CHAPTER 41

Ergonomics in Digital Environments

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1. INTRODUCTION

The design of workplaces and products continues to migrate from paper to the computer, where analysis accuracy, visualization, and collaboration utilities allow designs to be realized much faster and better than ever before. As the pace of this development accelerates with the increased capabilities of the software design tools, less time is spent on physical prototyping, allowing for shortened time-to-market for new products. Ergonomists, who in the past used the physical prototypes to perform human factors analyses, are now challenged to move the analysis into the virtual domain using new tools and methods. Usability, maintainability, physical ergonomic assessments, psychological perception, and procedural training are some of the human factors issues that might benefit from analysis prior to the first physical incarnation of the design. While this represents a challenge for the ergonomists, it provides an opportunity to effect change in the designs much earlier than was typically possible in the past and to take advantage of the dramatically reduced cost of design alterations in the early design phases. Commercial pressures that leverage the cost benefits offered by complete ‘‘in-tube’’ design are driving a rapid development of the available computer technologies. Human simulation technology is no exception. Contemporary human modeling software is assimilating a variety of human modeling knowledge, including population anthropometry descriptions and physical capability models. Companies are deploying these human modeling products to allow their ergonomists and designers to populate digital representations of products and workplaces efficiently with virtual human figures and ask meaningful questions regarding the likely performance of actual people in those environments. Identification of ergonomic design problems early in the design phase allows time-consuming and expensive reworking of the manufacturing process or design to be avoided.

Computerized human modeling itself has been evolving over some time. Perhaps the first attempt to develop a computer-integrated tool for performing reach tasks was performed by Vetter and Ryan for the Boeing Aircraft company in the late 1960s. This effort was referred to as the ‘‘First Man’’ program, which later became ‘‘Boeman.’’ This software was later expanded by the USAF Aerospace Medical Research Laboratory Crew Systems’ Interface Division, which added the ability to simulate a variety of male and female anthropometric dimensions while seated in different types of aircraft, culminating in the software COMBIMAN. In the 1980s, this software was further developed at AMRL to address maintenance tasks, adding performance models of lifting, pulling, and pushing on various tools and objects placed in the hands, and became CrewChief. During this same time in Europe, a wide variety of models were developed, perhaps the most widely known being SAMMIE (System for Aiding Man–Machine Interaction Evaluation), developed by Case, Porter, and Bonney at Nottingham and Loughborough Universities in the United Kingdom. SAMMIE was conceived as a very general model for assessing reach, interference, and sight-line issues within a CAD environment. The details of these developments are described in greater depth elsewhere (e.g., Chaffin 2000; Bubb 1999; Badler 1993). Perhaps as a testament to the rapid development in this field, new human models that are integrated in modern CAD, 3D visualization, and automation simulation products are now the most popular and seeing the most rapid development and deployment. These include Deneb Ergo, EAI Jack, Genicom Safeworks, TecMath Ramsis, and Tecnomatix RobCAD Man.

This chapter reviews the foundation of contemporary human modeling technology for physical ergonomics and presents examples of how digital humans are currently used in industry. The chapter concludes with a discussion of the current development efforts in the area of human modeling.

2. DIGITAL HUMAN FIGURES

2.1. Kinematic Representation

Human models are varied in both their complexity and construction. Any mathematical representation of human structure, physiology, or behavior can be considered to be a human model. For example, complex models of human musculoskeletal dynamics are commonly used to study motor control issues (Winters and Woo 1990). These models are typically quite detailed to allow the dynamic effects of individual muscle activation and contraction, and hypothesized neural control strategies, to be investigated. Moreover, this detail is typically focused on one part of the body, for example the lower extremity for gait analysis, or the upper limbs for investigation of movement control. In contrast, simple, sometimes incomplete, human forms are used in the investigation of cognitive models, wherein the human form acts as an agent to effect changes in its world. The pedagogical agent developed at the University of Southern California Information Sciences Institute (Johnson et al. 2000) is an example. These models focus on the cognitive rather than motor processes and simulate the interactions among multiple humans.

For physical ergonomics investigations in digital environments, the human models need to mirror our structure, shape, and size in sufficient detail to allow the figures to assume realistically the observed postures of actual individuals performing similar tasks. Such models typically consist of an underlying kinematic linkage system that closely parallels our own skeletal structure and an attached geometric shell that duplicates our surface shape.

Today's human models have kinematic linkages that include from 30 to 148 degrees of freedom, depending on the detail provided in the hands, feet, shoulder, and spine. The joints are constructed to move like our own joints, with the appropriate number of degrees of freedom, and typically also have physiological limits on the range of motion. In more detailed models, the shoulder and spine are modeled to behave naturally, with the links moving in concert as the particular segment is manipulated. For example, the shoulder complex consisting of the sternoclavicular, acromioclavicular, and glenohumeral joints is modeled to move in a realistic pattern when the upper arm is adjusted, moving the elevation and fore–aft position of the shoulder as the arm moves through its range of motion.

2.2. Anthropometry

The internal skeletal structure and surface topography of a digital human figure influence both the qualitative and quantitative use of the figures. As an engineering tool, the accuracy of the internal link structure affects the dimensional measures made between the environment and the human figure, such as head clearance and reach. The ability of the figure to take on physiologic surface topography directly adds to the perception of reality when one is viewing a simulation. While both of these aspects are important, to date more effort has been concentrated on the accurate scaling of the link lengths in commercial human modeling. This bias is in part motivated by the large amount of traditional 1D anthropometric data available (e.g., stature, sitting height, shoulder breadth), in contrast to the largely nonexistent 3D surface contour data available. Secondly, a driving factor of human modeling in visualization environments has been to produce a system that works in near real time (Badler et al. 1993). The complexity of the figure surface description presents a burden on the real-time performance, so a balance is sought in which there is sufficient surface detail for visual reality without undue computational load. As computer hardware technology improves, the ability to add to this surface complexity is afforded.

2.2.1. Anthropometric Databases

Of the many anthropometric databases available, one of the most widely used is the U.S. Army 1988 Anthropometric Survey (ANSUR) (Gordon et al. 1988). The ANSUR study was performed by the U.S. military to provide a representative anthropometric database of the U.S. military personnel. This database has a demographic representation that matches the U.S. army, which is known to differ from the gender, racial, age, and conditioning distributions of the population as a whole. Nevertheless, the statistical measures of the ANSUR data have been estimated to be within 3% of the general U.S. civilian population (Roebuck 1995). This study contains 132 standard anthropometric measurements from approximately 9000 military personnel, of which a sample of 1774 men and 2208 females were selected to represent accurately the military population demographics. Documents that contain the individual subject data as well as the summary statistics are publicly available, so publishers of human modeling software can independently develop statistical models for figure scaling and boundary manikin generation.

