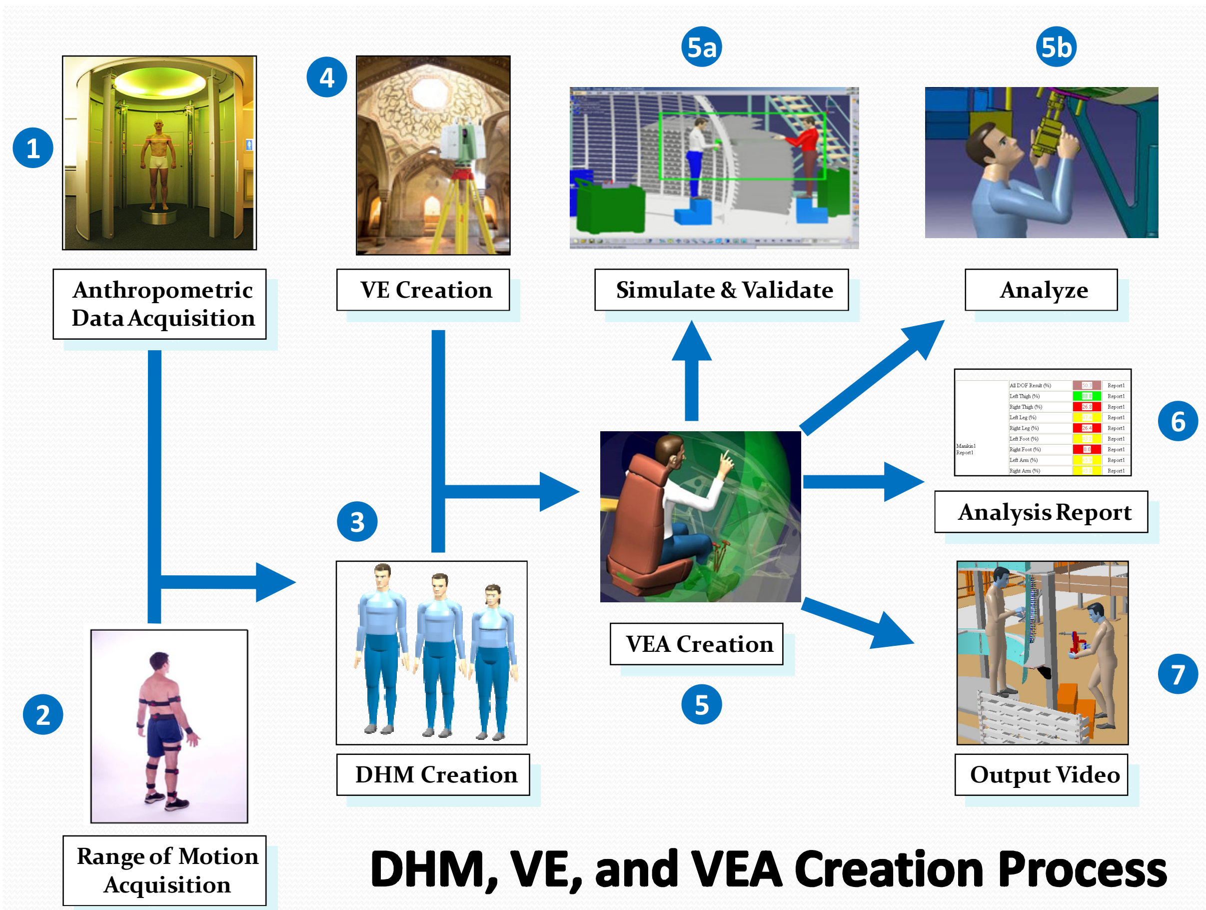


Figure 6: Shows the process for DHM, VE, and VEA creation and analysis. (Hamameh, 2010)

Chapter 6: Software Comparison

Software Comparison

The following section will discuss the different software programs that can be used for DHM and VE construction, simulation, and analysis. The major DHM software programs will be presented and discussed individually. The CAD software programs will only be touched upon and not discussed in detail.

Digital Human Modeling Software

The following covers manikin creation and analysis software only. These programs rely on CAD systems for all other objects to be used in the analysis. For example, if the goal is to analyze ingress and egress from a vehicle; the manikin and the motion is created in the DHM software, but the vehicle geometry is imported from a CAD or CAE system (Appendix E lists company and website information).

List of the major DHM software programs available:

- Delmia – Dassault Systemes
- Tecnomatix – Siemens
- RAMSIS – Human Solutions GMBH
- SantosHuman – Santos Human Inc.
- HADRIAN & SAMMIE

Advantages & Benefits of Using DHM Software

There are many advantages and benefits all throughout a product life-cycle, from concept to production, where a DHM software program can help save time and money for a company (Appendix F details a comprehensive list of the advantages and benefits) (Siemens, 2010a). The following are essential advantages and benefits that carry over from industrial processes to rehabilitation, vocational, and service processes. Based on decades of research and relevant experience, the advantages and benefits include:

- The software, through communication and collaboration, can facilitate coordinating the activities of the client, care giver, service provider, and assistive technology (AT) specialist, which reduces errors, miscommunication, and service delivery inefficiencies (Siemens, 2010a).

- Eliminate hazardous work and home environments and more efficiently design safe, accessible environments by using DHM/VE simulation to test 'what if' scenarios (Siemens, 2010a).

- Reduce service delivery time by applying best-practices and utilizing catalogs and other DHM movement, task and environmental objects that represent standardized operator procedures (Siemens, 2010a).

Delmia – Dassault Systemes

Delmia is widely used in industrial manufacturing and product design in multiple industries including: automotive, aerospace, defense, heavy machinery, etc. In the automotive industry, for example, it is used in the complete life-cycle of the vehicle:

- Concept
- Product Design
- Product Assembly
- Product Servicing

Simulations on early-concept designs through production designs are conducted on the products to make sure they can be:

- Manufactured
- Assembled onto the vehicle at the plant
- Serviced at dealerships or by the customer.

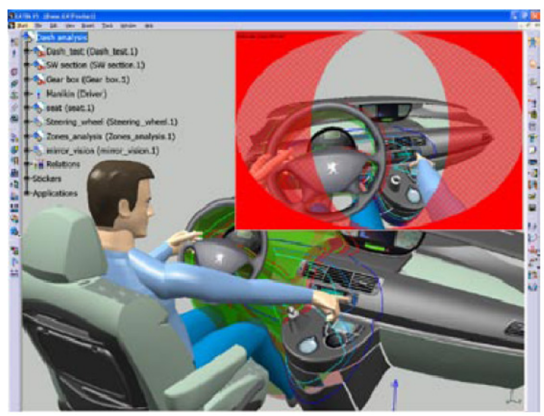


Figure 7: Examples of Delmia capabilities: reach study and vision analysis (Dassault Systèmes, 2010).

The GUI (graphic user interface) is the exact same as Catia, its sister CAD software, which makes it intuitive and easy to learn if one possesses knowledge of how to use Catia. It is not necessary to know Catia prior to learning Delmia, but it significantly lowers the learning curve. Knowing Catia before learning Delmia also helps when CAD created objects are required for importing into Delmia for simulation. An example of what Delmia can do is a reach study and vision-field analysis, as shown in Figure 7.

Tecnomatix– Siemens

Tecnomatix, like Delmia, is widely used in industrial manufacturing and product design in multiple industries including: automotive, aerospace, defense, heavy machinery, etc. Its capabilities and uses closely mimic Delmia's, so they will not be discussed further in this section. An important historical note though: Tecnomatix is based on the first DHM program designed and used for NASA in the early 1980's called JACK (Ames Research Center - Johnson Space Center, 1993). The Johnson Space Center (JSC) was the original investor in the development of JACK, which was at the Center for Human Modeling and Simulation at the University of Pennsylvania (UPENN) (Ames Research Center - Johnson Space Center, 1993).

"Conceived as an ergonomic assessment and virtual human prototyping system for NASA space shuttle development, it soon gathered funding from the U.S. Navy and U.S. Army for dismounted soldier simulation, from the U.S. Air Force for maintenance simulation, and from various other government and corporate users for their own applications." (Clements, 2009)

The development of Jack was the first time that the UPENN directly marketed technology from one of its research and development projects (Ames Research Center - Johnson Space Center, 1993). The company Transom was created by the university to market and sell Jack in 1996 (The Free Library, 1998).

Figure 8: Tecnomatix simulation of a repair in an airplane cockpit (Siemens).

Eventually, Transom sold Jack to Engineering Animation, Inc. (EAI) in 1998 (The Free Library, 1998). In 2000, EAI was acquired by Unigraphics Solutions (UGS) (Siemens, 2010c; The Free Library, 1998). Then in 2005, UGS acquired Tecnomatix and JACK officially became part of the Tecnomatix product line (Siemens, 2010c). Now, Siemens is the owner of the technology when they acquired UGS in 2007 (Siemens, 2010c).

RAMSIS – Human Solutions GmbH

Human Solutions N.A. is a company that specializes in human anthropometric data. Their DHM software, called RAMSIS, is very impressive and can be incorporated inside Dassault Systemes program Catia (RAMSIS does not have its own CAD system). It was mainly designed for a European consortium in the automotive industry that wanted more flexibility for manikin design and movement for VEA's than Delmia had at the time (Luebke, 2010).

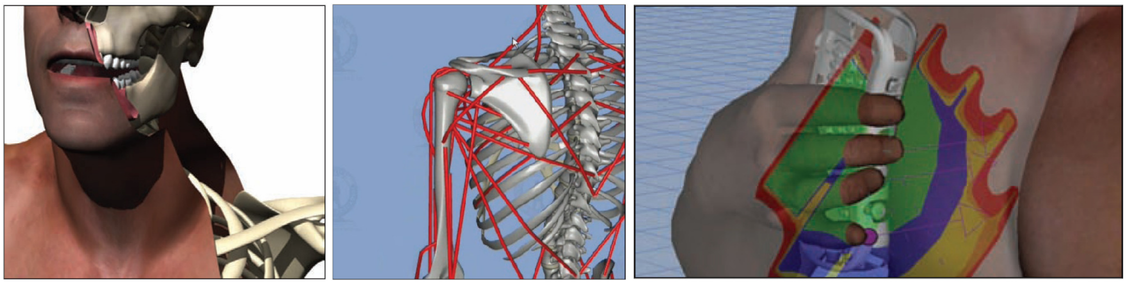
The digital human models created by RAMSIS appear to be much more user-friendly, easier to control, and can be manipulated and constrained faster than in Delmia. This helps in understanding why some companies are opting to purchase Catia as their CAD system and RAMSIS as their DHM system choice (Luebke, 2010). An onsite demonstration at Human Solutions N.A. in Troy, MI proved those statements. Figure 9 shows RAMSIS in an automotive application, and Figure 10 shows RAMSIS in an industrial setting.

Figure 9: Posture analysis and reach study simulation with RAMSIS (Human Solutions, 2010b).

Figure 10: Posture analysis and vision study simulation with RAMSIS (Human Solutions, 2010b).

SantosHuman – Santos Human Inc.