Another anthropometric database available is the National Health and Nutrition Examination Survey III (NHANES 1994), which contains the dimensions of 33,994 persons ages 2 months and older, of which 17,752 are age 18 and older. While the 21 measures of this database do not provide enough information to define adequately the dimensions of most contemporary human models, the database currently represents the most comprehensive and representative database for the U.S. population. These publicly available data contain weighting information based on the most recent U.S. census (1988–1994). The census weighting data allow U.S. representative population statistics to be computed for any population selections based on gender, race, ethnicity, and age. While both the ANSUR and NHANES data describe single dimension measures taken between anthropometric landmarks, a new anthropometric survey has been initiated to provide a database of population 3D body shapes. The CAESAR project (Civilian American and European Surface Anthropometric Resource) will scan approximately 6000 individuals in the United States and Europe. These data are in the form of both traditional anthropometric measures and new 3D data from whole body laser scanners, that provide a highly detailed data cloud describing the shape of the subject surface contour (Figure 1).

Both children- and nationality-specific anthropometric databases are also available, although these databases have not been adopted to the same degree as those previously mentioned due to their limited international availability and data restrictions (Table 1).

2.2.2. Accommodation Methods

One of the advantages digital ergonomics can bring to the development process is the ability to investigate accommodation issues early in the design process. In the past, physical mockups were created and evaluated using a large subject population to arrive at accommodation metrics. This approach is both expensive and time consuming and does not lend itself to rapid evaluation of design alternatives. In the digital space, a population of figures can be used to investigate many of the same

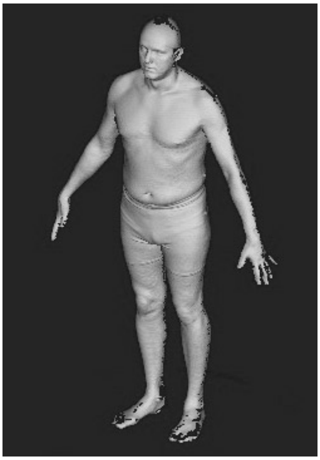

Figure 1 The CAESAR Data are Collected with Laser Body Scanners That Produce a 3D Point Cloud of Surface Topography. These data will allow accurate measures in such applications as accommodation analysis and clothing fit.

issues of clearance, visibility, reach, and comfort. Defining the sizes of the manikins to be used in the process is one of the first steps of these analyses.

To perform an accommodation study, the user defines a percentage of the population that he or she wishes to accommodate in their design or workplace and then scales representative figures using data from applicable anthropometric databases to represent the extreme dimensions of this accommodation range. As few as one measure, often stature, may be judged to be important to the design and used in the creation of the representative figures. For other applications, such as cockpit design, multiple measures, such as head clearance, eye height, shoulder breadth, leg length, and reach length, may all affect the design simultaneously. Several methods are in use to investigate the accommodation status of a design and are described below.

2.2.2.1. Monte Carlo Simulation The Monte Carlo approach randomly samples subjects from an anthropometric database to create a representative sample of the population and processes these figures through the design. Recording the success or failure of the design to accommodate each

TABLE 1 Sample of Recent Anthropometric Databases Used by Contemporary Human Models

Name	Dimensions	N (population and ages)	Survey Year	Availability
ANSUR 88	132	9,000 (U.S. Army)	1987	Summary statistics and individual subject data
NHANES III	21	33,994 (U.S. civilian ages 2 mo to 99 years)	1988–1994	Individual weighted subject data
CPSC Children	87	4,127 (U.S. children ages 2 weeks–18 years)	1975–1977	Summary statistics and individual subject data
CAESAR—3D	44 Traditional and 3D surface	~6,000 (U.S. and European)	Present	Planned: individual 3D landmark locations, summary statistics, 3D point cloud data
HQL—Japan	178	40,000 (Japanese ages 7–99 years)	1992–1994	Summary statistics and portions of individual subject data
KRISS—Korea	84	8,886 (Korean ages 6–50 years)	1992 (1997)	Dimensional statistics with display software

individual of the sample allows an indication of the percentage accommodation to be derived. This method is computationally fairly expensive because it requires that a large number of figures be generated and tested for a meaningful analysis. Also, because the distribution of sizes follows a bell-shaped distribution, many more people are close to the average than to the extremes, which results in many figures of fairly similar dimensions needlessly tested. This can make this approach somewhat inefficient.

2.2.2.2. Boundary Manikins In contrast, the boundary manikin approach can be used for multiple dimensional analysis (Zehner et al. 1993; Bittner et al. 1986). The statistics of principal components (factor analysis) can be used to identify bounding multidimensional ellipsoids that contain a portion of the population. For example a 95% hyperellipsoid can be found that defines the dimensional ranges for all variables of interest within which 95% of the population can be expected. This approach can reduce the number of manikins that need to be tested in a design to a practical number, which is beneficial in cases where the computer rendering speed or the effort to manually posture the figure is significant.

2.2.2.3. Whole-Population Analysis Both the Monte Carlo and boundary manikin approaches attempt to reduce the number of subjects that are run through the analysis while still providing statistical validity to the results. However, as computer technology improves and as models to posture the manikins realistically in the environment become available, it becomes not unreasonable to run several thousand figures through a design automatically. Because this approach does not use statistical models of the data but instead uses the measured data directly, the unexplained variability that is not captured by the statistical data modeling is avoided. This approach still requires substantial run time and is currently not a popular approach to accommodation analysis.

2.3. Human Figure Posturing

As mentioned briefly in the previous anthropometric discussion, figure posturing is a critical component, along with anthropometry, in accommodation studies. While automatic posturing methods based on empirical studies are becoming available and will be discussed in later sections, there are more fundamental lower-level tools that have been developed for general manipulation of figures in the virtual environments. Because contemporary figures may have over 100 DOF, adjustment of each joint angle individually is unworkably tedious.

2.3.1. Coupled Joints

Fortunately, the human skeleton, while infinitely adjustable, is held together by muscles and connective tissues that constrain the movement of certain joints to work as motion complexes. Examples include the shoulder, spine, and hands. While there are obvious freakish exceptions, most people cannot voluntarily dislocate their shoulders or move the carpal bones in the digits independently. Modelers take advantage of these relationships to build movement rules for these joints such that many degrees of freedom can be adjusted easily with a few angles that are defined in common human factors parlance. For example, the EAI Jack human model has 54 DOF in the spine below the neck, which can be manipulated using three standard angle definitions: flexion, extension, and axial rotation. Similarly, as described earlier, the shoulder comprises a clavicle link that moves in concert with the arm as it is manipulated, mimicking the natural kinematics of this joint. Such coupled joint complexes greatly simplify the posturing of high-degree of freedom human figures.

2.3.2. Inverse Kinematics

Even with the substantial reduction in degrees of freedom that coupled joints bring, there are still far too many degrees of freedom remaining in a contemporary figure for rapid posturing in production use. To address this, human modelers have drawn from the robotics field the concept of inverse kinematics (IK) or specifying joint kinematics based on a desired end-effector position. Inverse kinematics operates on a linked chain of segments, for example the torso, shoulder, arm, forearm, and wrist, and, given the location of the distal segment (i.e., hand), solves all of the joint postures along this chain based on some optimization criteria. For human models, these criteria include that the joints do not separate and that the joint angles remain within their physiological range of motion. Using inverse kinematics, the practitioner is able to grab the virtual figure's hand in the 3D visualization environment and manipulate its position in real time while the rest of the figure modifies its posture (i.e., torso, shoulder, arm) to satisfy the requested hand position. While the IK methods can be made to respect the physiologic range of motion limitations inherent to the joints, they tend not to have the sophistication always to select the most likely or physiologically reasonable postures. This is especially problematic when the number of joints in the joint linkage is large. If the number of degrees of freedom is too great, there is unlikely to be just one unique posture that satisfies the specified end-effector position. For specific cases, this is being addressed with empirical-based posturing models, which are discussed in greater detail below. However, even with the caveat that IK sometimes selects inappropriate postural solutions, it is currently the most popular and rapid method of general postural manipulation in 3D environments.