SantosHuman is the first 'biofidelic', or life-like in appearance and response, DHM out on the market that was built from the ground up. Santos DHMs are high-fidelity models using biomechanics, physics optimization, and clinical evaluation to simulate human activities with ergonomic analysis, human performance, human performance analysis, and human systems integration with predictive posture analysis (Santos Human Inc., 2010a). Santos was developed from the Virtual Soldier Research (VSR) Program at the University of Iowa (Abdel-Malek et al., 2007). Figure 11 shows three of the model types Santos has available for simulation.



(a) (b) (c)

Figure 11: SantosHuman: (a) Skeletal model, (b) Muscle model, (c) Physiological model (Santos Human Inc., 2010b)

HADRIAN & SAMMIE

HADRIAN stands for HUMAN ANTHROPOMETRIC DATA REQUIREMENTS INVESTIGATION AND ANALYSIS, and is a 3D human modeling and task analysis tool that works together with SAMMIE (Loughborough University; D. R. Marshall; R. Marshall, et al., 2009). HADRIAN was developed to support engineers and designers to develop products that meet the needs of people with disabilities and the elderly (R. Marshall, et al., 2009). It allows for “modeling of discrete physical interactions that are based on the complex limitations of real people rather than generic population data” (R. Marshall, et al., 2009). It was initially developed to support the design of kitchen and shopping based tasks for people with disabilities and the elderly, but has evolved to include transport related tasks (Porter, et al., 2008).

SAMMIE is also a DHM system, but specializes in the assessment of driver's seat adjustability ranges, visibility of controls and displays (Loughborough University; D. R. Marshall). SAMMIE is the result of ongoing research into anthropometry in the areas of DHM, ergonomics, biomechanical analysis, vision assessment, workplace and product design, and universal design (Loughborough University; D. R. Marshall). The SAMMIE research has been conducted mostly by the Design Ergonomics Research Group at the Design School at Loughborough University, UK (Loughborough University; D. R. Marshall). The research includes support for the ‘Design for All’ (aka universal design) (GR/M68510/01) and AUNT-SUE (GR/S90867/01) projects in the United Kingdom.

Together, HADRIAN with its unique database and capabilities, coupled with SAMMIE make this union a strong competitor in the DHM market in the UK and abroad.

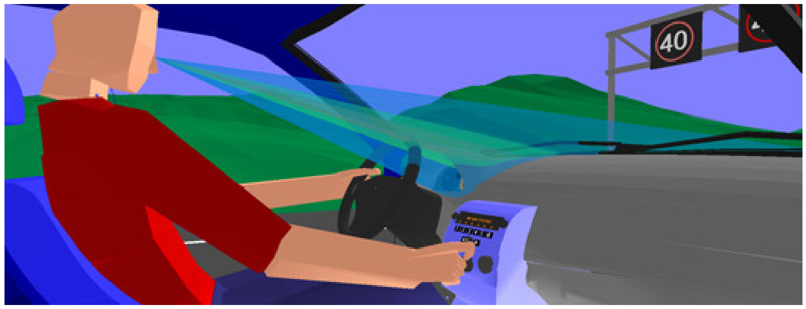


Figure 12: Image of a vision simulation in HADRIAN/SAMMIE (Loughborough University).

Figure 13: An example of screen displays for a particular individual within the HADRIAN database (Porter et al., 2008).

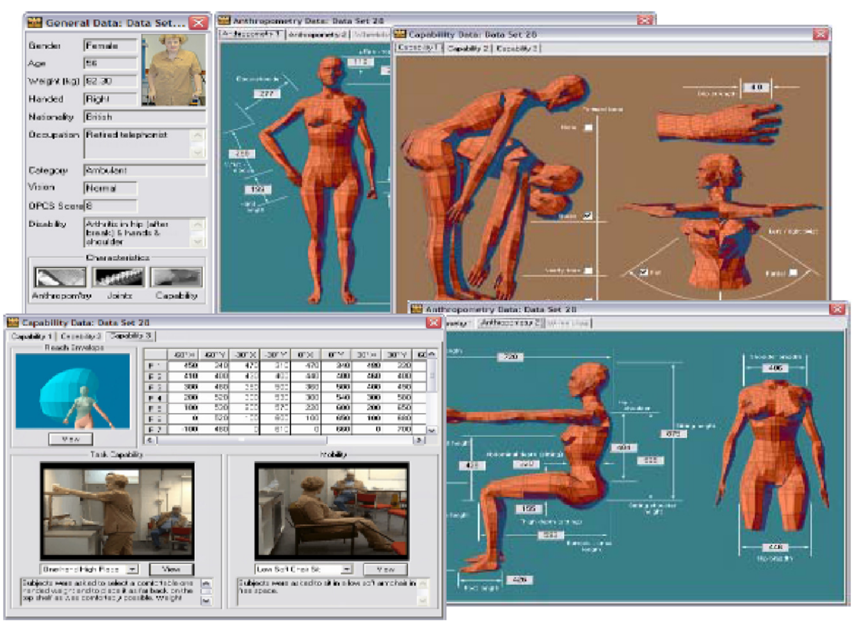


Figure 14: An example of screen displays for a particular individual within the HADRIAN database (Porter, et al., 2008).

CAD Software

There are many CAD software programs on the market that have the capabilities of creating basic Digital Human Models and performing simple motion and reach studies, but their DHM capabilities are limited. CAD software is needed for creation of other objects for placement in the DHM specific software, such as wheelchairs and other ATs, office equipment, or factory equipment. The CAD systems that are most widely used are Catia, UG, and ProE (Appendix E lists company and website information).

Chapter Summary

This chapter discussed the history of DHM software, and how Jack (now Tecnomatix) began a new evolution into virtual humans and ergonomics. Since those early days of Jack being the only DHM program available, many more have become commercially available. The most widely used DHM programs today were listed and discussed in this chapter, along with their advantages and disadvantages. The CAD programs that the DHM software relies on for VE creation were also mentioned.

Chapter 7: Hardware Comparison

Motion Tracking Systems

Motion tracking technology was briefly discussed in a previous section. This section will discuss two of the most widely used motion tracking systems today that are suitable for application to the target population. The two systems are similar in functionality and capabilities, so it would be up to the user to decide which system they would prefer to use (if that choice were available). The two systems are:

- Functional Assessment of Biomechanics (FAB) System – Biosyn Systems Inc.
- Flock of Birds (FOB) – Ascension Technology Corporation

FAB System – Biosyn Systems Inc.

The FAB system developed by Biosyn Systems was the first full-body wireless motion capture system based on inertial sensor technology without cameras (Biosyn, 2010). The previous generation technology was based on image capture technology involving cameras. The FAB is completely portable and can be setup in about five minutes, and has up to 10 hours of record time. The FAB is used in many industries that require motion capturing, some of which are: sports medicine for athletic training, physiotherapy, occupational therapy, ergonomic studies, industrial design, and even the entertainment industry. (Biosyn, 2007)

Figure 15: Image of FAB wireless senor placement on the body (Biosyn, 2007).

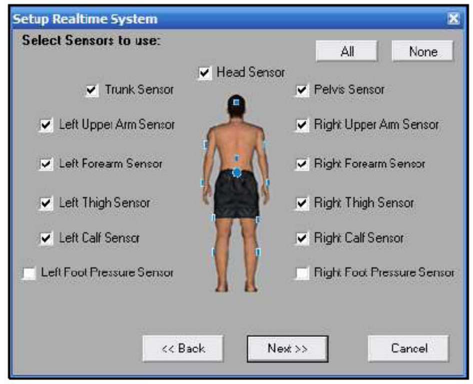


Figure 16: Image of sensor placement menu inside the FAB software (Biosyn, 2007).

The FAB system uses gyroscopes, accelerometers, and magnetometers that allow the system real-time detection of any angular displacement while the software calculates and displays the kinematic and kinetic information, also in real-time (Biosyn, 2007). The software allows for the recorded data to be played back in synchronization with any animated or graphical model; which is where it can help in creating a DHM of people with limited range-of-motion. Figures 15-17 show examples of the FAB system sensor placement, menus, and motion animation.

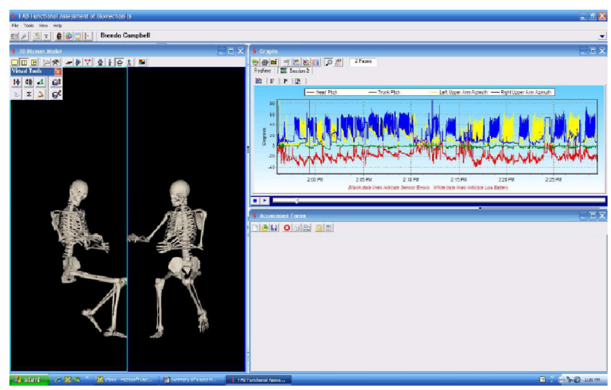


Figure 17: Screen capture of the FAB software data logger and animated skeleton avatar (Biosyn, 2007).

Flock of Birds (FOB) – Ascension Technology Corporation

The FOB system from Ascension Technologies Corporation is very similar to the FAB system in its uses and capabilities. The FOB system is Ascension's most popular and widely used tracker, but it has been recently discontinued and replaced by a few different products called trakSTAR, MotionSTAR, and MotionSTAR Wireless Lite (Ascension Technology

Corporation, 2010). The core of the system changes slightly, depending on the needs of the user. For DHM creation, the MotionSTAR system is recommended by Ascension based on the uses listed for the MotionSTAR (Ascension Technology Corporation, 2010):

- 3D Character Animation for TV, Movies, & Games
- Live Performance Animation
- CAD Simulation of Human Motions
- Virtual Prototyping
- Sports & Medical Analysis
- Biomechanical Analysis
- Human Performance Assessment
- Interactive Game Playing
- Rehabilitative Assessment/Feedback

Scanning Equipment

We have come into an age where lasers are cheap and safe to use for a multitude of purposes. There are multiple laser-scanners that can create 3D electronic representations of a room, factory, construction site, bridges, a human body, or small items like a hand, foot, or small product. The accuracy of the scanners varies, but even the least accurate scanners are within a few millimeters of the actual point scanned. 3D scanners have also been used in forensics to recreate a virtual crime scene. Scanners allow 3D pictures to be used as a reference when crime scene investigators (CSI) want to revisit a crime scene. Today, many of the 3D scanners have the capability to translate the scanned data into a CAD model for manipulation, and it is this laser-scanning-to-3D-model technology that would aid in creating a VEA of a DHM simulation in an office or other work environment.

3D Body Scanners

The latest 3D whole-body scanners can take up to 400 measurements in 0.6 – 17 seconds, depending on the scanner used. There are several 3D whole body scanners that are commercially available. Table 1 below shows the top 3D body scanners, the companies that make them, the number of body measurements they take, and the amount of time it takes for each scan. Figure 21 shows images of a scanner and some of the information that is obtained after a 3D full body scan.