2.4. Motion/Animation

While static posturing is often sufficient to analyze many ergonomic issues, such as reach, vision, clearance, and joint loading, often figure motion in the form of an animation is important. Examples include simulated training material, managerial presentations, and analyses that depend on observations of a person performing an entire task cycle, for example when assessing the efficiency a workplace layout. Realistically controlling figure motion is without question one of the most challenging aspects of human modeling. Humans are capable of an almost infinite number of different movements to accomplish the same task. Indeed, people may use several postural approaches during a single task, for example to get better leverage on a tool or gain a different vantage point for a complex assembly. This incredible postural flexibility makes it very difficult for human modeling software to predict which motions a worker will use to perform a task. Most current animation systems circumvent this dilemma by requiring the user to specify the key postures of the figure during the task. The software then transitions between these postures, driving the joint angles to change over time such that motions conform to correct times. A variety of mechanisms are used to perform the posture transitions, from predefined motion rules to inverse kinematics. Depending on the system, the level of control given to the user to define and edit the postures also varies, with some products making more assumptions than others. While built-in rules offer utility to the novice user, the inflexibility imposed by the system automatically selecting task postures can be restrictive and a source of frustration to the advanced user. In addition, the level of fidelity required in the motion varies greatly depending on the application. For applications such as the validation of a factory layout or animation of a procedure for training or communication purposes, a human motion simulation that simply looks reasonable may be sufficient. However, if sophisticated biomechanical analyses are to be run on the simulated motion, it may be necessary to generate motions that are not only visually reasonable but also obey physiologic rules. These include accurate joint velocities and accelerations, realistic positioning of the center of mass relative to the feet, and accurate specification of externally applied forces.

3. HUMAN PERFORMANCE MODELS

Human capability analysis is one of the primary motivations for simulation. Commercial modelers have implemented performance models from the academic literature into their software, taking advantage of the human figure sophistication and real-time visualization technologies. A review of the commonly available performance models reveals that independent research groups largely developed them. The development diversity is reflected in the variety of inputs that these tools require in order to provide an ergonomic assessment. This represents a challenge to the modelers as they work to seamlessly integrate these assessment tools into their animation and simulation offerings. Some tools lend themselves well to integration, such as those that can capture all required information from posture, figure, and load mass characteristics. Typically these are the tools that have as their foundation biomechanical models from which the inputs are derived. Others, which were originally intended to be used with a checklist approach, are more challenging in that they often require complex questions to be answered that are straightforward for a trained ergonomist but quite complex for a computer simulation system (Table 2).

Most often, simulation engineers expect to ask human performance questions of their simulation without having to redescribe the simulation in the language of the tool. Thus, ideally, the tools are implemented such that they can derive all the necessary information from the simulation directly. Less ideally, the engineer performing the assessment must explicitly identify details of the simulation using tool specific descriptors.

3.1. Strength

Strength assessments are a typical human performance analysis, regardless of whether the application involves manual handling tasks, serviceability investigations, or product operation. Questions of strength can be posed in a variety of ways. Designers may want to know the maximum operating force for a lever, dial, or wheel such that their target demographic will have the strength to operate it. Or the engineer may create a job design and might ask what percentage of the population would be expected to have the strength to perform the required tasks of the job. Strength data might also be used to posture virtual human figures by using an algorithm that optimally adjusts the individual joints of the manikin to produce most effectively the required forces for a task.

A large amount of strength data has been collected over the past quarter century. Most of these have been in the form of maximal voluntary exertions (MVEs) of large muscle groups. Subjects are placed in special strength testing devices (e.g., strength chairs) to isolate individual muscle groups, and standard methods controlling for repeatability and duration of effort are then used to capture the

TABLE 2 **Partial List of Performance Tools Available in High-End Human Simulation Tools**[a]

Performance Model	Data Source	Input Parameters	Integration Issues
NIOSH lifting equation	Waters et al. 1993	Posture and lift begin and end, object weight, hand coupling	Must determine start and end of lift. Must identify hand coupling
Low-back injury risk assessment	See Chaffin et al. 1999	Joint torques, postures	Suitable
Strength assessment	University of Michigan static strength equations	Body posture, hand loads	Suitable
	Burandt 1978 and Schultetus 1987	Body posture, hand loads	Table lookup
	Ciriello and Snook 1991	Task description, hand coupling, gender	Table lookup
	CrewChief	Gender, body size, posture, task condition	Suitable
Fatigue analysis	Rohmert 1973a, b; Laurig 1973	Joint torques, strength equations	Suitable
Metabolic energy expenditure	Garg et al. 1978	Task descriptions, gender, load description	Must identify the type of task motion (i.e., lift, carry, arm work, etc.).
Rapid upper limb assessment	McAtamney and Corlett 1993	Posture assessment, muscle use, force description	Must identify muscle use and force descriptions.
Ovako working posture	Karhu et al. 1977	Posture assessment	Suitable
Comfort	Variety of sources, including Dreyfuss 1993; Rebiffé 1966; Krist 1994	Posture assessment	Suitable

[a] The tools require different types of input that often cannot be accurately deduced from an animation sequence, requiring tool specific user input.

strength levels accurately. Strength can also be assessed while taking into account a subject's perception of the effort. These data, in which subjects' impression of the load strain is included, are called psychophysical strength data. They differ from the maximal voluntary exertions in that they are more task specific. Subjects are asked to identify the load amount they would be comfortable working with over the duration of a work shift. Typically, these are laboratory studies in which mockups of tasks very close to the actual work conditions are created and subjects are given an object to manipulate to which weight can be added. The worker has no knowledge of the weight amount (bags of lead shot in false bottoms are often used), and experimental techniques are employed to converge on the weight that the subject feels comfortable manipulating over the course of a workday. The data of Ciriello and Snook (1991) are of this nature. Finally, a few dynamic strength data have been collected. These data are complex to collect and for this reason are also the most scarce. Specific dynamic strength-testing equipment is required to control for the many variables that affect dynamic strength, including the movement velocity and posture. As a consequence of the data-collection limitations, these data are also quite restricted in terms of the range of conditions in which they can be applied, such as the prediction of dynamic strength capability for ratchet wrench push and pull operations (Pandya et al. 1992). Lately, the rise of cumulative trauma injuries for the lower arm, wrist, and hand has created a need for strength data specifically pertaining to the hand and fingers and estimates of hand fatigue. A extensive amount of data is available on grip strengths in various grip postures, but these data, because they do not adequately describe the distribution of exertion loads on the individual digits, do not lend themselves well to the estimation of hand fatigue issues. This problem is compounded by the challenge of accurately posturing the hands in digital models. There are many bones and joints that allow the complex movement of the fingers, most of which are included in contemporary human models. For example, the Jack human model has a total of 69 segments and 135 DOF, of which 32 segments and 40 DOF are in the hands alone. While a solution to the manipulation of these many degrees of freedom is presented in the section describing motion-tracking technologies, models that are able to analyze the postures and gripping conditions are still needed before hand fatigue issues can be addressed.

Whole body strength data in contemporary human models are available in a range of forms, from simple data lookup tables to statistical equations that are used in conjunction with biomechanical models to drive a measure of population strength capability. In the United States, perhaps the most widely used strength data are from the University of Michigan Center for Ergonomics (3DSSPP) and Liberty Mutual Insurance Co. (Ciriello and Snook 1991). Within the defense industry, the CrewChief strength data are also popular because the modeled strengths were obtained from military-related maintenance tasks. In Europe, particularly Germany, the data of Burandt and Schultetus are often used. As mentioned previously, a few of these data were obtained without the intent to incorporate them into human models. Instead, the data are presented in tables indexed by such factors as loading condition and gender. Those data that were collected and described with a focus toward eventual human model inclusion tend to be formulated such that all relevant information needed for a strength assessment can be deduced from the human model mass, loading, and posture information. These strength models now are very attractive to the human modeling community because they afford the real-time assessment of strength issues during a simulation without the user having to identify data-specific parameters or conditions (Table 2).

As discussed above, the availability of dynamic strength data is limited. The narrow scope of applications to which these data can be applied restricts their attractiveness to human modelers and the user community. An interesting associated note regarding these dynamic data and human models is that even if these data were more complete, the difficulty in accurately determining movement velocities from simulations would affect their use. Unless the virtual human motions are defined via motion-capture technology, the designer's guess of the movement speeds is fraught with error. Even under conditions in which actual motion capture data are used to animate the virtual figures, the velocities are derived by differentiation of the position information, which can result in noisy and unreliable input to the dynamic strength predictors. However, because people undeniably move during work and dynamic strength capability can differ greatly from static, this is clearly an area that will likely see research and technological attention in the near future.

3.2. Fatigue/Metabolic Energy Requirements

Once a simulation of a virtual human performing a task has been created, questions regarding the fatigue of the worker are commonplace. Can the worker be expected to perform at this cycle rate, or do we have to decrease the line rate or otherwise reengineer the task to avoid worker fatigue? Research suggests that whole-body fatigue increases the risk of musculoskeletal injury through premature decrease in strength. Unfortunately, the available empirical data are largely inadequate to predict a worker's fatigue level accurately. The lack of data can be explained by the large number of variables that affect fatigue, including exertion level, dynamism of the exertion, muscle temperature, previous exertion levels, the muscle groups involved, and individual conditioning. Nevertheless, two approaches are currently in modeling practice to provide at least some level of quantitative fatigue assessment for a work task. The strongest of these from a data perspective is the use of empirical metabolic energy prediction equations, in particular the equations published by Garg et al. (1978). These equations model a series of typical industrial materials-handling motions, such as walking, lifting, carrying, reaching, and arm work. Based on motion-specific parameters and load amount, the mathematical models provide an estimate of the energy consumption in kcal/min. These data were validated on a broad range of manual handling activities and were shown to predict actual energy-consumption rates well. The energy-consumption rate can be compared with accepted standards for exertion levels, such as the NIOSH 1991 recommended limits. The guideline put forth in the development of the NIOSH 1991 lifting equation recommends a limit of 33% of the maximum aerobic capacity of 9.5 kcal/min for healthy individuals performing whole body lifts over an eight-hour day (3.1 kcal/min). For work that involves mostly the arms, NIOSH recommends a reduction of 30% from this level or approximately 2.1 kcal/min (Waters et al. 1993). If the simulated task is found to require a higher energy-consumption rate than the recommended limit, it is assumed that the task is fatiguing and must be modified.

One of the challenges for modelers in using these energy-expenditure models is in the ability to deduce automatically which equations apply to the particular motion under simulation and then to provide the appropriate equation parameters. Some models include these data as a separate tool wherein the user explicitly defines the simulation in terms of the motion sets defined and modeled by Garg et al. A criticism of the approach regardless of implementation is that the granularity of the analysis is large, making it difficult to identify the particular body area that is fatigued, and that the data do not provide information on a broad enough range of activities.

In contrast to this approach, a variety of endurance equations may be used to estimate the amount of time static exertions can be held (see Van Dieën and Vrielink 1994). These equations describe the amount of time subjects can perform static exertions at various levels of effort relative to their maximum capability. Relevant to industrial work, some of these include the effects of interspersed rest periods (Sjogaard et al. 1988). Equations to describe the amount of time required to recover from these exertions were published by Rohmert (1973a, b) and Laurig (1973). If the estimated amount of time needed to recover from an exertion exceeds the amount of time available during a job cycle, then fatigue is assumed to accumulate. The endurance relations are applied to each body area separately, requiring an estimate of exertion level, or percentage of maximum capability, at these areas. While the original subjects were strength tested to derive their strength capability, these data are not available for workers in general and an estimate of strength capability must be used. One solution is to use biomechanically based strength models. A task simulation is analyzed with regard to the postures adopted by the virtual worker, and an estimate is given to the amount of time the worker spends in each of the postural conditions. The level of exertion required is estimated utilizing the strength equations, and this information is input to the endurance equations to provide the recovery time estimate.

While the methodologies for using these endurance data within the modeling tools have been implemented and are in use, the endurance data themselves are limited, as mentioned earlier. Gender and age effects are not taken into account, nor are most of the multitude of other factors that influence fatigue. Only the exertion level under static conditions is considered. However, the need to predict quantitative assessments of worker fatigue in simulations is high enough that users of human models look for ways to obtain a metric of fatigue, working around the limitations of the foundation data. Toward this end, joint use of the energy expenditure equations, endurance equations, and stress analysis using the strength tools will currently provide the best estimate of the task injury potential from fatigue.

3.3. Low-Back Injury Risk

Low-back injury is estimated to cost the U.S. industry tens of billions annually through compensation claims, lost workdays, reduced productivity, and retraining needs (NIOSH 1997; Cats-Baril and Frymoyer 1991; Frymoyer et al. 1983). Approximately 33% of all workers' compensation costs are for musculoskeletal disorders. Experience has shown that these injuries can be avoided with the proper ergonomic intervention. Biomechanical models available can be used for job analysis either proactively, during the design phase, or reactively in response to injury incidence, to help identify the injurious situations. The most common types of injury-assessment analyses performed using human models include low-back compression force analysis and strength analysis.

Low-back pain has been well researched over the past 20 years, including epidemiological studies that have identified spinal compression force as one of the significant predictors of low-back injury. In response, sophisticated biomechanical models have been developed to estimate this compression force accurately, taking into account not only the weight of the object and the body segments but also internal forces generated by the musculature and connective tissues as they balance the external loads (e.g., Nussbaum et al. 1997; Raschke et al. 1996; Van Dieën 1997). These internal contributions to the spinal forces can be an order of magnitude larger than the applied loads. NIOSH has recommended guidelines against which the predicted compression forces can be compared and job-design decisions can be made.