Company	Scanner	Body Measurements	Scan Time
Human Solutions	Vitus Smart XXL	over 140	12 sec
TC^2	NX-16	over 400	8 sec
Cyberware	WBX	N/A	17 sec
TELMAT Industrie	Symcad ST	over 160	2.5 sec
Creaform	MegaCapturor	N/A	0.6-1.1 sec

Table 1: 3D body scanners, the companies that make them, the number of body measurements they take, and the amount of time it takes for each scan. (Creaform, 2010; Cyberware, 2010; Human Solutions, 2010f; TC^2, 2010; TELMAT Industrie, 2008)

(a) (b) (c)

Figure 18: (a) Image shows a subject being scanned in the Human Solution's Vitus Smart XXL 3D body scanner, (b) image shows the scanned data in the software, (c) image shows a menu of the anthropometric measurements calculated from the scan. (Human Solutions, 2010a)

Environment Scanners

There are many companies that offer multiple scanners for different size jobs. Figures 19 and 20 show various applications for the scanners. There are two companies that appear to be the most popular in the area of environment scanners:

- Leica Geosystems with their flagship scanner: ScanStation C10
- Zoller+Fröhlich GmbH with their flagship scanner: Z+F Imager 5006i

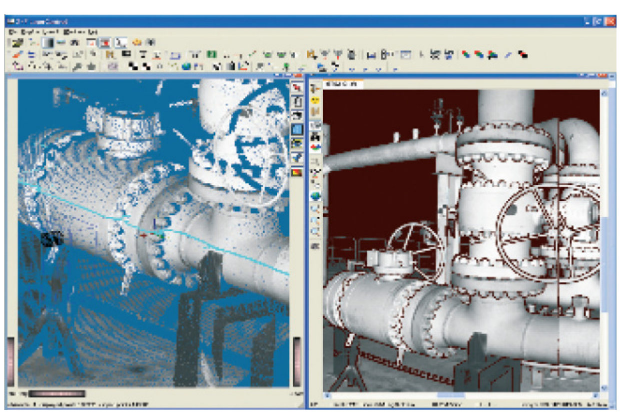


Figure 19: This figure is a snapshot of the software used that shows a point cloud of a 3D scan on the left, and a post-processed, 3D reconstruction model on the right (Zoller+Frohlich, 2010).

Figure 20: Image of bridge showing progression from scanned data on the left, automatic software distance calculations in the left-middle, 3D scan-to-model in the right-middle, and the normal picture of the bridge on the right (Leica Geosystems, 2010).

Chapter Summary

The chapter listed and discussed the most popular motion tracking and scanning equipment that could be used for application to DHM, VE and ultimately VEAs. The importance of this equipment cannot be emphasized enough. Accurate motion tracking is crucial for portraying the active range-of-motion limitations of a person with disabilities within the DHM software. The 3D body scanners are an integral part of the DHM creation and VEA process. Without the use of body scanners it would take much longer to create the DHMs in the software, and they would not be as accurate as they would with the scanners. Another critical component of a VEA is the VE which environment scanners can quickly and accurately duplicate. The alternative to environment scanners is to manually measure and create the VE in a CAD system. The alternative approaches to using motion tracking and scanning technology for VEA creation are extremely inefficient, time-consuming, and costly.

Chapter 8: Basic Human Motions

Basic Motions in a Kitchen Study

Introduction

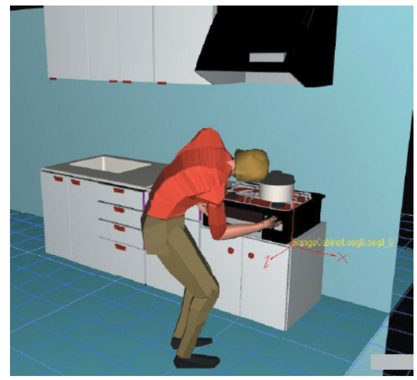


Figure 21: Image taken from the study (Osaka Gas Company Ltd., 2010).

A study of the basic motions people would use in a kitchen was conducted by Osaka Gas Co. Ltd., which is part of the Osaka Gas group (Osaka Gas Company Ltd., 2010; The American Society of Mechanical Engineers, 2004). The study was part of a national initiative for greater awareness of ergonomics and universal design during building construction and renovations. In 1999, Osaka Gas began development of a design-support system that addresses human behavior and comfort in a home or work environment, and they called it CUPS (comfort, usability, performance and safety). The project leaders identified three critical items they wanted development to focus on:

- Behavioral simulation
- Comprehensive evaluation method
- Development of a heart strain prediction system for the elderly

Figure 22: Images taken from the study (Osaka Gas Company Ltd., 2010).

A customized behavioral simulation solution

Osaka Gas evaluated the top DHM software programs and decided to use Tecnomatix. Through videotaping kitchen activities, like washing dishes and cooking, they developed functional behavioral simulation. The data was also integrated into the OWAS Evaluation, which is a method for assessing posture by means of a 4-step scale; a score of 1 or 2 is acceptable, and score of 3 – 4 could be problematic. Combining the OWAS Evaluation with Tecnomatix allowed for automatic functional behavioral assessment (Osaka Gas Company Ltd., 2010; The American Society of Mechanical Engineers, 2004).

Behavioral assessments according to lifestyle preferences

Osaka Gas carried out a comprehensive evaluation by developing deviation values for eight kinds of assessment criteria for CUPS. This greatly aided in assessing the differences in how different people like to wash dishes, or cooking styles, how they stock their refrigerators, etc. CUPS allows each subject to rate their preferences when performing these tasks, which represents a significant step forward in the area of functional behavioral modeling (Osaka Gas Company Ltd., 2010; The American Society of Mechanical Engineers, 2004).

Safe spaces for the elderly

Osaka Gas developed a heart-strain prediction system that measures strain on the elderly during activities in the kitchen. During development, they realized that they needed to first classify heart motions in order to carry out simulations for DHM/VE. They did so by classifying heart motions in three types, and created separate models for each:

- Isotonic contractions: motion that moves the joints
- Isometric contractions: motion that does not move the joints
- Rising action: a sudden change in the heart's position

Results

The analysis of the motion results showed that virtually all movements in a kitchen could be accounted for in nine basic movements (Osaka Gas Company Ltd., 2010; The American Society of Mechanical Engineers, 2004). Amazingly, the heart rate and blood pressure simulation results closely mirrored those which were obtained during live experiments. This was the first technology that could predict blood pressure and heart rate during daily activities (Osaka Gas Company Ltd., 2010; The American Society of Mechanical Engineers, 2004).

Chapter Summary

The relevance of this study to the research of this paper is significant. The study demonstrates that DHMs, VEs, and VEAs can accurately portray live humans in the home environment. It is reasonable to suggest that if motions in a kitchen can be described by nine steps, then a typical office or factory work environment can be studied in a similar way.

Industrial DHM and VE analyses have developed a large collection of catalogs which include postures for standing, walking, bending, lifting, carrying, and a large collection of hand grip and finger movements. Given a DHM, the analyst can apply the features of a catalog and simulate that activity by the DHM, i.e., walking to a box and picking it up. Integrating the individualized DHMs, in an anthropometric sense, with standardized activities as defined in the catalogs, creates a very powerful and efficient method for creating VEAs on an individualized basis. The equipment used for this technology (motion tracking, body scanning, environment scanning) can create a DHM, VE and VEA of varying fidelities as required by the situation.

The Osaka study considered people falling within the 5% to 95% percentile of the existing human databases. The question still remains as to the difficulty and problems associated with the creation of a simple task analysis for people with physical disabilities using a standard industrial grade DHM and CAD package.

Chapter 9: DHM Project

DHM Project

The project of this thesis was to build DHMs of two specific individuals who were disabled with SCIs, and create objects in CAD that the DHMs could interact with. There were three main questions the project addressed:

1. Can a DHM accurately portray the subjects in body size and shape with the correct anthropometric measurements?

2. Can the constrainable motions of the DHM in the software accurately portray the subjects' true active range-of-motion?

3. Can the motion in the software be controlled in such a way as to portray the true motion of the subjects?

The anthropometric measurements and active range-of-motion were recorded manually by an Occupational Therapist. Catia V5 was used for the project since Delmia was not available at the time the project commenced. The Catia software build was such that it included the toolkit Human Builder. This Human Builder toolkit allows the user to create a 3D manikin and conduct simple analysis, such as a reach study or vision study to be subsequently described. DHM software is needed for more intensive simulation, such as a walk or climb command.

The first part of the project was to see if the DHM in Catia could be constrained in such a way as to accurately portray the body type, body shape, and active range-of-motion of the individual it was supposed to model. The second part of the project was to see if the DHM motions could be constrained to accurately portray that of the subject. The last part of the project, and most time consuming, was to build the DHM simulations for each case study and see if the motions could accurately portray that of the subjects.

The first person that a DHM was created to model, Case Study 1, is a partial-quadriplegic with a C4-C5 spinal cord injury. The person has a limited range-of-motion in their upper body, but none in their lower extremities. Case Study 2 was a full-quadriplegic. This person had full motion of the neck and head, but none in the extremities. Body dimensions and range-of-motion data were collected by an occupational therapist using a tape measure and goniometer. The subjects were observed performing a task that demonstrated their range-of-motion capabilities, which gave a reference of their motions to build and compare the DHM with. The DHM was constrained to move in the same patterns as the subject, and within a range of joint-angles that conformed to the measured range-of-motion data. A video was created of each case study simulation, and images from each video could be seen in Figures 23 and 27.

Case Study 1

The goal of this case study was to create a simulation of subject 1 using a gripping-assist device to pick up a beverage can off the floor, place it on the desk, then take the can and drink from it. Subject 1 (partial-quadriplegic) was observed at an in-person interview to see this person's movements and range-of-motion.

A DHM of the subject was created, and the attempt to fully constrain them according to the anthropometric measurements was completed. There was an issue while creating the 3D manikin though. The DHM software assumed symmetric limb lengths for the 3D manikin (a normal, healthy human), but some people have deformities and their bodies are asymmetric from one side to the other. In this case, the subject has been wheelchair-bound long enough that their muscles have atrophied, and their bone density and bone length in their limbs have changed.

Constraining all the joints of the DHM for this subject, in three degrees of freedom (DOF), was very time-consuming, but it was mostly completed. Unfortunately, the software did not have as many constrainable options as was needed to accurately portray the active range-of-motion of this unique individual. So, with careful planning, building a catalog of this unique individual, and creating dozens of individual steps (frames) for the motions, the simulation was completed successfully.

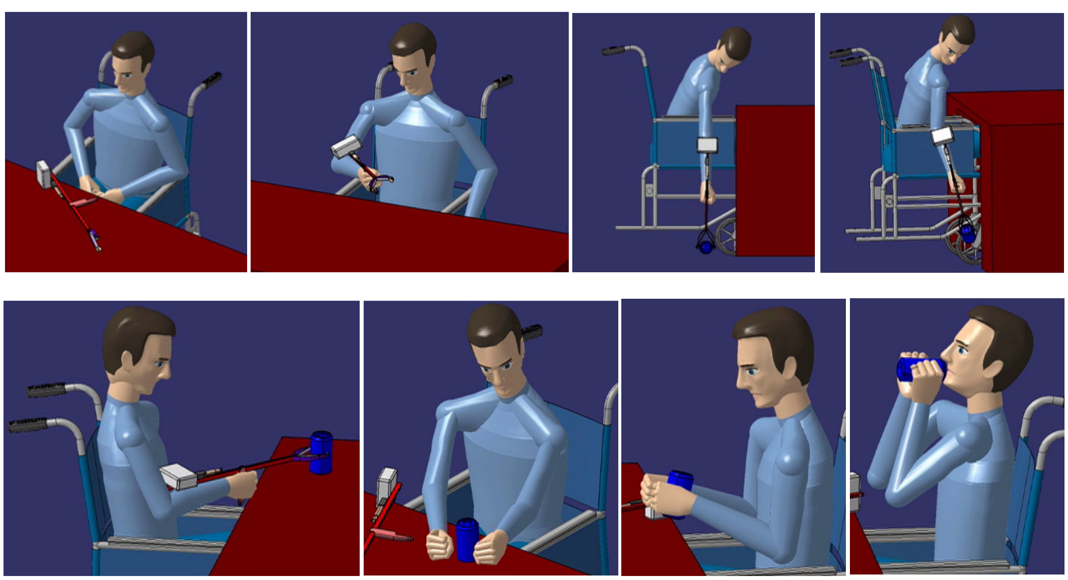


Figure 23: These images are computer print-screen captures taken from the video created for Case Study 1. The images are in chronological order from top left to right, and bottom left to right. (Hamameh, 2010)

Case Study 2

The goal of this case study was to create two simulations of subject 2 (full-quadriplegic) using his computer with an eye-gaze computer control assistive technology (AT) device at different posture positions. This case study was completed after subject 2 had already received the computer and AT device. The reason for this was to investigate whether a DHM simulation could have saved the design team a lot of time and trouble. They reported they had a hard time finding the correct alignment of the computer monitor with eye-gaze camera attached and the sensor the subject had to wear on his forehead (or hat) to work the computer, and they had to return several times to adjust the setup (Kayser, et al., 2009). It was important to show the camera's sensor zone and his head motion (with vision line turned on) in the DHM simulation. Subject 2 was observed from a video and not in-person.

Figure 25 shows subject 2's bedroom workstation before any modifications were made. A bed stands opposite the computer workstation (not shown). The room is very small and has very little room left for a wheelchair. The eye-gaze camera height was not adjustable because it was affixed to a monitor that rested on a non-adjustable surface: the bedroom dresser. Subject 2 is a large man and consequently there was very little space in the room when he was in his wheelchair. He could not tolerate extended periods in his wheelchair and, as a result, changed his positioning frequently to reclined or laying on the bed. These frequent changes in position made it impossible to configure the workstation, in the original unmodified configuration, so that he could use his computer sitting, laying down, or reclining at some angle in between.

Figure 25 (left)**:** The new workstation with the monitor on an articulating arm, and automatic surface height adjustment. (Kayser, et al., 2009)

Figure 24 (below)**:** The original computer workstation was placed on a wooden desk. (Kayser, Drulia, & Banachowski, 2009)

Figure 24 shows the new workstation configuration. This workstation was designed and built by a student design team at the request of an MRS case worker. The team did not have access to the DHM and VEA tools described in this project. The team solved several problems by consolidating the printer, cords and cables, fax and copy machine, telephone, computer and monitor onto one mobile unit. First, the new workstation created more space in the bedroom. The monitor, mounted on an articulating arm, could be positioned for the eye-gaze equipment to work properly at any position subject 2 was using. Lastly, the workstation top could be raised or lowered by an electric motor to accommodate him in multiple positions: equal to bed height when laying down, upright when seated in his wheelchair, and any position in between. Figure 26 shows Subject 2 sitting in his wheelchair receiving instructions on operation of the computer eye-gaze system.

Creation of the DHM for subject 2 was relatively straight forward since a standard 3D manikin could be used from Catia's Human Builder toolkit. The only joint angles and DOF that needed constraining was the neck, so that was completed relatively quickly and easily.

Figure 28: An Occupational Therapist is providing instruction on the operation of the eye-gaze computer access device. (Kayser, et al., 2009)

The first simulation involved the subject sitting upright at his desk. The second simulation involved the subject reclined at a 50° angle from vertical, and this highlighted why the MRS team had trouble. To understand the issue the definition of viewing angle will be introduced: the viewing angle is the maximum angular limits of visual performance, see Figure 26. The eye-gaze camera and the sensor need to be in view of each other, but each has its own viewing angle limits for functioning properly, see Figure 27. The problem the MRS team faced turned out to be the camera to sensor angle

Figure 26: This figure shows a human's viewing angle for clear vision. Anything outside that viewing angle gets distorted. (Bleau, 2010)

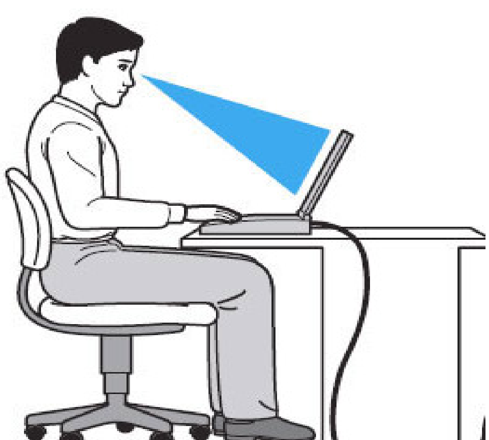
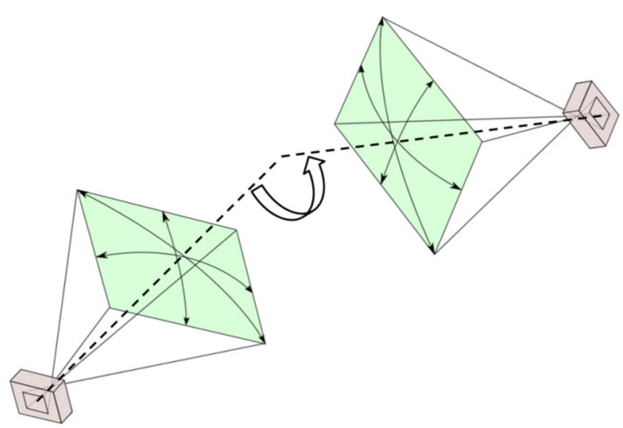


Figure 27: This figure represents the camera and sensor. The dashed lines must be at an angle between 135° and 180° for the camera to properly read the signal from the sensor. (Hamameh, 2010)



was too steep even though the sensor was still in the vision field of the camera. The solution to the problem was to mount the monitor on an articulating arm that also had enough up/down tilt to allow the system to work properly even when he was lying in bed, see figure 28 for the setup in use by subject 2. If the design team had the capability of using the DHM software and create a VEA, then the design and installation of the AT would have been a much quicker and smoother process.

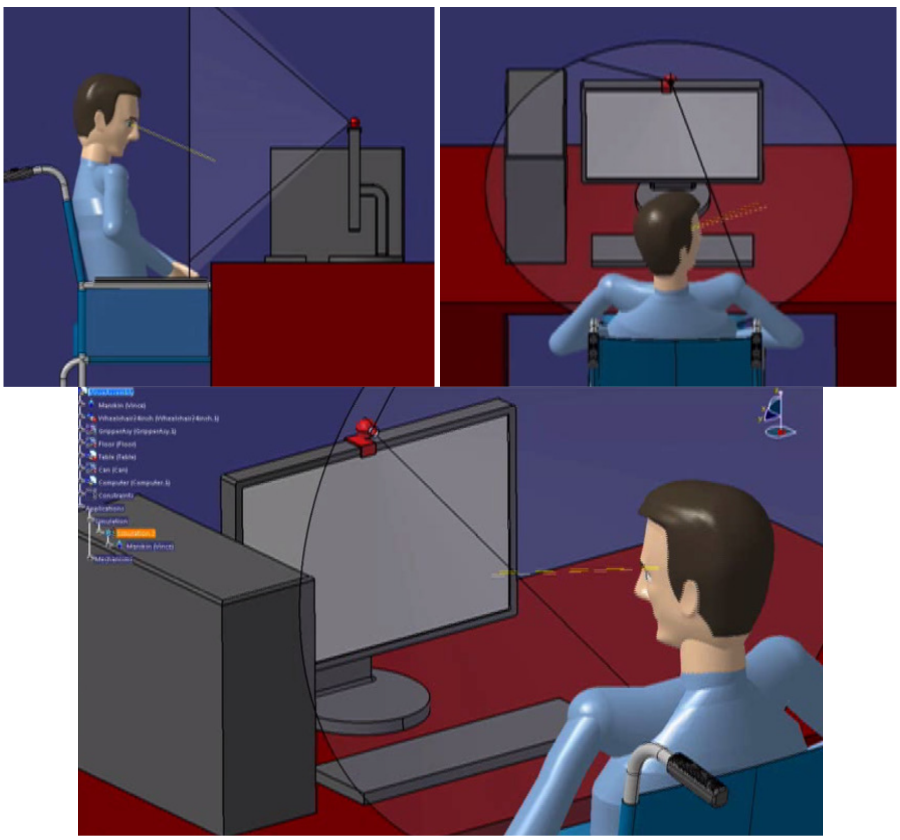


Figure 29: These are computer print-screen images taken from the video created for Case Study 2. The images are in chronological order clockwise, starting from the top left. The yellow line represents the vision line, and the transparent cone is the head-tracking camera's sensor field. (Hamameh, 2010)

Results

It was discovered that the quality of the motion is directly dependent upon the number of steps (or frames) that define the motion; i.e. the quality of the motion improves when the number of steps is increased. This creates a more 'fluid' and natural looking motion.

There were a few issues that presented during DHM creation and simulation. The software lacks the ability to create asymmetric anthropometric features (different length limbs, etc.). The software also lacks the necessary levels of constraints to properly model someone of subject 1's level of injury and SML (severe motion limitation). Ironically, people with a complete transection of the spinal cord in the C-Spine are easier to model than an incomplete transection. This is because the people with a complete C-Spine spinal cord transection do not have any motion below the neck, but people with an incomplete transection may still have motion capabilities in their arms (albeit severely limited). Therefore, people with an incomplete transection SCI present a much more complicated and challenging DHM creation process.

Fixing these issues, along with creating a new database that includes the target population, would give engineers and designers no excuse for improper testing of their products or designs against 'design for all' (aka universal design).

Chapter 10: Findings

Findings

The results of the project were very encouraging and proved that customized DHMs of people with physical disabilities can be created! The DHM software, in its current state, is still very usable for the majority of people with physical disabilities, but the time required to create and constrain the DHM for people with severe motion limitations (SML) would be discouraging.

The results show that with minor modification to the commercially available DHM software, the time needed for DHM creation would be greatly reduced while the efficiency of the process can be greatly increased. These modifications include: being able to create a DHM with physical asymmetries, compensatory motions that people with physical disabilities generate would be accounted for (ballistic motions, etc.), gravitational considerations would be accounted for (gravity aids in some situations while hindering in others), and creation of catalogs that includes SCIs. However, even if these modifications could be addressed the time required to create and constrain the DHM for people with severe motion limitations (SML) would still be considerable.

Databases need to be created which include a wide variety of people with a variety of different disabilities. The material from SCI research and the National SCI Database at UAB can provide a starting point. The HADRIAN database is also available and would allow an immediate upgrade to all DHM software programs in the area of 'design for all', or universal design.

As we learned from Case Study 2 of the project, an accurate VE of the home or workplace is essential to a good DHM simulation and VEA analysis. The right model fidelity is also important for creating the simulations. If a high-fidelity model is used, but not needed, then time, energy, and money would have been wasted. For instance, if a simulation is required to check wheelchair or walker accessibility, then a low-fidelity model is sufficient. But, if a simulation is required in a hazardous environment (i.e. factory floor with moving machines and/or vehicles), then a higher-fidelity model and VE is required for a much more detailed analysis.