3.4. Comfort

Assessment of worker comfort using digital models can be based on both posture and performance model analysis. However, since comfort is influenced by a wide variety of interacting factors, these tools are largely insufficient to quantify the perception of comfort with accuracy. Most comfort studies performed to date have been centered around a specific task, such as VDT operation or vehicle driving (Rebiffé 1966; Grandjean 1980; Porter and Gyi 1998; Krist 1994; Dreyfuss 1993). Within the boundaries of these tasks, subjects are observed in different postures and asked to report on their comfort via a questionnaire. The joint angles are measured and correlated with the comfort rating to arrive at a postural comfort metric. Because these data are mostly collected under specific, often seated, task conditions, some caution is required to apply these to the analysis of comfort in standing postures such as materials-handling operations. In addition to the posture-based comfort assessment, a variety of the performance tools can be used to help with the assessment of comfort, including strength capability, fatigue, and posture duration information. Certainly the multifactorial nature of the comfort assessment makes it challenging, and perhaps for this reason it is seldomly used in the analysis of physical tasks.

3.5. Motion Timing

A typical simulation question regards the estimated time it will require a person to perform a task. Digital human models can draw on a wealth of predetermined time data available. Motion-timing data are collected in studies where elemental motions (walk, turn, reach, grasp, etc.) are observed performed by skilled operators in the workplace, and timed using a stopwatch. The motion time data are then published in an easily indexed form with associated movement codes. The best known of these is the methods time measurement (MTM-1) system published by the MTM Association. This system has the advantage that it has a large number of elemental motions defined, allowing for a precise partitioning of the work motions within a job task and subsequent accurate assessment of the movement time. One drawback of this high resolution is that considerable overhead is required to break the motion into the elemental movements. To address this, the MTM association as well as other groups have published grosser movement times, which combine several elemental movements into one. Several of the human modeling solutions now provide simulation solutions that can define movement duration with input from these movement time systems.

4. ERGONOMIC ANALYSIS IN DIGITAL ENVIRONMENTS

The large cost of worker injury, in both social and economic terms, has motivated considerable research in the development of models that predict potentially injurious situations in the workplace. According to the Bureau of Labor Statistics (1999), 4 out of 10 injuries and illnesses resulting in time away from work in 1997 were sprains or strains. In the following sections, the key steps in a human modelings based ergonomic assessment are outlined.

4.1. Workplace Analysis

4.1.1. Setting up the Workplace Environment

The first step to using the human simulation technology typically involves the construction of the work area to be analyzed. While pressures for integration of the CAD, process simulation, and human modeling solutions is paramount in the marketplace, at present the geometry data are mostly created in an external piece of software to the human simulation tool. This work cell layout, part and tooling geometry is mostly imported to the human modeling software from these external systems via standard file formats (e.g., IGES, VRML, STL). If the digital form of these data is not available, as may be the case in an analysis of an older existing workplace, primitive geometry-creation tools available in the human simulation environment can be used to mock up the critical parts.

4.1.2. Identify Test Population Anthropometry

Most companies have design criteria that define the percentage of the population that must be accommodated by their product and manufacturing designs. For example, all individuals ranging from a small female (5% in stature) to a large male (95% in stature) might be prescribed. Often only the extremes are tested, but a more comprehensive practice includes a figure with average-sized proportions as well because it may help to identify unexpected stature-dependent postural effects. Under more complex types of analyses that may include other ergonomic factors such as reach, the range of anthropometric dimensions comprising the digital figures (known as a cadre family) can be selected through sophisticated multidimensional statistical methods such as the principle component analysis (PCA) mentioned earlier. The added anthropometric ranges of the figure dimensions will help to test for the effects of multiple criteria (e.g., low-back compression and reach) concurrently.

4.1.3. Accurately Posture (or Animate) the Figures at the Workplace

Research has demonstrated that the biomechanical models that predict injury risk are quite sensitive to posture (Chaffin and Erig 1991). This makes it important to pose the digital figures such that they realistically represent the actual postures or movements required by a worker. If the workplace under analysis exists, still photography or video recordings of the workers performing these tasks can be used to guide the engineer to pose the digital figures accurately. Conversely, if the workplace is still under design, the engineer may have to draw on his or her human movement intuition, or perhaps even virtual reality body tracking methods (described in Section 5), to posture the figures realistically. However, new research efforts that are expected to provide posture-prediction methodologies to aid designers with this process are underway. Currently the posturing task is left largely as the responsibility of the simulation engineer.

Depending on the human performance tool, the postural information required for an assessment may require a static posture at an instance in time, or multiple key postures at different times in the task. For example, the NIOSH lifting guide (NIOSH 1991) requires starting and ending postures of a lift to arrive at an assessment of the lift conditions. In contrast, analysis tools based on biomechanical models, such as low-back injury risk-assessment tools, can analyze loading conditions continuously for each posture throughout the simulation.

Once the geometry has been populated with the correct humans and these have been postured or animated to reflect the task, the host of ergonomic assessment tools discussed in Section 3 can be applied.

A typical manufacturing analysis includes the investigation of design for assembly and service, in which the question is asked whether the task can be performed. Can the person reach into the opening while holding the part and assemble the pieces? Can the object be reached by short and tall workers? Is there sufficient clearance for the part and the hands? Can the worker have an unobstructed view of the assembly so that it can be performed accurately? Will the worker have sufficient strength to perform the assembly task, or will it require potentially injurious exertions?

4.1.4. Service Analysis

The application of human models to the analysis of maintenance and service operations is one of the original targets of 3D human modeling. Particularly in the military and aerospace industry, the issues surrounding rapid serviceability motivated the development and use of this technology. One specific modern example can be found in the serviceability analysis of aircraft engines in the commercial airline industry, where the very dense nature of the engine packaging and the economics of service downtime make questions of how parts can be extracted for maintenance critical. These questions must be asked while the engine is still under design in CAD to avoid expensive reworks later on. Very complex software has been created to find collision-free extraction paths for virtual parts, both as validation that the part can be extracted from the surroundings and to provide training for maintenance personnel on how to perform the extraction operation. Unfortunately, these methodologies to date have not included the human, so the challenge posed to the human modeling publishers is to determine whether the part can actually be held, and extracted, with sufficient clearance for the part, fingers, and arm. Depending on the complexity of the environment, this is an incredibly difficult problem to solve without user input, and to date no solution is available that finds a solution in a reasonable amount of time. To address this, human models can be used in conjunction with immersive technologies in which the design engineer moves the virtual part in the environment with an avatar (virtual human) representing their arm and hand in the scene (see Section 5). Collision-detection capabilities of the human modeling software are used to identify if a free path can be found. This technology is now being evaluated to identify serviceability issues prior to the first physical build, and also to provide task timing estimates (cost) of performing a particular service operation (Figure 2).