Chapter 11: Future Direction

Future Direction

The work started with this research can move in several directions. The first, and most obvious, would be to apply the DHM, VE and VEA methods to real-world cases working in collaboration with organizations such as Michigan Rehabilitation Services (MRS), Paralyzed Veterans of America (PVA), the Veteran's Administration (VA), and others. Some efforts have started in that direction, such as HADRIAN and Osaka Gas's study, and more work should follow.

Working with the National SCI Database presents other avenues for research. The first would be building standardized catalogs that describe the movements and functional capabilities representing a complete transection of the spinal-cord at specific levels. The second would be using 3D full body laser scanning systems to collect very detailed anthropometric data that can be integrated with functional capabilities (FIM scores) for longitudinal studies. The third would be using a motion capture system to better quantify functional motion capabilities, and thereby provide additional data for individualized digital human models which could become part of an individual's medical record.

In order for the DHM, VE and VEA methods to become widely used the cost associated with the process must be decreased, and the perceived and actual value demonstrated. To give an idea of the cost of some of these systems, the following price data was collected:

- DHM and CAD software cost tens of thousands of dollars each (Hassan, 2010).

- Body scanners cost between $40,000 - $240,000 for hardware and software (Cyberware, 2007; Hassan, 2010)

- Environment scanners are roughly $100,000 - $200,000 for hardware and software (FLT Geosystems)

- Motion tracking equipment and related software is roughly $40,000 (Biosyn, 2010).

A variety of business models have been discussed with project collaborators, and while they need to be more carefully and fully developed, the most feasible option remains a centralized data processing (CDP) approach. For example, all the MRS offices in Michigan could be serviced by one data processing center. CDP staff could gather anthropometric and range-of-motion data, either as currently done with tape measures and goniometers, or some combination of tools that could include laser scanning and a motion tracking equipment.

DHM software task catalogs would need to be created that capture the “essential functions” of the most commonly found jobs. The collection of task catalogs would grow as new “essential functions” are realized. Just as Osaka Gas’s study found nine basic motions in a kitchen, workplace catalogs would need to be developed so that different workplace environments, i.e. factory or office, could quickly and easily be created. The relatively complex user interface for DHM software systems currently requires extensive training in use and capabilities. One of the ways for the DHM, VE, and VEA creation process to be financially feasible is a dramatically simpler user interface; this would be required for a general user population. Data would need to be collected regarding the costs and benefits associated with this service delivery process. Benefits would accrue for CDP clients as well as CDP staff, and these would need to be documented. Clearly, any real-world application would lead to a spectrum of research activities.

Lastly, there are social and legal areas for research. In particular, could the DHM, VEA methods be truly considered as part of a "reasonable accommodation" under the Americans with Disabilities Act? If the cost of DHM, VE and VEA could be reduced to something comparable with a full physical and psychological evaluation, then would the process be more feasible? How about if the real-world demonstrations showed that barriers to employment could be effectively recognized and eliminated… would clients and employers be willing to use the service? Lastly, if the following preconditions are met: (1) simulations of workplace accommodations and assistive technology showed that a client could in fact perform a specific job, (2) people with disabilities were employed, and (3) the process was verified by their work performance; then is there sufficient evidence to warrant DHM and VEA as a "reasonable accommodation?"

Chapter 12: Conclusion

Conclusion

The research and findings have shown that there is a lot that VEAs utilizing DHMs and VEs can do for people with physical disabilities. The need for the technology use is great - just ask one of the millions of people with physical disabilities that are looking for work and can use all the help they can get. The technology modification would greatly aid in the efficiency of the DHM creation process, and in turn, aid in job placement for people with disabilities.

The short-term goal of this research was to show that this technology can help those individuals that are seeking help in finding jobs that they can safely and successfully work at with their physical disabilities. The case studies prove that the software is usable in its current state, without modification. However, by updating the databases and implementing modifications, as discussed, the new format may precipitate even more investigations for helping those with disabilities.

The long term goal of this research is to demonstrate the commercial feasibility and cost-effectiveness of DHM, VE and VEA technologies to better serve people with physical disabilities. The research that was presented is only a stepping stone towards the long term goal. Given the opportunity and enough financial resources, a centralized data processing facility could be created to provide a platform to do this research with the technological resources which were mentioned herein.

Something that may aid in the advancement of the technology in this research may come from an unlikely source: the average movie-goer. The movie Avatar was mentioned in an earlier chapter for its use of DHM and motion capturing technology. It was discovered during research for this thesis that Avatar has generated over $2.7 billion in worldwide gross ticket sales (Nash Information Services LLC, 2010). Further research showed that 1,419,484,044 movie tickets were sold in the U.S. in 2009 for a gross of $10,646,130,248 ($7.50 per ticket average) (Nash Information Services LLC, 2009). This revelation is a boon for the technology in this research! The demand for more 3D movies like Avatar will only help in the advancement of the technology. This can be done by raising the public visibility of the technology, creating a broader consumer base for the technology, and increasing the number of professionals working in the related areas. Hopefully, these reasons will lead to lower cost for the equipment, and thereby increasing the likelihood for more innovation.

With the injured veterans from the Iraq and Afghanistan wars returning home and the baby boomer generation exceeding retirement age, there is an increase in: the disabled population, the elderly population, and in the need by both those populations for assistive technologies. With DHM software programs being utilized by more and more industries, including the medical device and assistive technology industries, it only reinforces the notion that DHM software use will increase dramatically over the next few years. The increase in use will, in turn, bring new modifications to the software, and hopefully the recommendations from this research will be implemented.

"A man's real limitations are not the things he wants to do and cannot; they are the things he ought to do but does not." – Author unknown.

Appendix A - Disability Information

Definition of a Disability

Americans with Disabilities Act (ADA) of 1990

The Americans with Disabilities Act (ADA) of 1990 (updated with amendments in 2008) defines a disability as (Americans with Disabilities Act, 1990, 2008):

"Sec. 12102. Definition of disability

As used in this chapter:

(1) Disability. The term 'disability' means, with respect to an individual

(A) a physical or mental impairment that substantially limits one or more major life activities of such individual;

(B) a record of such an impairment; or

(C) being regarded as having such an impairment (as described in paragraph (3)).

(2) Major Life Activities

(A) In general. For purposes of paragraph (1), major life activities include, but are not limited to, caring for oneself, performing manual tasks, seeing, hearing, eating, sleeping, walking, standing, lifting, bending, speaking, breathing, learning, reading, concentrating, thinking, communicating, and working.

(B) Major bodily functions. For purposes of paragraph (1), a major life activity also includes the operation of a major bodily function, including but not limited to, functions of the immune system, normal cell growth, digestive, bowel, bladder, neurological, brain, respiratory, circulatory, endocrine, and reproductive functions.

(3) Regarded as having such an impairment. For purposes of paragraph (1)(C):

(A) An individual meets the requirement of 'being regarded as having such an impairment' if the individual establishes that he or she has been subjected to an action prohibited under this chapter because of an actual or perceived physical or mental impairment whether or not the impairment limits or is perceived to limit a major life activity.

(B) Paragraph (1)(C) shall not apply to impairments that are transitory and minor. A transitory impairment is an impairment with an actual or expected duration of 6 months or less.

(4) Rules of construction regarding the definition of disability. The definition of 'disability' in paragraph (1) shall be construed in accordance with the following:

(A) The definition of disability in this chapter shall be construed in favor of broad coverage of individuals under this chapter, to the maximum extent permitted by the terms of this chapter.
(B) The term 'substantially limits' shall be interpreted consistently with the findings and purposes of the ADA Amendments Act of 2008.
(C) An impairment that substantially limits one major life activity need not limit other major life activities in order to be considered a disability.
(D) An impairment that is episodic or in remission is a disability if it would substantially limit a major life activity when active.
(E) (i) The determination of whether an impairment substantially limits a major life activity shall be made without regard to the ameliorative effects of mitigating measures such as

(I) medication, medical supplies, equipment, or appliances, low-vision devices (which do not include ordinary eyeglasses or contact lenses), prosthetics including limbs and devices, hearing aids and cochlear implants or other implantable hearing devices, mobility devices, or oxygen therapy equipment and supplies;
(II) use of assistive technology;
(III) reasonable accommodations or auxiliary aids or services; or
(IV) learned behavioral or adaptive neurological modifications.

(ii) The ameliorative effects of the mitigating measures of ordinary eyeglasses or contact lenses shall be considered in determining whether an impairment substantially limits a major life activity.
(iii) As used in this subparagraph

(I) the term 'ordinary eyeglasses or contact lenses' means lenses that are intended to fully correct visual acuity or eliminate refractive error; and
(II) the term 'low-vision devices' means devices that magnify, enhance, or otherwise augment a visual image."

United States Census Bureau

The language the U.S. Census Bureau uses in its version is as follows:

> "In the 1970s, the concept of a disability referred to an underlying physical or mental condition. A person with leg paralysis would have been considered disabled based solely on their physical condition. Today, disability is seen as a complex interaction between a person and his or her environment. The same person with leg paralysis may be considered disabled due to their physical impairment as well as the barriers in the environment that prevent full social participation." (U.S. Census Bureau, 2009b)

Disabled World

According to Disabled World, the definition of disability is as follows:

"A disability is a condition or function judged to be significantly impaired relative to the usual standard of an individual or group. The term is used to refer to individual functioning, including physical impairment, sensory impairment, cognitive impairment, intellectual impairment mental illness, and various types of chronic disease." (Disabled World, 2010b)

World Health Organization (WHO)

The World Health Organization (WHO) created an International Classification of Functioning, Disability, and Health (ICF), which provides a standard language and framework for the description of health and a health-related state (World Health Organization, 2010).

"These domains are classified from body, individual and societal perspectives by means of two lists: a list of body functions and structure, and a list of domains of activity and participation. Since an individual's functioning and disability occurs in a context, the ICF also includes a list of environmental factors" (World Health Organization, 2006, 2010).