4.2. Product Design

The availability of human modeling technology during the product-design phase expands the range of analyses that can be performed prior to a physical prototype construction. In the past, SAE recommended practices, or "J-standards," were among the limited tools available for benchmarking and design. These tools, derived from empirical studies of people in vehicles, provide population response models that describe such functional information as reach, eye location, and head clearance. However, these data are presented as statistical summaries of the population response, which do not maintain information on the response of any particular individual. The SAE eye-ellipse zone, for example, provides an ellipsoid that defines a region where the eye locations of a specific portion of the

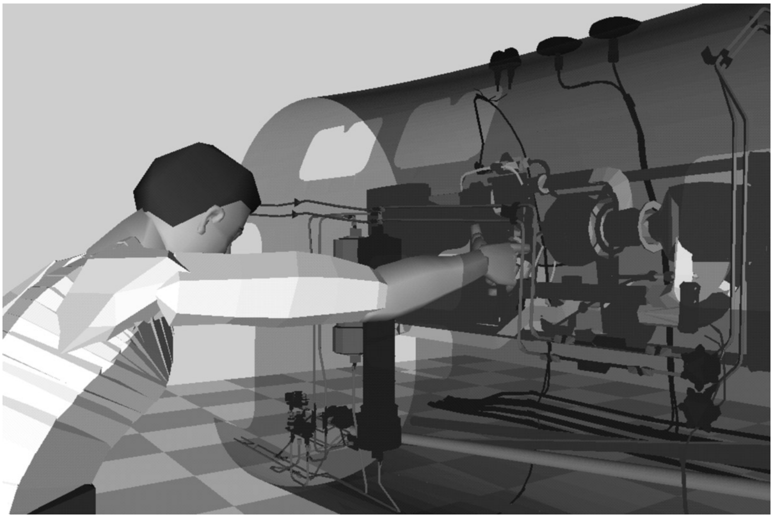

Figure 2 Serviceability Analysis of a Design Can Be Performed Prior to a Prototype Build. Here the Jack human figure is used to analyze the maintenance access to an electrical box inside of the aircraft nose cone. Eye views and collision detection can help the designer during the evaluation process. (*Courtesy EMBRAER*)

population can be expected. The specific location where a small or tall person's eyes might fall within this distribution is not defined (Figure 3). For this reason, when the behavior of a specifically sized individual or group is required, such as when a design is targeted to a specific demographic, human modeling tools can be used to answer these questions.

4.2.1. Accommodation

Once a design proposal is in place, accommodation questions can be posed. The process generally mirrors that for workplace analysis, with a few modifications.

4.2.2. Definition of the Test Population Anthropometry

Most often the accommodation needs for product design are more involved than during manufacturing ergonomic analysis because more anthropometric dimensions typically need to be taken into account. For example, the product design may have to accommodate individuals with a variety of sitting eye heights, shoulder breadths, and arm lengths. As mentioned in the sections describing anthropometric methods, statistical methods such as factor analysis (principal components) can be used to select a family of figures or boundary manikins that will adequately test the range of these multiple dimensions.

4.2.2.1. Figure Posturing Posturing a figure within the digital environment can impact the design analysis dramatically. As evidence of the importance of this issue, various posture-prediction methodologies have been developed in different industries. Pioneering work at Boeing led to a posture prediction method for the aerospace industry (Ryan and Springer 1969). In the late 1980s, a consortium of German automotive manufactures and seat suppliers sponsored the development of driver posture-prediction methodologies for the RAMSIS CAD manikin (Seidl 1993). Most recently, a global automotive industrial consortium sponsored new and more comprehensive methodologies to predict the postures of drivers and passengers through the ASPECT program (Reed 1998). These latest methods have been made available to modelers for inclusion in their software, allowing for sophisticated accommodation studies in automotive environments. Data for posture prediction in heavy truck and earth-moving equipment environments are still needed.

The boundary manikins are postured in the environment and tested for clearance, reach, vision, and comfort issues. Measurements from these boundary manikins can be used to establish design zones with which product design decisions can be made. A common technique for considering reachability, for example, is to generate zones representing the space where the boundary manikins

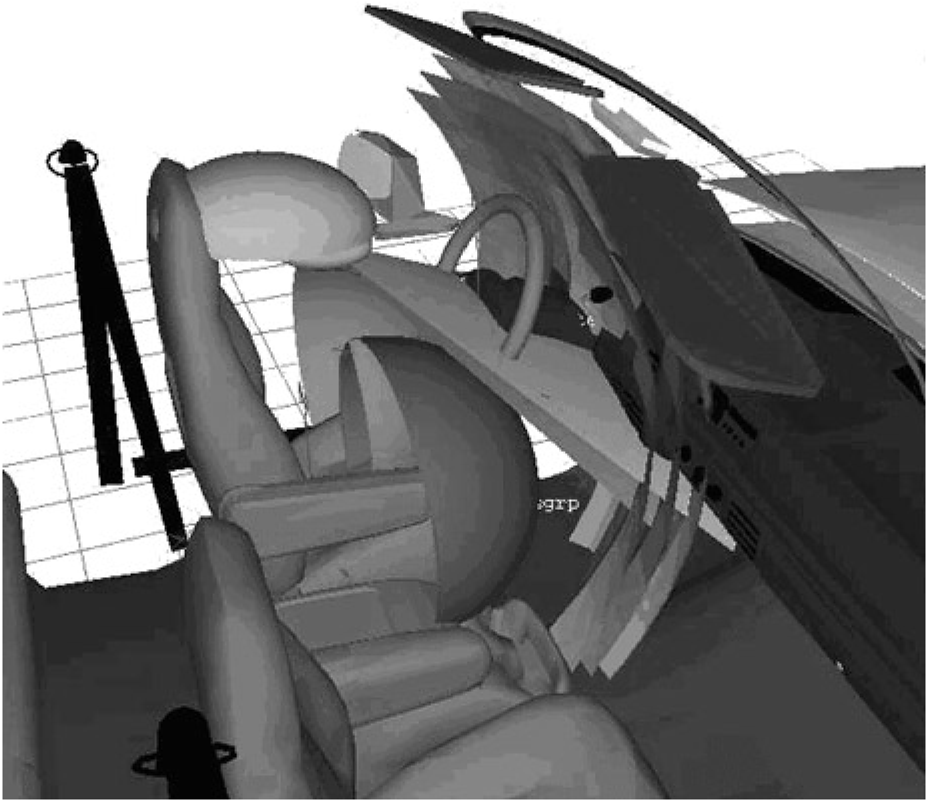

Figure 3 The SAE-J Standards Are Used Worldwide in Benchmarking and Design. The statistical summary descriptions describe posturing and functional information for a predefined population of male and female drivers. Design questions regarding a specifically sized individual cannot be asked using these zones but are suited for human simulation (see text).

can reach under different circumstances. Such reach zones can be used to make design decisions about where controls should or shouldn't be placed. An alternative approach to the sequential test of boundary manikins involves the simultaneous display of important landmark data in the form of data clouds (Figure 4). With this technique, the 3D locations of landmarks are collected either from actual subjects sitting in a mockup or from digital boundary manikins in the electronic environment. The complete set of landmarks from all the test figures is subsequently displayed as a data cloud and used in the design process. This technique provides a concise view of the population anthropometric variability, making it well suited to guide control placement and adjustment range analyses.