Appendix B - People with Disabilities – U.S. Statistics

By the Numbers

Using or Needing Assistance

- **11 million**

  "Number of disabled people 6 and older who need personal assistance with everyday activities. These activities include such tasks as getting around inside the home, taking a bath or shower, preparing meals and performing light housework." (Disabled World, 2010c)

- **3.3 million**

  "Number of people 15 and older who use a wheelchair. Another 10 million use a walking aid, such as a cane, crutches or walker." (Disabled World, 2010c)

On the Job

- **13.3 million**

  "Number of 16- to 64-year-olds who reported difficulty finding a job or remaining employed because of a health condition." (Disabled World, 2010c)

- **46%**

  "Percentage of people 21 to 64 having some type of disability who were employed. The employment rate ranged from 75 percent of those with a nonsevere disability to 31 percent with a severe disability. For those without a disability, the employment rate is 84 percent for the same period." (Disabled World, 2010c)

- **48%**

  "Percentage of people 21 to 64 with a nonsevere disability who work full time. This compares with 63 percent without a disability and 16 percent with a severe disability." (Disabled World, 2010c)

- **21%**

  "Percentage of disabled workers 16 and older who worked in the educational services and health care and social assistance industries." (Disabled World, 2010c)

Income and Poverty

- **$2,250**

  "Median monthly earnings for people 21 to 64 with a nonsevere disability. This compares with $2,539 for those with no disability and $1,458 for those with a severe disability." (Disabled World, 2010c)

- **$2,252**

  "Median monthly earnings for people 21 to 64 with difficulty hearing. The corresponding figure for those with difficulty seeing was $1,932." (Disabled World, 2010c)

- **12%**

  "The poverty rate for people 25 to 64 with a nonsevere disability. This compares with 27 percent for those with a severe disability and 9 percent of those without a disability." (Disabled World, 2010c)

Appendix C - Anthropometric Data Sets

(a) Civilian

1975 Law Enforcement Officers

"The Law Enforcement Officers survey consists of body dimensions critical to the design and sizing of protective equipment. The survey was made on approximately 2,060 male law enforcement officers, including 521 officers from various Sheriff's Departments, 176 Highway Patrolmen, and 236 Prison Guards. The anthropometric data were collected in 17 regions throughout the United States. The data included in this report includes 21 anthropometric measurements and 2 background variables." (Defense Technical Information Center, 2010a)

1972 American Airline Stewardesses

"The 1972 American Airline Stewardesses survey was performed on 423 trainees enrolled at the American Airlines Stewardess Training Academy in Ft. Worth, Texas. The survey was initiated to provide adequate criteria for improving the emergency equipment availability and workspace design for the stewardess. A total of 73 body measurements, plus age, and 28 background variables was recorded for each trainee." (Defense Technical Information Center, 2010a)

1960-1962 The Health Examination Survey – Male

"The Health Examination Survey was sponsored by the Health Education and Welfare Department and as one of three programs of the National Health Survey developed to secure statistics on the health status of the population of the United States. Data were obtained through medical examinations, tests, and measurements on a scientifically selected random sample of the population. The anthropometric data were collected in the first cycle of the survey for the following purposes: 1) as reference standards to describe the physique of the adult population of the nation at a point in time; 2) to provide anthropometric data essential to the designing of equipment for human use; and 3) to provide data that can be used in the study of various physiological functions and human health problems. A total of 3,091 males were measured for this survey. Each subject has a complete set of data that includes 16 body measurements and 5 background variables." (Defense Technical Information Center, 2010a)

1960-1962 The Health Examination Survey – Female

"The Health Examination Survey was sponsored by the Health Education and Welfare Department and was one of three programs of the National Health Survey developed to secure statistics on the health status of the population of the United States. Data were obtained through medical examinations, tests, and measurements on a scientifically selected random sample of the population. The anthropometric data were collected in the first cycle of the survey for the following purposes: 1) as reference standards to describe the physique of the adult population of the nation at a point in time; 2) to provide anthropometric data essential to the designing of equipment for human use; and 3) to provide data that can be used in the study of various physiological functions and human health problems. A total of 3,581 females were measured for this survey. Each subject has a complete set of data that includes 16 body measurements and 5 background variables." (Defense Technical Information Center, 2010a)

1961 Air Traffic Controllers

"The Air Traffic Controllers survey was conducted in 1960 and 1961 on 684 male students enrolled in training programs conducted at the Federal Aviation Agency Aeronautics Center in Oklahoma City. Sixty-three body measurements were collected on most of the subjects." (Defense Technical Information Center, 2010a)

(b) U.S. Military

Army

1988 Anthropometric Survey of the U.S. Army Female Working Data Set

"The 1988 Anthropometric Survey of the U.S. Army was conducted from August 1987 through July 1988 at 11 U.S. Army posts throughout the continental U.S. The survey contains anthropometric, biographical, and headboard data for each of its subjects. The data reported is a subset of all individuals measured. The subset was created in such a way that the age/race profile of the sample is the same as the age/race profile of the U.S. Army as of June 1988. This survey consists of two raw ASCII data files which contain a total of 132 measurements for 2,208 female." (Defense Technical Information Center, 2010c)

1988 Anthropometric Survey of the U.S. Army Male Working Data Set

"The 1988 Anthropometric Survey of the U.S. Army was conducted from August 1987 through July 1988 at 11 U.S. Army posts throughout the continental U.S. The survey contains anthropometric, biographical, and headboard data for each of its subjects. The data reported is a subset of all individuals measured. The subset was created in such a way that the age/race profile of the sample is the same as the age/race profile of the U.S. Army as of June 1988. This survey consists of two raw ASCII data files which contain a total of 132 measurements for 1,774 males." (Defense Technical Information Center, 2010c)

1970 U.S. Army Aviators

"The 1970 U.S. Army Aviators survey was conducted at Ft. Rucker, Alabama, on 1,477 subjects (388 enlisted men, 259 warrant officers, 410 rated pilots [warrant], 186 commissioned trainees, and 234 rated pilots [commissioned]). All subjects that are included in the survey have a complete set of data that includes 85 body measurements and 8 background variables." (Defense Technical Information Center, 2010c)

1959 Survey of U.S. Army Aviators

"The 1959 Anthropometric Survey of Army Aviators was conducted at three U.S. Army bases on a sample of 500 rated U.S. Army Aviators. A total of 55 measurements was recorded for each subject. This included 45 body measurements and 9 background variables plus age." (Defense Technical Information Center, 2010c)

1946 Survey of U.S. Army Female Separatees

"The Survey of Army Female Separatees was conducted at the end of World War II at the separation center on 3,164 nurses, 4,445 enlisted WACs, and 484 WAC commissioned officers. A total of 64 body measurements, plus age, and 14 background variables was collected." (Defense Technical Information Center, 2010c)

Navy/Marine

1966 Survey of U.S. Marine Corps Personnel

"The Survey of Marine Personnel was conducted in late 1965 and early 1966 on men of the Navy and Army. A total of 72 body measurements and 16 background variables was collected for this survey. No comprehensive report of this survey has been published." (Defense Technical Information Center, 2010c)

1966 Survey of U.S. Navy Personnel

"The Survey of Navy Personnel was conducted in late 1965 and early 1966 along with surveys on men of the Marines and Army. A total of 4,095 men was measured for this survey. Seventy body measurements, plus age, and seventeen background variables were collected." (Defense Technical Information Center, 2010c)

Air Force

1990 U.S. Air Force Male Flyers

"The 1990 Air Force Male Flyers is a small anthropometric survey that was conducted between 1989 and 1990. The sampling strategy was to survey TAC, SAC, MAC, and ATC personnel. The primary reason for this survey was a statistical comparison and "matching procedure" to create a flyer database. There were 353 subjects measured and 33 measurements taken (25 body measurements and 8 background variables). A few enlisted males and females were measured in an effort to increase the sampling of women and minorities for the matching study; however, for this data set only the male rated officers are used. This reduced the number of subjects to 326. The limited number of measurements taken in this survey is intended to give only a "quick look" at the body size of flyers. ” (Defense Technical Information Center, 2010c)

1968 Survey of U.S. Air Force Women

“The 1968 Survey of Air Force Women contains data for 1,905 subjects and includes 123 body measurements, and 17 background variables, plus age and grip strength.” (Defense Technical Information Center, 2010c)

1967 Survey of U.S. Flying Personnel – Male

“The 1967 Survey of Air Force Flying Personnel was conducted at almost 20 bases throughout the United States. A total of 186 body dimensions, plus age and grip strength, and 13 background variables was recorded for each of the 2,420 subjects.” (Defense Technical Information Center, 2010c)

1965 U.S. Air Force Male Personnel

“The 1965 survey of U.S. Air Force Personnel survey was performed on male recruits, enlisted personnel and officers. In the first portion of the survey, 549 officers (396 pilots and navigator; 153 nonflyers), 4 warrant officers and 683 enlisted men were measured. In the second half, 2,632 men undergoing basic training and one sergeant were measured at Lackland Air Force Base, Texas. A total of 158 body measurements plus, and 17 background variables was recorded for each of the 3,869 subjects.” (Defense Technical Information Center, 2010c)

1950 Survey of U.S. Air Force Flying Personnel

“The U.S. Air Force Survey of Flying Personnel, conducted in the spring and summer of 1950, was the U.S. Air Force’s first major anthropometric survey. The survey was carried out at 14 Air Force bases in Massachusetts, Michigan, Colorado, Washington, California, Texas, and Louisiana. A total of 132 body measurements, plus age, and 15 background variables was collected on 4,063 subjects.” (Defense Technical Information Center, 2010c)

(C) Other Military

1976 Anthropometric Survey of Royal Transport Corpsmen

This Royal Transport Corpsmen Survey consists of a sample of 161 personnel that were measured as part of a series of surveys of U.K. Army Anthropometry by the British Research Establishment's Applied Physiology Division. A total of

60 dimensions, plus age, and 7 background variables was recorded for each subject." (Defense Technical Information Center, 2010b)

1975 Survey of English Guardsmen

"This Anthropometric Survey of English Guardsmen consists of a sample of 100 guardsmen that were measured as part of a series of surveys of U.K. Army Anthropometry by the British Research Establishment's Applied Physiology Division. A total of 60 dimensions, plus age, and 7 background variables was recorded for each subject." (Defense Technical Information Center, 2010b)

1974 Canadian Forces Survey

"The Canadian Forces Survey was conducted in 1974 on 565 personnel representing all major trade fields. All subjects have a complete set of data that includes 32 body measurements and 7 background information variables." (Defense Technical Information Center, 2010b)

1972-1975 British Army

"The 1972-1975 British Army survey is a combination of three subsamples of the United Kingdom Army. The survey was conducted on a total of 1,537 service members (The Royal Artillery [503], The Royal Infantry [534], and The Royal Armored Corps [500]). This was part of a series of surveys of U.K. Army anthropometry conducted by the British Research Establishment's Applied Physiology Division. A total of 60 body measurements and 9 background variables were recorded for each subject." (Defense Technical Information Center, 2010b)

1972 Survey of 500 Royal Air Force Aircrew Heads

"The Royal Air Force Head Survey was conducted in 1972 on 500 service members to obtain detailed information on head dimensions. Sixty-two head dimensions were recorded." (Defense Technical Information Center, 2010b)

1971 Survey of Royal Air Force Crewmen

"The 1971 Survey of Royal Air Force Crewmen was performed to provide current information on body measurements. The information was required for cockpit workspace and functional clothing sizing studies. The original data included 71 body measurements, plus age for a total of 2,000 subjects (1,028 pilots, 613 navigators, and 359 other flight deck aircrew.)" (Defense Technical Information Center, 2010b)

1971 Royal Australian Air Force

"The Royal Australian Air Force survey was conducted on 462 Australian Air Force crewmen in 1971 to provide baseline anthropometric data on the RAAF aircrew. In addition, these data were used to determine whether significant anthropometric differences existed between different categories of aircrew within the RAAF and also between the RAAF and the Royal Air Force and the United States Air Force. Each subject has a complete set of data that includes 18 body measurements plus age and 3 background variables." (Defense Technical Information Center, 2010b)

1969 Imperial Iranian Armed Forces

"The Imperial Iranian Armed Forces survey was taken between November 1968 and March 1969 on 9,414 service members. The breakdown between the Military branches consisted of 7,884 Army, 790 Air Force, and 740 Navy men. A total of 68 body measurements and 29 background variables was collected for this survey." (Defense Technical Information Center, 2010b)

1968 German Air Force

"This German Air Force survey was conducted in 1967 and 1968 on 1,465 flying personnel. The first 1,004 subjects were measured during 1967 and the remainder during 1968. This survey contains 153 body measurements." (Defense Technical Information Center, 2010b)

1963 Vietnam Military

"The survey of Vietnam Military was taken during June 1963 on 2,129 service members. The sample consisted of 1,225 Army personnel, 299 Navy personnel, 301 Marine personnel, and 304 Air Force personnel. A total of 51 body dimensions, plus age, and 8 background variables was recorded for each subject." (Defense Technical Information Center, 2010b)

1960-1961 NATO Anthropometric Survey

"The NATO Anthropometric Survey was conducted in 1960 and 1961 to gather data on the body dimensions of 3,325 Turkish, Greek, and Italian Military personnel. The data were used to assure the correct sizing of protective equipment, clothing, and workspaces. The survey includes data for 912 Turks, 1,071 Greeks, and 1,342 Italians. All subjects have a complete set of data, including 150 body measurements and 3 background variables." (Defense Technical Information Center, 2010b)

1959 Survey of Latin American Military

"The Survey of Latin American Military was conducted on 1,985 enlisted Military trainee personnel in the Canal Zone from September 1965 to February 1970. The sample consists of 1,852 airmen at the U.S. Air Force Inter-American Air Forces Academy and 133 Army personnel at the Army school of the America. Fifteen Latin-American countries are represented in the sample. A total of 76 body measurements and 20 background variables was collected for this survey." (Defense Technical Information Center, 2010b)

Appendix D - Spinal Cord Injury Database

Etiology of Spinal Cord Injury by Sex

Rank	Etiology	Males n (%)	Females n (%)	Total n (%)
1	Auto accident	6,546 (30.2)	2,571 (50.0)	9,117 (34.0)
2	Fall	4,510 (20.8)	1,028 (20.0)	5,538 (20.6)
3	Gunshot wound	3,747 (17.3)	522 (10.1)	4,269 (15.9)
4	Diving	1,563 (7.2)	135 (2.6)	1,698 (6.3)
5	Motorcycle accident	1,493 (6.9)	100 (1.9)	1,593 (5.9)
6	Hit by falling/flying object	759 (3.5)	32 (0.6)	791 (2.9)
7	Medical/surgical complication	411 (1.9)	236 (4.6)	647 (2.4)
8	Pedestrian	325 (1.5)	116 (2.3)	441 (1.6)
9	Bicycle	312 (1.4)	35 (0.7)	347 (1.3)
10	Person-to-person contact	204 (0.9)	59 (1.1)	263 (1.0)
11	Other unclassified	225 (1.0)	21 (0.4)	246 (0.9)
12	All other penetrating wounds	188 (0.9)	50 (1.0)	238 (0.9)
13	Other vehicular	154 (0.7)	15 (0.3)	169 (0.6)
14	All-terrain vehicle (ATV) and all-terrain cycle (ATC)	133 (0.6)	20 (0.4)	153 (0.6)
15	Football	136 (0.6)	0 (<0.1)	136 (0.5)
16	Snow skiing	118 (0.5)	14 (0.3)	132 (0.5)
17	Horseback riding	61 (0.3)	64 (1.2)	125 (0.5)
18	Winter sports	98 (0.5)	26 (0.5)	124 (0.5)
19	Other sport	85 (0.4)	18 (0.3)	103 (0.4)
20	Surfing: includes body surfing	101 (0.5)	2 (<0.1)	103 (0.4)
21	Fixed-wing aircraft	65 (0.3)	28 (0.5)	93 (0.3)
22	Wrestling	82 (0.4)	2 (<0.1)	84 (0.3)
23	Trampoline	53 (0.2)	8 (0.2)	61 (0.2)
24	Gymnastics	31 (0.1)	18 (0.3)	49 (0.2)
25	Snowmobile	37 (0.2)	5 (0.1)	42 (0.2)
26	Field sports	37 (0.2)	1 (<0.1)	38 (0.1)
27	Hang gliding	31 (0.1)	2 (<0.1)	33 (0.1)
28	Rotating wing aircraft	29 (0.1)	2 (<0.1)	31 (0.1)
29	Water skiing	29 (0.1)	1 (<0.1)	30 (0.1)
30	Boat	19 (0.1)	8 (0.2)	27 (0.1)
31	Air sports	23 (0.1)	0 (<0.1)	23 (0.1)
32	Rodeo	21 (0.1)	0 (<0.1)	21 (0.1)
33	Baseball/softball	19 (0.1)	0 (<0.1)	19 (0.1)
34	Explosion	13 (0.1)	1 (<0.1)	14 (0.1)
35	Basketball/volleyball	11 (0.1)	0 (<0.1)	11 (<0.1)
36	Track and field	6 (<0.1)	0 (<0.1)	6 (<0.1)
37	Skateboard	5 (<0.1)	0 (<0.1)	5 (<0.1)
	Total	21,680	5,140	26,820

Table 2: Etiology of SCI from the National SCI Database (National Spinal Cord Injury Statistical Center, 2009).

Cumulative Survival - National

Years Post Injury	(1) Patients Entered	(2) Withdrawn Alive	(3) Lost	(4) Dead	(5) Effective Number Exposed	(6) Proportion Dead	(7) Proportion Surviving	(8) Cumulative Survival at End of Interval
0 - 1	41,661	1,656	4,544	1,742	38,561.0	0.0452	0.9548	0.9548
1 - 2	33,719	1,119	1,191	712	32,564.0	0.0219	0.9781	0.9339
2 - 3	30,697	356	412	491	30,313.0	0.0162	0.9838	0.9188
3 - 4	29,438	329	311	473	29,118.0	0.0162	0.9838	0.9039
4 - 5	28,325	556	420	425	27,837.0	0.0153	0.9847	0.8901
5 - 6	26,924	777	731	369	26,170.0	0.0141	0.9859	0.8775
6 - 7	25,047	675	290	403	24,564.5	0.0164	0.9836	0.8631
7 - 8	23,679	506	213	392	23,319.5	0.0168	0.9832	0.8486
8 - 9	22,568	427	145	344	22,282.0	0.0154	0.9846	0.8355
9 - 10	21,652	679	218	297	21,203.5	0.0140	0.9860	0.8238
10 - 11	20,458	776	330	322	19,905.0	0.0162	0.9838	0.8105
11 - 12	19,030	798	145	265	18,558.5	0.0143	0.9857	0.7989
12 - 13	17,822	712	92	297	17,420.0	0.0170	0.9830	0.7853
13 - 14	16,721	675	54	263	16,356.5	0.0161	0.9839	0.7727
14 - 15	15,729	781	97	268	15,290.0	0.0175	0.9825	0.7591
15 - 16	14,583	798	141	227	14,113.5	0.0161	0.9839	0.7469
16 - 17	13,417	724	21	242	13,044.5	0.0186	0.9814	0.7331
17 - 18	12,430	707	8	225	12,072.5	0.0186	0.9814	0.7194
18 - 19	11,490	657	5	222	11,159.0	0.0199	0.9801	0.7051
19 - 20	10,606	619	60	200	10,266.5	0.0195	0.9805	0.6914
20 - 21	9,727	584	60	176	9,405.0	0.0187	0.9813	0.6784
21 - 22	8,907	610	21	177	8,591.5	0.0206	0.9794	0.6644
22 - 23	8,099	524	38	198	7,818.0	0.0253	0.9747	0.6476
23 - 24	7,339	535	11	173	7,066.0	0.0245	0.9755	0.6318
24 - 25	6,620	622	35	140	6,291.5	0.0223	0.9777	0.6177
25 - 26	5,823	679	113	149	5,427.0	0.0275	0.9725	0.6007
26 - 27	4,882	497	49	120	4,609.0	0.0260	0.9740	0.5851
27 - 28	4,216	424	25	112	3,991.5	0.0281	0.9719	0.5687
28 - 29	3,655	632	8	97	3,335.0	0.0291	0.9709	0.5521
29 - 30	2,918	505	58	80	2,636.5	0.0303	0.9697	0.5354
30 - 31	2,275	489	46	59	2,007.5	0.0294	0.9706	0.5197
31 - 32	1,681	464	12	41	1,443.0	0.0284	0.9716	0.5049
32 - 33	1,164	369	3	29	978.0	0.0297	0.9703	0.4899
33 - 34	763	299	1	26	613.0	0.0424	0.9576	0.4691
34 - 35	437	233	0	15	320.5	0.0468	0.9532	0.4472
35 - 36	189	186	0	3	96.0	0.0312	0.9688	0.4332
Total	41,661	21,979	9,908	9,774				

(1) Number of individuals alive at start of interval.
(2) Number of individuals alive at start of interval ineligible for further follow-up due to study termination.
(3) Number of individuals lost to follow-up (survival status was unknown) during the interval.
(4) Number of individuals dying during the interval.
(5) Number of individuals exposed to risk of dying in interval [patients entered - 0.5 * (withdrawn alive + lost)].
(6) Conditional probability of death during the interval (dead / effective number exposed).
(7) Conditional probability of surviving the interval (1 - proportion dead).
(8) Cumulative survival rate (previous cumulative survival * proportion surviving present interval).

Table 3: Cumulative survival of individuals entered in the National SCI Database (National Spinal Cord Injury Statistical Center, 2009).

Life Expectancy 24 Hours Post Injury

Age At Injury	Life Expectancy (Years)					
		Not Ventilator Dependent				Ventilator Dependent
	No SCI	Motor Functional Any Level	Paraplegia	Tetraplegia C5-C8	Tetraplegia C1-C4	Any Level
10 years	68.5	61.9	54.0	48.5	43.9	25.2
15 years	63.6	57.0	49.1	43.8	39.2	21.0
20 years	58.8	52.3	44.6	39.4	35.1	18.1
25 years	54.0	47.7	40.3	35.3	31.2	15.9
30 years	49.3	43.0	35.9	31.1	27.2	13.3
35 years	44.5	38.4	31.5	26.9	23.2	10.5
40 years	39.9	33.9	27.2	22.9	19.4	8.0
45 years	35.3	29.5	23.1	19.1	15.9	5.9
50 years	30.9	25.3	19.3	15.7	12.8	4.2
55 years	26.6	21.3	15.8	12.5	10.0	2.9
60 years	22.5	17.5	12.6	9.6	7.5	1.8
65 years	18.7	14.1	9.7	7.2	5.4	1.0
70 years	15.1	11.0	7.2	5.1	3.7	0.3
75 years	11.9	8.3	5.1	3.5	2.3	<0.1
80 years	9.1	5.9	3.4	2.1	1.3	<0.1

Table 4: Life expectancy for SCI persons surviving at least 24 hours post injury (National Spinal Cord Injury Statistical Center, 2009).