4.2.2. Usability

Usability can be considered part of the accommodation process. Traditionally, accommodation considered mostly the analysis of fit, and not necessarily the functional aspects of operating the product. With digital human models, this boundary is rapidly disappearing as anthropometric accommodation, vision, performance models, reach, and movement can all be analyzed using the same tool. Traditional methods such as the SAE J-standards are based on static symmetric zones for analysis, but designers are increasingly interested in taking advantage of the increased functionality modern human models provide. For automotive analyses, these more involved analyses include investigations of reach under various constraint conditions, vision coverage using mirror views, vision obscuration during head check procedures, psychological effects of roominess, obscuration, and collision. Research into natural human motion prediction provides guidelines on layout to accommodate maximally the natural motion of the operator.

Figure 4 The Anthropometric Landmark Data from Multiple Subjects Is Displayed in the Form of Data Clouds. The simultaneous view of the data allows for rapid assessment of control location and adjustment questions. (*Courtesy Dr. Jerry Duncan, John Deere Corporation*)

5. IMMERSIVE VIRTUAL REALITY

Many of the predictive technologies available for human modeling currently do not adequately answer the questions designers pose to their human modeling solutions. This limitation is especially pronounced in the areas of natural complex motion simulation and cognitive perception. As mentioned in previous sections, a designer might ask how a person will move to perform an operation, or ask if there is sufficient clearance for a person to grasp a part within the confines of surrounding parts. Situations that require nontypical, complex motions currently cannot be answered adequately with the movement prediction algorithms available. Only through the use of immersive virtual reality technology that allows the mapping of a designer's movements to an avatar in the virtual scene can these complex movement situations be adequately and efficiently analyzed. Similarly, cognitive models providing subjective perceptions of an environment, such as feelings of spaciousness, control, and safety, are not currently available, yet a designer looking through the eyes of a digital human can assess these emotions of the virtual environment under design. For these reasons, immersive virtual reality (VR) is increasingly being used in both design, and manufacturing applications. Early in a design cycle when only CAD models are available, VR can allow the design to be experienced by designers, managers, or even potential users. Such application allows problems to be identified earlier in the design cycle and can reduce the need for physical prototypes. Immersive VR usually includes a combination of motion tracking and stereo display to give the user the impression of being immersed in a 3D computer environment. Auditory and, increasingly, haptic technology are also available to add realism to the user's perspective.

Virtual reality does not necessarily require a digital human model. Simply tracking a subject's head motion is sufficient to allow the stereo view to reflect the subject's view accurately and thus provide the user with a sense of being present in the computerized world. However, the addition of a full human model, tracking the subject's body and limb movements in real time, allows for additional realism because the user can see a representation of themselves in the scene. Additional analysis is also possible with full-body motion tracking. For example, collisions between limbs and the objects in the scene can be detected so that reach and fit can be better assessed. This capability is especially useful in design for maintainability or design for assembly applications. Another area where the full body tracking can be useful is for a designer to gain experience in interacting with the design from the perspective of a very short or very tall person. By scaling the environment in proportion to the increase or decrease in anthropometric size he or she wishes to experience, the designer can evaluate such issues as clearance, visibility, and reachability of extreme-sized individuals without actually having to recruit a subject pool of these people. Real-time application of the tracked motions to the virtual human also gives observers a realistic third-person view of the human motion in relation to the design geometry.

In addition to the qualitative assessments provided by the engineer's subjective perceptions of interacting with the design, quantitative assessments are possible. Analysis tools, such as those described in Section 3, can often be run in real time while immersed. For example, an engineer can perform a virtual operation using virtual tools, while in real time the performance tools evaluate the postures, forces, and motions to derive performance metrics such as population strength capability, low-back strain, fatigue, or postural affects. The designer gets immediate feedback as to the specific actions that are likely to put the worker at an elevated risk of injury without exposing the test subject to unsafe loading conditions. The design surrounding these actions can then be assessed and modified to reduce the injury risk, all while in the digital design space. Alternatively, motions can be captured and then played back for human performance analysis or presentation purposes.

Such quantitative analyses may be performed in the context of a full immersive VR application or may simply make use of the same human motion-tracking and capture technology to assist in the generation of accurate human postures. For example, a dataglove with posture-sensing electronics incorporated can be a valuable tool with which to obtain accurate hand postures while avoiding the tedium of trying of manipulate each individual finger joint irrespective of the actual application.

5.1. Motion-Tracking Technologies

A number of technologies are available for tracking human motions, including piezioelectric strain gages, magnetic and optical. Such human motion-tracking technologies have long been used for scientific and clinical applications (e.g., Chao 1978; Davis et al. 1991). In recent years, real-time forms of these technologies have become feasible and made VR possible. In addition to VR applications, such real-time technologies have found application in the entertainment industry, enabling quick generation of realistic human movements for computer games, 3D animation, and movie special effects.

Data gloves, such as Virtual Technology, Inc.'s Cyberglove (www.virtex.com), and other such devices measure relative motion between two body segments using either fiberoptic or strain gage-based technologies. The location of the segment in space is not reported. This limitation has ramifications for how these devices are used in human models. For example, the data gloves can measure the amount of finger flexion and splay, yet these gloves do not provide information about where the hand is located relative to the body or in the scene. For this reason, they cannot be used in isolation in such applications as maintenance part extraction, where the orientation and position of the hand is equally as important as the hand posture. This global positioning information can however be captured using whole-body-tracking technologies.

Both magnetic and optical motion-tracking devices are used to capture the global spatial position of the body in space. Magnetic systems are composed of a transmitter that emits an electric field and sensors that can detect their position and orientation (six DOF) in this field. The magnetic sensors are attached to body segments (e.g., the hand, forearm, arm, torso) to determine the relative positions of adjacent body segments. These data are then used to animate a digital human figure. Magnetic systems until recently were the only systems that could track multiple segments in real time and thus are very popular for immersive applications. However, metallic objects in the environment can affect the magnetic fields emitted by these systems. The field distortion caused by metal in the surroundings, including structural metal in the floor, walls, and ceiling, can cause measurement inaccuracies. In contrast, video-based methods use retroreflecting or LED markers placed on the subject and cameras in the environment to triangulate the position of the markers. Multiple markers can be arranged on segments to derive both position and orientation of individual segments. Although multiple markers are required to obtain the same position and orientation information as one magnetic sensor, these markers are typically passive (simply balls covered with reflective material) and so do not encumber the motion of the subject as dramatically as the wires of magnetic systems. The downside of optical motion-tracking technology is that it is necessary for every marker to be seen by at least two (and preferably more) cameras. Placement of cameras to meet this requirement can be a challenge, especially in enclosed spaces such as a vehicle cab.

Examples of commercially available magnetic systems include the Ascension MotionStar (www.ascension-tech.com) and Polhemus FastTrak (www.polhemus.com). Examples of optical systems include those sold by Vicon Motion Systems (www.vicon.com), Qualysis AB (www.qualysis.com), and Motion Analysis Corp. (www.motionanalysis.com).