Life Expectancy One Year Post Injury

Current Age	Life Expectancy (Years)					
		Not Ventilator Dependent				Ventilator Dependent
	No SCI	Motor Functional Any Level	Paraplegia	Tetraplegia C5-C8	Tetraplegia C1-C4	Any Level
10 years	68.5	62.3	54.6	49.5	45.5	32.8
15 years	63.6	57.4	49.8	44.7	40.8	28.3
20 years	58.8	52.7	45.3	40.3	36.6	24.9
25 years	54.0	48.1	40.9	36.2	32.6	21.8
30 years	49.3	43.4	36.4	31.9	28.6	18.6
35 years	44.5	38.8	32.0	27.7	24.5	15.2
40 years	39.9	34.2	27.7	23.6	20.6	12.1
45 years	35.3	29.9	23.6	19.8	17.0	9.4
50 years	30.9	25.7	19.8	16.3	13.8	7.1
55 years	26.6	21.6	16.2	13.1	10.8	5.2
60 years	22.5	17.8	12.9	10.1	8.2	3.6
65 years	18.7	14.4	10.0	7.6	6.0	2.3
70 years	15.1	11.2	7.5	5.5	4.2	1.3
75 years	11.9	8.5	5.3	3.7	2.7	0.6
80 years	9.1	6.1	3.5	2.3	1.6	<0.1

Table 5: Life expectancy for SCI persons surviving at least 1 year post injury (National Spinal Cord Injury Statistical Center, 2009).

Age At Injury: Frequency Distribution

Age	N	Percent	Cumulative Percent
<1	3	0.01	0.01
1	12	0.04	0.06
2	9	0.03	0.09
3	17	0.06	0.15
4	21	0.08	0.23
5	14	0.05	0.28
6	20	0.07	0.36
7	16	0.06	0.42
8	18	0.07	0.48
9	20	0.07	0.56
10	30	0.11	0.67
11	15	0.06	0.73
12	35	0.13	0.86
13	101	0.38	1.23
14	206	0.77	2.00
15	380	1.42	3.42
16	741	2.76	6.17
17	1040	3.87	10.05
18	1224	4.56	14.61
19	1264	4.71	19.31
20	1122	4.18	23.49
21	1107	4.12	27.62
22	1035	3.85	31.47
23	961	3.58	35.05
24	907	3.38	38.43
25	834	3.11	41.53
26	764	2.85	44.38
27	713	2.66	47.03
28	677	2.52	49.55
29	672	2.50	52.06
30	598	2.23	54.28
31	583	2.17	56.46
32	579	2.16	58.61
33	472	1.76	60.37
34	413	1.54	61.91
35	476	1.77	63.68
36	452	1.68	65.36
37	422	1.57	66.94
38	435	1.62	68.56
39	377	1.40	69.96
40	370	1.38	71.34
41	373	1.39	72.73
42	337	1.26	73.98
43	345	1.28	75.27
44	339	1.26	76.53
45	337	1.26	77.78
46	293	1.09	78.88
47	304	1.13	80.01
48	316	1.18	81.19
49	285	1.06	82.25
50	262	0.98	83.22
51	231	0.86	84.08
52	250	0.93	85.01
53	237	0.88	85.90
54	231	0.86	86.76
55	217	0.81	87.56
56	227	0.85	88.41
57	220	0.82	89.23
58	204	0.76	89.99
59	181	0.67	90.66
60	187	0.70	91.36
61	191	0.71	92.07
62	159	0.59	92.66
63	145	0.54	93.20
64	141	0.53	93.73
65	126	0.47	94.20
66	140	0.52	94.72
67	141	0.53	95.24
68	120	0.45	95.69
69	105	0.39	96.08
70	85	0.32	96.40
71	97	0.36	96.76
72	78	0.29	97.05
73	91	0.34	97.39
74	76	0.28	97.67
75	84	0.31	97.99
76	74	0.28	98.26
77	77	0.29	98.55
78	54	0.20	98.75
79	57	0.21	98.96
80	45	0.17	99.13
81	39	0.15	99.27
82	35	0.13	99.40
83	33	0.12	99.53
84	23	0.09	99.61
85	23	0.09	99.70
86	23	0.09	99.78
87	14	0.05	99.84
88	14	0.05	99.89
89	10	0.04	99.93
90	7	0.03	99.95
91	4	0.01	99.97
92	4	0.01	99.98
94	2	0.01	99.99
95	1	<0.01	99.99
97	1	<0.01	100.00
98	1	<0.01	100.00

Table 6: Age at injury in a frequency distribution (National Spinal Cord Injury Statistical Center, 2009).

Appendix E - Software & Hardware List

Company	Program	Website
	CAD Software	
Dassault Sytemes	Catia	http://www.3ds.com/products/delmia
Siemens	Unigraphics	http://www.plm.automation.siemens.com/en_us/products/nx/
PTC	Pro-Engineer	http://www.ptc.com/products/proengineer/manikin-extension
	DHM Only Software	
Dassault Sytemes	Delmia	http://www.3ds.com/products/delmia
Siemens	Tecnomatix (formerly JACK)	http://www.plm.automation.siemens.com/en_us/products/tecnomatix/
Human Solutions	RAMSIS	http://www.human-solutions.com/
SantosHuman Inc.	SantosHuman	www.santoshumaninc.com
HADRIAN & SAMMIE	HADRIAN & SAMMIE	http://www.lboro.ac.uk/departments/lds/research/groups/design-ergonomics/key-interests/hadrian.html
	Motion Tracking	
BIOSYN SYS-TEMS INC.	Functional Assessment of Biomechanics (the FAB system)	http://www.biosynsystems.com/
Ascension Technology	Flock of Birds (FOB)	http://www.ascension-tech.com/realtime/RTflockofBIRDS.php
	3D Body Scanners	
Human Solutions	Vitus Smart XXL	http://www.human-solutions.com/
TC^2	NX-16	http://www.tc2.com/index_3dbodyscan.html
Cyberware	WBX	http://www.cyberware.com/products/scanners/wbx.html
TELMAT Industrie	Symcad ST	http://www.symcad.com/eng/products_001.htm
Creaform	MegaCapturor	http://www.creaform3d.com/en/3d-body-digitizer/mega-capturor.aspx
	Environment Scanners	

Leica Geosystems	3D Scanning	http://www.leica-geosystems.com
Zoller+Fröhlich GmbH	3D Scanning	http://www.zf-laser.com/

Table 7: Software & hardware comparison. (Hamameh, 2010)

Appendix F - Advantages & Benefits of DHM Software

- **Optimized Manufacturing Productivity**
  - "Reuse certified processes and reduce capital equipment costs by capturing and managing within a single source of manufacturing knowledge." (Siemens, 2010a)
  - "Detect and eliminate problems within production systems that would otherwise require time-consuming and cost-intensive corrective measures during production ramp-up." (Siemens, 2010a)
  - "Reduce assembly planning tasks, planning time and their associated costs." (Siemens, 2010a)
  - "Sharing and analyzing information within a digital environment provides insight into the various stages of process development and the impacts of those processes." (Siemens, 2010a)
  - "Streamline communications so you can adapt to customer demands quicker, with decisions based on facts." (Siemens, 2010a)
- **Increased Plant Productivity**
  - "Program information is available at all levels of the enterprise – from executive to plant floor personnel." (Siemens, 2010a)

- "Achieve smaller launch windows, increased plant capacity and material cost control through comprehensive visibility into quality issues." (Siemens, 2010a)
- "Reduce capital investment costs via commonization and reuse." (Siemens, 2010a)

- **Single Source for Alignment and Accountability**
  - "Assembly and manufacturability validation provides accelerated feedback to design and process teams." (Siemens, 2010a)
  - "BOM/BOP configuration and management reduces planning errors by ensuring all components of a product are accounted for and aligned." (Siemens, 2010a)
  - "In-context collaboration and communication operate globally within the supply chain networks by coordinating workflow processes ensuring timing is maintained." (Siemens, 2010a)
  - "In-context collaboration and communication of workflow processes ensures that timing is extended throughout the global supply chain." (Siemens, 2010a)

- **Optimize Performance & Leverage "Best Practice" Processes**
  - "Reduce process development time up to 40% by identifying and applying best-in-class processes with master process and operation templates." (Siemens, 2010a)
  - "Achieve 20-to-80% reuse of certified manufacturing processes within the first year." (Siemens, 2010a)
  - "Significantly reduce and even eliminate production disruptions caused by manufacturing shop floor issues, by balancing processes for optimum value added content." (Siemens, 2010a)
  - "Optimized manufacturing lines through virtual commissioning to reduce time-to-volume by up to 80%" (Siemens, 2010a)
- **Managed Environment for Safety and Ergonomics**
  - "Reduce corporate liabilities and expenses for worker related injuries." (Siemens, 2010a)
  - "Eliminate hazardous work environments by integrating ergonomic simulation and validation into the development process." (Siemens, 2010a)

- **3D Factory Design and Visualization**
  - "Reduce factory design time, from concept through installation, by up to 50% when compared to traditional 2D design methods." (Siemens, 2010a)
  - "Reduce tooling and equipment changes 15% by discovering design flaws and issues early in the creation phase, as opposed to later in the installation phase." (Siemens, 2010a)
- **Factory Logistics Analysis and Optimization**
  - "Reduce material handling costs up to 70% by analyzing cost, time, and travel distances across multiple factory layouts." (Siemens, 2010a)
  - "Optimize space utilization at both the plant and transportation truck level by analyzing and evaluating material requirements, container sizes, container stacking criteria as well as ingress/egress guidelines." (Siemens, 2010a)
- **Factory Production Throughput Simulation**
  - "Reduce throughput time as much as 20-60% by taking into consideration internal and external supply chains, production resources, and business processes." (Siemens, 2010a)

- “Increase productivity for existing systems 15-20% with easy to interpret statistical analysis.” (Siemens, 2010a)
- “Decrease new system costs 5-20% by detecting and eliminating problems before having installed the real system.” (Siemens, 2010a)
- “Reduce inventories 20-60% by evaluating different line control strategies as well as verifying synchronization of lines and sub-lines.” (Siemens, 2010a)

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ABSTRACT

DIGITAL HUMAN MODELS OF PERSONS WITH DISABILITIES

by

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The current state-of-the-art in Digital Human Modeling (DHM) allows for full simulation and analysis of any task a person is required to perform at home, at work, in the military, in space, in sports, etc. These analyses help identify tasks that may lead to bodily injury, or can help identify efficiency concerns. The problem is that the software is missing a very important population: people with physical disabilities. What modifications and enhancements must be made to existing, commercially available DHM software to include this population?

AUTOBIOGRAPHICAL STATEMENT

The author is a graduate of Wayne State University with a Bachelor of Science in Mechanical Engineering (BSME) in 2005, and earned his Master of Science in Biomedical Engineering in 2010. He began his career in the automotive industry in 1992, and spent the next 16 years learning the many different sides of the industry.

When he first began he was on the automation side of the industry working on drawings of assembly automation where he was using 2D CAD, but in 1993 he switched to 3D CAD. He reached senior-level designer status after several years before switching to the product side of the industry where he began designing automotive components. He continued using 3D CAD throughout his career, and after receiving his BSME he held the position of CAD Engineer. The CAD Engineer position was multiple positions conjoined: designer and engineer.

The last few years of his automotive career were spent in Advanced Vehicle Engineering and Hybrid technology positions. As his experience grew so did his responsibilities, hence more positions were added under the title of CAD Engineer: senior level designer, product engineer, release engineer, systems engineer, and project management. The recent economic instability provided an incentive for him to pursue a Master of Science in Biomedical Engineering. His area of research built on his extensive 3D CAD design experience and seeks to bring the benefits of digital human modeling and virtual ergonomic analyses to better serve people with disabilities.