6. HUMAN SIMULATION CHALLENGES

As human modeling becomes an integral part of the design process, the need for visual realism and analysis sophistication also increases. For better or worse, the visual appearance of human figures plays an important role in the acceptance of the technology and the perceived confidence of the results. Efforts in several areas focus on the increased realism of the human skin form. For performance reasons, current commercial human models are "skinned" using polygonal segment representations that are either completely static or pseudostatic. The figures are composed of individual segments, such as feet, lower and upper legs, pelvis, and torso. The segments are drawn as a collection of static polygons arranged to give the segment its anthropomorphic shape. Prudent selection of the shape at the ends of the segments allows joints to travel through the physiological range of motion without the creation of gaps. Pseudostatic skinning solutions "stitch" polygons between the nodes of adjacent segments in real time to avoid the skin breaking apart at the joints. These solutions can be made to look very realistic and are adequate for most ergonomic assessments and presentations. However, they do not model the natural tissue deformation that occurs at the joints throughout the range of motion. This is visually most noticeable at complex joints, such as the shoulder joint, or quantitatively at joints to which measurements are taken, such as the popliteal region of the knee. To better model these areas, a variety of methods have been described in the literature that deform the surface polygons according to parametric descriptions or underlying muscle deformation models (e.g., Scheepers et al. 1997). However, these methods have generally not been commercially adopted because they are computationally expensive and mostly unnecessary from the ergonomic analysis standpoint. Nevertheless, as the computer hardware capability increases and the availability of highly detailed whole-body-surface scans elevates the expected level of visual realism, these deformation techniques will become more prevalent.

6.1. Performance Models

6.1.1. Performance Factors

Performance models used in current commercial models are largely an amalgamation of models and data available in the ergonomics and human factors literature. As mentioned in the review of the performance models, the presentation of most of these research findings was originally not intended for integration into real-time simulation environments. The studies from which these data were derived also did not address some of the more contemporary ergonomic issues, such as the performance limitations of the elderly, cumulative trauma, shoulder injury, and movement modeling.

The aging population is elevating the need to have more specific performance models for this demographic. Questions of functional limitations resulting from decreased strength, reaction time, and joint range of motion all affect the design, both of products and workplaces. In the automotive design space, ingress/egress capability is an example of a task that may be influenced by these limitations. In the workplace, questions of strength and endurance need to be addressed. Cumulative trauma prediction presents a particular academic challenge because the etiology of the injury is largely unknown. Biomechanical factors clearly play a role but to date do not provide sufficient predictive power upon which to base a risk-assessment tool. At best, conditions associated with an increased likelihood of cumulative trauma can be flagged. Similarly, shoulder fatigue and injury prediction is not developed to the point where models incorporated into modeling software can accurately predict the injurious conditions. The significant social and economic cost of low-back injury has motivated considerable research in low-back modeling over the past 20 years. The research findings have resulted in sophisticated models and quantitative design guidelines and have allowed manufacturing organizations to reduce dramatically the incidence rates of low-back pain. Shoulder injury and cumulative trauma now need the same level of investment to mature the available data in these areas.

6.1.2. Variation Modeling

Even with the sophistication of the currently available biomechanical models, human model users are becoming increasingly interested in asking questions of these tools for which there are insufficient data. One such example is describing the expected population variability within the performance of a task. Each person will perform actions in a slightly different way, and these variations are not represented in models that describe an "average" response. However, human modeling simulation software is ideally suited to visualize this variability between people (i.e., data clouds). Future human performance and movement models may have this variability modeled so that it can be displayed in the human modeling environment.

6.2. Human Motion Control

One of the significant advantages contemporary human modeling tools provide in ergonomic assessments is the ability to assemble simulations of the workers performing their tasks. Simulations can add value for task-timing information, workcell layout optimization, training, and technical presentations. If we are confident of the motion realism, we can apply the posture-sensitive ergonomic assessment tools to help identify the situations with the greatest injury risk potential. Considerable effort has been spent searching for methods that accurately predict how humans move under different task and environmental conditions (Raschke et al. 1998). Dynamic simulation (Hodgkins and Pollard 1997; Popovic and Witkins 1999), statistical models (Faraway 1997), warping techniques (Bruderlin 1995; Witkins et al. 1995) and optimization (Chao and Rim 1973; Pandy and Zajac 1991) have all been applied to this problem. However, many of the methods for simulating human motion and behavior are computationally intensive and do not lend themselves to real-time solution. While some methods show promise, no single method for modeling human motion has yet proven to be concise, flexible, and accurate. Modeling human movements accurately in constrained surroundings and when obstacles need to be avoided presents additional challenges.

6.2.1. *Modeling Motion Data*

Simulating human movements, whatever method is applied, requires a detailed understanding of how people really move. Much detailed research has been conducted in understanding lifting and arm movements, and the subject continues to be extensively studied (e.g., Chaffin et al. 2000). However, the wide variety of ways that humans can move and the flexibility we have to do the same task using different postural approaches create a challenge for trying to generalize these measurements to use in human modeling tools. It is one thing to measure the time sequence of joint angles involved in a typical lift task, but it is quite another to try to use these data to simulate accurately how people perform a lift under different conditions. Start and end conditions, the size, shape, or weight of the object being lifted, and obstacles that need to be avoided all influence the motion. Clearly a great deal of detailed data describing how we move under different circumstances is needed.

6.2.2. *Multiple-figure Interactions*

Humans do not necessarily work in isolation. Many tasks involve more than one human interacting with another. Two people carrying a single large load or manipulating the same object and one person slowing down or speeding up to avoid running into one another are just a few examples. All the motion-control challenges associated with modeling the movement of a single individual apply and are magnified when multiple individuals, each contributing differently to the task, are involved.

6.2.2.1. Interactive "Smart" Avatars Ultimately an accurate representation of humans needs to model not only how they move but how they think and make decisions about what movements to do and how they react to a given situation. Such "smart" humans would obviously aid in the generation of a complex motion sequence involving several humans and have application to the development of workplace simulations. However, at this point in time, the development of intelligent human's agents has been motivated by applications such as interactive training simulations (Badler et al. 1999), pedagogical agents (Johnson et al. 2000), intelligent characters in computer games (Funge et al. 1999), and conversational agents (Cassell and Vilhjalmsson 1999) and have not yet been applied to any great extent to workplace simulations.

7. CONCLUSION

Digital human modeling is being actively used in industries around the world to reduce the need for physical prototypes and create better and safer designs faster than was previously possible. Contemporary human modeling software tools are actively assimilating a variety of previously disconnected human modeling knowledge, including population anthropometry descriptions and physical capability models. The large amount of ergonomic and anthropometric knowledge integrated into these solutions makes them efficient tools to answer a wide variety of human factors questions of designs. At the same time, the global nature of these tools is serving to consolidate and expose research findings from around the world and steering academic research direction and focusing the presentation of the results for model inclusion. While there are many areas that can be explored using the current offering of modeling solutions, many interesting challenges remain as we work to make virtual humans as lifelike as technology and our knowledge of humans allow.

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